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Edo

WESTERN CORPORATION

Edo WESTERN CORPORATION
2645 SOUTH 2ND WEST
SALT LAKE CITY, UTAH 84115
TELEPHONE (801) 486-7481

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FINAL REPORT

"IMPACT SHOCK ON PIEZOELECTRIC CERAMICS"

Contract Nonr-4917(00)

1 May 1965 to 30 April 1967

SC-52-1309 Report No. 11003-9

May 1, 1967

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1. First Quarterly Progress Report, "Impact Shock on Piezoelectric Ceramics," dated 7 September 1965. Report No. 11003-2

2. Second Quarterly Progress Report, "Impact Shock on Piezoelectric Ceramics," dated 30 November 1965. Report No. 11003-3

3. Third Quarterly Progress Report, "Impact Shock on Piezoelectric Ceramics," dated 3 March 1966. Report No. 11003-4

4. Interim Report, "Impact Shock on Piezoelectric Ceramics," dated 24 June 1966. Report No. 13003-5

5. Fifth Quarterly Progress Report, "Impact Shock on Piezoelectric Ceramics," dated 15 August 1966. Report No. 11003-6

6. Sixth Quarterly Progress Report, "Impact Shock on Piezoelectric Ceramics," dated 2 December 1966. Report No. 11003-7

7. Seventh Quarterly Progress Report, "Impact Shock on Piezoelectric Ceramics," dated 21 February 1967. Report No. 11003-8

Edo WESTERN CORPORATION

REPORT NO. 11003-9

ABSTRACT

This is the final report on Contract Nonr-4917 (00), "Impact Shock on Piezoelectric Ceramics," and emphasizes the work performed and the results obtained by the Edo Western Corporation during the second phase of the program which includes the period from 1 May 1966 to 30 April 1967. This report also summarizes the work performed and the results obtained during the first phase of the program covering the period from 1 May 1965 to 30 April 1966.

Life expectancy tests performed on ceramic rings of compositions EC-55, EC-64, EC-65 and EC-69 have resulted in extensive data regarding the effects of impact shocks on the physical and electrical characteristics of the ceramic rings. The results have indicated that the dissipation and the mechanical Q of the ceramic were the parameters most affected by impact shocks. The dielectric constant was the only electrical characteristic that remained stable under impact shock. Ceramic rings of composition EC-65 were able to withstand higher and more impact shocks than rings of the other three compositions. The results on composition EC-69 indicated that this composition has the lowest mechanical strength with respect to impact shock.

The results obtained from life expectancy tests performed on ceramic discs and rings were in agreement regarding the effects of impact shock on their electrical characteristics. The mechanical strength of the ceramic ring configuration was better than that of the ceramic disc configuration. This was true for all four ceramic compositions tested.

Hydrostatic shock tests were performed on mass loaded ceramic rings and discs. The ceramic compositions tested were EC-55, EC-64, EC-65 and EC-69. The hydrostatic

ABSTRACT (Cont'd)

shock to which the mass loaded transducers were subjected originated from an underwater detonation. These tests were conducted in open water to simulate the actual operating conditions of the transducers. The results from these tests have indicated the effects of environmental conditions and mass loading on the behavioral characteristics of the ceramics under hydrostatic shocks. The environmental conditions, especially temperature, affects the mechanical strength of the ceramic. Results from tests conducted in 0°C water indicated that the mechanical strength of the ceramic decreased at this temperature. This was particularly true for the lead titanate zirconate ceramics. Mass loading of ceramics will dampen some of the multiple responses present in a ceramic stack. Also, mass loading increases the dissipation of the transducer because of the compressive force applied on the ceramic stack by the clamping bolt.

Because of the effects of mass loading and the environment on the behavior of the ceramics, the effects of hydrostatic shocks on the electrical characteristics of the transducers were not conclusive. The results do indicate that the dielectric constant remains relatively stable under hydrostatic shock.

Impact shock tests were conducted on mass loaded transducers using the laboratory shock apparatus. Ceramic rings and discs of compositions EC-55, EC-64, EC-65 and EC-69 were tested. The results obtained from these tests were in agreement with results obtained from life expectancy tests performed on unloaded ceramic stacks. The changes in the electrical characteristics due to impact shock and the relative mechanical strengths of the ceramic compositions and configurations were similar to that obtained from life expectancy tests.

Driving voltage tests were conducted on ceramic discs of compositions EC-55,

ABSTRACT (Cont'd)

EC-64, EC-65 and EC-69. The results obtained confirmed the theory that driving voltages in ceramics will propagate fractures. The results indicated that driving voltages applied in the planar mode of vibration are more effective in propagating fractures than driving voltages applied in the thickness mode of vibration.

Studies were conducted to develop a method of improving the mechanical strength of ceramics. Methods such as surface layer diffusion, prestressing by embedding metallic wires in the ceramic, and fiber winding were studied. The method of fiber winding the ceramic proved to be more effective and feasible than the other methods studied. Ceramic rings of EC-55, EC-64 and EC-65 were fiber wound to 1,500 psi and 3,000 psi compression. Impact shock tests indicated that fiber winding improved the mechanical strength of the ceramic rings. Some of the fiber wound ceramic rings withstood impact shocks as high as 79,000 psi.

1.0 INTRODUCTION

As more improved and sophisticated sonar systems are developed, the knowledge of the performance characteristics of piezoelectric ceramics becomes more important. The work performed by the Edo Western Corporation during the period from 1 May 1966 to 30 April 1967 was focused towards determining some of the performance characteristics of piezoelectric ceramics when subjected to impact shocks. The areas pursued were:

(a) The life expectancy of ceramics subjected to repeated impact shocks. The objective of this test was to determine the effects of impact shock on the electrical and physical properties of the ceramics.

(b) The effects of hydrostatic shocks originating from an underwater detonation on the physical and electrical properties of piezoelectric ceramics in a mass loaded condition. The objectives were to test the ceramics under conditions closely simulating the actual operating conditions, and to determine whether or not a correlation exists between the results from this test and that obtained from the life expectancy tests.

(c) The effects of impact shock on the electrical and physical properties of mass loaded ceramics. The objective was to determine whether or not the results obtained from this test agreed with the results obtained from the life expectancy tests and/or hydrostatic shock tests.

(d) To determine whether or not driving voltages applied to ceramics would propagate fractures in the ceramic.

(e) To determine the effects of fiber winding on the mechanical strength of ceramic rings.

Tests were conducted on four piezoelectric ceramic compositions and two configurations (rings, 1.125" OD x 0.625" ID x 0.25" thick, and discs, 1.50" diameter x 0.25" thick.) The following is a brief description of the four ceramic compositions tested:

(a) Composition EC-55: This is a hard barium titanate material, developed to operate at high power levels and is ideally suited for high power projectors in the -10° to +60°C temperature range. This material is characterized by its low dielectric losses under high driving fields.

(b) Composition EC-64: This is a hard lead titanate zirconate material developed for high power acoustic projectors. It is characterized by its high coercive field, high coupling coefficient and low dielectric losses under high driving fields.

(c) Composition EC-65: This is a soft lead titanate zirconate material developed specifically for a high dielectric constant with high voltage sensitivity. It has a very low aging rate and is ideally suited for high sensitivity hydrophones or other receiving devices.

(d) Composition EC-69: This is a modified lead titanate zirconate material, considered to be the hardest piezoelectric ceramic. The modification provides maximum stability for high driving fields and high pressure operations. It is ideally suited for high power acoustic projectors and deep water transducers.

Life expectancy tests were conducted on rings and discs of piezoelectric ceramic compositions EC-55, EC-64, EC-65 and EC-69. The test samples were subjected to one-dimensional impact shocks to determine the effects of these impact shocks on the physical and electrical characteristics of the ceramics. A detailed discussion of this test is reported in Section 3.0 of this report.

Hydrostatic shock tests were also conducted on rings and discs of the same four piezoelectric ceramic compositions. The ceramic samples were tested as active elements in mass loaded transducers in open water. The shock wave to which the transducers were subjected originated from an underwater detonation of 7.3 lbs. of T.N.T. The environment of this test closely simulated the actual operating conditions of the ceramics. The test is discussed in detail in Section 4.0 of this report.

Section 5.0 discusses the results obtained when mass loaded transducers were subjected to impact shock using the laboratory impact shock apparatus. The mass loaded transducers were similar to those used in the hydrostatic shock test.

The effects of driving voltages on ceramics subjected to impact shock were studied using ceramic discs of the same four compositions. Tha primary objective of this test was to determine whether or not driving voltages would propagate fractures in the ceramic. Section 6.0 of this report presents a detailed discussion of this test.

Studies were conducted on rings and discs of the four compositions to develop a method of improving the mechanical strengths of these compositions. Tests were conducted to determine the effectiveness and feasibility of several different methods of improving mechanical strength. These were: (1) fiber winding; (2) prestressing the ceramic with metallic wires; (3) surface layer diffusion; and (4) additions to promote sintering to reduce the porosity of the ceramic. The studies indicated that the fiber winding method was more effective and feasible than the other three methods. Section 7.0 presents a detailed discussion of this study.

Section 9.0 of this report summarizes the results obtained from the various tests conducted during the period from 1 May 1966 to 30 April 1967.

2.0 SUMMARY OF WORK PERFORMED AND RESULTS OBTAINED DURING THE PERIOD 1 MAY 1965 TO 30 APRIL 1966

The following paragraphs of this section describe the work performed and the results obtained by the Edo Western Corporation during the period from 1 May 1965 to 30 April 1966.

The work performed during this period was directed towards: (1) development of an impact shock apparatus; (2) determining the effects of impact shock on piezoelectric ceramic discs; (3) determining the mechanical strength of piezoelectric discs; (4) microstructure studies of ceramic discs subjected to impact shock; and (5) studies of the effects of impact shock on the aging rates of piezoelectric ceramic electrical characteristics.

2.1 DEVELOPMENT OF IMPACT SHOCK APPARATUS

Three methods of generating impact shocks were evaluated. These were mechanical, hydraulic, and explosive. The studies conducted indicated that the big difference between the three methods was the rise and decay time of the shock wave produced. Both the mechanical and hydraulic methods produced shock waves with durations of four times the required duration.

The method of generating impact shocks by the detonation of an explosive charge was chosen because the shock wave generated by this method most closely simulated the shock wave from an underwater detonation in open water. The decay time of the shock wave produced by this method was approximately 0.3 millisecond, which is very close to the desired decay time of 0.5 millisecond.

Figure 2-1 shows the impact shock apparatus developed. Figure 2-2 shows the internal mechanism of the impact shock apparatus. The body of the apparatus is a modified 16-inch projectile. The cavity of the projectile is filled with water and an explosive charge is detonated in the water. The shock wave generated by the detonation is transmitted through the water to the piston, which in turn, applies an impact shock to the ceramic stack being tested. The amplitude of the impact shock is controlled by the distance between the explosive charge and the piston, and the size of the explosive charge. A specially designed piezoelectric ceramic pressure transducer was used to measure the amplitude of the impact shock. The output voltage from the pressure transducer was fed into an oscilloscope which presented a display of the output voltage relative to time. A photograph was taken of the oscilloscope display, thus obtaining a permanent record of the shock waveform and its peak amplitude.

The impact shock apparatus produced impact shocks of similar waveforms from 6,000 to 33,000 psi amplitudes. The impact shock amplitudes were repeatable to approximately ±1500 psi in the low range and ±2500 psi in the high range. These deviations in amplitude are probably due to the positioning of the charge in the water, and also due to the difference in the amounts of explosives in charges of the same size. It was not possible to position the charge in the same position each time. Because of this, the reflections of the shock wave from the walls of the projectile would differ with each detonation, causing variations in the impact shock amplitude.

Although the explosive charges used were of the same size (No. 6 blasting cap), the amount of explosives in the cap can vary. Also, the Primacord used in conjunction with the blasting caps to obtain the higher amplitudes were cut to size. In the process of cutting, some of the powder is lost. Because of the smallness of the charge size, small losses or variations produce differences which cannot be neglected.

2.2 EFFECTS OF IMPACT SHOCK ON PIEZOELECTRIC CERAMIC DISCS

The previously described impact shock apparatus was used to determine the effects of impact shock on the electrical characteristics of ceramic discs and also the mechanical strength of the ceramic. Ceramic compositions studied were EC-55, EC-64, EC-65 and EC-66 (EC-66 is a soft lead titanate zirconate composition).

The ceramic discs of each composition were formed into stacks consisting of five elements (reference Figure 2-3), and were subjected to impact shocks of different amplitudes. In addition to the tests performed to determine the effects of impact shock on the electrical characteristics and mechanical strength, microstructure studies and aging rate studies were conducted on the shocked discs.

The results of the microstructure studies indicated that the barium titanate composition (EC-55) was stable under impact shock. No great changes were observed in the domain formation or structure. More mechanical twinning was observed in the shocked test samples than the control samples, indicating a change in the grain and domain configuration. This mechanical twinning tends to lock the domains and twins into a metastable state. The lack of appreciable changes in the domain formation indicates that there should be no loss of polarization, and the electrical characteristics of the ceramics should change very little with impact shock. The results of the electrical measurements made before and after impact shock indicated that the dielectric constant changes less than +2.5% after impact shock. The dissipation increased a maximum of 20% and the coupling coefficient was scattered, exhibiting as high as +8% and as low as -15% changes. The mechanical Q decreased rapidly with increasing impact shock. Decreases in mechanical Q as great as 60% were observed after impact shock.

The mechanical twinning which tends to lock the domain and twins into a metastable state, increases the dissipation of the ceramic and may also account for some of the increase in dielectric constant. The behavior of the coupling coefficient under impact shock is apparently caused by several effects. Small changes in the coupling coefficient are probably caused from domain changes such as the increase in mechanical twinning. The larger changes in the coupling coefficient are probably due to fractures in the ceramic. These conditions affect the mechanical Q of the ceramic in a similar manner.

The microstructure studies indicated that the lead titanate zirconates were not stable under impact shock. There was a change in the domain pattern exhibited by the lack of 90° twinning in the shocked samples. There were no indications of mechanical twinning in the zirconates; therefore, the impact shock probably depolarizes the ceramic. This depolarization should cause the dielectric constant, coupling coefficient and dissipation to decrease, and the mechanical Q should increase.

All of the ceramics exhibiting a low mechanical Q after impact shock were fractured; however, the dielectric constant does not behave as predicted from the microstructure studies. There is an increase of up to 33% in the dielectric constant due to poling in the formation of the 90° domains. The impact shock appears to switch the 90° domains into 180° domains, which would increase the dielectric constant, and the coupling coefficient would be expected to decrease. The low values for dissipation and mechanical Q are due to the switching of domains and fractures in the ceramic. EC-64 test samples exhibited the largest changes in domain formation. EC-65 and EC-66 test samples displayed small changes in mechanical Q and also small changes in the domain formation.

The studies conducted on ceramic aging indicated that the phenomena responsible for aging in ceramics is not affected by impact shock; however, the rate of aging changes after impact shock. The impact shock changes the domain into a configuration such that the decay activation energies causing aging are higher after impact shock. After impact shock, it is more difficult for the domains to achieve equal area configuration and reduce residual stresses; hence, the impact shock decreases the rate of aging. Domain counts on the freshly poled ceramic and the aged ceramic showed an increase in domains in the aged ceramic. The number of 90° domain twinning in the freshly poled ceramic have relaxed into more domains of a smaller area to reduce residual stresses.

The impact shock tests showed that the fracture limit for the barium titanate was from 16,000 psi to 18,000 psi. The fracture limit for lead titanate zirconates was from 14,600 psi to 16,000 psi. Therefore, the barium titanate composition was mechanically stronger than the lead titanate zirconate composition; however, neither composition was able to withstand impact shocks greater than 20,000 psi. Impact shock tests on aged and freshly poled ceramics indicated that the aged ceramic was mechanically stronger than the freshly poled ceramic due to the relief of residual stresses in the aged ceramic.

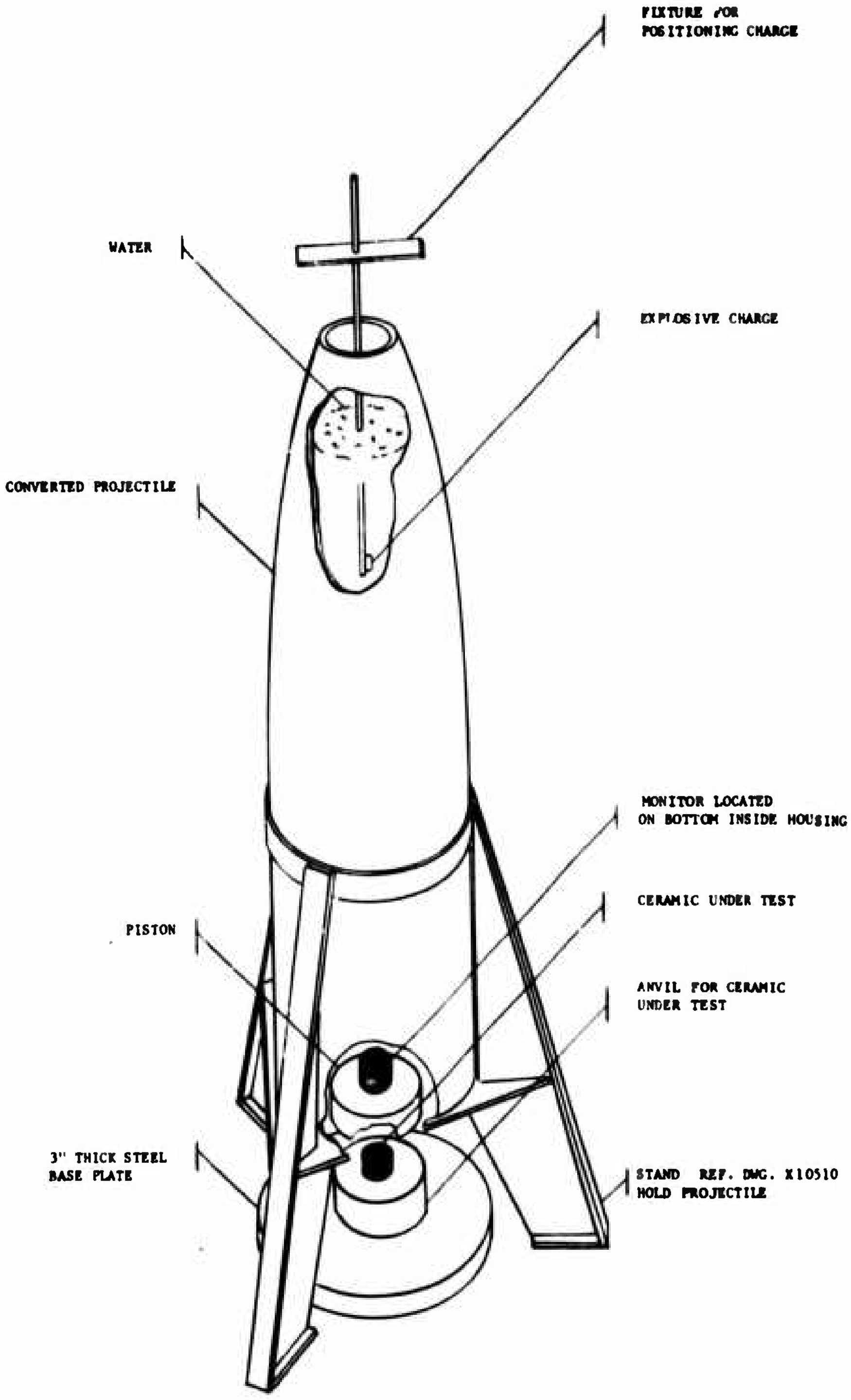


FIGURE 2-1
LABORATORY IMPACT SHOCK APPARATUS

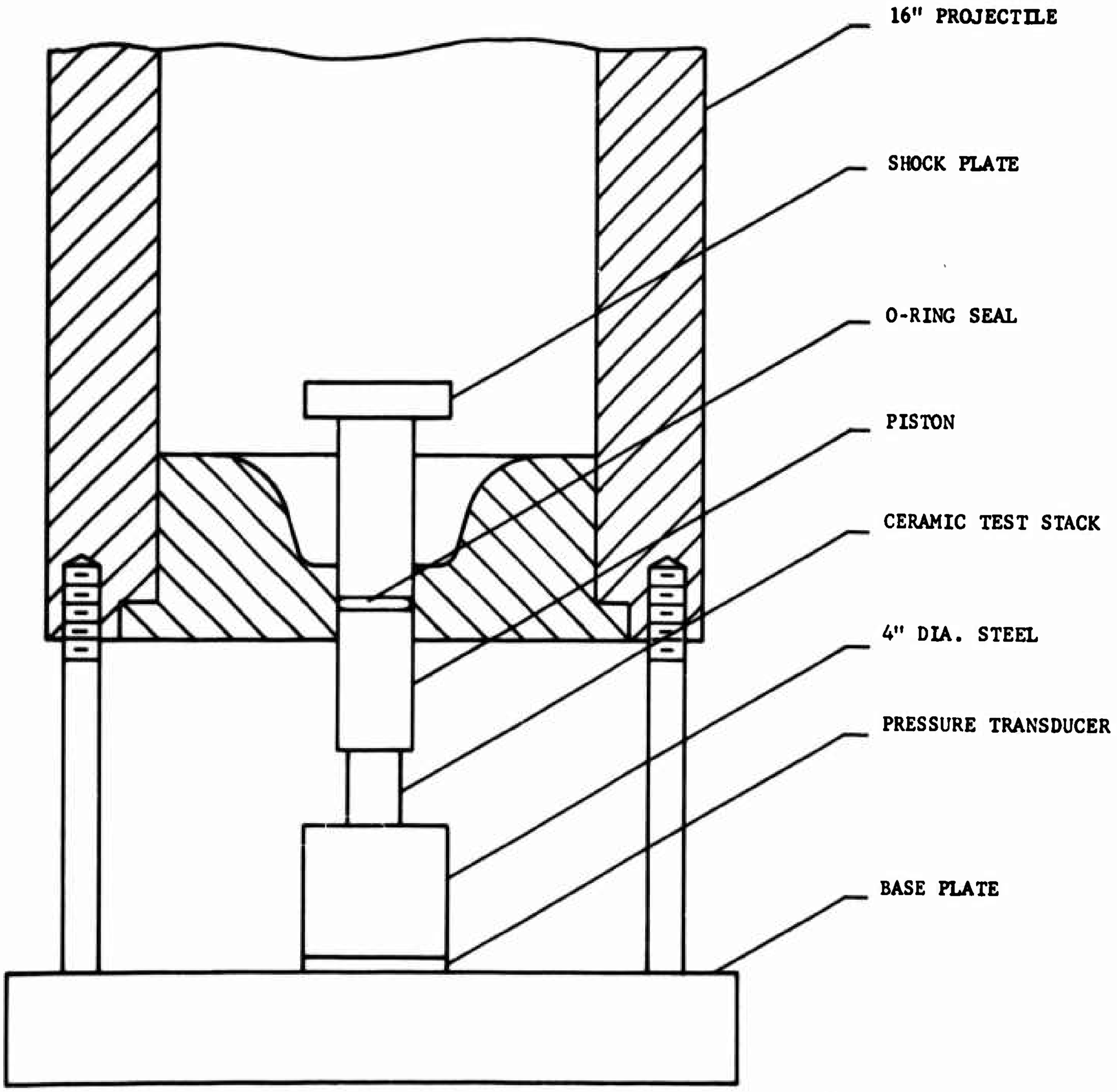


FIGURE 2-2
INTERNAL MECHANISM OF LABORATORY IMPACT SHOCK APPARATUS

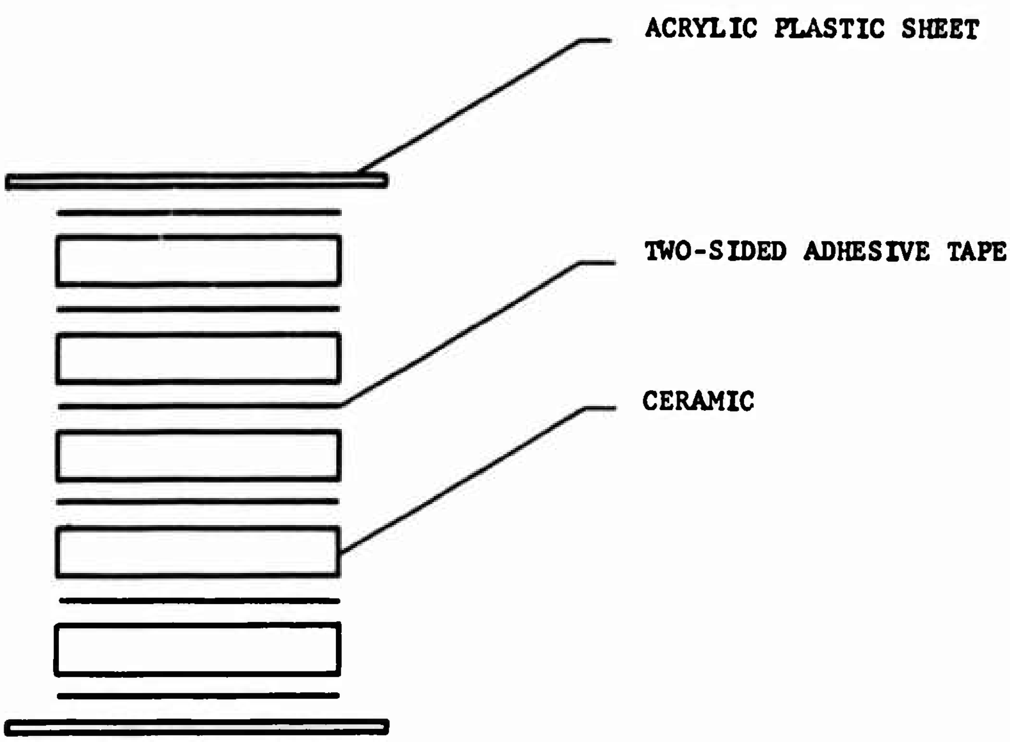


FIGURE 2-3
CERAMIC STACK FOR IMPACT SHOCK STUDIES

3.0 LIFE EXPECTANCY TESTS

Life expectancy tests were conducted on piezoelectric ceramic rings and discs of compositions EC-55, EC-64, EC-65 and EC-69. The tests were conducted to determine the effects of impact shocks on the physical and electrical characteristics of the ceramics.

The test samples were formed into stacks consisting of five ceramic elements of the same composition and configuration. The individual elements were bonded together with two-sided adhesive tape. An acrylic plastic sheet was bonded on the top and bottom of the stack using the two-sided adhesive tape. The adhesive tape and the acrylic plastic sheets were used to obtain uniform pressure distribution over the surface of the ceramics in the same manner as an epoxy bond. Figure 2-3 shows the ceramic stack as described above.

3.1 TEST PROCEDURE

All of the test samples were subjected to similar tests. The following is a discussion of the test procedures used in performing the life expectancy tests.

Before the test samples were formed into stacks, their electrical characteristics were measured individually. The measurements made were: (1) dissipation; (2) capacitance; (3) resonant frequency and the corresponding output voltage; and (4) anti-resonant frequency and the corresponding output voltage. The resonant and anti-resonant frequencies were measured in the planar mode of vibration. Conventional industrial methods were used in obtaining these measurements. These initial values of the electrical characteristics were used as the basis of relating any changes which occur in these characteristics after each impact shock.

The test samples were then formed into stacks and subjected to the desired impact shock amplitude. Figure 2-1 shows the impact shock apparatus used. After being shocked, the individual ceramic elements were separated and their electrical characteristics measured individually. Time lapse between impact shock and electrical measurements was less than 24 hours. This test procedure was repeated for each stack until fractures were present in the ceramic or a trend in the changes in the ceramic electrical characteristics developed.

The above test procedures were used because it allowed the measurement of the electrical characteristics of the individual ceramic elements, and provided a means of subjecting a ceramic stack to impact shock.

3.2 DISCUSSION OF RESULTS

The life expectancy tests performed on ceramic rings and discs have presented extensive information on the effects of impact shock on the electrical characteristics of the ceramics. The tests have also determined the relative mechanical strengths of the ceramic rings and discs of all compositions tested.

The following is a discussion of the results obtained from the life expectancy tests performed on ceramic rings and discs during the period from 1 May 1966 to 30 April 1967.

Figures 3-1 to 3-24 present the percent change after impact shock of the ceramics' electrical characteristics. Table 3-1 presents the relative mechanical strengths of the ceramic rings and discs.

3.2.1 COMPOSITION EC-55

The changes that occurred in the dielectric constant after impact shock were random for ceramic rings and discs of this composition. The maximum change observed was approximately -6.0 percent for the rings. In general, the changes in the dielectric constant were within the normal statistical distribution of the unshocked test samples.

The effect of impact shocks on the dissipation was more pronounced. Maximum changes observed were +24 percent for the discs and +36 percent for the rings. The dissipation for both the discs and rings increased after impact shock, as expected. The largest change in dissipation did not necessarily occur at the highest impact shock amplitude. This substantiates the findings from previous tests indicating that the dissipation increases to a maximum at a specific pressure and decreases as the applied pressure is increased further. This coincident point of maximum dissipation and pressure varies for each composition. The changes in dissipation for the discs were random while a definite relationship between the impact shock amplitude and the changes in dissipation exists for the ceramic rings.

The changes that occurred in the coupling coefficient for both the rings and discs were random. There is no definite relationship between changes in coupling coefficient and impact shock amplitude. The maximum change that occurred was -1.4 percent for the discs and +7.0 percent for the rings. In general, the changes in coupling coefficient were within the normal statistical distribution of the unshocked test samples.

The mechanical Q for both the rings and discs was most affected by impact shocks. Maximum change which occurred was -42 percent for the discs and

-68 percent for the rings. The changes in mechanical Q were random for the discs; however, the changes for the rings were related to the impact shock amplitude.

Table 3-1 shows the relative mechanical strength of the rings and discs of composition EC-55. The strength of the ceramic ring is superior to that of the ceramic disc.

3.2.2 COMPOSITION EC-64

The changes that occurred in the dielectric constant were random; however, the changes were well within the normal statistical distribution of the unshocked test samples.

The dissipation for the ceramic rings increased with increasing impact shock amplitude; however, the changes in dissipation for the ceramic discs subjected to 6000 psi impact shock decreased. In general, the dissipation of the ceramic rings and discs did increase after impact shock as expected. The maximum change in dissipation was higher for the rings than the discs (+38 percent for rings and +19 percent for discs).

A general trend of decreasing coupling coefficient was observed for ceramic rings and discs subjected to impact shock. The trend is more definite in the rings than in the discs. The changes in coupling coefficient for the discs were within the normal statistical distribution of the unshocked test samples; however, the rings shocked at 33,000 psi displayed a decrease in coupling coefficient of -16 percent.

As observed in other compositions, the mechanical Q of EC-64 rings and discs was most affected by impact shocks. The ceramic rings showed a definite trend of the dependence of the degree of change in mechanical Q on the amplitude of impact shock. The change in mechanical Q increased with increasing impact shock amplitude. This trend was not observed for the ceramic discs.

Evaluation of Table 3-1 indicates that the ceramic ring configuration is superior to the ceramic disc configuration regarding their relative mechanical strengths. The table also shows that the relative mechanical strength of composition EC-55 (both rings and discs) is higher than that of composition EC-64.

3.2.3 COMPOSITION EC-65

A general trend of increasing dielectric constant for both the rings and discs was observed. Both the rings and discs displayed the dependence of the change in dielectric constant on the impact shock amplitude. As the impact shock amplitude increased, the change in dielectric constant increased. The changes in the dielectric constant due to impact shock were generally within the normal statistical distribution of the unshocked test samples.

The changes in the dissipation for the ceramic rings and discs were generally positive. Maximum increase in dissipation for the discs was +27 percent and for the rings, +13 percent. The changes due to impact shocks were random for both the rings and discs.

The changes occurring in the coupling coefficient due to impact shocks were relative to the amplitude of the impact shock. As the impact shock amplitude increased, the change in coupling coefficient increased. This was true for both the ceramic rings and discs. There is a definite trend in the changes in coupling coefficient due to impact shocks. The coupling coefficient decreases with increasing impact shock amplitude and the number of impact shocks.

The mechanical Q was the most affected by impact shocks. There is no definite relationship between the changes in mechanical Q and the impact shock amplitude since the changes were random.

The relative mechanical strength of the rings and discs is shown in Table 3-1. The rings were subjected to and survived higher impact shocks than the discs.

3.2.4 COMPOSITION EC-69

The effects of impact shock on the electrical characteristics of EC-69 rings were not determined; however, the relative mechanical strength of this composition is lower than that of the other three compositions tested. This was expected since EC-69 is the hardest ceramic composition tested.

3.3 CONCLUSION

The results of the life expectancy tests performed on compositions EC-55, EC-64, EC-65 and EC-69 have presented valuable information regarding the effects of impact shock on the physical and electrical characteristics of these piezoelectric ceramics.

In regards to the relative mechanical strengths of these four compositions, EC-65 is superior to the other three compositions. Also, the ceramic ring configuration is mechanically stronger than the ceramic disc configuration. This is true for all compositions tested.

The dielectric constant remained relatively constant after repeated impact shocks for all compositions tested. Any changes that did occur were within the normal statistical distribution of the unshocked test samples.

The mechanical Q and the dissipation were most affected by impact shocks. The general trend was towards increasing dissipation and decreasing mechanical Q after impact shock. The mechanical Q and dissipation of the hard ceramic compositions (EC-55 and EC-64)were more affected by impact shock than the soft ceramic composition (EC-65).

The coupling coefficient of EC-65 was more affected by impact shock than that of EC-55 and EC-64.

TABLE 3-1
CERAMIC MECHANICAL STRENGTH
AS A FUNCTION OF THE NUMBER AND AMPLITUDE OF IMPACT SHOCKS

			PERCENT FRACTURE AFTER SHOCK NO:						
OSITION	CONFIGURATION	SHOCK PRESSURE-PSI	1	2	3	4	5	6	7
C-55	DISC	6,000	0	0	0	0	0	0	
		11,000	0	0	0	0	20		
		16,000	0	0	20				
		21,000	0	40					
	RING	16,000	0	0	0	0	0	0	
		23,000	0	0	20				
		27,000	0	0	20				
		33,000	0	0	40				
C-64	DISC	6,000	0	0	0	0	0		
		11,000	0	0	0	0	0		
		16,000	0	40					
		21,000	100						
	RING	16,000	0	0	0	0	0	0	
		23,000	0	0	40				
		27,000	0	20					
		33,000	0	20					
C-65	DISC	6,000	0	0	0	0	0	0	0
		11,000	0	0	0	0	0	0	0
		16,000	0	0	0	0	0	0	0
		21,000	0	0	0	0	0	0	0
	RING	16,000	0	0	0	0	0	0	
		23,000	0	0	0	0	0	0	
		27,000	0	0	0	0	0	0	
		33,000	0	0	0	0	0	100	
C-69	RING	16,000	0	0					
		23,000	0	0					
		27,000	0	0					
		33,000	100						

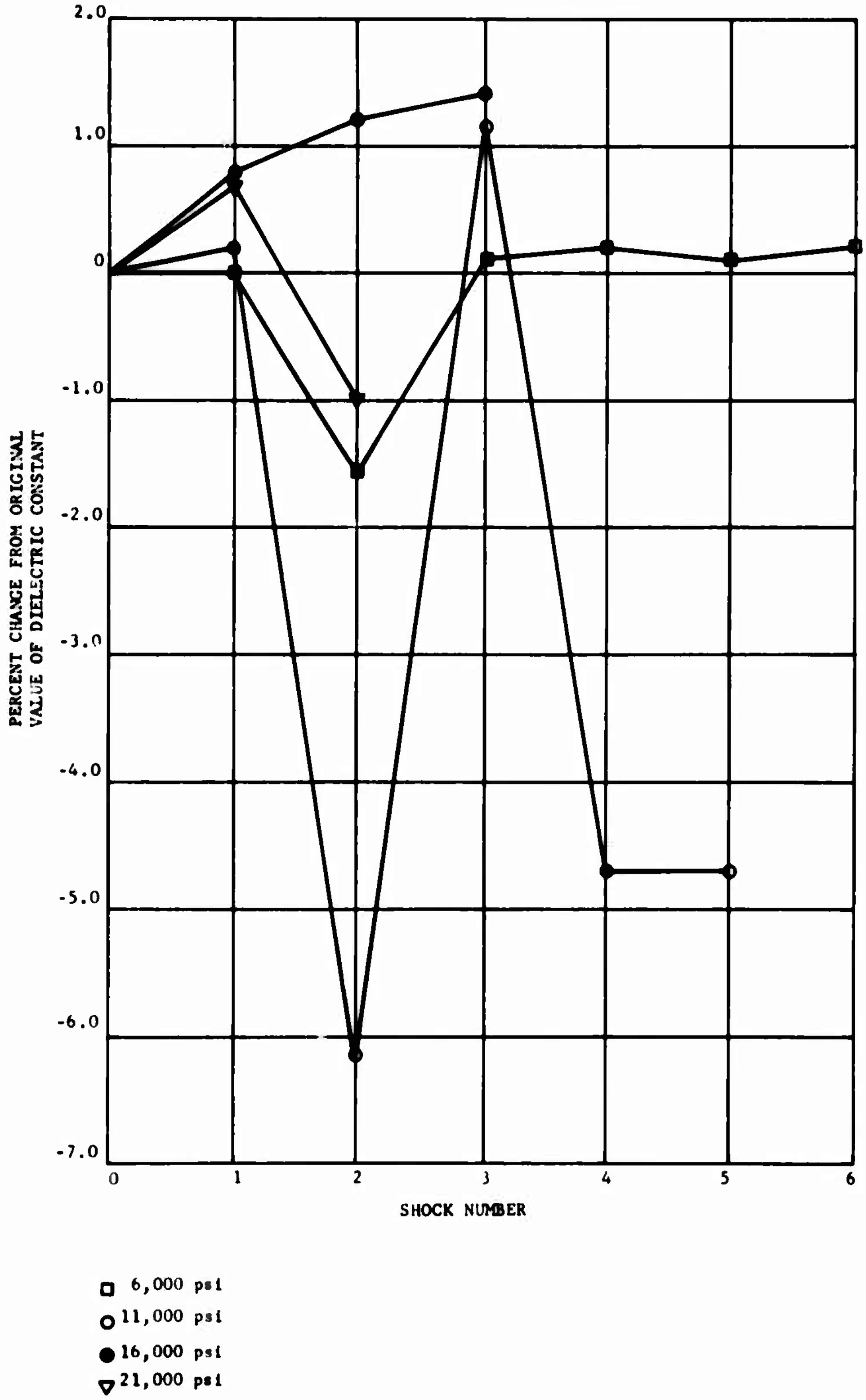


FIGURE 3-1
EFFECT OF IMPACT SHOCKS ON THE DIELECTRIC CONSTANT OF EC-55 DISCS

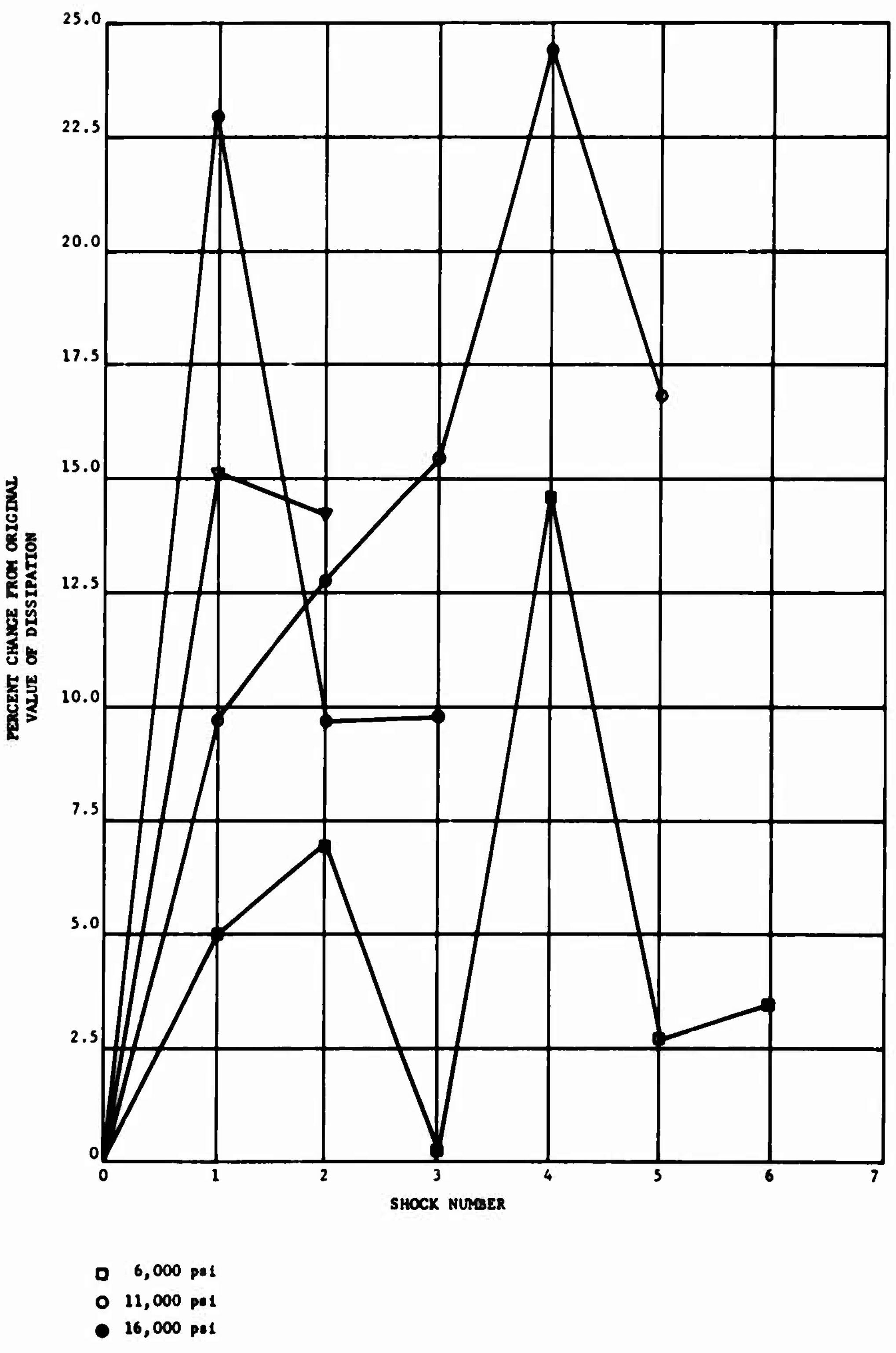


FIGURE 3-2
EFFECT OF IMPACT SHOCKS ON THE DISSIPATION OF EC-55 DISCS

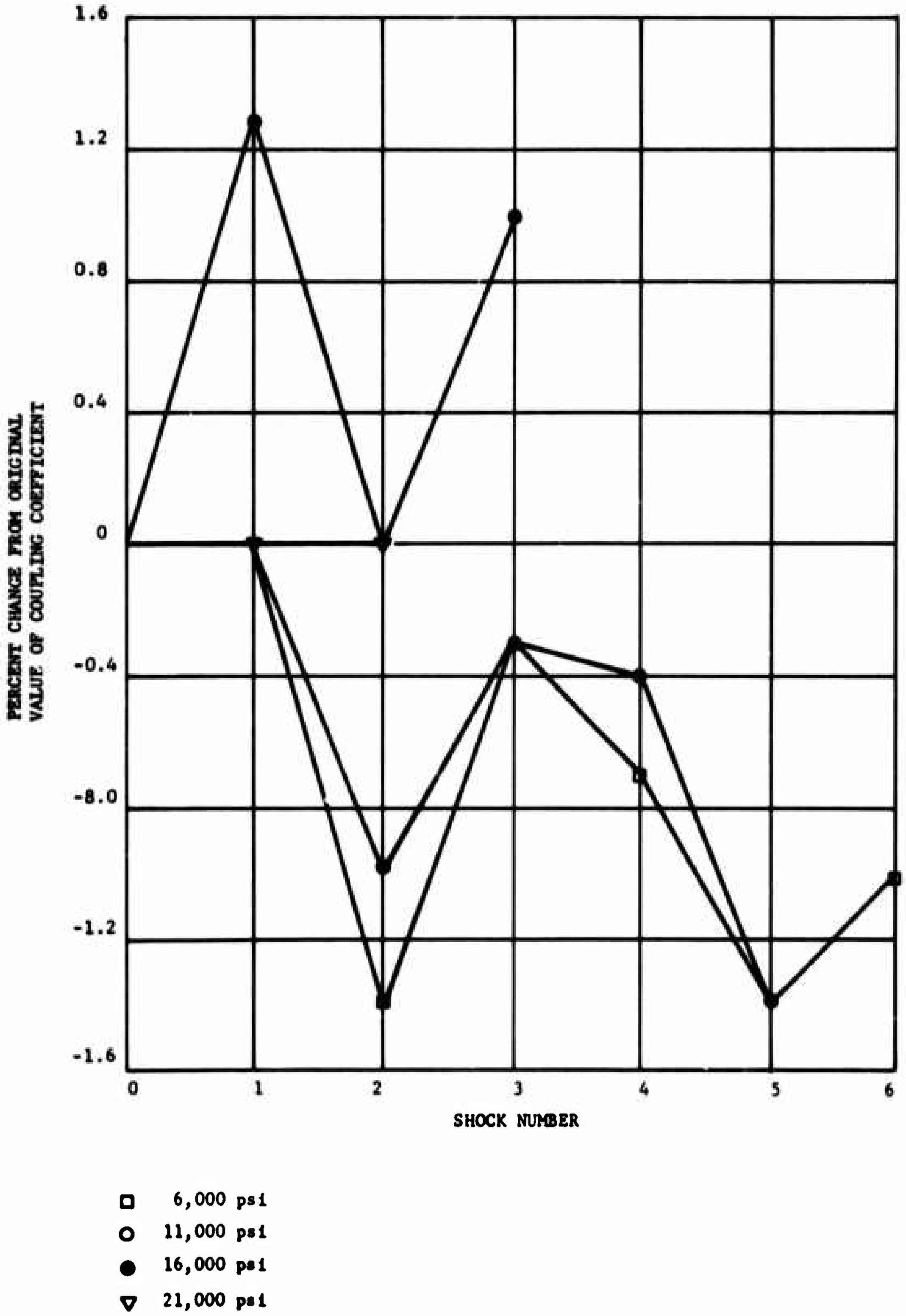


FIGURE 3-3
EFFECT OF IMPACT SHOCKS ON THE COUPLING COEFFICIENT OF EC-55 DISCS

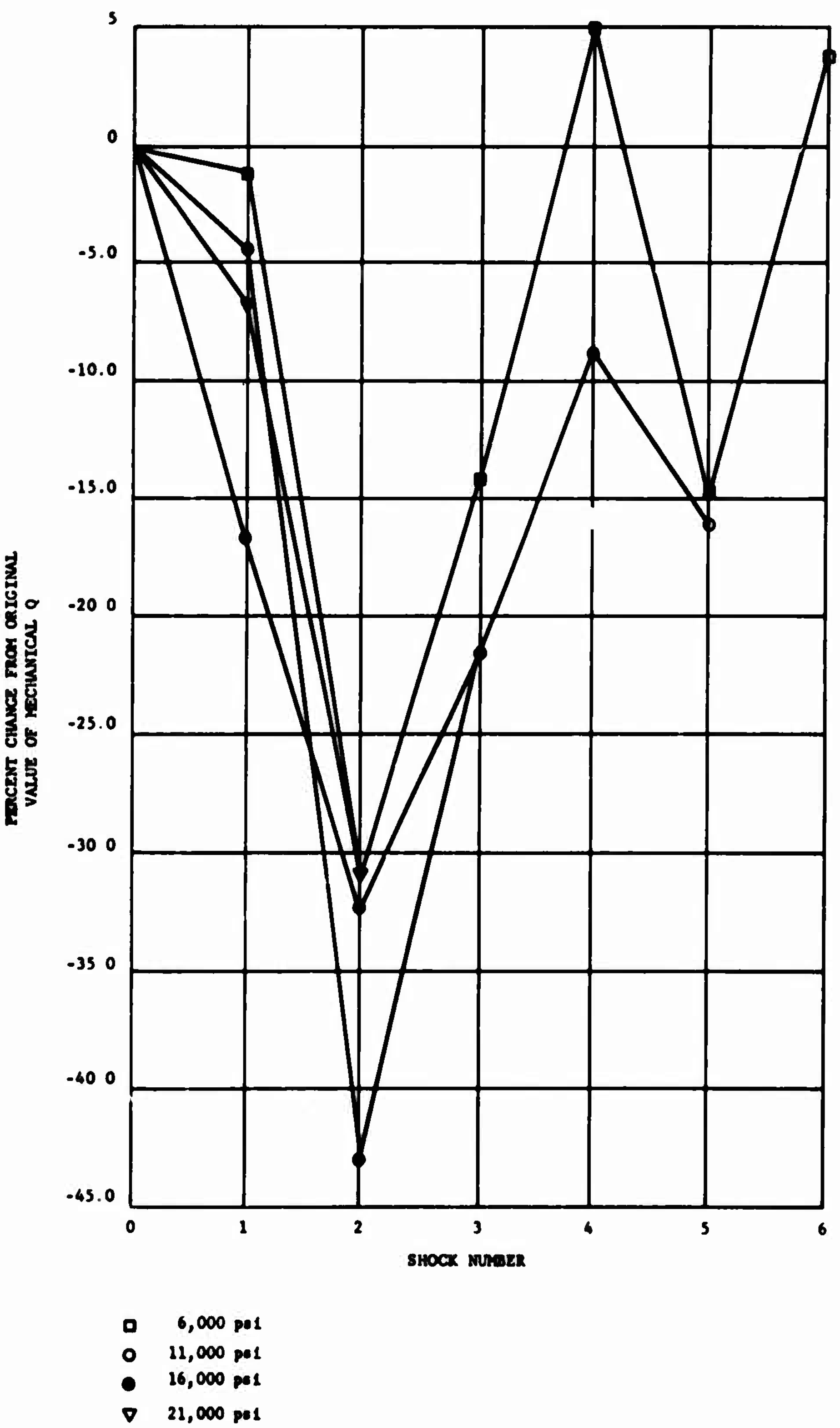


FIGURE 3-4
EFFECT OF IMPACT SHOCKS ON THE MECHANICAL Q OF EC-55 DISCS

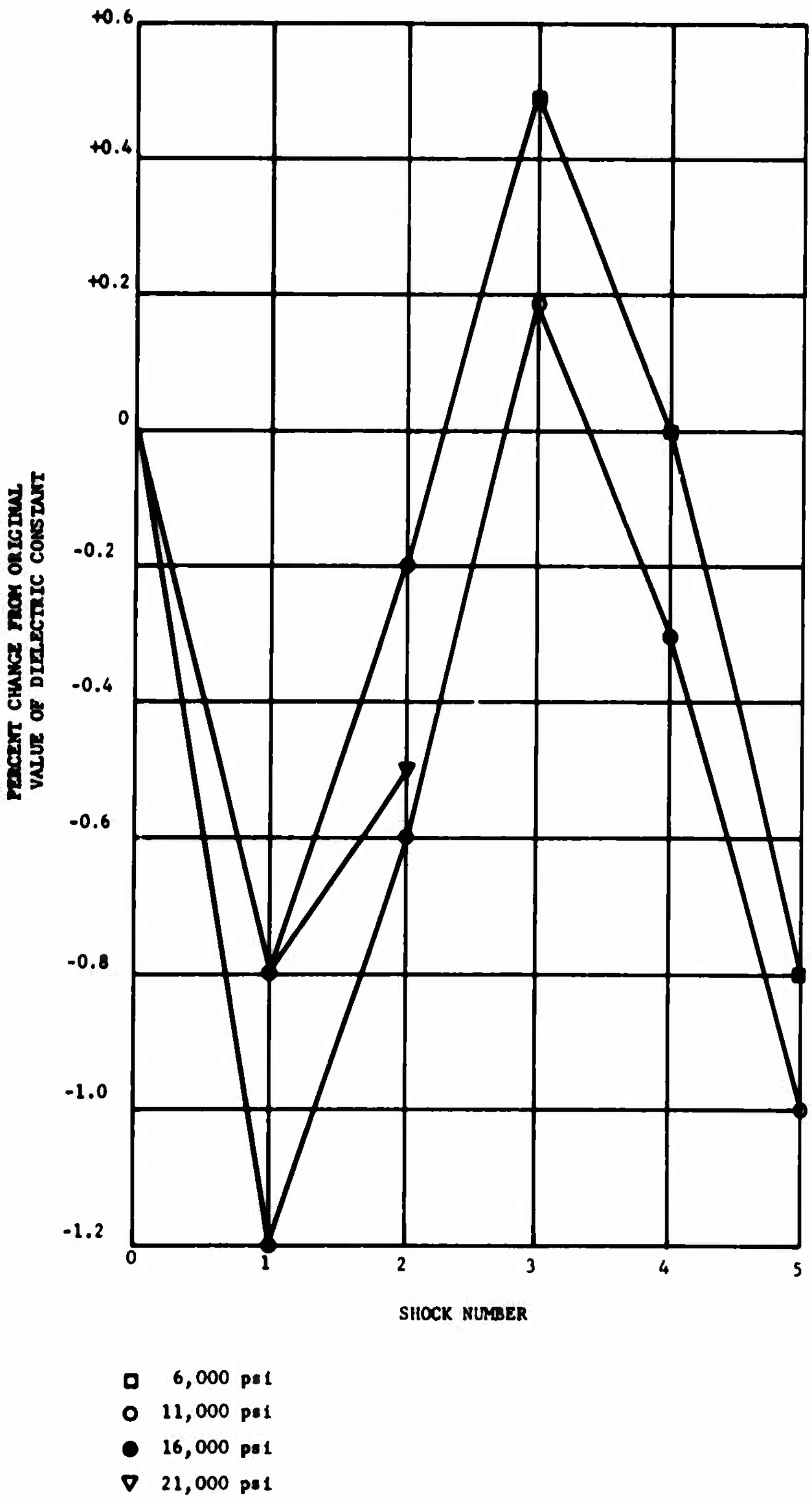


FIGURE 3-5
EFFECT OF IMPACT SHOCKS ON THE DIELECTRIC CONSTANT OF EC-64 DISCS

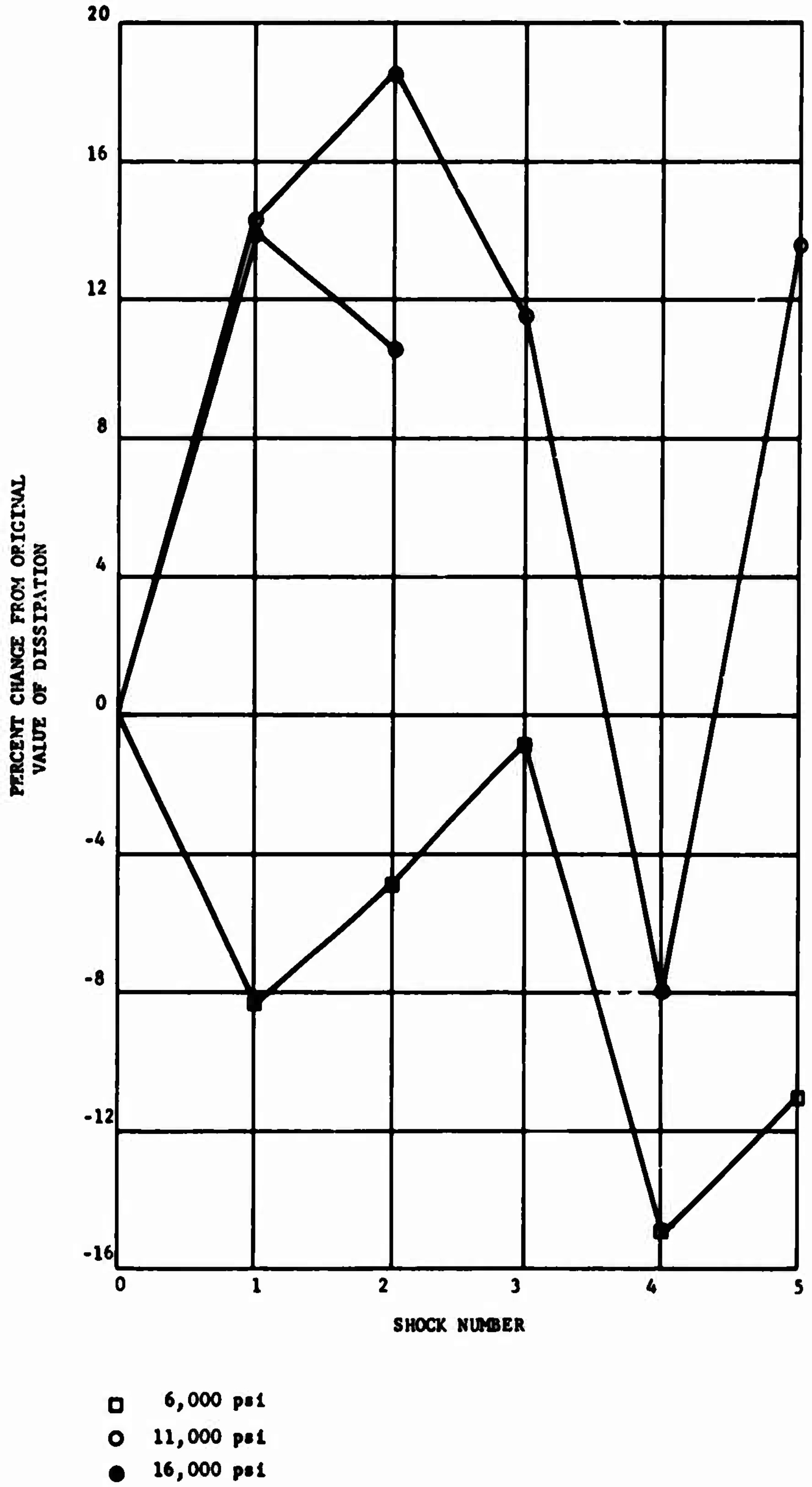


FIGURE 3-6
EFFECT OF IMPACT SHOCKS ON THE DISSIPATION OF EC-64 DISCS

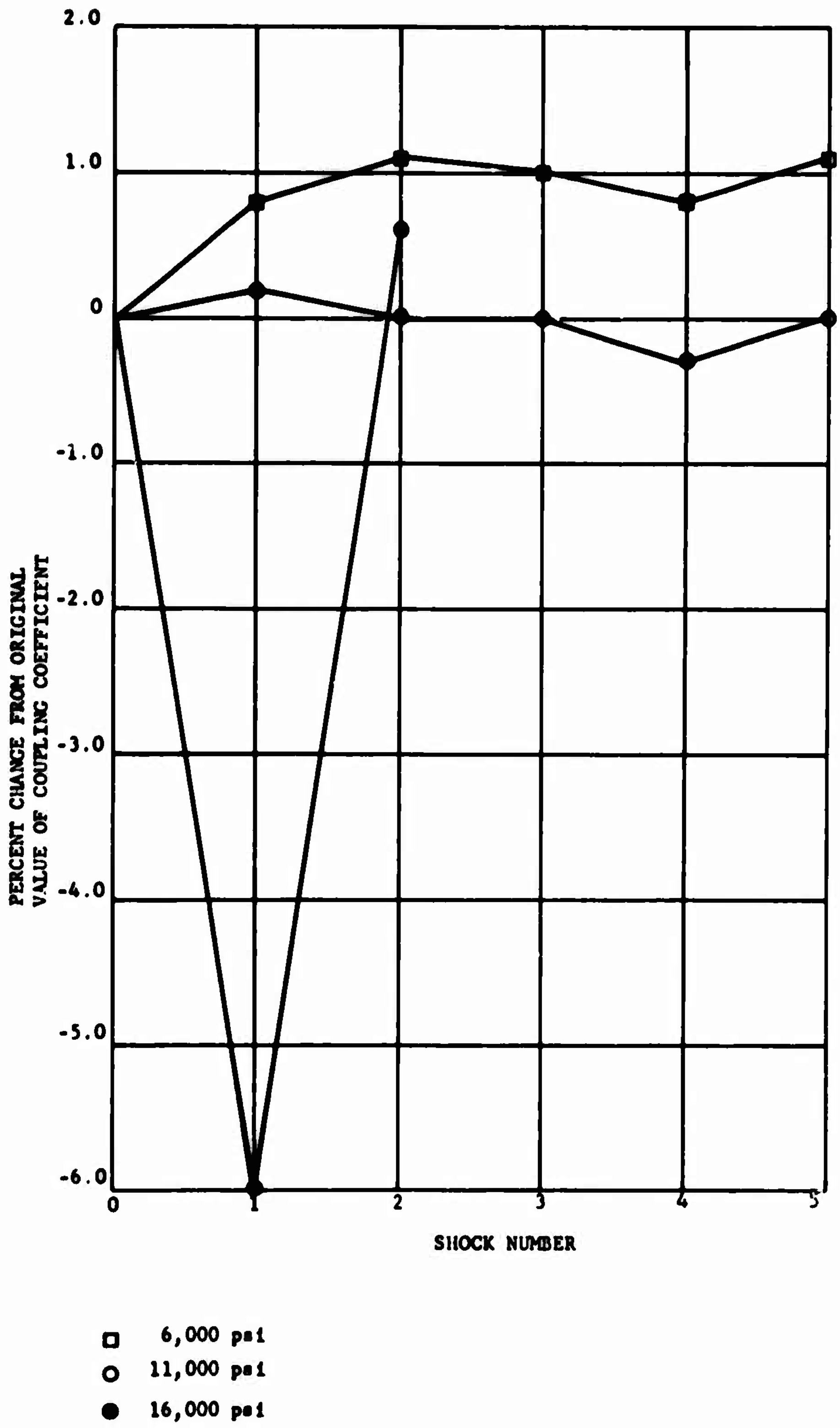


FIGURE 3-7
EFFECT OF IMPACT SHOCKS ON THE COUPLING COEFFICIENT OF EC-64 DISCS

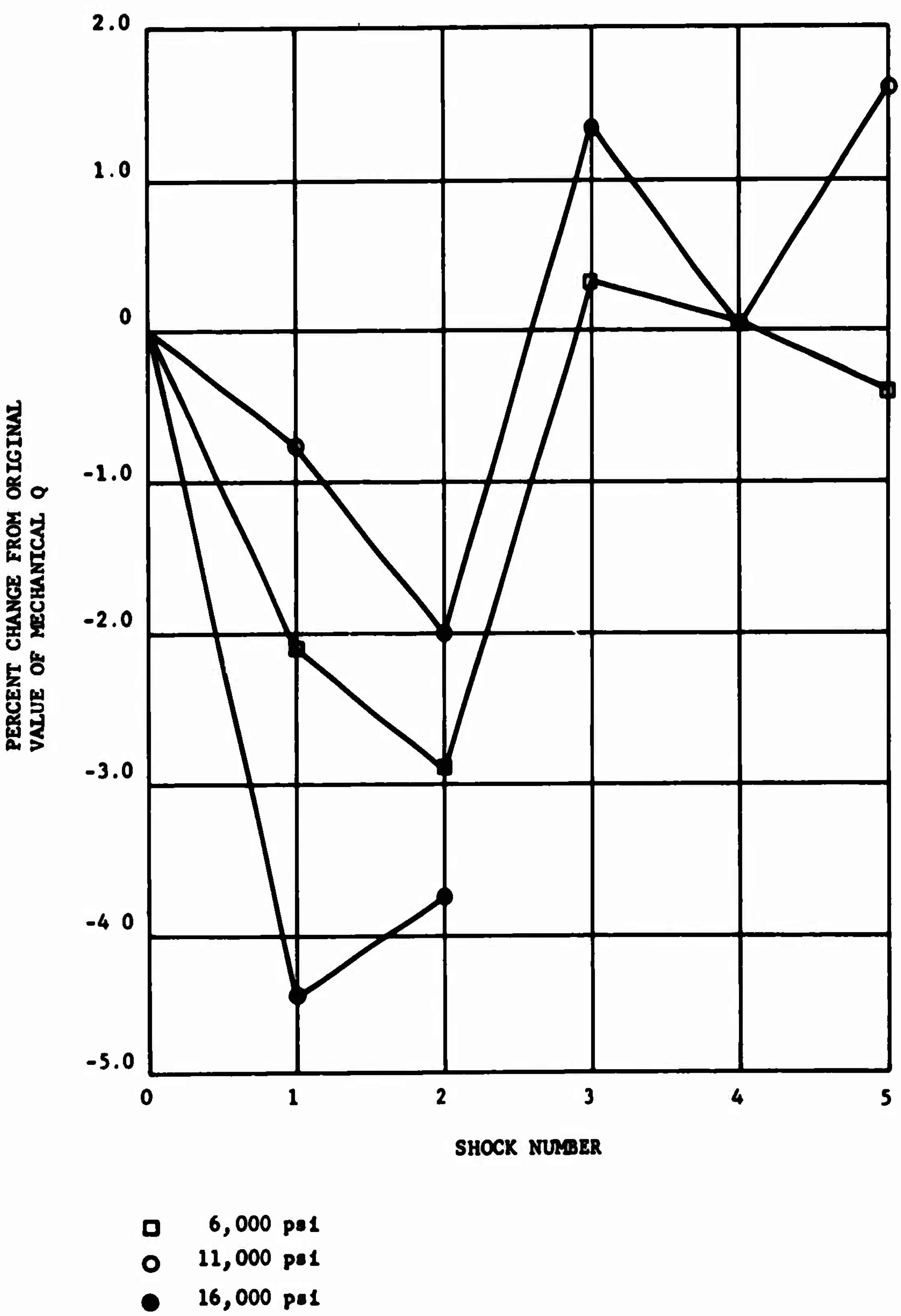


FIGURE 3-8
EFFECT OF IMPACT SHOCKS ON THE MECHANICAL Q OF EC-64 DISCS

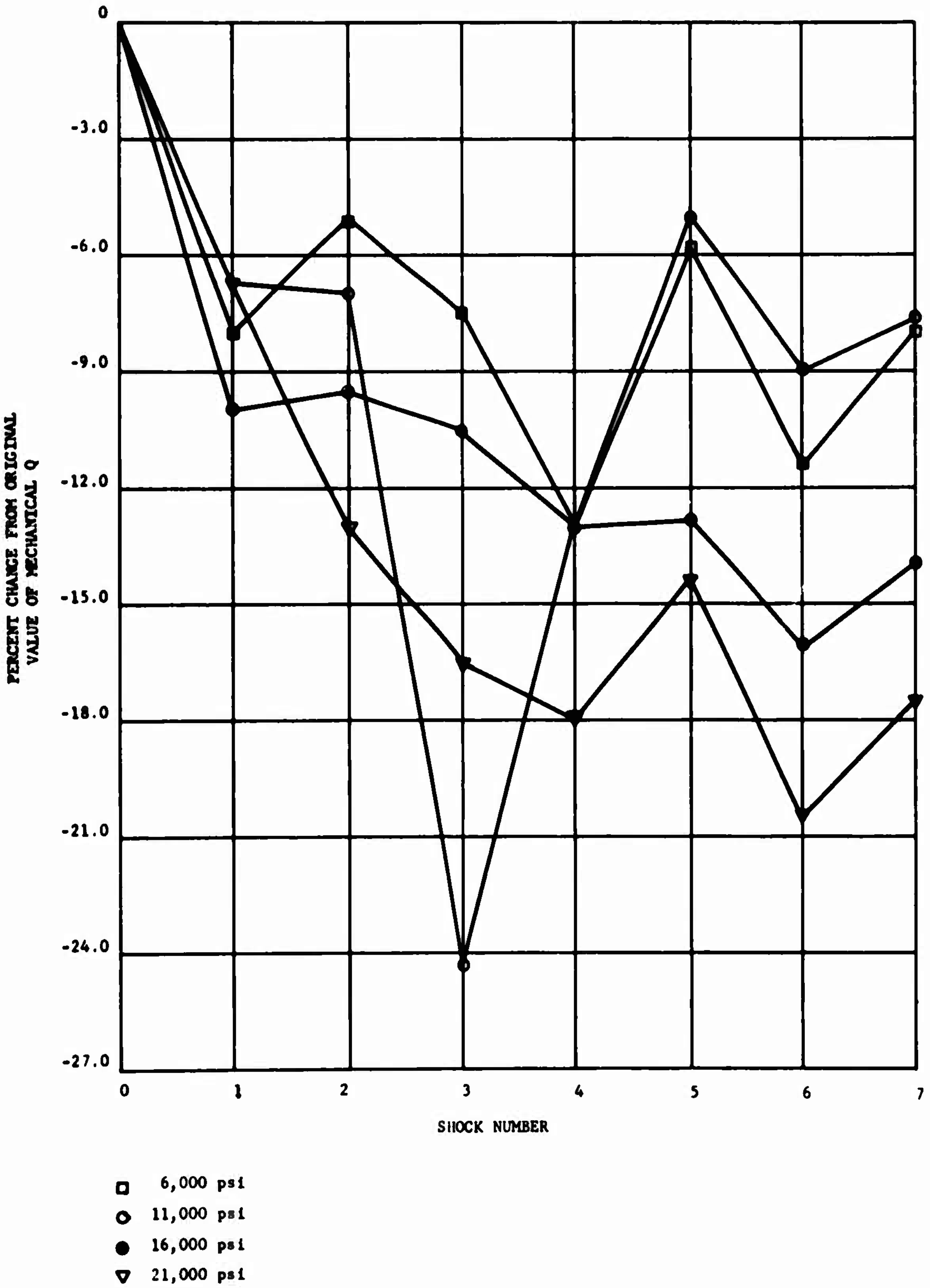


FIGURE 3-9
EFFECT OF IMPACT SHOCKS ON THE DIELECTRIC CONSTANT OF EC-65 DISCS

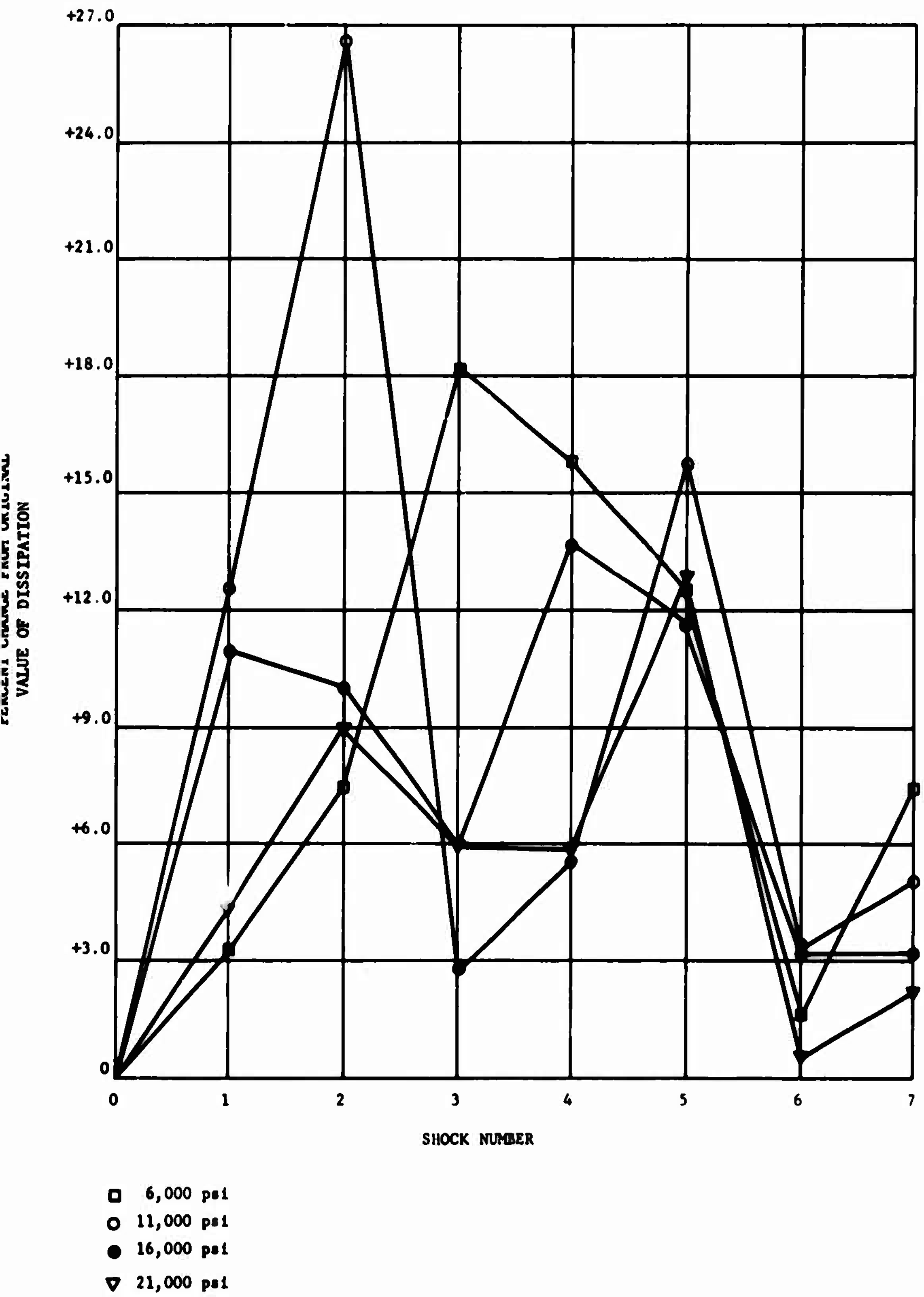


FIGURE 3-10
EFFECT OF IMPACT SHOCKS ON THE DISSIPATION OF EC-65 DISCS

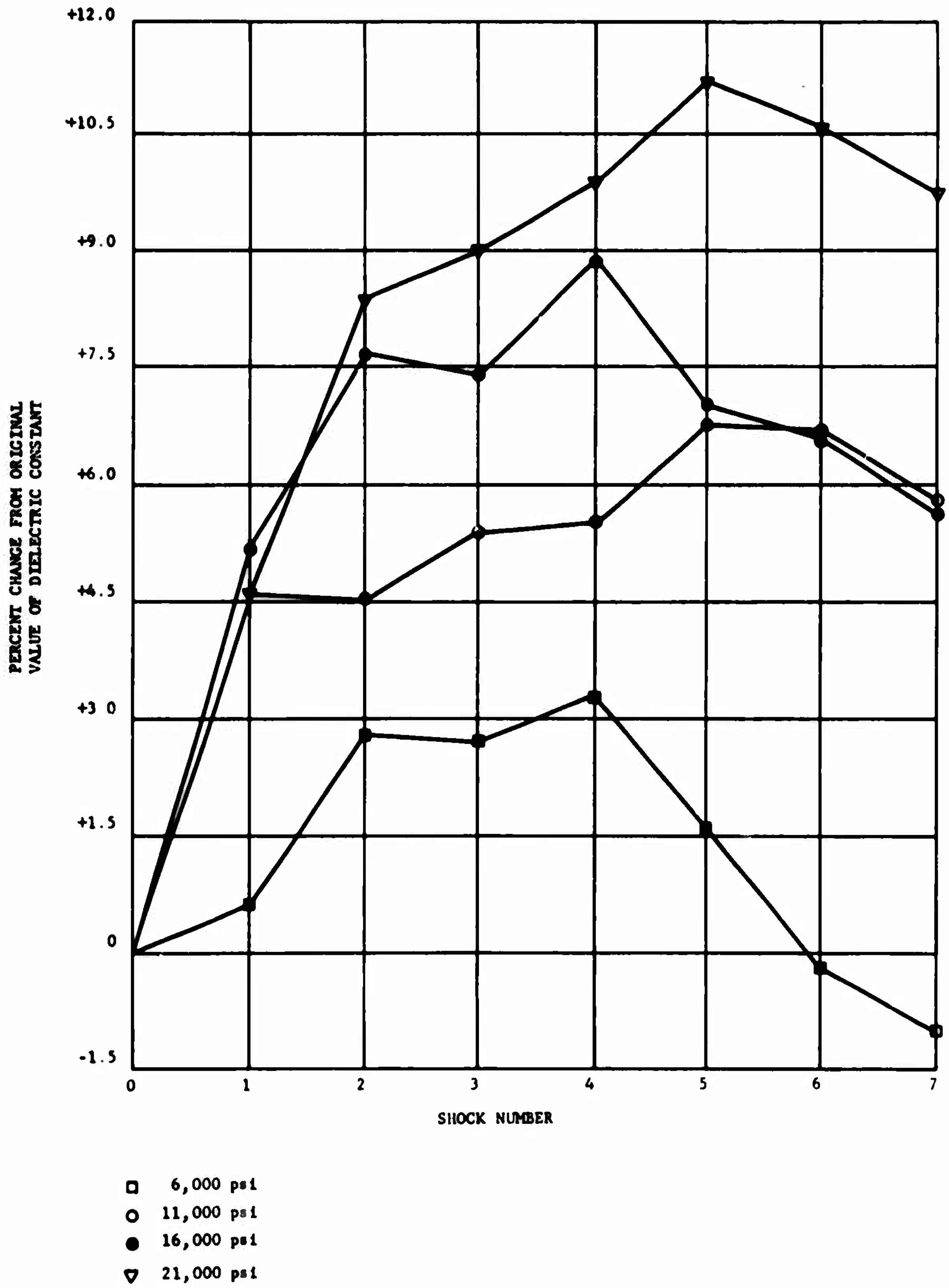


FIGURE 3-11
EFFECT OF IMPACT SHOCKS ON THE COUPLING COEFFICIENT OF EC-65 DISCS

PERCENT CHANGE FROM ORIGINAL

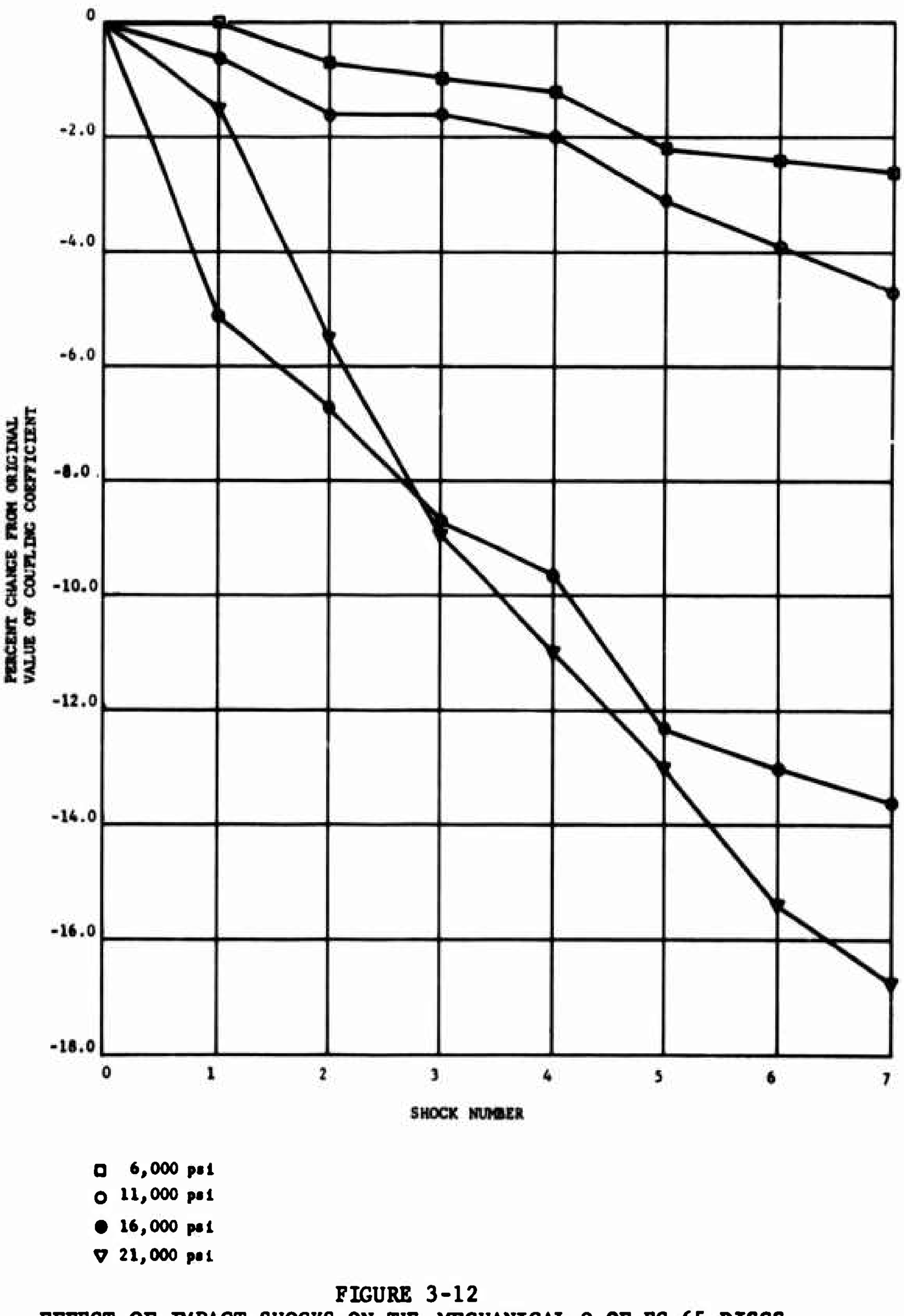


FIGURE 3-12
EFFECT OF IMPACT SHOCKS ON THE MECHANICAL Q OF EC-65 DISCS

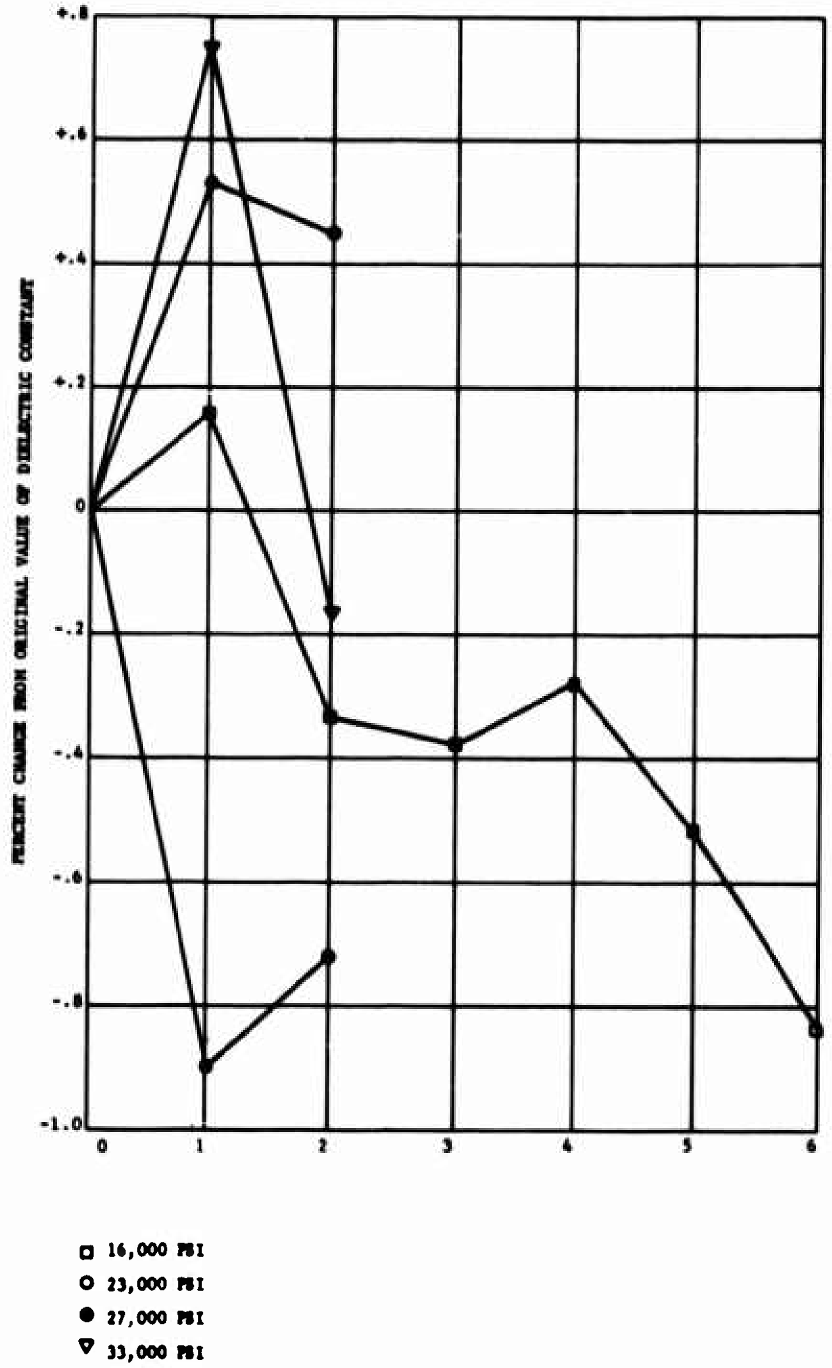


FIGURE 3-13
EFFECT OF IMPACT SHOCKS ON THE DIELECTRIC CONSTANT OF EC-55 RINGS

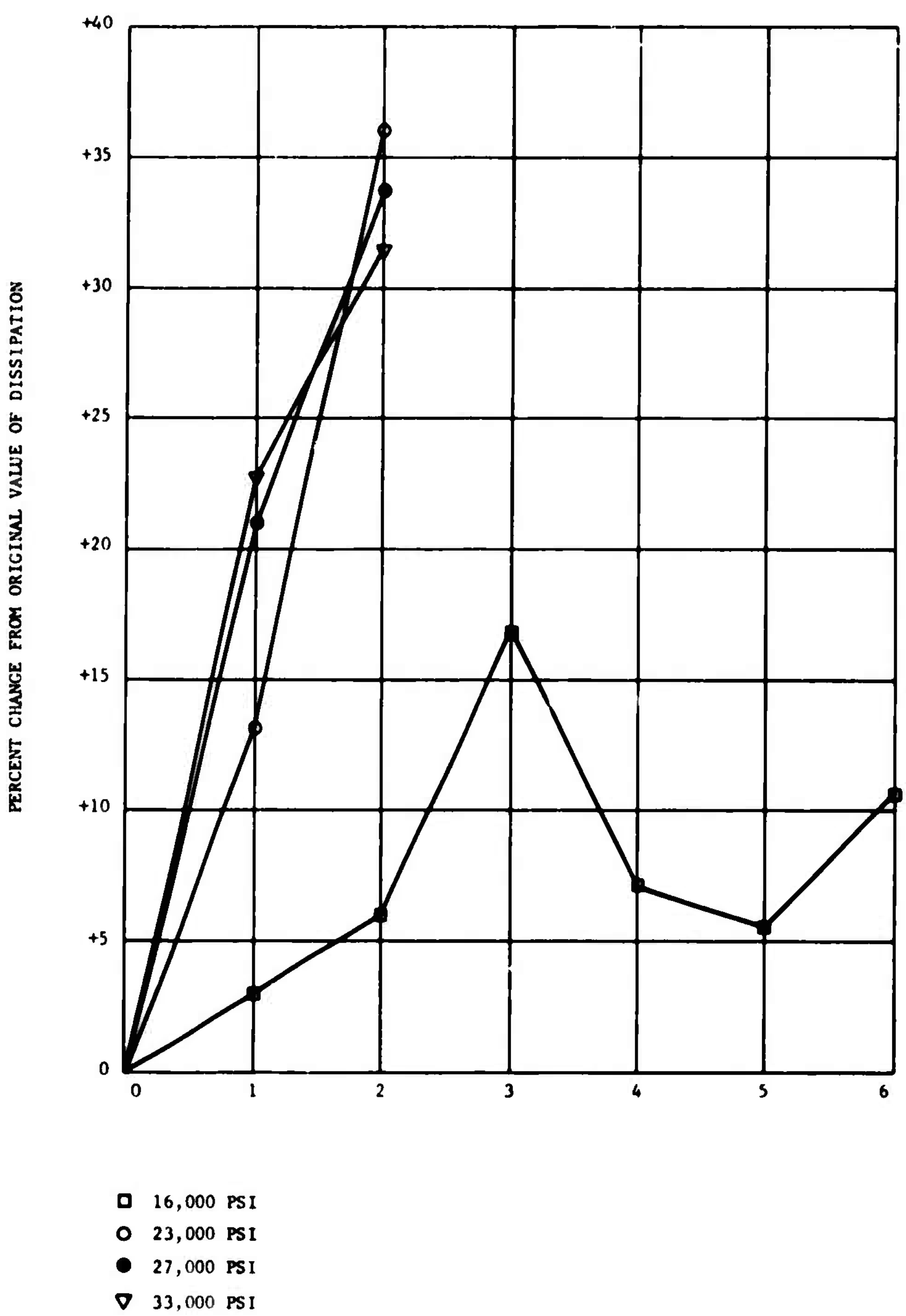
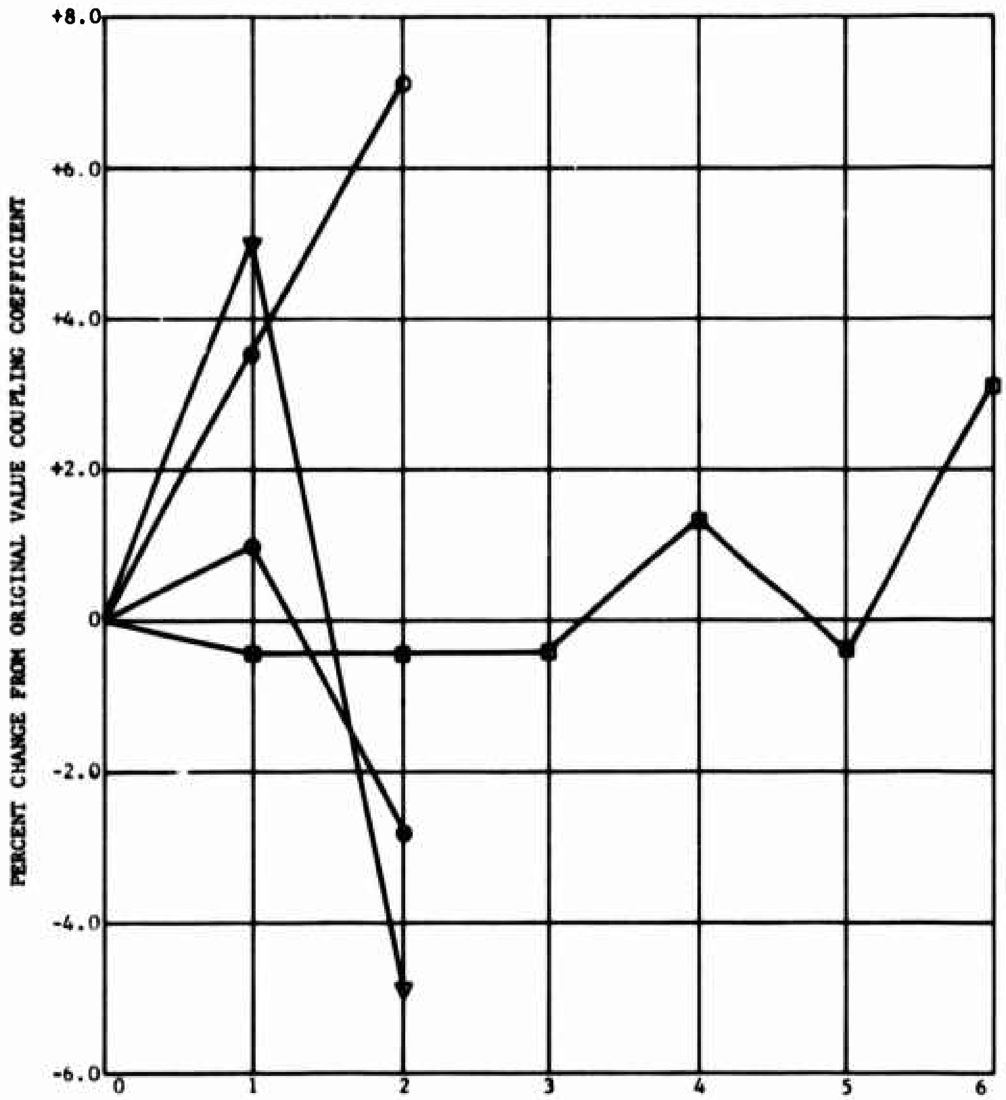


FIGURE 3-14
EFFECT OF IMPACT SHOCKS ON THE DISSIPATION OF EC-55 RINGS



□ 16,000 PSI
○ 23,000 PSI
● 27,000 PSI
▽ 33,000 PSI

FIGURE 3-15
EFFECT OF IMPACT SHOCKS ON THE COUPLING COEFFICIENT OF EC-55 RINGS

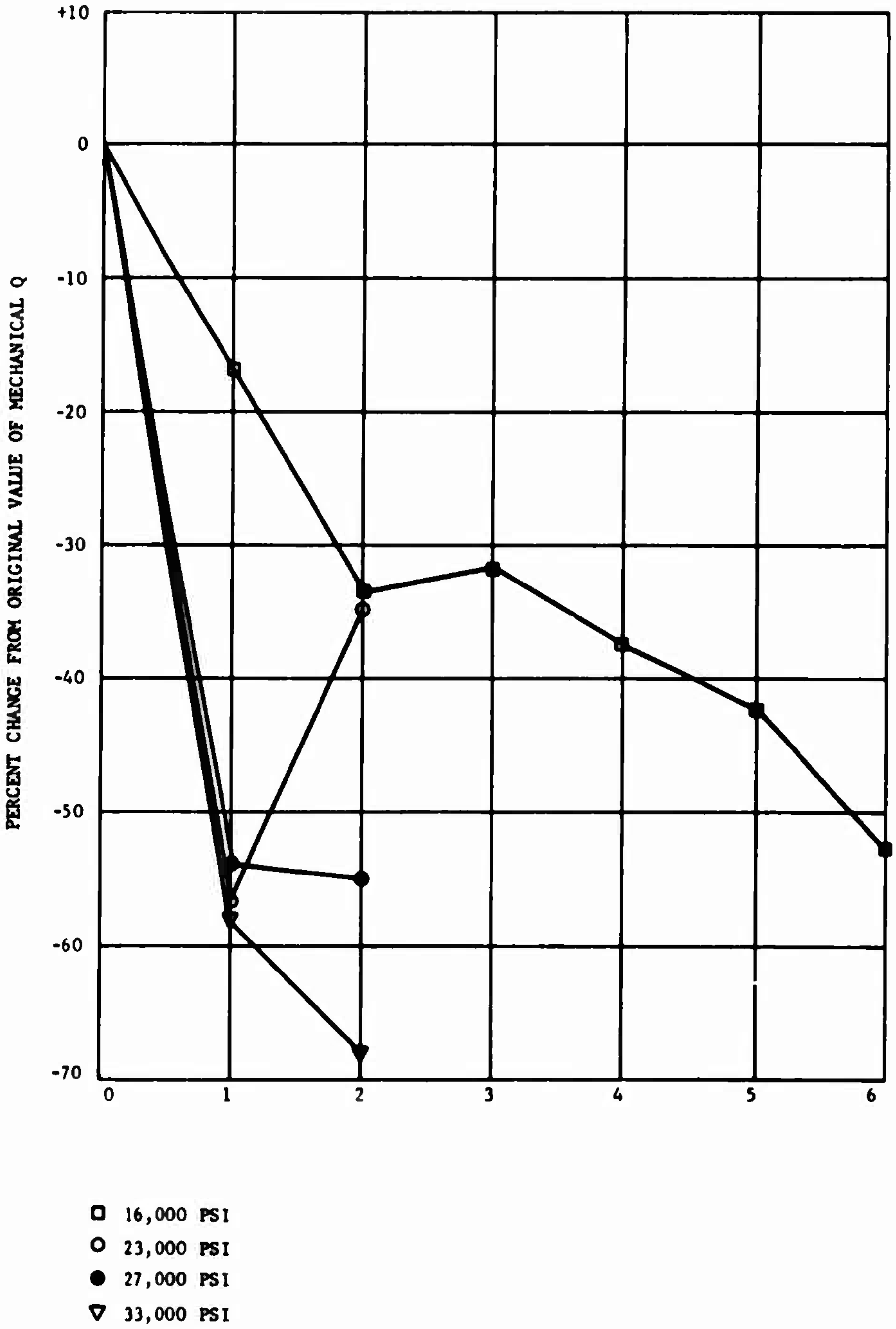


FIGURE 3-16
EFFECT OF IMPACT SHOCKS ON THE MECHANICAL Q OF EC-55 RINGS

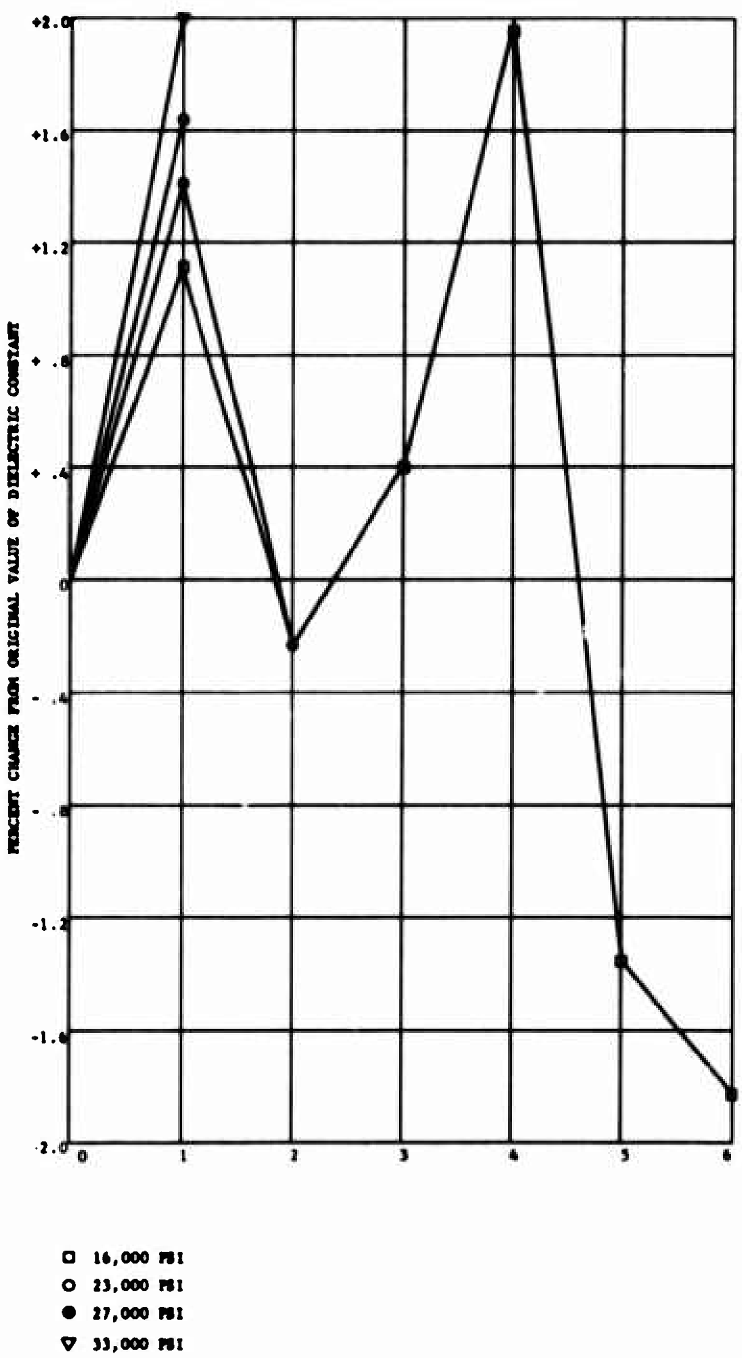


FIGURE 3-17
EFFECT OF IMPACT SHOCKS ON THE DIELECTRIC CONSTANT OF EC-64 RINGS

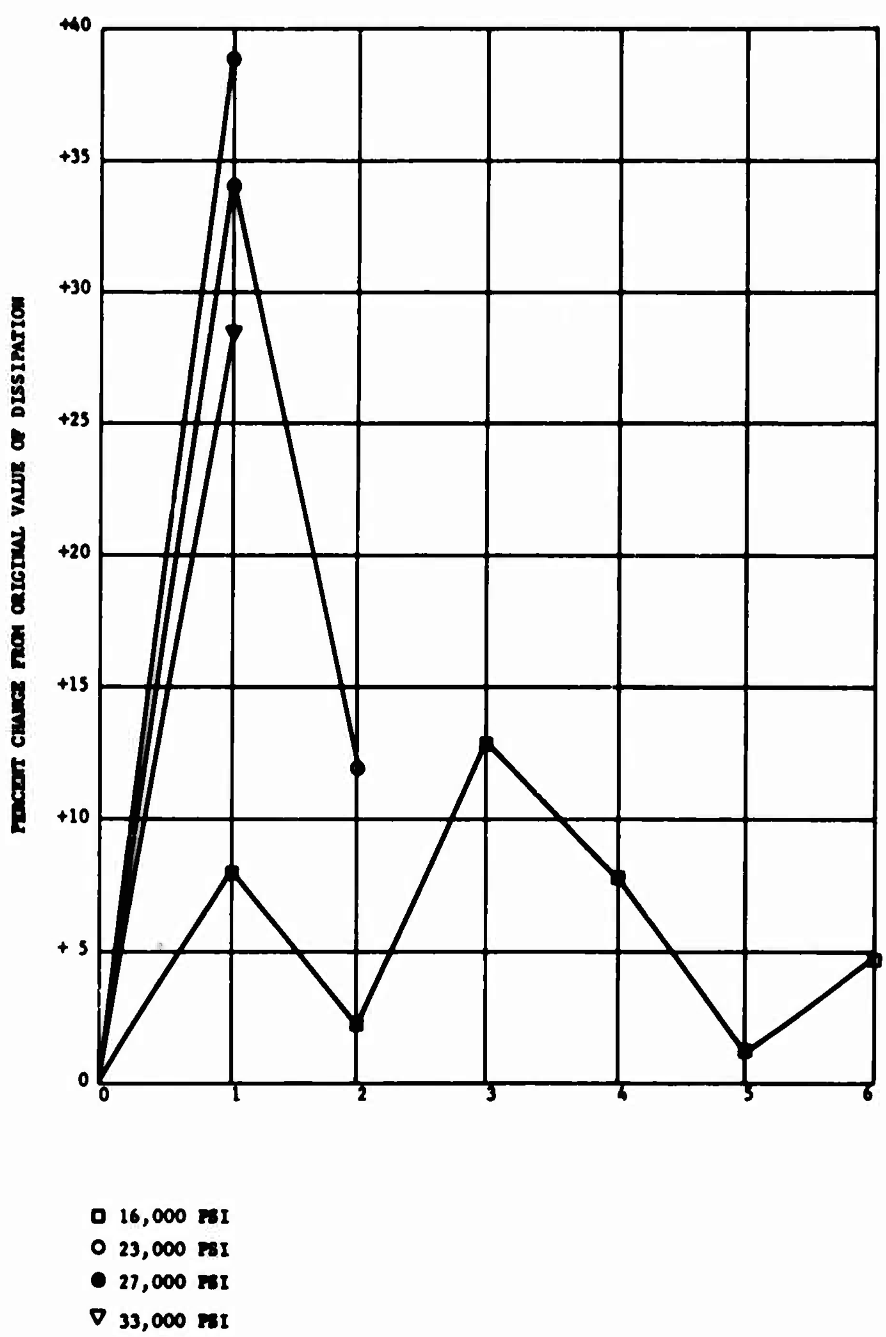


FIGURE 3-18
EFFECT OF IMPACT SHOCKS ON THE DISSIPATION OF EC-64 RINGS

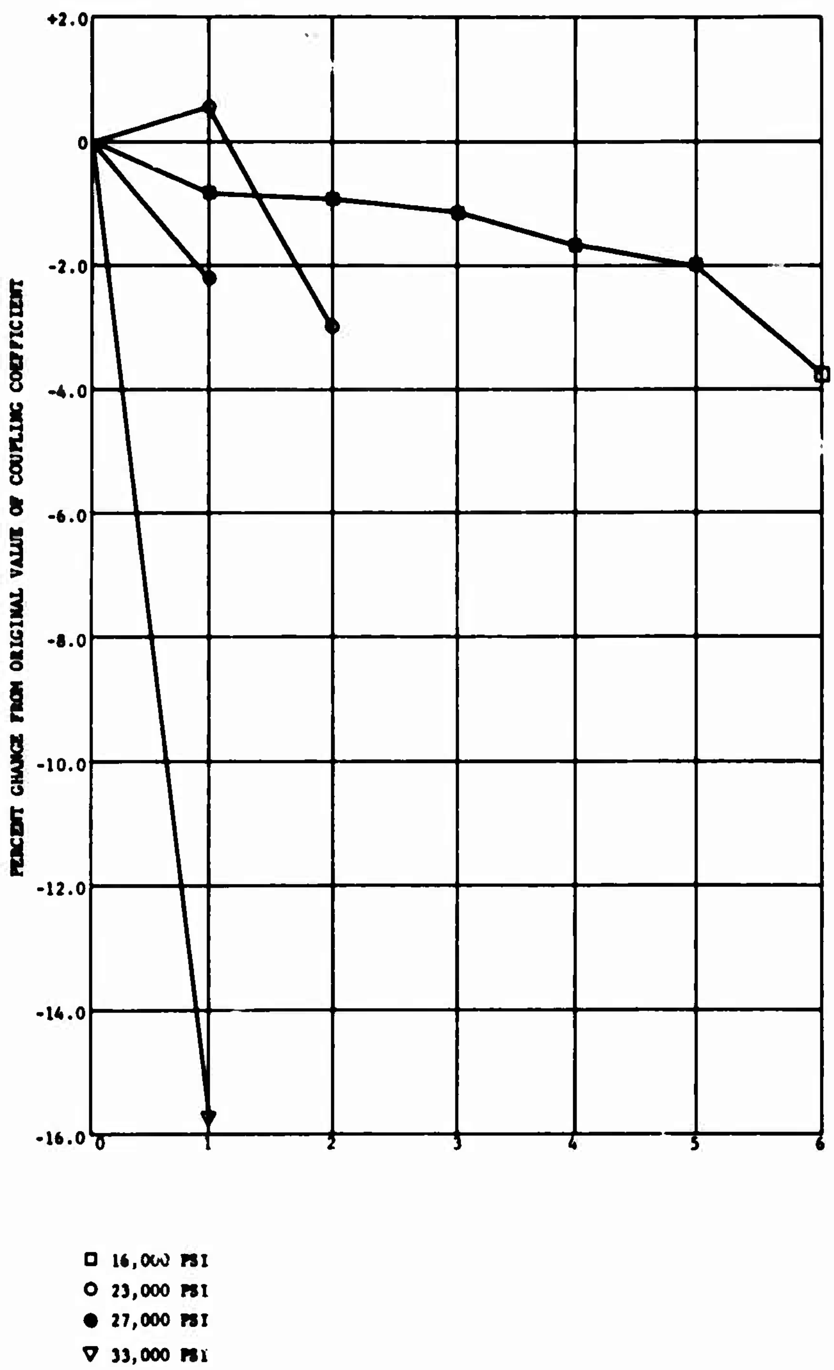


FIGURE 3-19
EFFECT OF IMPACT SHOCKS ON THE COUPLING COEFFICIENT OF EC-64 RINGS

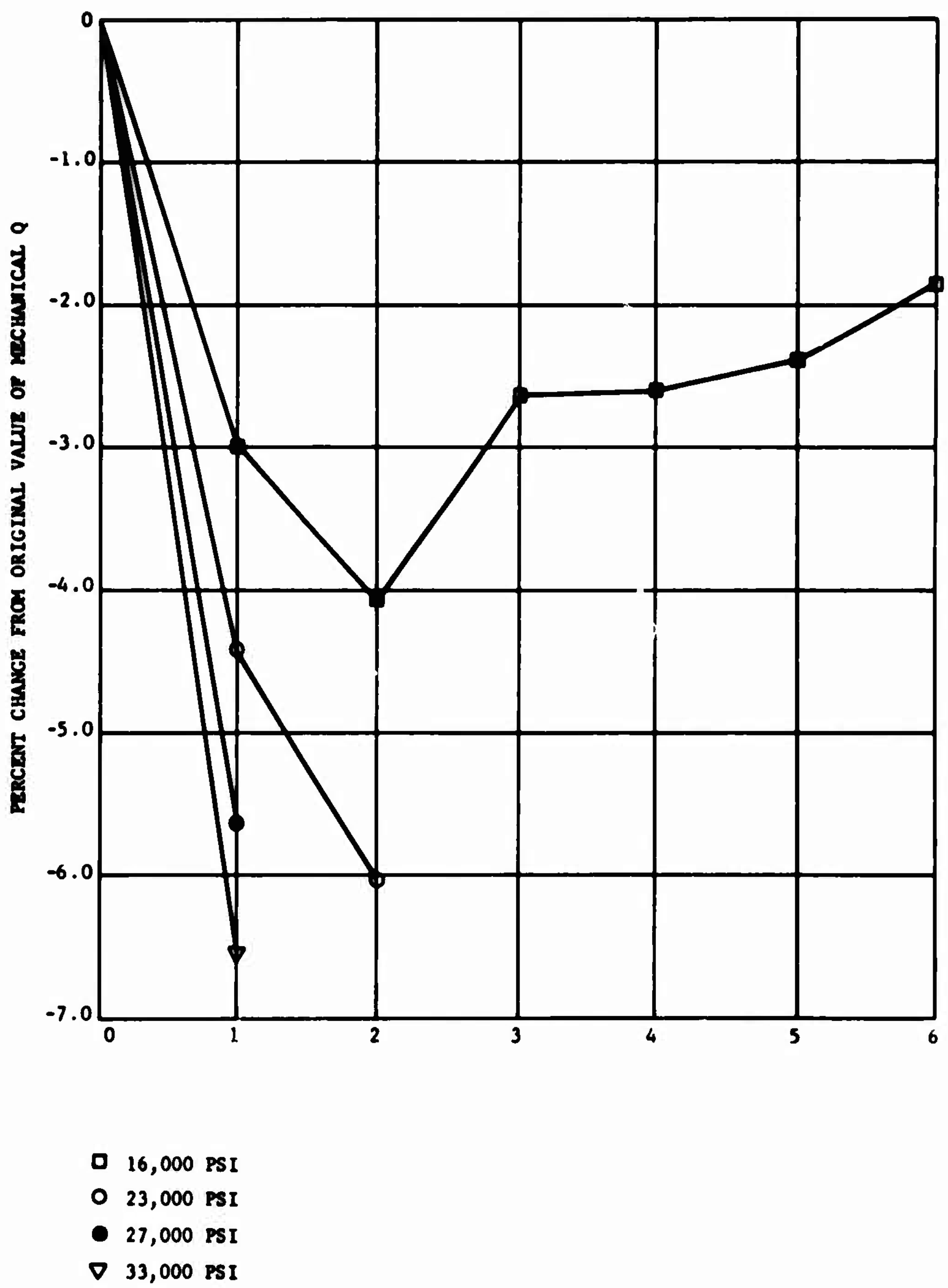


FIGURE 3-20
EFFECT OF IMPACT SHOCKS ON THE MECHANICAL Q OF EC-64 RINGS

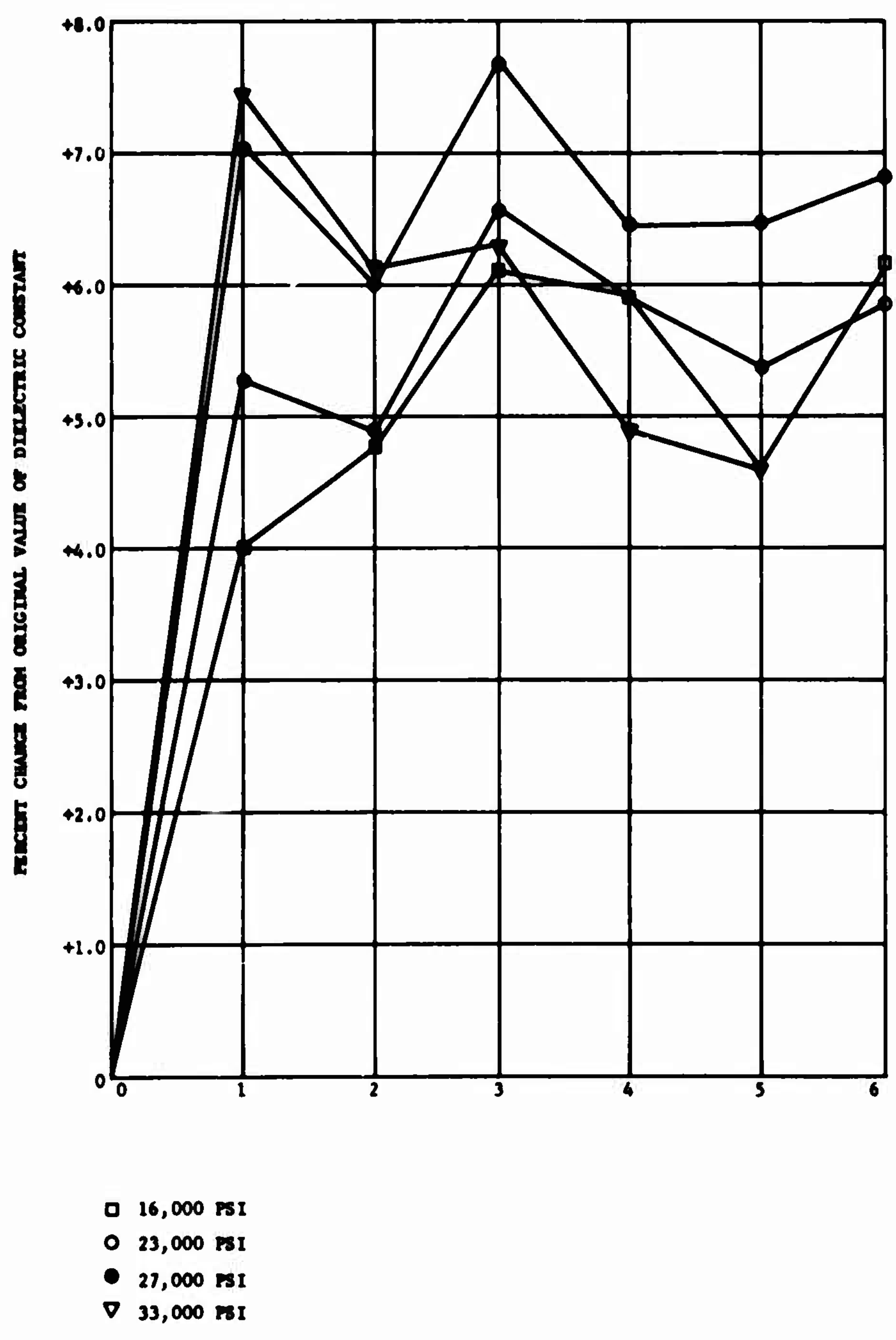


FIGURE 3-21
EFFECT OF IMPACT SHOCKS ON THE DIELECTRIC CONSTANT OF EC-65 RINGS

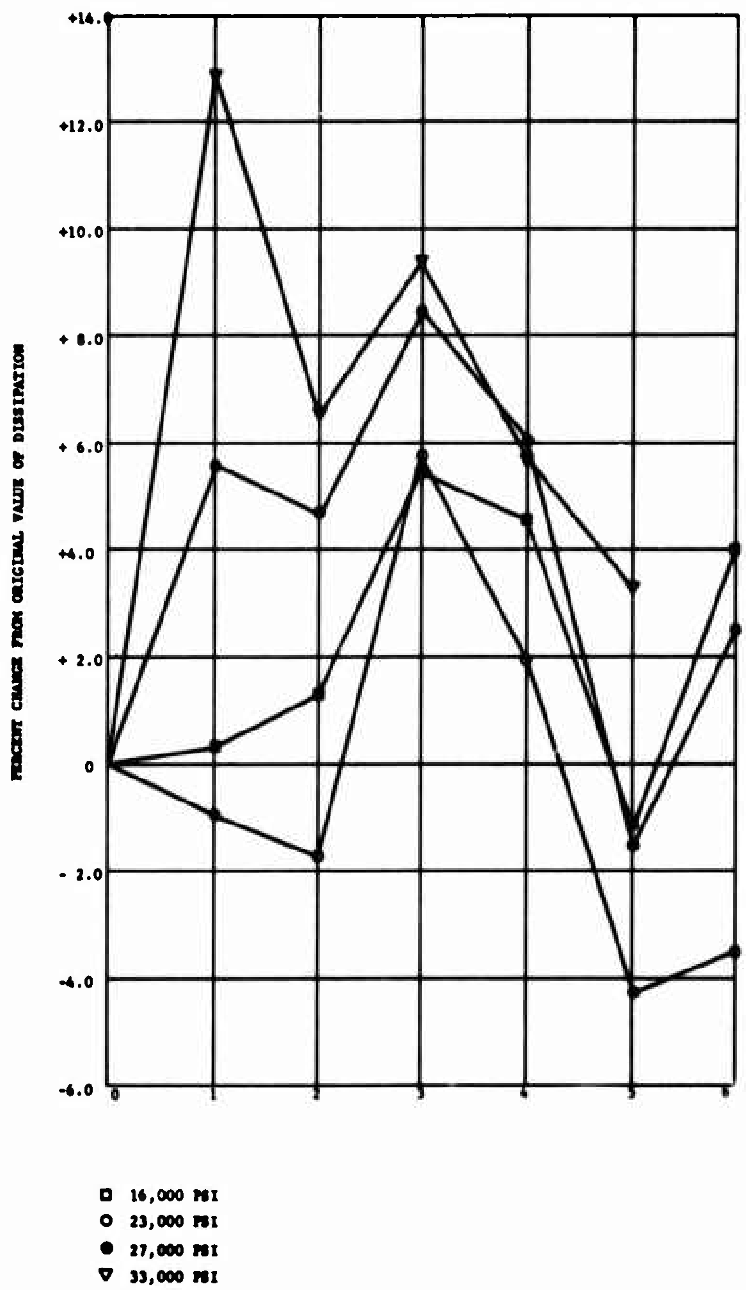


FIGURE 3-22
EFFECT OF IMPACT SHOCKS ON THE DISSIPATION OF EC-65 RINGS

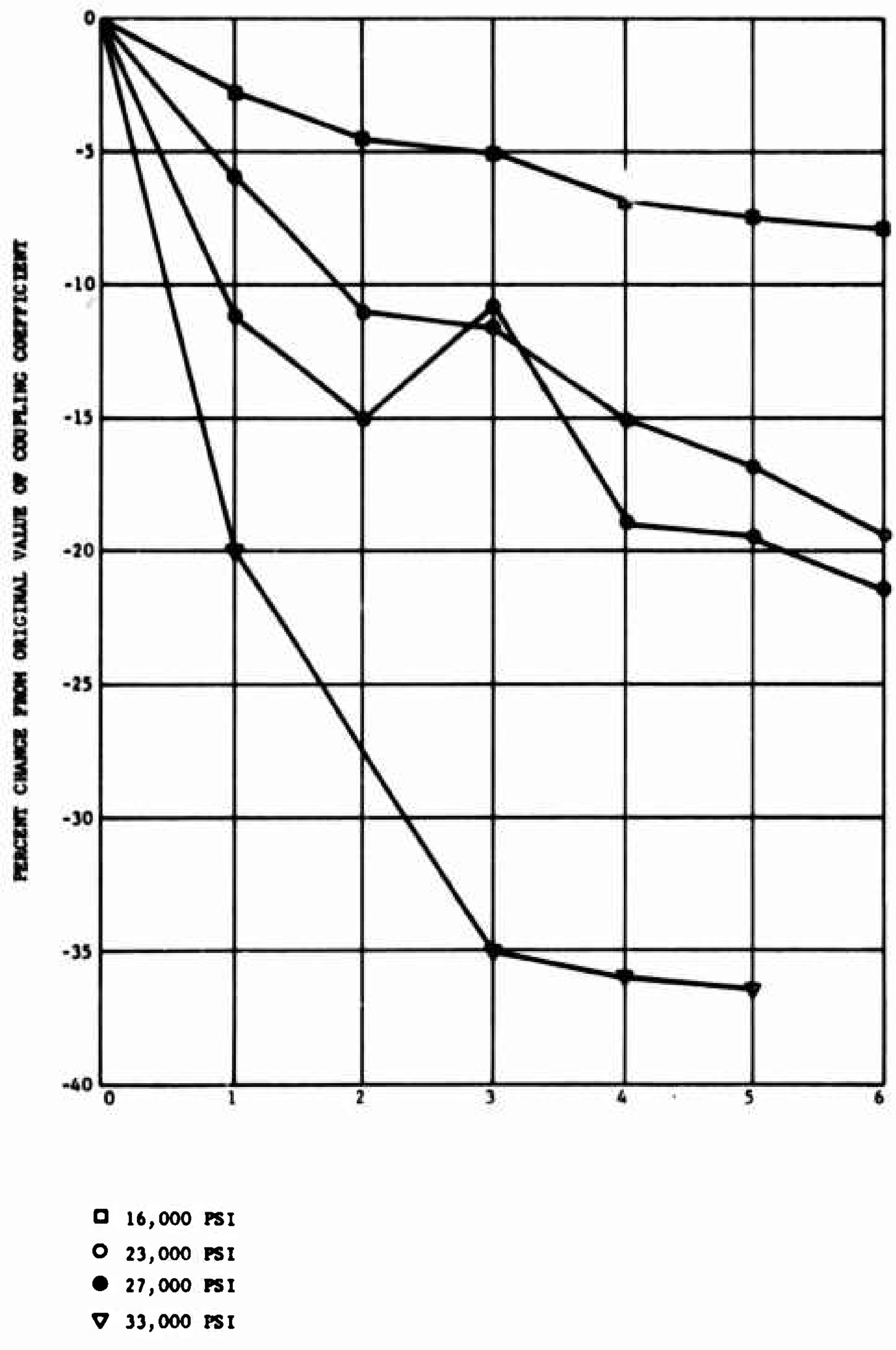


FIGURE 3-23
EFFECT OF IMPACT SHOCKS ON THE COUPLING COEFFICIENT OF EC-65 RINGS

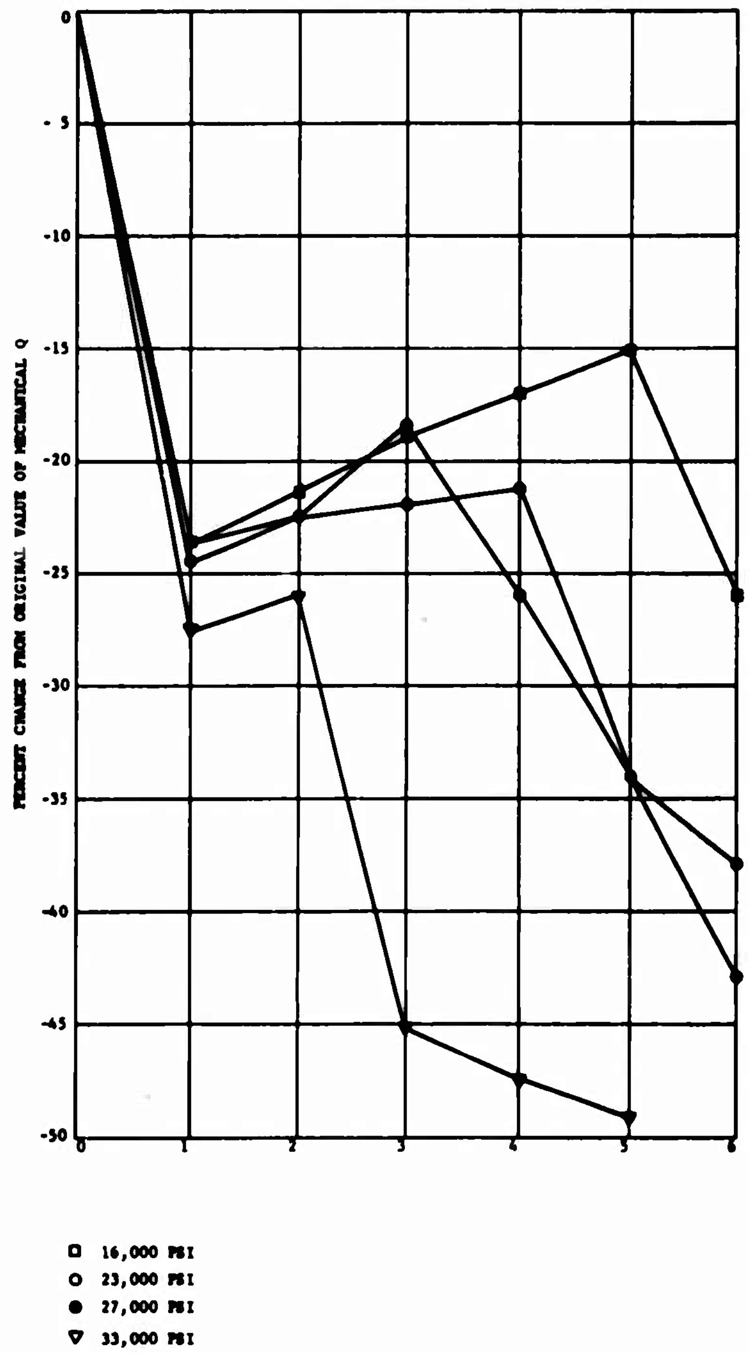


FIGURE 3-24
EFFECT OF IMPACT SHOCKS ON THE MECHANICAL Q OF EC-65 RINGS

4.0 HYDROSTATIC SHOCK TEST

The hydrostatic shock tests were performed to determine the effects of underwater shock waves on the physical and electrical characteristics of mass loaded transducers. These tests were conducted under conditions which simulated the actual operating conditions of the transducers. The shock waves to which the mass loaded transducers were subjected were produced by an underwater detonation of an explosive charge. The shock waves were transmitted through the water directly to the face of the mass loaded transducers.

The results obtained from these tests were compared with results obtained from the life expectancy tests performed on ceramic rings and discs in an unloaded condition, using the laboratory impact shock apparatus. Comparison was made to determine whether or not the mass loading of ceramics and the difference in test conditions between the two tests have any effect on the performance characteristics of piezoelectric ceramic when subjected to impact shocks.

Hydrostatic shock tests were performed on four piezoelectric ceramic compositions of ring and disc configurations. The compositions tested were EC-55, EC-64, EC-65 and EC-69. The ceramic ring configuration was tested because it is most commonly used in the design of mass loaded transducers. The disc configuration was tested so that a comparison could be made between the two configurations.

Hydrostatic shock tests were also performed on ceramic cylinders (1.50" OD x 1.25" ID x 1.50" long) of composition EC-31. EC-31 is a modified barium titanate composition, commonly used in hydrophones or other receiving devices, and low power projectors. The cylinders were electroded using two materials; the conventional fired silver and electroplated nickel. The tests were conducted to determine whether or not the nickel plating would improve the mechanical strength of the cylinder. Theoretically, the nickel plating on the ceramic will apply a compressive force on the walls of the cylinder, thereby increasing its mechanical strength.

4.1 TEST SAMPLE ARRANGEMENT

The ceramic rings and discs were subjected to hydrostatic shocks in a mass loaded condition (reference Figure 4-1). Since the ceramic ring configuration is used primarily in mass loaded transducers, this condition was simulated in the hydrostatic shock test. The mass loaded transducer was comprised of six active ceramic elements, the front and rear masses, and the clamping bolt(s). The ceramic elements were bonded together with Epon VI adhesive with 0.003" copper mesh between ceramics. The purpose of the copper mesh was to maintain a uniform thickness of Epon VI and also for electrical connections of the ceramics. The front and rear masses were secured to the ceramic stack with clamping bolt(s). A torque of 120 in-lb. was applied to each clamping bolt, resulting in a tensile force in the bolt of approximately 667 pounds. This tensile force applies a compression of 377 psi on the ceramic discs, and 972 psi on the ceramic rings.

A Lucite housing for each transducer was used to isolate the transducer from the water (reference Figure 4-2). Isolation of the transducer was necessary to minimize off-axis shock waves. The desired direction of applied pressure to the ceramic stack is parallel to its thickness. Any force not parallel to the ceramic thickness will affect the results of this test. The radiating face of the transducer was covered with Scotch Cast #221 polyurethane. The Scotch Cast #221 does not present a boundry condition to the approaching shock wave because of its matched impedance with water.

The ceramic cylinders were tested in pairs, as shown in Figure 4-3. Each pair consisted of one nickel-plated cylinder and one silvered cylinder. The pair was covered with approximately 3/16" thick PRC-1538 polyurethane. The inside diameter was also filled with PRC-1538. This arrangement closely simulated the conditions of an actual hydrophone.

4.2 TEST PROCEDURE

The electrical characteristics of the individual ceramics were measured with the ceramics in a mass loaded condition. Measurements made were capacitance, dissipation, resonant frequency and corresponding voltage output, and anti-resonant frequency and corresponding voltage output. The resonant and anti-resonant frequencies were measured in the planar mode of vibration. The transducers were then subjected to hydrostatic shock in pairs, as shown in Figure 4-4. The test arrangement in the water is shown in Figure 4-5. The transducers and the explosive charge was suspended in water to a depth of five feet. At this depth, reflections of the shock wave from the surface of the water and the bottom of the pond will have a minimum effect on the transducers. The radiating face of the transducers was positioned to face the explosive charge. All transducers were subjected to the same amplitude hydrostatic charge.

The ceramic cylinders were tested in the arrangement shown in Figure 4-6. One pair of cylinders had its inside diameter filled with PRC-1538 while the other pair was not. The cylinders were subjected to hydrostatic shock in an arrangement similar to that used for the mass loaded transducers.

4.3 DISCUSSION OF RESULTS

The results obtained from two hydrostatic shock tests regarding the mechanical strength of the ceramics were not repeatable. Table 4-1 presents the relative mechanical strengths of the ceramic obtained from the two tests. The results of the first test indicate that the ceramic disc configuration is stronger than the ceramic ring configuration. The second test indicates that both the ring and disc configurations of all compositions have comparable mechanical strengths when subjected to hydrostatic shock of 32,600 psi amplitude. This is lower than the hydrostatic shock amplitude of the first test (34,400 psi). The first test also indicated that the EC-65 rings and discs were stronger than EC-64 and EC-69 rings and discs.

The variations in the results obtained from the two tests may be due to the following:

(a) The water temperature was different for each test. The first test was conducted during the summer months when the water temperature was approximately 20°C. The second test was conducted in 0°C temperature water. At 0°C, the ceramic properties may change, thus decreasing its ability to absorb shocks.

(b) The method of evaluating the changes in the electrical characteristics was unreliable. Electrical measurements for each ceramic is made with the ceramic stack in a mass loaded condition. Tests showed that ceramic stacks displayed multiple responses even when no fractures were present in the ceramic. Mass loading dampens some of the responses.

The electrical measurements for ceramics which had undergone the first hydrostatic shock test could not be made. The acceleration of the transducer caused by the shock wave tore the electrical connections from the ceramic. It is very probable that if electrical measurements were made, they would have indicated that all of the ceramics were fractured. It is believed that the hydrostatic shock amplitudes used (32,600 and 34,400 psi) are greater than the fracture limits of the ceramics in a mass loaded condition.

The capacitance of the ceramics remained relatively unchanged after hydrostatic shock (reference Table 4-2). Any changes that did occur were within the normal statistical distribution of the capacitance of unshocked ceramics.

The mechanical Q and coupling coefficient which are functions of $\Delta f/f_r$ generally increased after hydrostatic shock. The normal trend is a decrease in these two values after shock. The results obtained may be due to the method of evaluating the change in $\Delta f/f_r$ values. Since the ceramic displayed multiple responses, it was difficult to decide which response should be used for calculations.

The general trend of increasing values for dissipation was observed; however, the large changes (as high as x36) in dissipation was not expected. The large changes that occurred after hydrostatic shock may be due to the mass loaded condition of the ceramics. Previous tests indicated that the dissipation of the ceramics does increase with applied pressure. There is also a specific pressure for each composition at which the dissipation of the ceramic reaches a maximum. This may account for the unusually large changes observed.

Table 4-3 presents the test results for ceramic cylinders subjected to hydrostatic shocks. Apparently, 2000 psi is the threshold of the fracture limit for these cylinders. In this amplitude range, 50 percent of the nickel-plated cylinders fractured, and 100 percent of the silvered cylinders fractured. At 1900 psi, no fractures were observed, while at 4500 psi, 100 percent fractures occurred. At the threshold value of 2000 psi, the indications are that the nickel plating did improve the ceramic mechanical strength. No definite statement can be made regarding the effects of the PRC-1538 filling on the mechanical strength of the cylinders.

4.4 CONCLUSIONS

Although the hydrostatic shock tests performed on mass loaded transducers have not resulted in conclusive evidence as to the effects it has on the electrical and physical characteristics of the ceramics, the results obtained do emphasize the necessity and importance of additional testing in this area. The results indicate that the mass loading of ceramics may alter the behavior of the ceramics subjected to impact shocks. Indications of the environmental affects on the ceramic characteristics were also observed, particularly in the lead titanate zirconate compositions.

TABLE 4-1
RELATIVE MECHANICAL STRENGTH

COMPOSITION	CONFIGURATION	SHOCK PRESSURE-PSI	FRACTURES*	TEST NO.**
EC-64	RING	34,400	6/6	1
	DISC	34,400	2/6	1
	RING	32,600	6/6	2
	DISC	32,600	6/6	2
EC-65	RING	34,400	1/6	1
	DISC	34,400	1/6	1
	RING	32,600	6/6	2
	DISC	32,600	6/6	2
EC-69	RING	34,400	6/6	1
	DISC	34,400	1/6	1
	RING	32,600	6/6	2
	DISC	32,600	6/6	2
EC-55	RING	32,600	6/6	2
	DISC	32,600	6/6	2

*THE FRACTIONS REPRESENT THE NUMBER OF CERAMIC RINGS OR DISCS FRACTURED OUT OF A STACK COMPRISED OF SIX TEST SAMPLES.

**DIFFERENT TEST SAMPLES WERE USED ON EACH TEST.

TABLE 4-2
CHANGES IN CERAMIC CHARACTERISTICS DUE TO HYDROSTATIC SHOCK

COMPOSITION	SERIAL NO.	CONFIGURATION	CALCULATED SHOCK AMP PSI	% CHANGE IN $\Delta f/fr$	% CHANGE IN CAPACITANCE	% CHANGE IN DISSIPATION	REMARKS
EC-55	25	RING	32,600	+8.3	+1.4	-2.2	NO VISIBLE FRACTURES OBSERVED. PRESENCE OF MULTIPLE RESPONSES FOR ALL SAMPLES INDICATE FRACTURES.
	26	RING	32,600	+7.6	+1.6	-6.5	
	27	RING	32,600	+15.3	+1.6	+6.8	
	28	RING	32,600	+23.0	+1.7	+6.8	
	29	RING	32,600	+7.1	+1.8	+6.8	
	30	RING	32,600	0	+1.9	+6.8	
			AVERAGE -	+10.2	+1.7	+3.1	
	73	DISC	32,600	+66.7	+1.8	+25.0	NO VISIBLE FRACTURES OBSERVED. PRESENCE OF MULTIPLE RESPONSES FOR ALL SAMPLES INDICATE FRACTURES.
	74	DISC	32,600	+40.0	+1.7	+26.6	
	75	DISC	32,600	+66.7	+1.6	+20.0	
	76	DISC	32,600	+40.0	+1.7	+22.2	
	77	DISC	32,600	+66.7	+1.6	+20.0	
	78	DISC	32,600	+133.3	+3.0	+388.6	
			AVERAGE -	+68.9	+1.9	+79.7	
EC-64	70	RING	32,600	+82.6	+33.6	+11666.7	NO VISIBLE FRACTURES OBSERVED. PRESENCE OF MULTIPLE RESPONSES FOR ALL SAMPLES INDICATE FRACTURES.
	76	RING	32,600	+40.7	+10.8	+1200.0	
	93	RING	32,600	+30.3	+12.7	+4533.3	
	78	RING	32,600	+23.5	+9.4	+1766.6	
	71	RING	32,600	+51.8	+6.8	+900.0	
	75	RING	32,600	+46.1	+9.5	+1766.6	
			AVERAGE -	+45.8	+13.8	+3638.9	
	177	DISC	32,600	-40.0	+1.9	-6.9	NO VISIBLE FRACTURES OBSERVED. PRESENCE OF MULTIPLE RESPONSES FOR ALL SAMPLES INDICATE FRACTURES.
	176	DISC	32,600	-44.4	+2.1	-2.3	
	175	DISC	32,600	-57.1	+2.1	-4.8	
	171	DISC	32,600	-44.4	+2.1	-7.3	
	169	DISC	32,600	-57.1	+2.4	+2.5	
	182	DISC	32,600	-66.7	+2.7	+40.4	
			AVERAGE -	-51.6	+2.2	+3.6	

TABLE 4-2 (Cont'd)
CHANGES IN CERAMIC CHARACTERISTICS DUE TO HYDROSTATIC SHOCK

COMPOSITION	SERIAL NO.	CONFIGURATION	CALCULATED SHOCK AMP PSI	% CHANGE IN $\Delta f/fr$	% CHANGE IN CAPACITANCE	% CHANGE IN DISSIPATION	REMARKS
EC-65	-	RING	32,600	-	-	-	ALL SAMPLES FRACTURED.
	129	DISC	32,600	0	+5.6	+18.3	NO VISIBLE FRACTURES OBSERVED. PRESENCE OF MULTIPLE RESPONSES FOR ALL SAMPLES INDICATE FRACTURES.
	130	DISC	32,600	0	-37.3	+5.6	
	123	DISC	32,600	0	-2.8	+13.8	
	117	DISC	32,600	18.1	-2.6	+15.1	
	118	DISC	32,600	0	-37.7	+9.2	
	119	DISC	32,600	0	+6.0	+12.6	
			AVERAGE -	-3.0	-11.5	+12.4	
EC-69	-	RING	32,600	-	-	-	ALL SAMPLES FRACTURED.
	69	DISC	32,600	+66.7	+1.7	+287.5	NO VISIBLE FRACTURES OBSERVED. PRESENCE OF MULTIPLE RESPONSES FOR ALL SAMPLES INDICATE FRACTURES.
	43	DISC	32,600	0	+1.2	+255.5	
	37	DISC	32,600	0	+1.2	+300.0	
	51	DISC	32,600	+28.5	+1.3	+325.0	
	50	DISC	32,600	+40.0	+1.8	+141.1	
	55	DISC	32,600	+200.0	+12.3	+5150.0	
			AVERAGE -	+55.9	+3.3	+1076.5	

TABLE 4-3
TEST RESULTS
HYDROSTATIC SHOCK ON EC-31 CYLINDERS

ELECTRODE MATERIAL	SHOCK PRESSURE-PSI	FRACTURES
NICKEL PLATED	2000	1/2
SILVERED	2000	2/2
NICKEL PLATED	4500	1/1
SILVERED	4500	1/1
NICKEL PLATED	1900	0/2
SILVERED	1900	0/2
*NICKEL PLATED	1900	0/2
*SILVERED	1900	0/2

*INSIDE DIAMETER FILLED WITH PRC-1538 POLYURETHANE

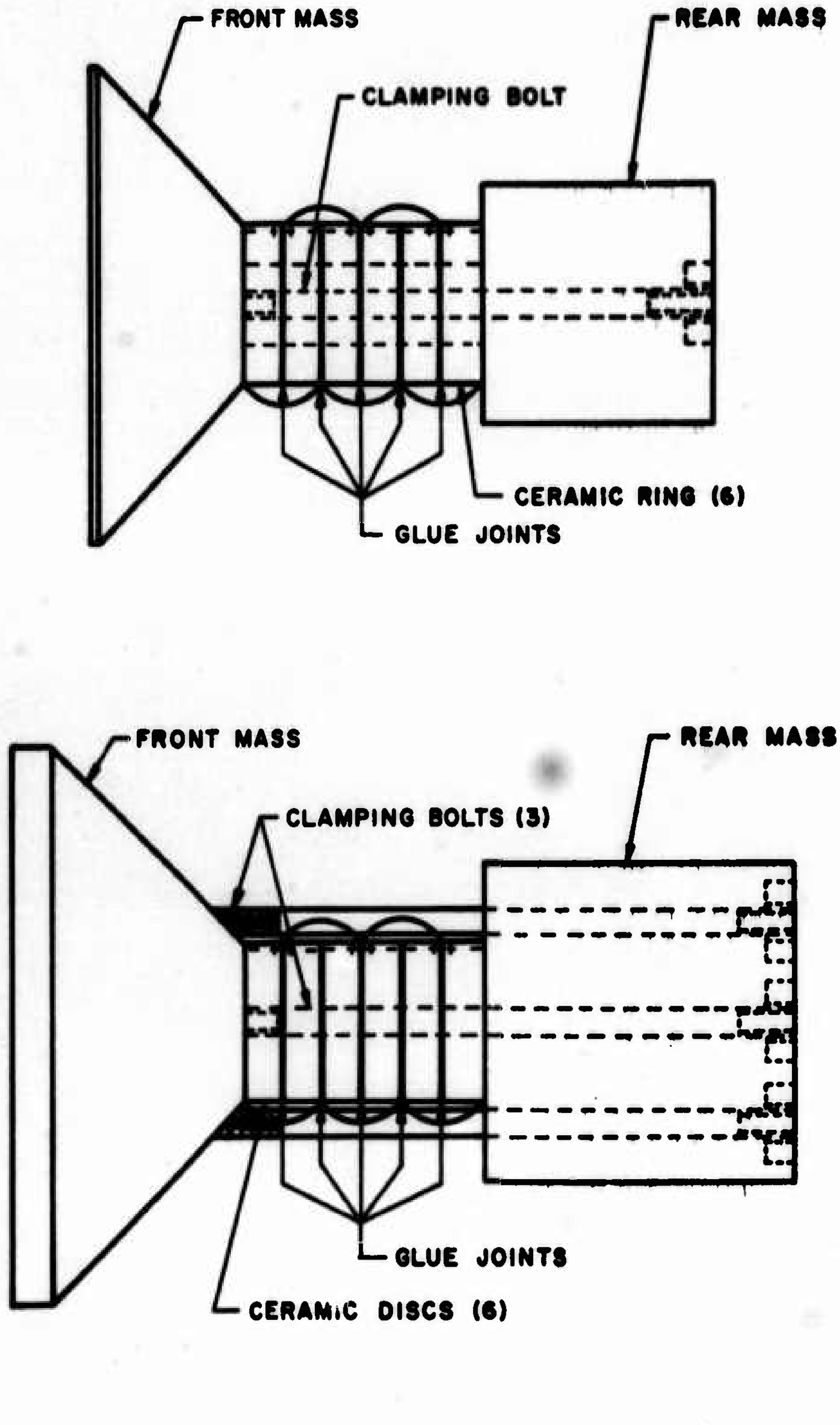


FIGURE 4-1
MASS LOADED TRANSDUCER

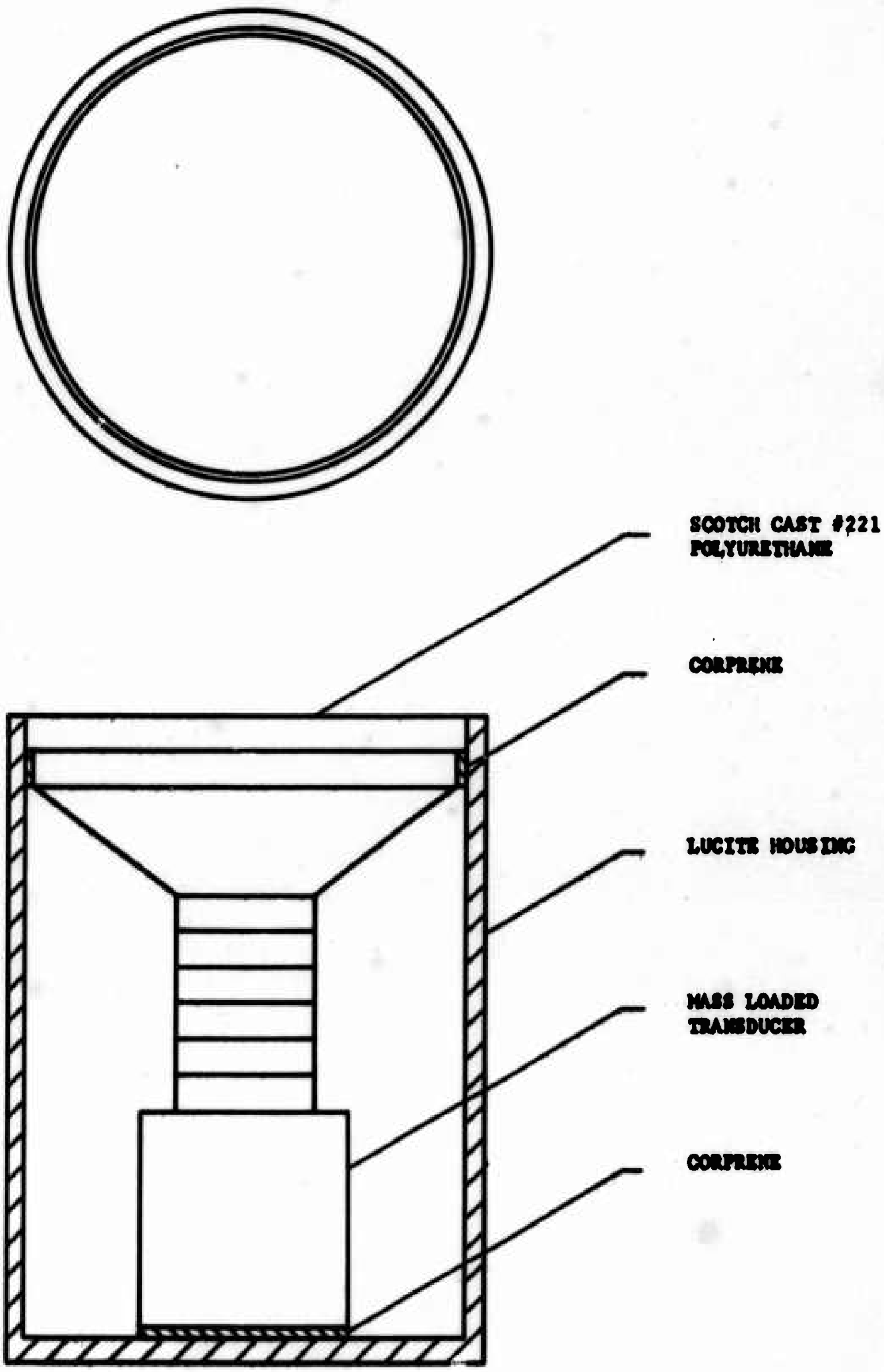


FIGURE 4-2
TRANSDUCER HOUSING

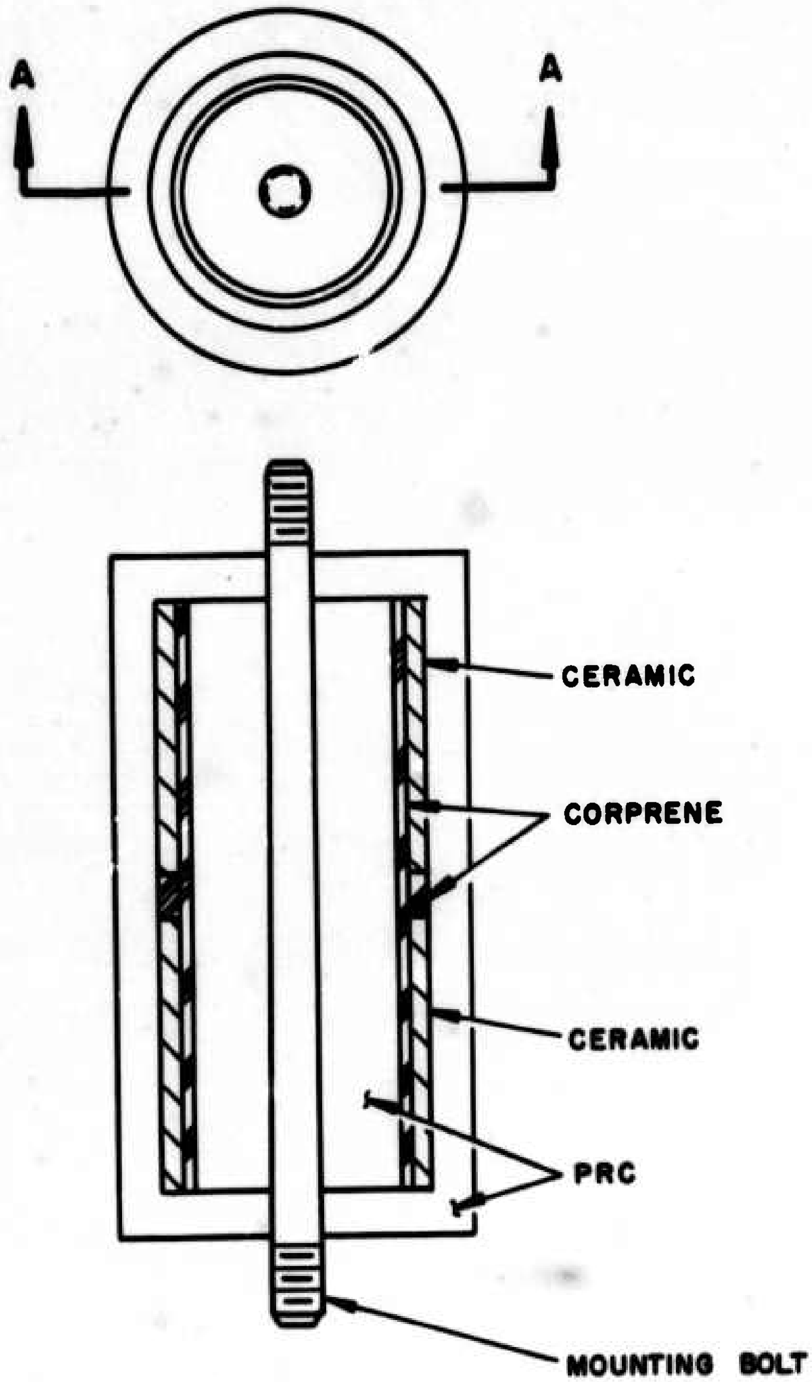


FIGURE 4-3
CERAMIC CYLINDER

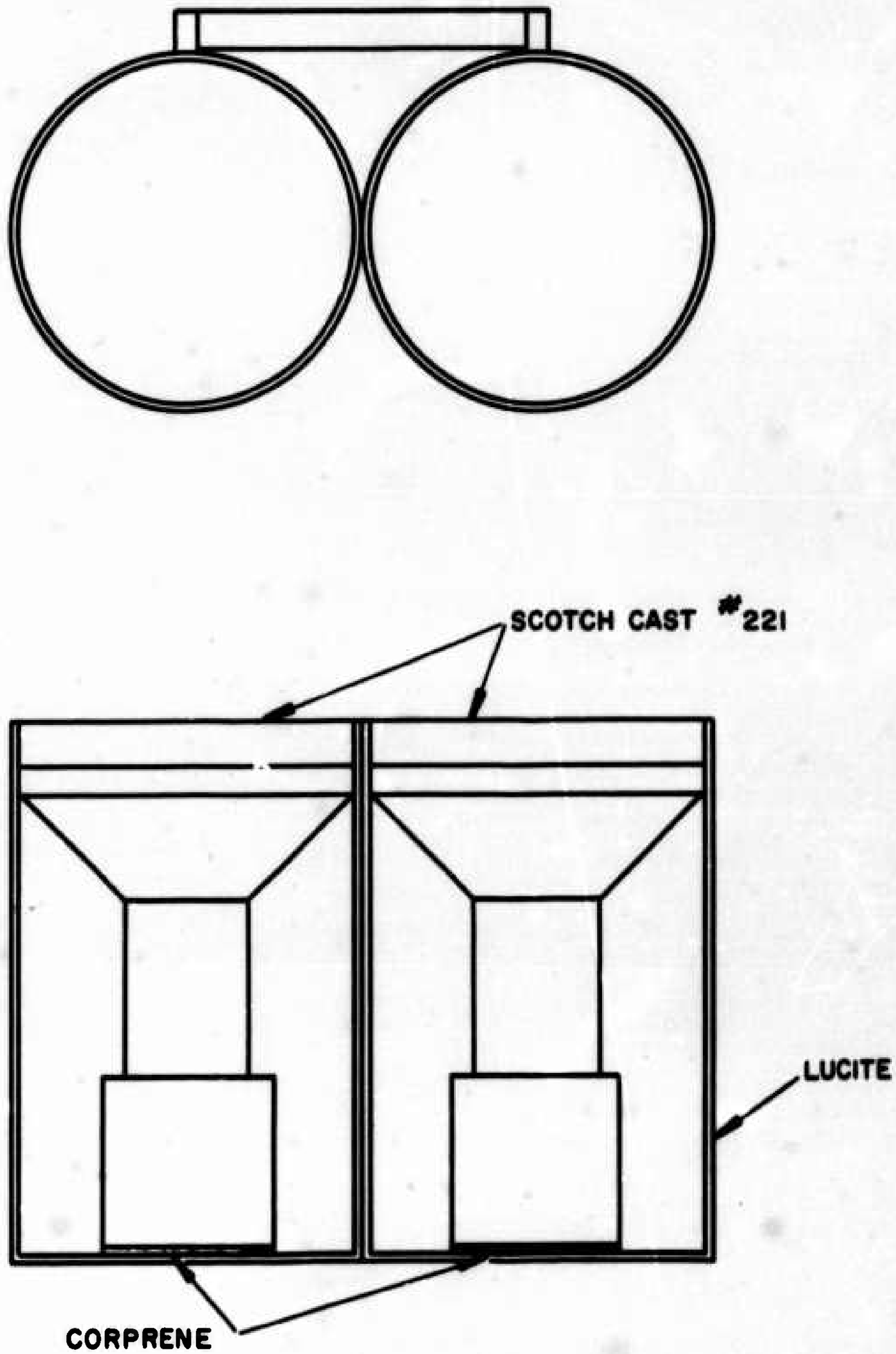


FIGURE 4-4
MASS LOADED TRANSDUCER TEST ARRANGEMENT

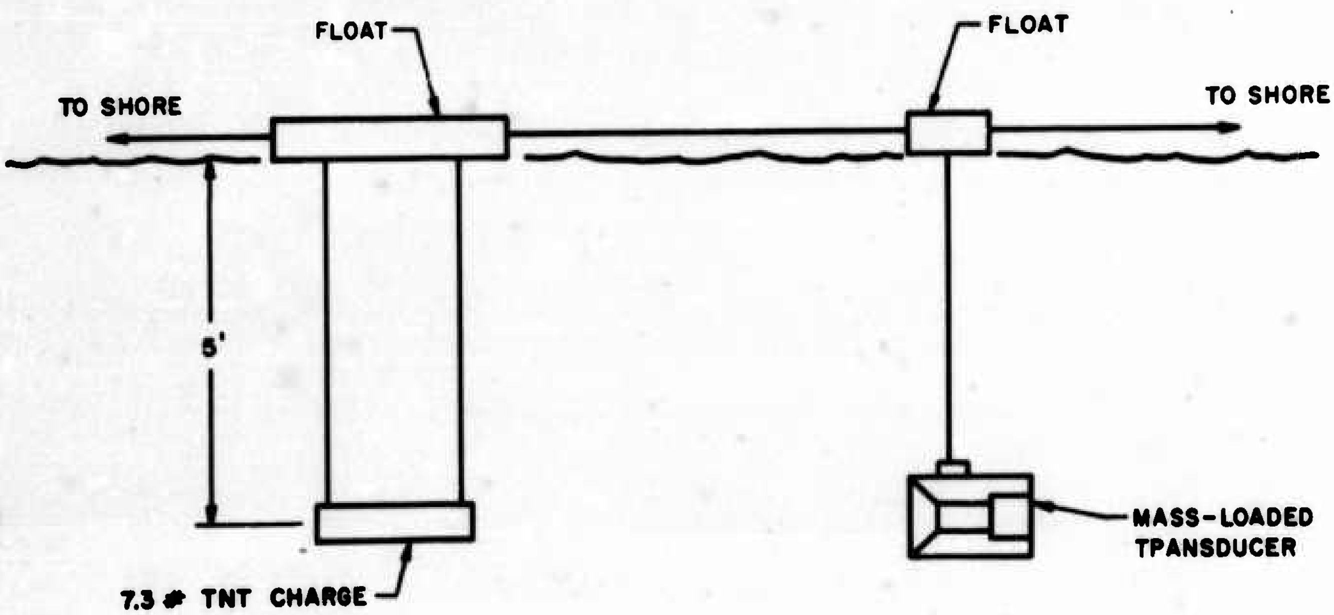


FIGURE 4-5
MASS LOADED TRANSDUCER AND EXPLOSIVE CHARGE ARRANGEMENT IN WATER

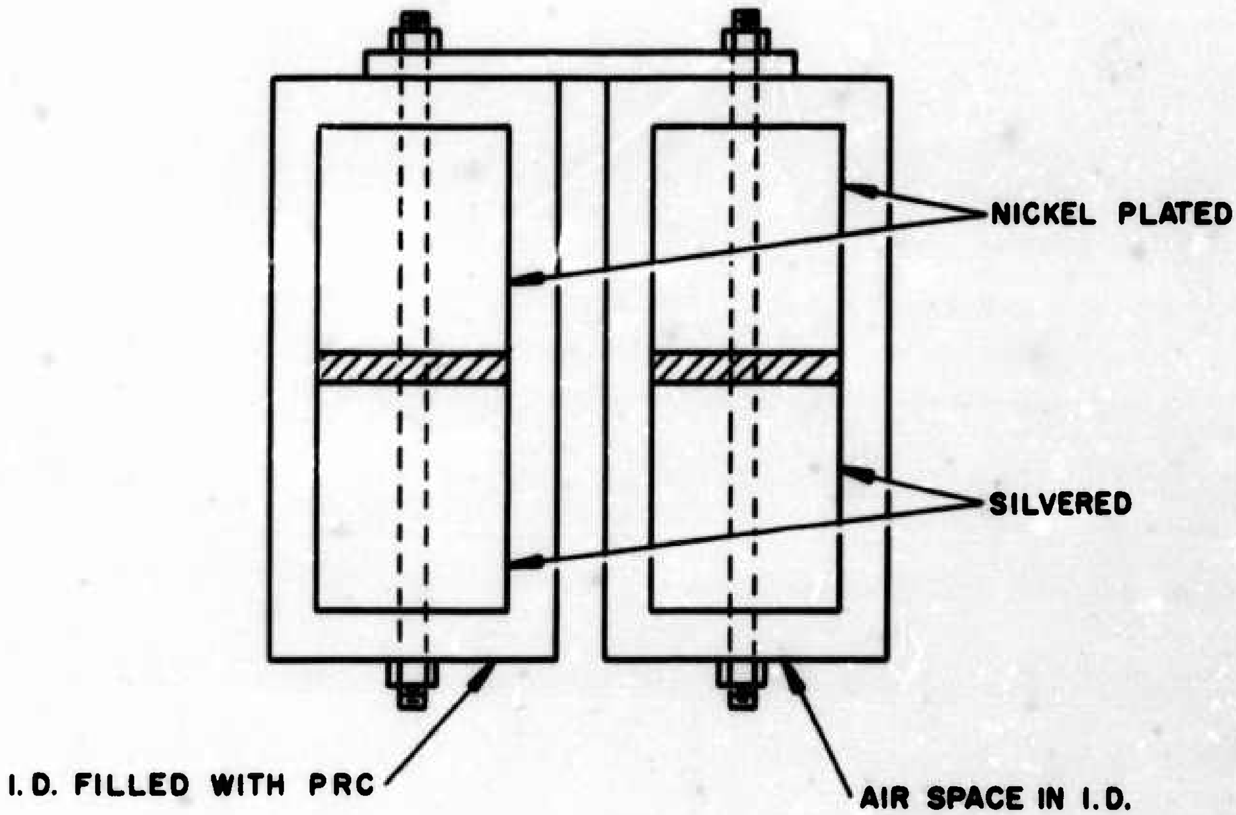


FIGURE 4-6
CERAMIC CYLINDER TEST ARRANGEMENT

5.0 IMPACT SHOCK TEST ON MASS LOADED TRANSDUCERS

Impact shock tests were conducted to determine the effects of impact shock on mass loaded transducers, and also to correlate the results obtained from this test and results obtained from life expectancy tests. Results from the hydrostatic shock test indicated that the performance of the ceramic in a mass loaded condition differed from non-mass loaded ceramics when subjected to impact shock. It is believed that the hydrostatic shock test conditions may have contributed to the contradictory results obtained from these tests and the life expectancy tests. Therefore, it was necessary to perform the impact shock test on mass loaded transducers to determine if mass loading and/or hydrostatic test conditions affect the performance of the ceramics.

Ceramic rings and discs of compositions EC-55, EC-64, EC-65 and EC-69 were tested in the mass loaded condition. The mass loaded transducers were similar to those used in the hydrostatic shock test (reference Figure 4-1).

5.1 TEST PROCEDURE

The electrical properties of each transducer were measured. Frequency response curves were also taken for each transducer. Electrical measurements for the individual ceramic elements were not made because previous tests indicated that this method of evaluation was unreliable. The transducers were then subjected to impact shock using the laboratory impact shock apparatus shown in Figure 2-2. Each disc transducer was subjected to one 21,000 psi impact shock and each ring transducer was subjected to one 54,000 psi impact shock. The electrical properties were measured and frequency response curves were taken for each transducer after impact shock. It should be noted that the temperature during testing was approximately 4°C.

5.2 DISCUSSION OF RESULTS

The changes that occurred in the electrical characteristics of the mass loaded transducers after impact shock are presented in Table 5-1. Generally, the changes that did occur in the electrical characteristics were in agreement with results obtained from the life expectancy tests. Changes in the dielectric constant were within the normal statistical distribution of the test samples before impact shock. The dissipation for the mass loaded transducers increased after impact shock as indicated by life expectancy tests. The values of $\Delta f/f_r$, where $\Delta f = fa - f_r$ and fa = anti-resonant frequency and f_r = resonant frequency, decreased after impact shock, resulting in a decrease in the values of the coupling coefficient. The changes in the values of mechanical Q were not consistent with results obtained from life expectancy tests. These values either increased or decreased after impact shock; however, the results do indicate the susceptibility of this characteristic to impact shock.

All of the mass loaded ceramic discs displayed multiple responses, while only the mass loaded EC-69 rings displayed multiple responses. Therefore, the mass loaded ceramic rings were able to withstand higher impact shock than the mass loaded ceramic discs. This was also indicated by life expectancy test results.

Figures 5-1 through 5-8 present the frequency response curves for the mass loaded ceramic discs and rings, respectively. Changes in the frequency response after impact shock are indicated by arrows.

5.3 CONCLUSION

The results obtained from the impact shock test on mass loaded transducers are in agreement with the results obtained from life expectancy tests; however, the results do not agree with the results from hydrostatic shock tests on mass loaded transducers. This indicates that the test conditions in the hydrostatic shock test are probably contributing to the performance characteristics of the ceramics, such that contradictory results are obtained. Also, the shock wave produced by an underwater detonation (as in the hydrostatic shock test) and transmitted through the water directly to the test sample may have a different waveform than produced by the impact shock apparatus. Still another factor is that the front and rear masses are accelerated due to the hydrostatic shock. The masses are not accelerated when subjected to impact shock using the laboratory apparatus.

TABLE 5-1
EFFECT OF IMPACT SHOCK ON MASS LOADED TRANSDUCERS

COMP.	CONFIG.	PRESS. PSI	% CHANGE CAPACITANCE	% CHANGE DISSIPATION	% CHANGE COUPL. COEFF.	% CHANGE MECH. Q	% CHANGE $\Delta f/fr$
EC-55	RING	54,000	+0.6	+8.0	-0.8	+20.1	-3.6
	DISC	21,000	0.0	+103.3	----	-----	-37.5
EC-64	RING	54,000	0.0	+38.7	-2.4	+125.0	-5.5
	DISC	21,000	-4.9	+2.5	-1.8	-19.0	-4.6
EC-65	RING	54,000	+3.7	+16.6	-6.1	+152.0	-15.3
	DISC	21,000	-3.5	+7.6	----	----	-44.4
EC-69	RING	54,000	+1.1	+2700.0	-34.8	-58.3	-62.5
	DISC	21,000	-5.4	+8.6	-15.7	+119.0	-36.5

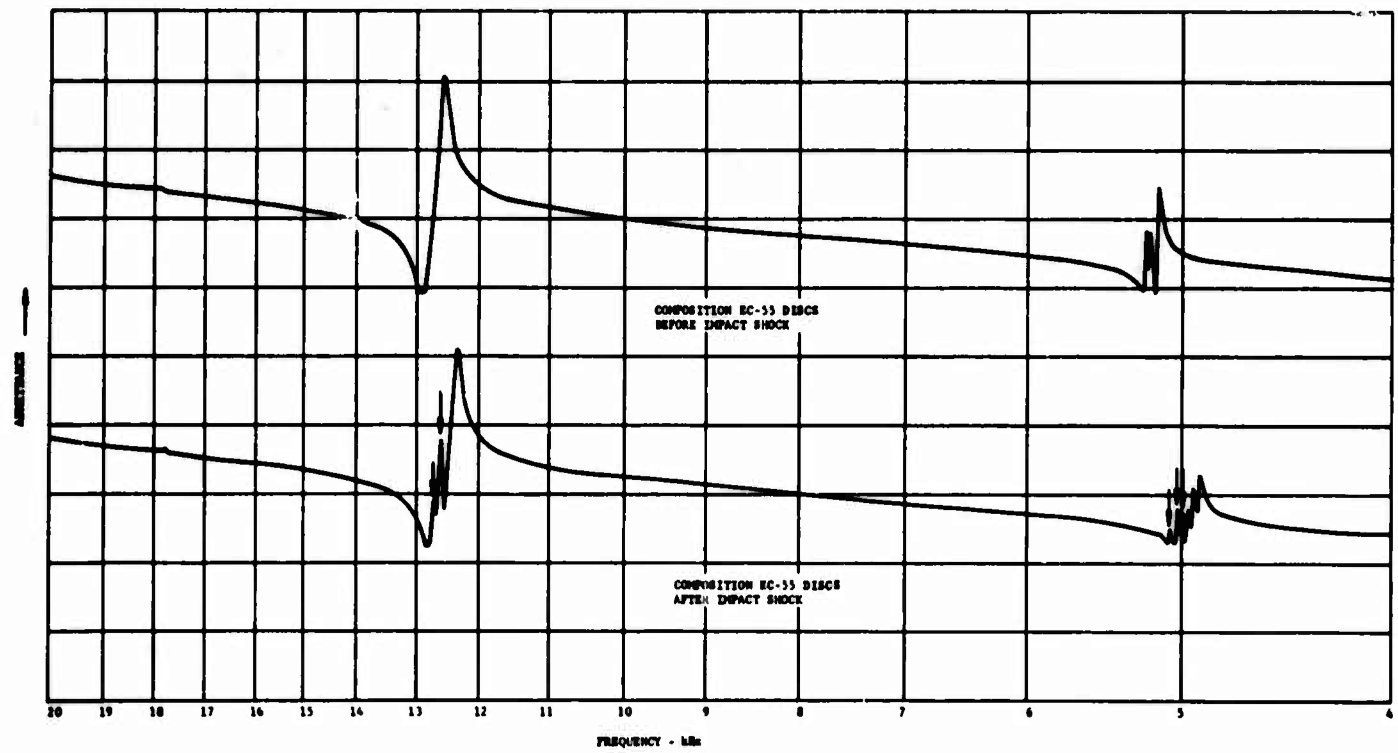


FIGURE 5-1
FREQUENCY RESPONSE FOR MASS LOADED EC-55 DISCS

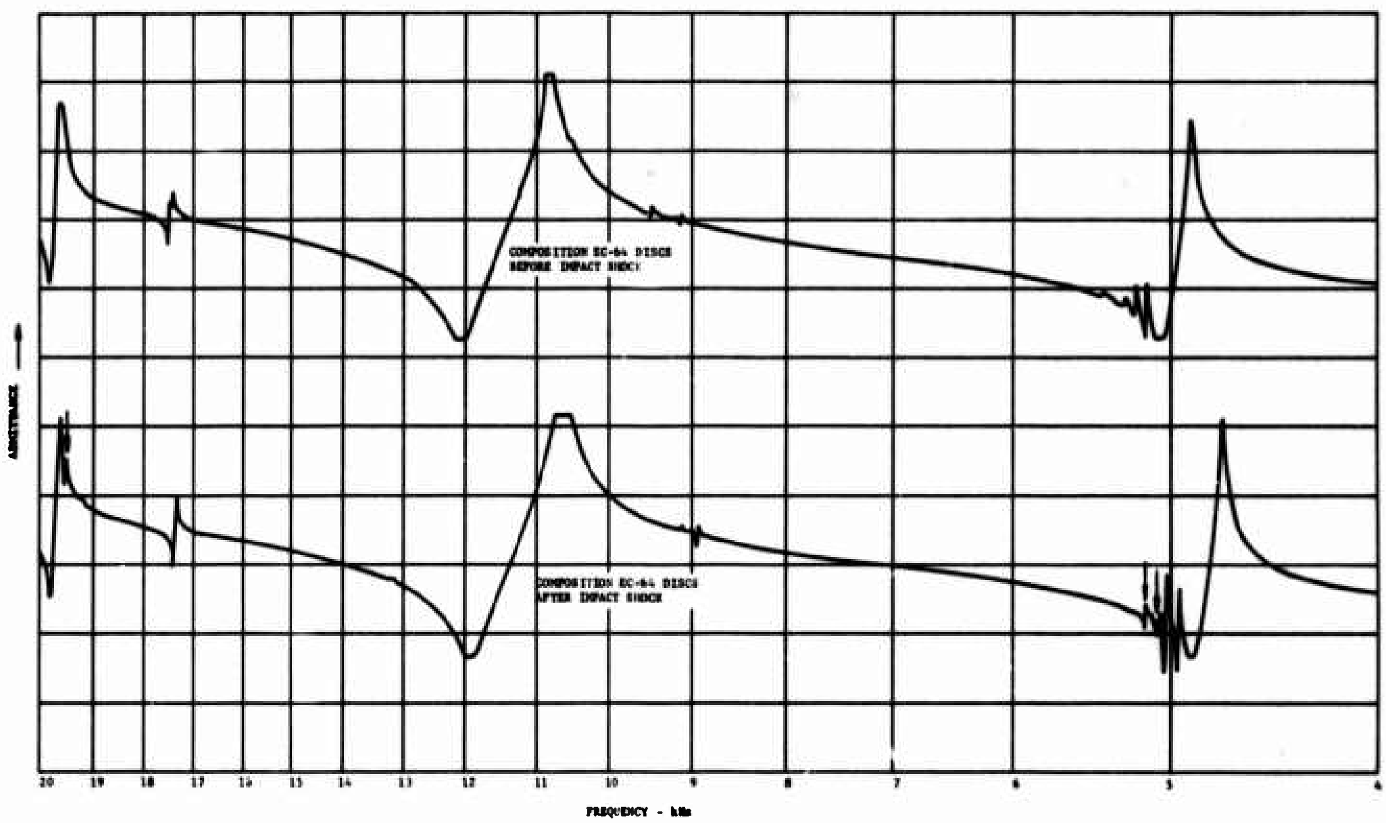


FIGURE 5-2
FREQUENCY RESPONSE FOR MASS LOADED EC-64 DISCS

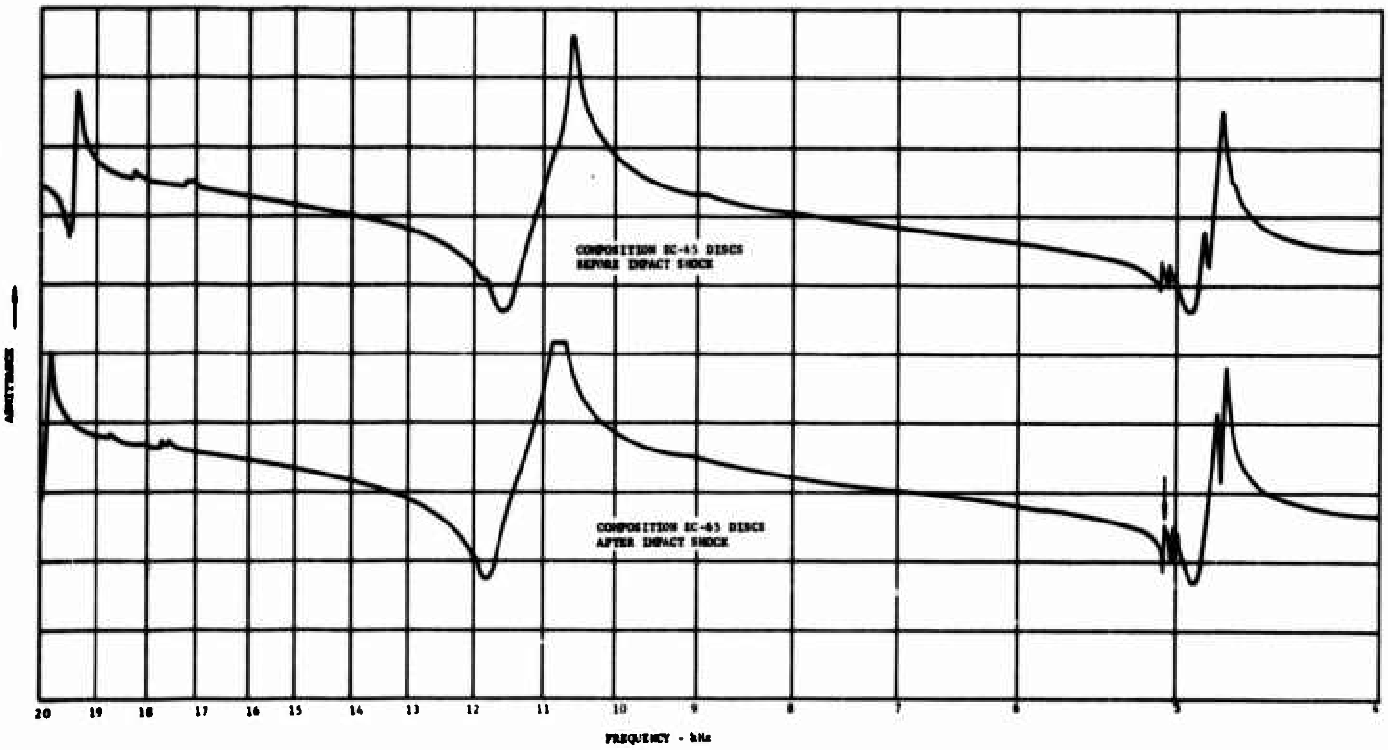


FIGURE 5-3
FREQUENCY RESPONSE FOR MASS LOADED EC-65 DISCS

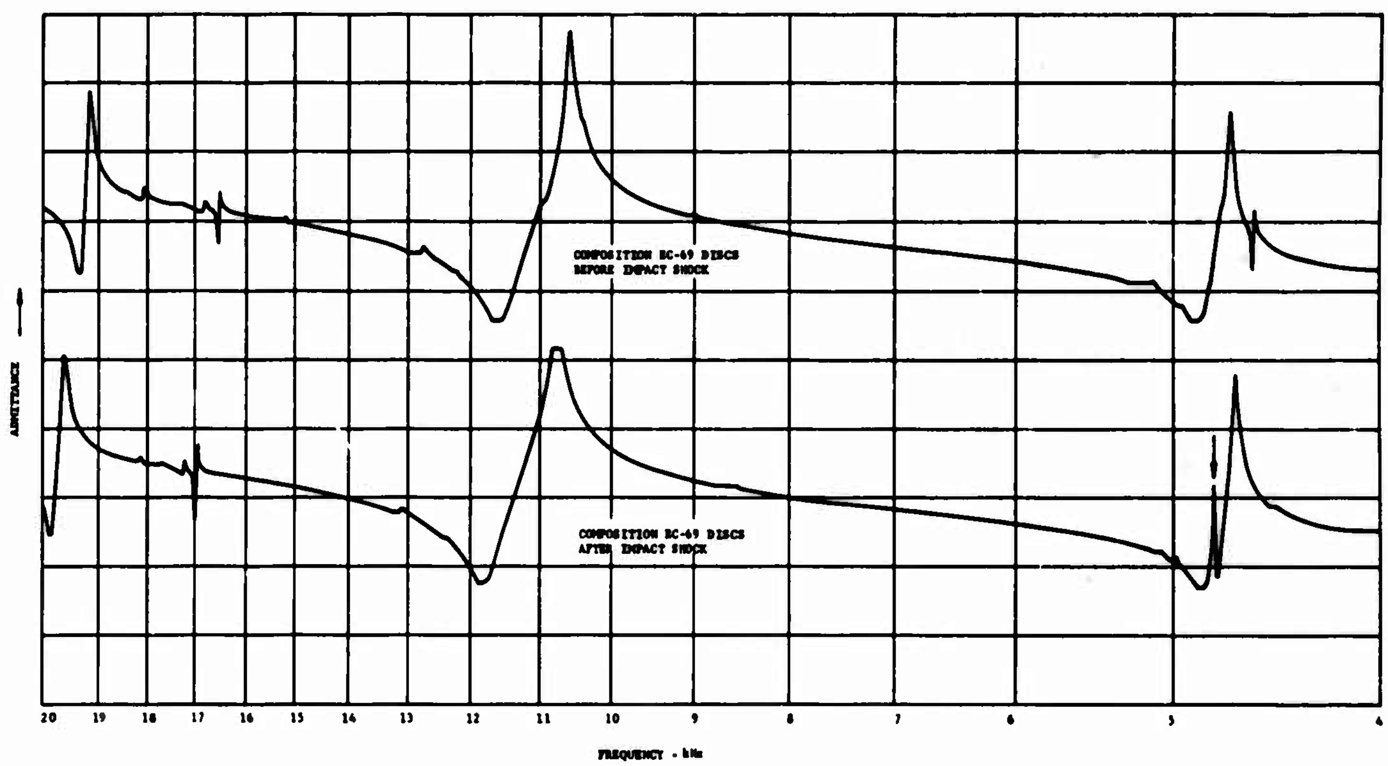


FIGURE 5-4
FREQUENCY RESPONSE FOR MASS LOADED EC-69 DISCS

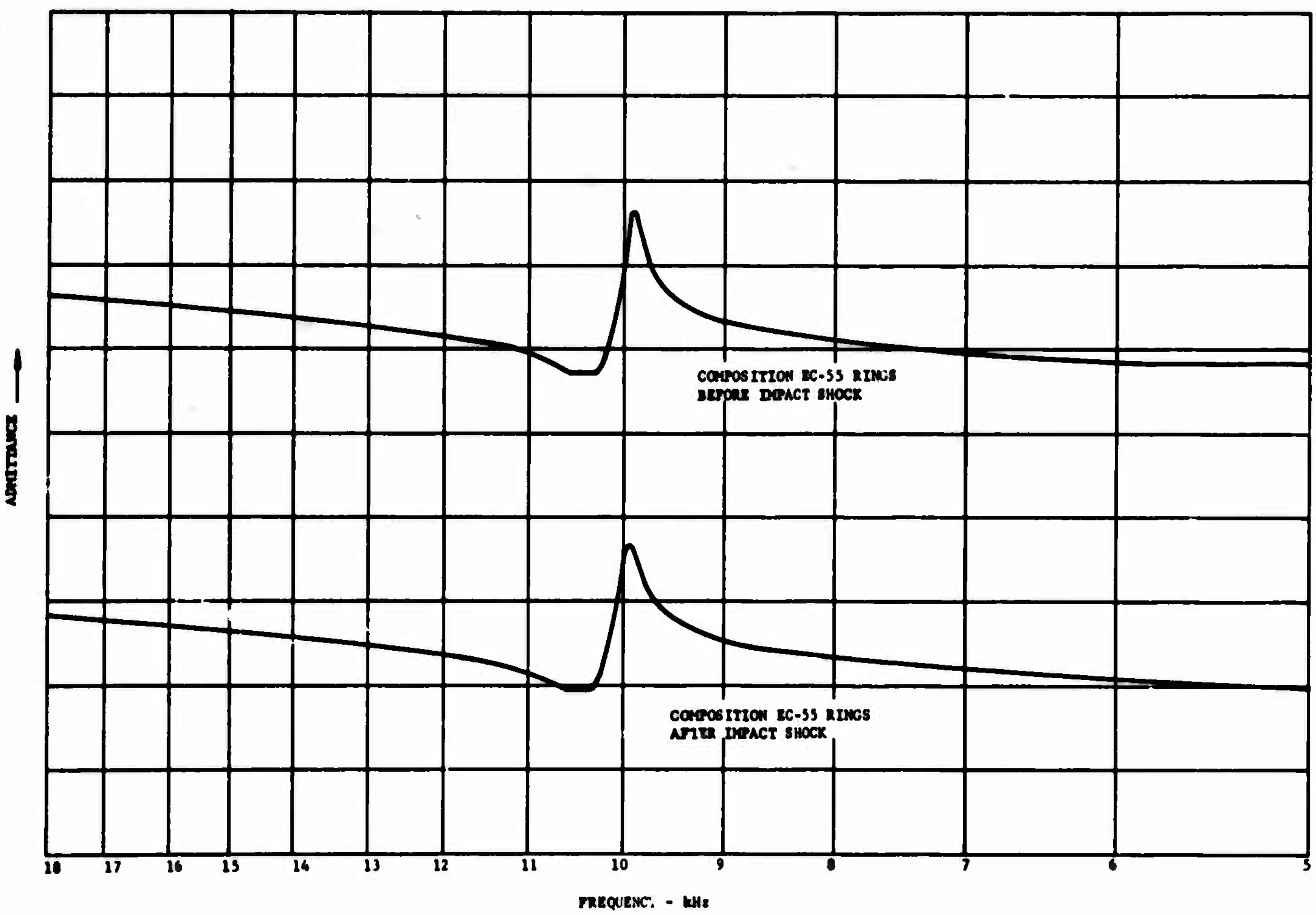


FIGURE 5-5
FREQUENCY RESPONSE FOR MASS LOADED EC-55 RINGS

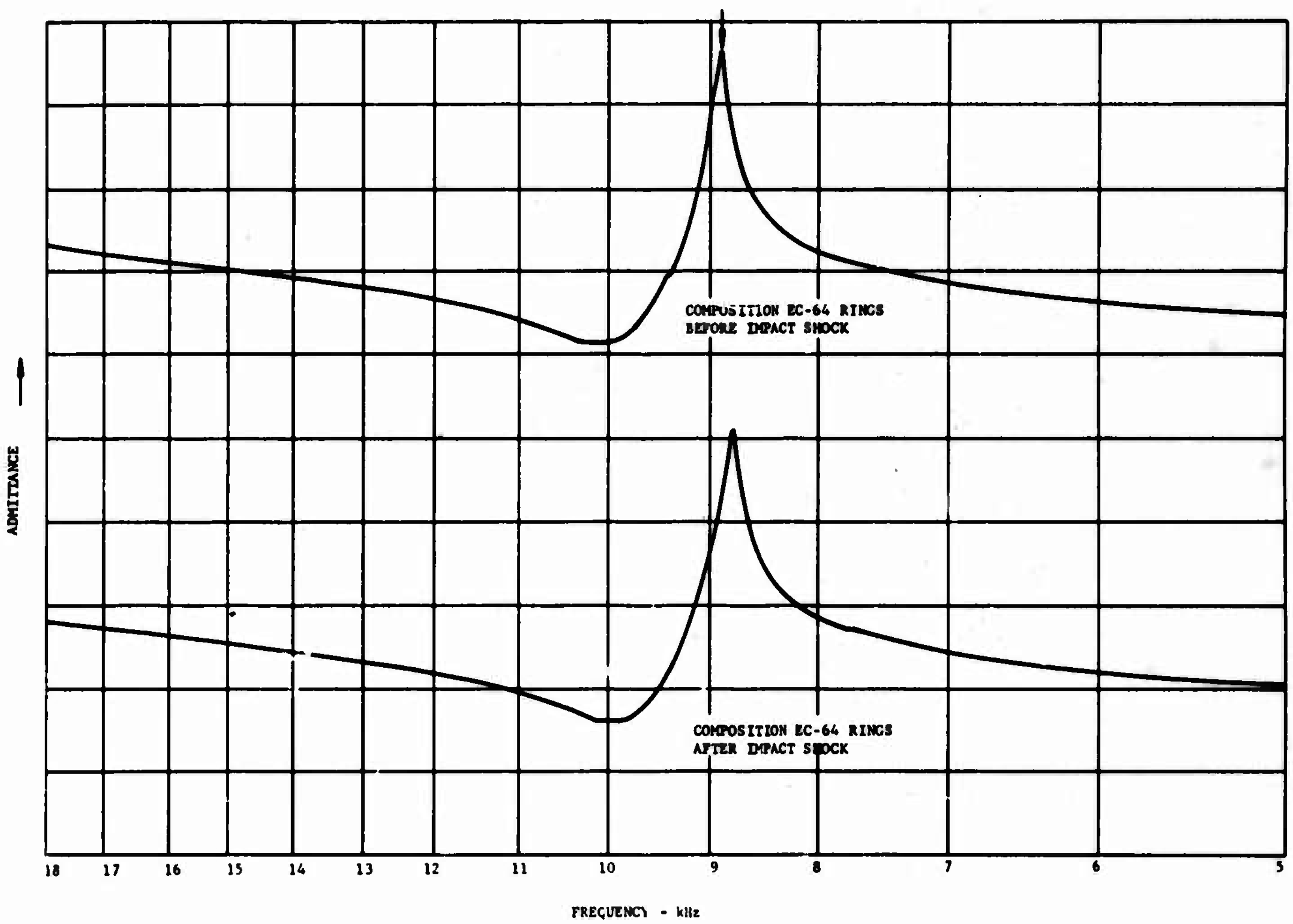


FIGURE 5-6
FREQUENCY RESPONSE FOR MASS LOADED EC-64 RINGS

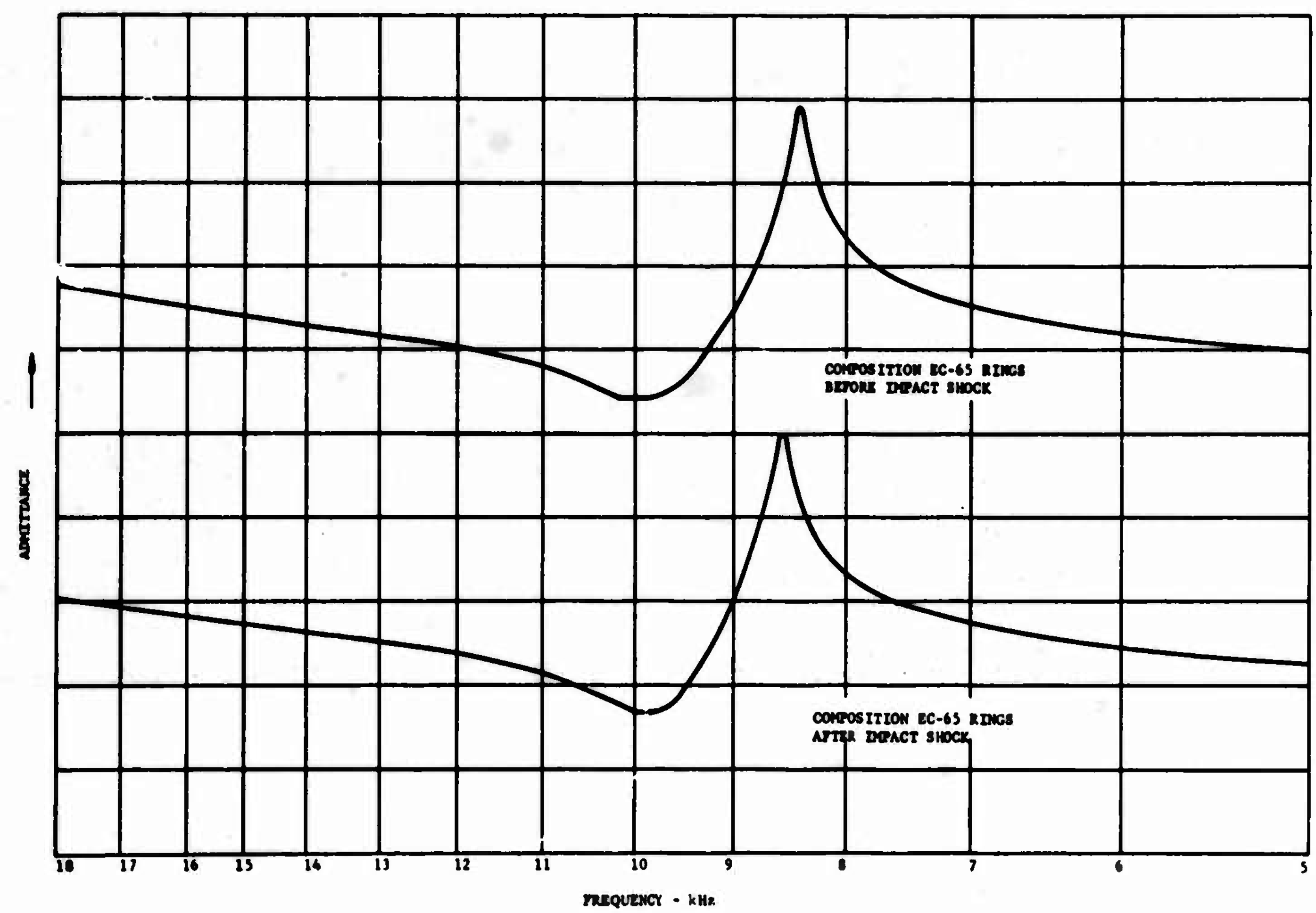


FIGURE 5-7
FREQUENCY RESPONSE FOR MASS LOADED EC-65 RINGS

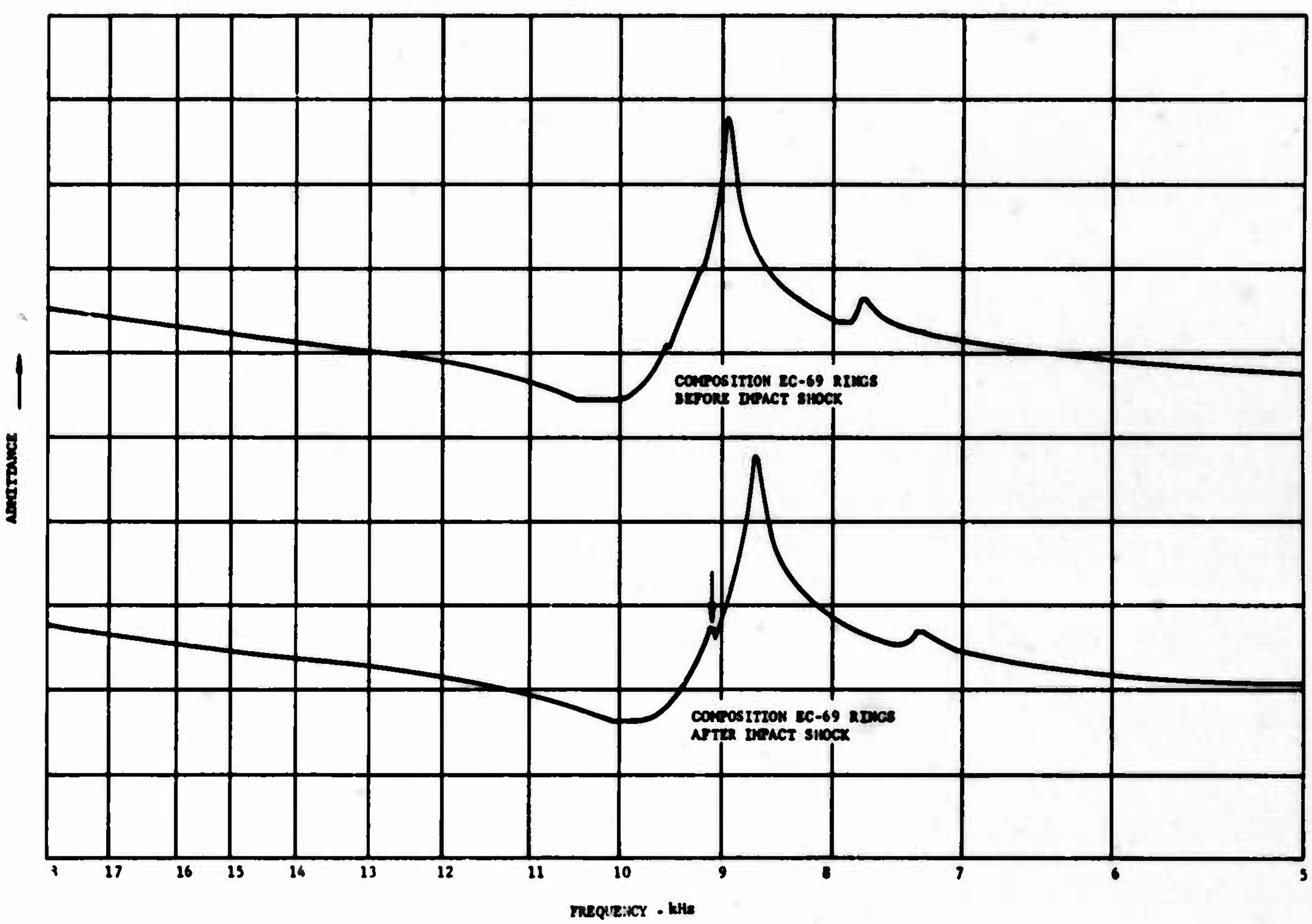


FIGURE 5-8
FREQUENCY RESPONSE FOR MASS LOADED EC-69 RINGS

6.0 DRIVING VOLTAGE TEST

The driving voltage test was performed to determine whether or not microfractures in ceramics can be propagated by driving the ceramic in the planar and thickness modes of vibration.

Four piezoelectric ceramic compositions were studied in this test. These were EC-55, EC-64, EC-65 and EC-69. All of the test samples were of a disc configuration. The disc configuration was used because previous tests performed indicated that this configuration was more susceptible to impact shocks than the ring configuration. The change in the values of $\Delta f/f_r$, which is indicative of fractures occurring in the ceramic, is more prominent in discs than in rings. Therefore, by using the disc configuration, it is more probable that microfractures are present making the test results more valid.

6.1 TEST PROCEDURES

The ceramic discs were first measured for their electrical characteristics. Four discs of each composition were measured for the resonant frequency in the radial mode and four for the resonant frequency in the thickness mode. The discs were then arranged in stacks comprised of eight elements, as shown in Figure 6-1. Four of the discs in a stack were measured in the thickness mode and the other four discs were measured in the radial mode. Each stack was comprised of discs of the same composition and was subjected to one impact shock. The stacks were shocked at 6,000 psi, 11,000 psi, 16,000 psi and 21,000 psi, using the laboratory shock apparatus. All stacks were electrically shorted when shocked. The discs were then separated and the resonant and anti-resonant frequencies were measured. The discs were then driven individually in their respective vibration mode (radial or thickness).

The driving voltage test apparatus used is shown in Figure 6-2. Driving voltages of 0.04, 0.32 and 1.0 volts per mil, and 0.04, 0.32 and 0.64 volts per mil, respectively, were used to drive the ceramics in the radial and thickness modes.

6.2 DISCUSSION OF RESULTS

The ceramic characteristics measured were the resonant and anti-resonant frequencies. The reason for measuring only the resonant and anti-resonant frequencies was because previous tests concerning impact shocks on piezoelectric ceramics showed that the mechanical Q and the coupling coefficient were affected by impact shocks. In all previous cases where fractures occurred, the mechanical Q and the coupling coefficient decreased and the ceramic possessed multiple resonant and anti-resonant frequency responses. Since the mechanical Q, coupling coefficient and the ceramic response are a function of the resonant and anit-resonant frequencies, there was no need to measure the other ceramic characteristics, such as capacitance and dissipation.

Tables 6-1 and 6-2 list the results of the driving voltage test for discs driven in the thickness and radial modes, respectively. The percent change in values of $\Delta f/f_r$ after the discs were driven, relative to the values of $\Delta f/f_r$ after the discs were shocked, are listed. As can be seen in the tables, discs driven in the radial mode resulted in more consistent changes (generally negative) than the thickness driven discs. Changes in the values of the resonant frequencies were also computed and listed in the tables. The resonant frequencies remained constant after the discs were driven, the maximum change being 13.5 percent. Two unshocked discs of each composition were driven in the radial mode at 0.32 volt per mil, and the changes that occurred in the values of $\Delta f/f_r$ were within the normal statistical distribution of the unshocked discs.

6.3 CONCLUSIONS

Microfractures in ceramics can be propagated by driving voltages as indicated by the results obtained. Driving voltages applied to the ceramic in the radial mode of vibration are more effective in propagating fractures than driving voltages applied in the thickness mode. This is due to the fact that most fractures in the ceramic occur radially. Stresses applied by radial vibrations are exerted perpendicular to the fractures, causing them to separate. Stresses applied by thickness vibrations are parallel to the fractures.

The fact that fractures are propagated to a lesser degree when the ceramic is driven in the thickness mode than in the radial mode is favorable as far as transducers are concerned, since the thickness mode of vibration is used in the design of mass loaded transducers.

TABLE 6-1
DISCS DRIVEN IN THICKNESS MODE

COMPOSITION	SHOCK PRESSURE-PSI	PERCENT CHANGE Δf/fr	DRIVING VOLTAGE VOLTS PER MIL	PERCENT CHANGE fr
EC-55	6,000	-5.4	.04	-0.2
	11,000	+0.9	.04	-0.2
	16,000	-5.6	.04	-0.1
EC-64	6,000	-3.9	.04	+0.1
	11,000	-38.4	.04	0
	16,000	-2.0	.04	0
EC-65	6,000	-2.8	.04	0
	11,000	+2.6	.04	+0.2
	16,000	0	.04	0
	21,000	-7.4	.04	+0.3
EC-69	6,000	-6.6	.04	0
	11,000	0	.04	0
	16,000	+8.7	.04	0
	21,000	0	.04	+0.2
EC-55	6,000	-7.2	.32	-0.3
	11,000	+14.3	.32	-0.4
	16,000	+7.2	.32	-0.3
EC-64	6,000	+0.2	.32	+0.2
	11,000	+9.4	.32	-0.2
	16,000	-6.5	.32	-0.1
EC-65	6,000	+7.0	.32	0
	11,000	+3.5	.32	-0.2
	16,000	-6.4	.32	+0.2
	21,000	+1.1	.32	-0.3
EC-69	6,000	-54.5	.32	0
	11,000	+33.5	.32	0
	16,000	-10.2	.32	-0.3
EC-55	6,000	0	.64	+0.1
	11,000	-22.2	.64	+0.2
	16,000	0	.64	+0.1
EC-64	6,000	+8.3	.64	-0.1
	11,000	-46.2	.64	+0.6
	16,000	-60.0	.64	-0.4

TABLE 6-1 (Cont'd)
DISCS DRIVEN IN THICKNESS MODE

COMPOSITION	SHOCK PRESSURE-PSI	PERCENT CHANGE Δf/fr	DRIVING VOLTAGE VOLTS PER MIL	PERCENT CHANGE fr
EC-65	6,000	0	.64	-0.3
	11,000	0	.64	0
	16,000	+3.6	.64	0
	21,000	+3.2	.64	0
EC-69	6,000	0	.64	0
	11,000	0	.64	0
	16,000	0	.64	+0.1
	21,000	0	.64	-0.2

TABLE 6-2
DISCS DRIVEN IN RADIAL MODE

COMPOSITION	SHOCK PRESSURE PSI	PERCENT CHANGE $\Delta f/fr$	DRIVING VOLTAGE VOLTS PER MIL	PERCENT CHANGE fr
EC-55	6,000	-6.2	.04	0
	11,000	-3.7	.04	0
	16,000	-2.5	.04	0
EC-64	6,000	-5.9	.04	-0.1
	11,000	-24.4	.04	-0.3
EC-65	6,000	-5.8	.04	+0.2
	11,000	-11.6	.04	+0.1
	16,000	-5.6	.04	-0.2
EC-69	6,000	-6.9	.04	0
	11,000	-5.1	.04	+0.2
	16,000	-5.3	.04	-0.6
EC-55	6,000	-7.0	.32	+0.2
	11,000	-7.1	.32	0
	16,000	-6.0	.32	+0.2
EC-64	6,000	-5.1	.32	-0.1
	11,000	-47.0	.32	0
EC-65	6,000	-3.8	.32	0
	11,000	-3.2	.32	-0.2
	16,000	-6.4	.32	+0.3
	21,000	-12.1	.32	+0.1
EC-69	6,000	-6.9	.20	+0.1
	11,000	-8.1	.32	+0.3
	16,000	-22.9	.32	-2.5
EC-55	6,000	-2.4	1.0	0
	11,000	+2.4	1.0	0
	16,000	+2.4	1.0	-0.1
EC-64	6,000	+3.2	1.0	-0.6
	11,000	+17.3	1.0	+0.7
EC-65	6,000	+2.3	1.0	-0.6
	11,000	-42.9	1.0	-6.7
	16,000	-1.9	1.0	+0.2
	21,000	-93.5	1.0	+13.5
EC-69	6,000	0	1.0	-0.1
	11,000	-90.2	1.0	+3.0
	16,000	-78.9	1.0	-0.2

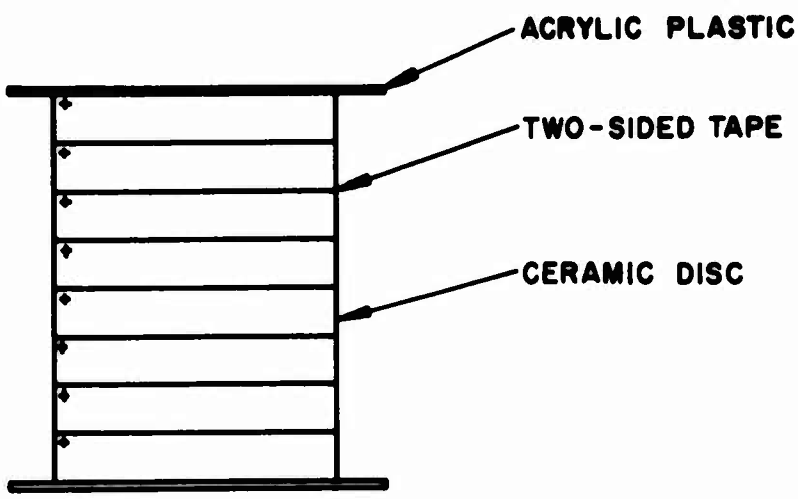


FIGURE 6-1
CERAMIC STACK FOR DRIVING VOLTAGE TEST

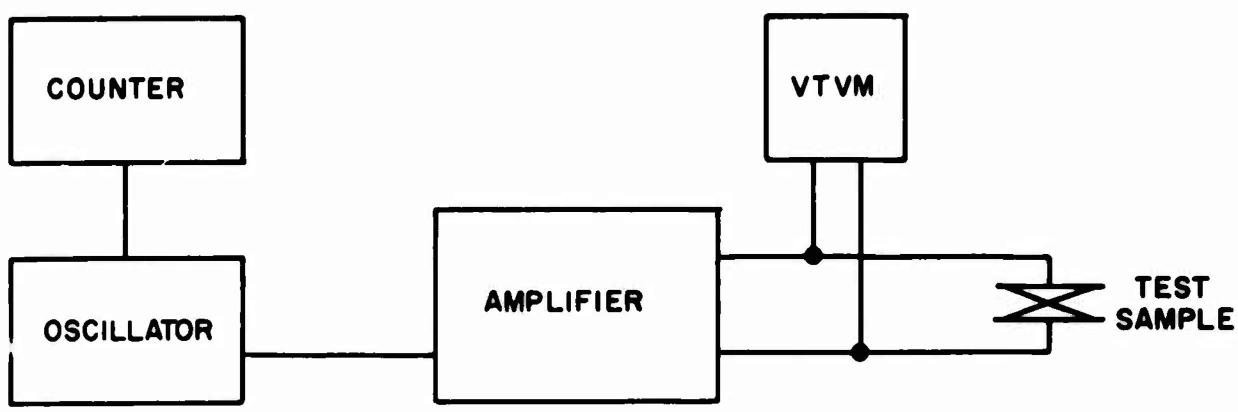


FIGURE 6-2
DRIVING VOLTAGE TEST APPARATUS

7.0 FIBER WINDING

Impact shock tests conducted on piezoelectric ceramics have indicated that the ceramic always breaks in tension. One method of improving the ceramic mechanical strength is to prestress the ceramic by applying a compressive force. In this manner, the forces acting on the ceramic must overcome the molecular bonding force plus the applied compressive force before fracture can occur. Therefore, the mechanical strength of the ceramic is increased as a function of the applied compressive force.

Fiber winding was found to be the most effective method of prestressing a ceramic. Glass fibers are wound around the circumference of the ceramic, thereby applying a compressive force on the ceramic. The amount of compression applied on the ceramic is a function of the tension in the glass fibers when winding. To illustrate the effects of fiber winding on the ceramic, consider the unit cross section of a ceramic ring, as shown in Figure 7-1.

P is the pressure exerted on the ceramic ring when it is subjected to impact shock.

The axial stress in the ceramic ring is:

$$\sigma_{C_A} = E_C \, S_{C_A} \qquad (1)$$

where, σ_{C_A} is the axial stress, E_C is the Young's Modulus for the ceramic, and S_{C_A} is the axial strain in the ceramic. A radial strain is also present in the ceramic ring, and is a function of the axial strain, such that:

$$S_{C_R} = \gamma_C \, S_{C_A} \qquad (2)$$

where, S_{C_R} is the radial strain in the ceramic and γ_C is the Poisson's Ratio for the ceramic. The radial strain in the glass fiber can be neglected. Since the fiber winding is comprised of layers of glass fibers, its axial compression will be absorbed and the corresponding radial strain will be very small. The radial force of the glass fiber and the ceramic must be considered. Since the difference in radii of the ceramic ring and fiber winding is small, the unit strain in the glass fibers and the ceramic can be assumed to be equal. Therefore,

$$S_{F_R} = S_{C_R} \qquad (3)$$

where S_{F_R} = unit radial strain in the glass fiber.

The radial stress in the glass fiber is then:

$$\sigma_{F_R} = E_F \, S_{F_R} \qquad (4)$$

where σ_{F_R} is the radial stress in the glass fiber and E_F is the Young's Modulus for the glass fiber. Substituting equations (2) and (3) into equation (4),

$$S_{F_R} = S_{C_R} = \sigma_C \, S_{C_A}$$

and

$$\sigma_{F_R} = E_F \gamma_C \, S_{C_A} \qquad (5)$$

Since the fiber wound ceramic is in a static condition, the forces on the glass fiber and the ceramic are equal. The unit force on the glass fiber is

$$F_{F_R} = \sigma_{F_R} \, A_{F_R}, \qquad (6)$$

where F_{F_R} is the unit radial force in the glass fiber and A_{F_R} is the unit cross sectional area of the glass fiber. The unit force on the ceramic (F_{C_R}) in the radial direction is

$$F_{C_R} = \gamma_{C_R} \, A_{C_R}, \qquad (7)$$

where A_{C_R} is the unit cross sectional area of the ceramic. As previously stated, the forces on the glass fiber and the ceramic are equal, therefore,

$$F_{F_R} = F_{C_R} \qquad (8)$$

or

$$\sigma_{F_R} A_{F_R} = \sigma_{C_R} A_{C_R} \qquad (9)$$

By rearranging equation (9),

$$\sigma_{F_R} = \sigma_{C_R} A_{C_R} \qquad (10)$$

or by substituting A_{F_R} equation (5) for σ_{F_R},

$$E_F \gamma_C S_{C_A} = \frac{\sigma_{C_R} A_{C_R}}{A_{F_R}} \qquad (11)$$

or

$$\sigma_{C_R} = \frac{A_{F_R} E_F \gamma_C S_{C_A}}{A_{C_R}} \qquad (12)$$

Substituting $S_{C_A} = \frac{\sigma_{C_A}}{E_C}$ (obtained from equation (1) into equation (12),

$$\sigma_{C_R} = \frac{A_{F_R}}{A_{C_R}} \frac{E_F}{E_C} \gamma_C \sigma_{C_A} \qquad (13)$$

Since $\sigma_{C_A} = P$, equation (13) becomes

$$\sigma_{C_R} = \frac{A_{F_R}}{A_{C_R}} \frac{E_F}{E_C} (\gamma_C P) \qquad (14)$$

Equation (14) can be used to determine the additional compressive stress applied on the ceramic by the fiber winding when the fiber wound ceramic is subjected to impact shock. This equation can be used to conduct first order analysis of fiber wound ceramic rings to determine the approximate impact shock amplitude required to break the ceramic.

7.1 TEST PROCEDURE

Piezoelectric ceramic rings and discs were fiber wound to 1500 psi and 3000 psi compression. The compositions tested were EC-55, EC-64 and EC-65. The electrical characteristics of each test sample were measured before and after fiber winding to determine whether or not the fiber winding causes any changes in these characteristics. The test samples were then formed into stacks of five and subjected to impact shock using the laboratory shock apparatus. The test samples were separated after impact shock and their electrical characteristics were again measured. This test procedure was used for all test samples studied.

7.2 DISCUSSION OF RESULTS

Tables 7-1 and 7-2 present the changes in the electrical characteristics of the ceramic discs and rings, respectively, due to fiber winding at 1500 psi and 3000 psi compression. The changes in the dielectric constant, dissipation, coupling coefficient and mechanical Q were negative. The mechanical Q was the most affected by fiber winding. This was true for both the rings and discs of the three ceramic compositions. The dielectric constant and the coupling coefficient remained relatively unchanged. The dissipation also remained relatively unchanged.

Table 7-3 shows the changes that occurred in the fiber wound ceramic discs and rings after being subjected to impact shocks of 23,000 psi and 51,000 psi, respectively. Again, the dielectric constant and the coupling coefficient of the rings and discs of all compositions tested remained relatively unchanged. The dissipation and mechanical Q were the most affected by impact shocks; the dissipation increased and the mechanical Q decreased. The mechanical strength of the ceramic rings were superior to that of the ceramic discs. Approximately 40 percent of the fiber wound ceramic discs fractured under 23,000 psi impact shock, while all of the fiber wound ceramic rings survived impact shocks of 51,000 psi.

Table 7-4 shows the changes in the electrical characteristics of EC-64 ceramic rings fiber wound to 1500 psi compression and subjected to impact shocks of 79,000 psi. None of the fiber wound rings fractured under impact shock. The dielectric constant remained unchanged after impact shock; however, the coupling coefficient did change slightly. The mechanical Q was the most affected followed by the dissipation. Apparently, 79,000 psi is still below the fracture limit of the fiber wound EC-64 rings. Equation (14) approximates the fracture limit to be 85,450 psi.

7.3 CONCLUSION

The effect of fiber winding upon the ceramic electrical properties is greatest on mechanical Q, followed by dissipation. Dielectric constant and coupling coefficient are relatively unchanged by fiber winding.

Fiber winding does improve the mechanical strength of ceramic rings; however, it does not improve the mechanical strength of ceramic discs appreciably.

Equation (14) as derived in the beginning of this section does give a close approximation of the fracture limit of the fiber wound ceramic rings.

TABLE 7-1
PERCENT CHANGE IN THE ELECTRICAL PARAMETER OF THE DISCS DUE TO FIBER WINDING AT 1,500 PSI

COMPOSITION	PERCENT CHANGE FROM ORIGINAL VALUE			
	DIELECTRIC CONSTANT	DISSIPATION	COUPLING COEFFICIENT	MECHANICAL Q
EC-55	0.413%	-5.03%	-1.78%	-3.94%
EC-64	0.524%	-4.29%	-1.71%	-3.99%
EC-65	-	-	-	-

TABLE 7-2
PERCENT CHANGE OF ELECTRICAL PARAMETERS DUE TO FIBER WINDING OF RING

COMPOSITION	ELECTRICAL PARAMETERS							
	DIELECTRIC CONSTANT		DISSIPATION		COUPLING COEFFICIENT		MECHANICAL Q	
	1500 PSI	3000 PSI	1500 PSI	3000 PSI	1500 PSI	3000 PSI	1500 PSI	3000 PSI
EC-55	-0.414	-0.675	+0.849	-1.69	-2.20	-1.77	-31.7	-42.2
EC-64	-1.37	-1.63	-3.88	-0.278	-2.46	-3.26	-30.4	-32.0
EC-65	-3.50	-4.23	+2.45	+0.625	-3.87	-4.84	-25.3	-19.0

TABLE 7-3
CHANGE IN ELECTRICAL CHARACTERISTICS OF FIBER WOUND DISCS AND RINGS AFTER IMPACT SHOCKS OF 23,000 PSI AND 51,000 PSI RESPECTIVELY

COMPOSITION	CONFIGURATION	PERCENT CHANGE FROM ORIGINAL VALUES			
		$\epsilon/\epsilon o$	Kp	Qm	Disc
EC-55	DISCS	+1.5	+3.1	-28	+28
	RINGS	+3.2	+6.0	-29	+31
EC-64	DISCS	-1.0	-4.7	-31	+23
	RINGS	-4.0	-2.2	-36	+25
EC-65	RINGS	-5.9	-0.8	-9.2	+21

TABLE 7-4
PERCENT CHANGE OF ELECTRICAL PARAMETERS OF ONE STACK OF EC-64 RINGS FIBER WOUND AT 1500 PSI AND SUBJECTED TO IMPACT SHOCK OF 79,000 PSI

ELECTRICAL PARAMETERS	AFTER FIBER WINDING AT 1500 PSI	AFTER IMPACT SHOCK AT 79,000 PSI
DIELECTRIC CONSTANT	-1.74%	-0.604%
DISSIPATION	-5.82%	+19.7%
COUPLING COEFFICIENT	-2.69%	-6.11%
MECHANICAL Q	-34.3%	-63.0%

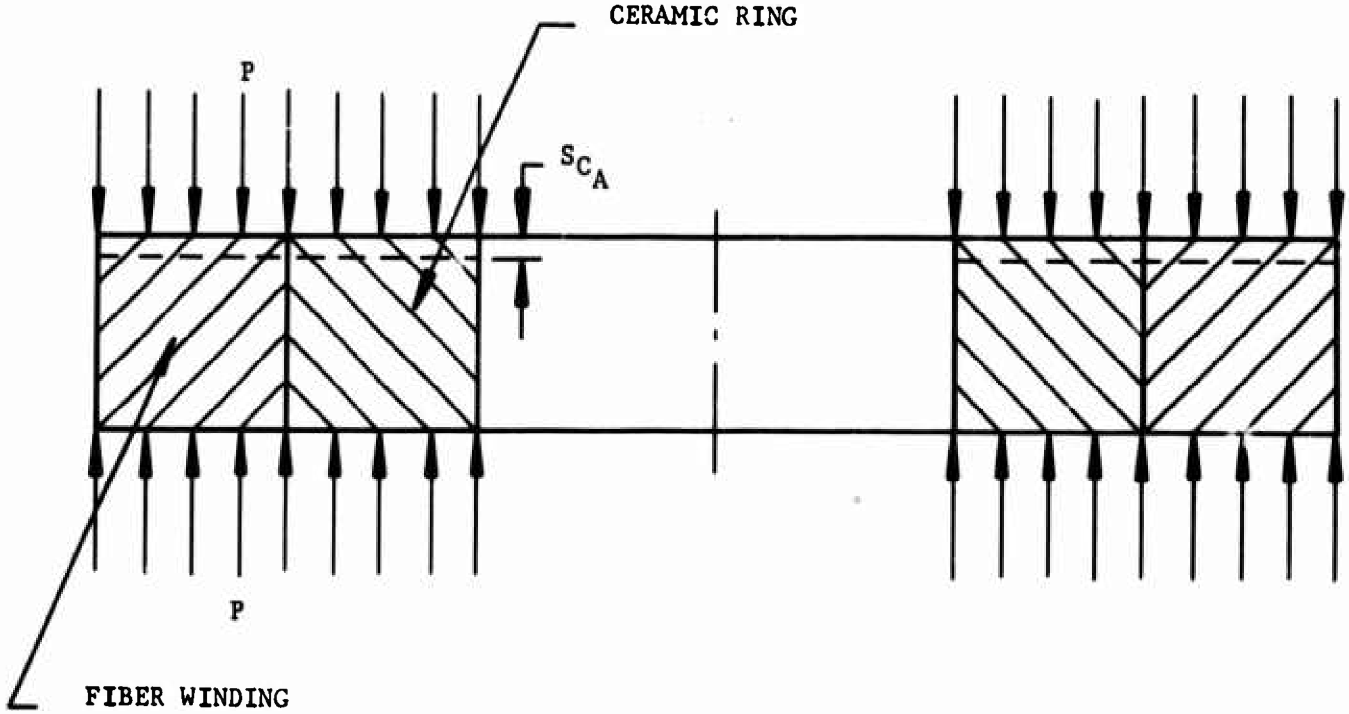


FIGURE 7-1
CROSS SECTION OF FIBER WOUND CERAMIC RING

8.0 OTHER METHODS OF IMPROVING CERAMIC MECHANICAL STRENGTH

The methods of improving the mechanical strength of ceramics as described in this section were studied to determine their effectiveness and feasibility.

8.1 FIBER EMBEDDING

Fiber embedding is a means of increasing the ceramic strength by pre-stressing the ceramic with metallic wires.

Tests were conducted using tungsten, molybdenum and iron wires embedded in the green ceramic powder compact. The coefficient of thermal expansion of the tungsten and molybdenum wires was lower than that of the ceramic while the coefficient of thermal expansion of the iron wire was slightly higher than that of the ceramic. The difference in the coefficient of thermal expansion between the metal wire and the ceramic creates forces in the ceramic when the ceramic is cooled from sintering temperature. The tests were conducted to determine whether the coefficient of thermal expansion of the metal should be lower or higher than that of the ceramic.

All of the metal embedded ceramics were fractured after they were cooled from sintering temperature; however, the ceramic embedded with iron wires was not fractured as much as the ceramics embedded with tungsten and molybdenum wires. The metal with a coefficient of thermal expansion higher than that of the ceramic was more effective in prestressing the ceramic.

Although the results obtained from the tests provided promising data, further tests using different metallic materials were not possible due to the extensiveness of the study.

8.2 SURFACE LAYER DIFFUSION

The method of surface layer diffusion as a means of improving ceramic strength was studied. In this method, a thin layer of material was diffused into the ceramic surface. The material chosen is capable of forming a solid solution with the ceramic composition. The atoms of the diffusing material, being larger than the atoms comprising the ceramic, causes the coefficient of thermal expansion of the surface to decrease. This difference in coefficient of thermal expansion between the ceramic surface and interior allows the ceramic to go into compression upon cooling.

The surface layer diffusion studies were conducted on composition EC-64 ceramics, using barium zirconate as the diffusing material. The fired test samples did have barium zirconate diffused into their surfaces; however, the diffusion was not uniform. This non-uniform diffusion is undesirable, since it creates localized stresses in the ceramic. If surface layer diffusion is to be used to improve ceramic strength, the diffusion must be uniform over the ceramic surface.

This brief study has provided valuable information as to the possibility of utilizing surface layer diffusion for improving ceramic strength. The study has indicated that surface layer diffusion is possible, and the results obtained from the tests conducted do justify the need for further investigation into this area. The study could not be continued in the allotted time due to the extensive studies involved in other areas of impact shock.

9.0 SUMMARY OF CONCLUSIONS

The results of the life expectancy tests performed on ceramic rings and discs of compositions EC-55, EC-64, EC-65 and EC-69 have made available extensive information regarding the effects of impact shock on the physical and electrical properties of piezoelectric ceramics. The tests have indicated that the dissipation and mechanical Q of ceramics are most affected by impact shocks. They have also indicated that mechanical failure of the ceramic is generally reflected upon the values of $\Delta f/f_r$, where $\Delta f = fa - f_r$, fa = anti-resonant frequency, and f_r = resonant frequency. The test results indicate that fractures in ceramics can be detected when multiple frequency responses are present in one mode of vibration. The results also indicate that the dielectric constant of the ceramics remain relatively stable under repeated impact shocks.

The relative mechanical strengths of the ceramics were also determined from the life expectancy test results. Composition EC-65 was able to withstand higher and more impact shocks than the other four compositions, probably because of its soft piezoelectric characteristic. On the other hand, composition EC-69 had the lowest relative mechanical strength due to its hard piezoelectric characteristic. The ceramic ring configuration was mechanically stronger than the ceramic disc configuration.

The results obtained from the hydrostatic shock tests performed on mass loaded transducers indicate that the environmental conditions (especially temperature) had an effect on the behavior of the mass loaded ceramics under hydrostatic shock. The results obtained from the first test conducted in approximately 20°C water did not agree with results from the second test conducted in approximately 0°C water.

The effects of mass loading on the ceramics was also indicated in the results from the hydrostatic shock test. The relative mechanical strength of the ceramics under mass loading did not agree with results from life expectancy tests. Also, the effects of hydrostatic shocks on the ceramics' electrical characteristics did not coincide with the effects of impact shock on the electrical characteristics of non-mass loaded ceramics. On the other hand, the tests conducted on mass loaded transducers using the laboratory shock apparatus produced results which agreed very closely with results from life expectancy tests.

The difference in results obtained from the two separate tests on mass loaded transducers is probably due to the difference in behavior of the masses under the two test conditions. In the hydrostatic shock test, the masses are accelerated due to the shock wave; however, when the transducers are subjected to impact shock using the laboratory shock apparatus, the masses do not accelerate.

The driving voltage test performed on ceramic discs of the same four compositions, which were subjected to impact shock, has indicated that microfractures in ceramics can be propagated by applying a driving voltage in the ceramic. The degree of propagation was greater when the disc was driven in the planar mode than in the thickness mode. This is a favorable condition since the ceramic elements in a mass loaded transducer are driven in the thickness mode. Also, when the ceramic was driven in the thickness mode, the change in resonant frequency, due to the propagation of microfractures, was very small (0.6% maximum).

The mechanical strength of ceramic rings can be greatly improved by fiber winding of the rings. Ceramic rings fiber wound to 1500 psi compression were able to withstand impact shocks as high as 79,000 psi. Fiber winding on ceramic discs was ineffective. Three ceramic compositions were tested in this program. These were EC-55, EC-64, and EC-65.

The data contained in this report on the behavior of piezoelectric ceramics subjected to impact shocks under laboratory test conditions and open water conditions answer many questions that are confronted in the design of transducers. Valuable information regarding the mechanical strength of the ceramic and the effects of impact shock on the electrical properties of the ceramic was obtained through extensive testing. Although the compiled information does not constitute the rules of transducer design, it does provide a guideline for the transducer designer.

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Office of Naval Research

13. ABSTRACT

This is the final report on Contract Nonr-4917(00), "Impact Shock on Piezoelectric Ceramics," and emphasizes the work performed and the results obtained by the Edo Western Corporation during the second phase of the program which includes the period from 1 May 1966 to 30 April 1967. This report also summarizes the work performed and the results obtained during the first phase of the program covering the period from 1 May 1965 to 30 April 1966.

Life expectancy tests performed on ceramic rings of compositions EC-55, EC-64, EC-65 and EC-69 have resulted in extensive data regarding the effects of impact shocks on the physical and electrical characteristics of the ceramic rings. The results have indicated that the dissipation and the mechanical Q of the ceramic were the parameters most affected by impact shocks. The dielectric constant was the only electrical characteristic that remained stable under impact shock. Ceramic rings of composition EC-65 were able to withstand higher and more impact shocks than rings of the other three compositions. The results on composition EC-69 indicated that this composition has the lowest mechanical strength with respect to impact shock.

The results obtained from life expectancy tests performed on ceramic discs and rings were in agreement regarding the effects of impact shock on their electrical characteristics. The mechanical strength of the ceramic ring configuration was better than that of the ceramic disc configuration. This was true for all four ceramic compositions studied.

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13. ABSTRACT (Cont'd)

Hydrostatic shock tests were performed on mass loaded ceramic rings and discs. The ceramic compositions tested were EC-55, EC-64, EC-65 and EC-69. The hydrostatic shock to which the mass loaded transducers were subjected originated from an underwater detonation. These tests were conducted in open water to simulate the actual operating conditions of the transducers. The results from these tests have indicated the effects of environmental conditions and mass loading on the behavioral characteristics of the ceramics under hydrostatic shocks. The environmental conditions, especially temperature, affects the mechanical strength of the ceramic. Results from tests conducted in 0°C water indicated that the mechanical strength of the ceramic decreased at this temperature. This was particularly true for the lead titanate zirconate ceramics. Mass loading of ceramics will dampen some of the multiple responses present in a ceramic stack. Also, mass loading increases the dissipation of the transducer because of the compressive force applied on the ceramic stack by the clamping bolt.

Because of the effects of mass loading and the environment on the behavior of the ceramics, the effects of hydrostatic shocks on the electrical characteristics of the transducers were not conclusive. The results do indicate that the dielectric constant remains relatively stable under hydrostatic shock.

Impact shock tests were conducted on mass loaded transducers using the laboratory shock apparatus. Ceramic rings and discs of compositions EC-55, EC-64, EC-65 and EC-69 were tested. The results obtained from these tests were in agreement with results obtained from life expectancy tests performed on unloaded ceramic stacks. The changes in the electrical characteristics due to impact shock and the relative mechanical strengths of the ceramic compositions and configurations were similar to that obtained from life expectancy tests.

Driving voltage tests were conducted on ceramic discs of compositions EC-55, EC-64, EC-65 and EC-69. The results obtained confirmed the theory that driving voltages in ceramics will propagate fractures. The results indicated that driving voltages applied in the planar mode of vibration are more effective in propagating fractures than driving voltages applied in the thickness mode of vibration.

Studies were conducted to develop a method of improving the mechanical strength of ceramics. Methods such as surface layer diffusion, prestressing by embedding metallic wires in the ceramic, and fiber winding were studied. The method of fiber winding the ceramic proved to be more effective and feasible than the other methods studied. Ceramic rings of EC-55, EC-64 and EC-65 were fiber wound to 1,500 psi and 3,000 psi compression. Impact shock tests indicated that fiber winding improved the mechanical strength of the ceramic rings. Some of the fiber wound ceramic rings withstood impact shocks as high as 79,000 psi.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ceramics						
Piezoelectric						
Aging						
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