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FUEL ELONGATION DETECTORS FOR NSRR HIGH-TEMPERATURE WATER CAPSULE

Prototype Differential Transformer and the Test

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Fuel Elongation Detectors for NSRR High-Temperature Water Capsule

— Prototype Differential Transformer and the Test —

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The prototype of differential transformer for measuring the transient elongations of fuel clad and fuel stack was constructed, followed by its test. The purpose was to examine its performance characteristics at high-frequency excitation condition in connection with the practical elongation detectors, involving its optimal design.

The optimum excitation frequency giving the maximum sensitivity is 10 kHz in fuel clad, and is 4 kHz in fuel stack elongation measurements. This low value of optimum excitation frequency results from the eddy current lose in the zircaloy fuel cladding tube in the latter. As a compromise of the two, the excitation frequency is determined to be 7 kHz for both the fuel clad and fuel stack elongation measurements.

In high-frequency excitation, the self-compensation, in which the differential output of transformer is divided by the sum of outputs of the two secondary coils, is still useful to compensate for the sensitivity change due to variation of the excitation condition and ambient temperature, though its effectiveness is reduced by the eddy current induction. In conclusion, the excitation with a constant current having frequency stability and the calibration at the temperatures of transformer usage, as well as application of self-compensation technique, are necessary for performing accurate elongation measurement with the transformer.

NSRR高温水キャプセル用燃料伸び計の開発
－プロトタイプ差動変圧器の試作と試験－

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NSRRの高温水キャプセルにおける燃料伸び測定に使用する目的で，差動変圧器の試作を行ない，その特性を調べた。燃料伸び測定には速い応答速度が要求されているので，差動変圧器を高い周波数で励振しなければならないが，あまり高い周波数では，うず電流の影響で感度が低くなる。実験の結果，燃料クラッドの伸び測定には10kHz，燃料スタックの伸び測定には4kHz が最適であることがわかった。両者の比較から，7kHz の励振周波数が選ばれた。

励振条件や周囲温度の変化により，差動変圧器の感度変化が生じるが，これを補正するために，2つの二次巻線に誘起した出力電圧の差動出力を和出力で割る，いわゆる自己補償法がある。しかし，高周波励振の条件下では，うず電流の影響により，補償特性が多少損われることがわかった。したがって，実際の使用に当っては，自己補償法を採用するとともに，励振周波数の安定化と，使用温度での較正が必要である。

試作した差動変圧器の直線範囲は，燃料クラッド伸び測定条件下で約16mm，燃料スタック伸び測定条件下で約10mmであった。

Contents

1. Introduction.

The Nuclear Safety Research Reactor (NSRR: TRIGA-ACPR Type) has been constructed for investigating behaviors of nuclear fuel and reactor core at reactivity-initiated accidents . The experiments are to be first initiated with a low - temperature water capsule after performance tests of the reactor; and the experiments with high-temperature water capsules will be started late next year. In these experiments, measurements of various physical quantities such as temperatures and pressures of capsules and test fuels are planned , and developments of some instruments for the purposes are already in progress.

One of the important measurements is that of fuel elongation. In the low-temperature water capsules, ordinary water-proof differential transformers which are commercially available will be used for detecting the elongation. However, the differential transformers , which must stand the severe environments in the high-temperature water capsule , are not found in the market in Japan ; and therefore the development of a differential transformer for the high-temperature water capsule was started.

The differential transformer must do not only withstand the high-temperature water environment but also have a fast time response to follow the transient elongation of fuel clad or fuel stack during pulse-mode reactor operation. This means that the transformer must be excited by an alternating current of high frequency . High-frequency excitation, however, induces much eddy current in and around the transformer, and this appears to present a trouble in getting the enough sensitivity; there must be limitation in getting the fast time response with keeping a sufficient sensitivity even by a high-frequency excitation.

In the first stage of development, emphasises were placed on investigating performance characteristics of the transformer under high - frequency excitation conditions and examining its capability as a transient fuel elongation detector , and also on obtaining some experiences concerning the know-how for fabrication . The results obtained are all given in the report.

2. Desing Considerations and Fabrication.

In designing the differential transformer, the environmental conditions under which the transformer is used must be taken into consideration as well as the requests of users for measuring characteristics. Since the high-temperature water capsules are used for experiments under simulated in-core conditions of BWT's and PWR's, the environmental conditions such as temperature and pressure in the capsules are equal to those of the reactors. This means that the transformers must stand PWR in-core conditions; i.e., the temperature of about 320°C and the pressure of 160 kg/cm^2 . In addition , we also have to consider a high impact pressure, which will be caused from explosive deformation or failure of the test fuel during a simulated reactivity-initiated accident in the capsule. The maximum rated conditions which the transformers must stand were , therefore, set up as follows: maximum temperature, 350°C; and maximum pressure, 200 kg/cm^2 at steady and 500 kg/cm^2 at transient conditions.

These requirements may not be difficult to overcome, if stainless-steel transformer body and ceramic-insulated coil wire are used as in the case of HBWR[1) , where fuel elongation measurements by differential transformers are performed successfully under the heavy water environment of 240°C-34 kg/cm^2.

Besides the environmental conditions, large linear measuring range of more than 20 mm (-10 mm to +10 mm) and fast response time of less than 1 msec are required for measuring characteristics.

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The linear range is generally proportional to length of the transformer , and therefore it is not difficult to obtain the desired linear range if the length is made sufficiently long. However, there is obviously limitation in the length due to space capacity inside the capsule ; and maximum acceptable length of the transformer body may be 100 mm when this space limitation and also the way of installing the transformers in the capsule are considered.

Figure 1 illustrates how the transformers are set up around the test fuel . The magnetic core for fuel clad elongation detection is placed at an end of the clad , and that for fuel stack elongation detection is in the fuel clad , pressed against the end pellet with a spring.

Since the magnetic core for fuel stack elongation detection is set in the fuel cladding tube, the eddy current induced in the tube seems to make sensitivity of the transformer less than that of the transformer for fuel clad elongation detection and also to change the linear measuring range or the linearity. However, the linearity change may be adjusted to obtain the maximum linear range by changing length of the magnetic core properly , as already experienced$^{2)}$.

On the other hand , the decrease of sensitivity due to the eddy current must be discussed with the excitation frequency which is closely related to the time response. Excitation by a higher frequency induces much eddy current which decreases the sensitivity . Therefore, in some range of high frequency excitation, the sensitivity decreases with increase of the excitation frequency , though it increases generally in the range of low frequency excitation . This means that there is a limitation of increasing the excitation frequency , even though the need for fast time response requires high frequency excitation . The optimum excitation frequency must be determined through experiments with a compromise of the requirements for sensitivity and response time.

After these considerations , the prototype of differential transformer was constructed as shown in Fig. 2. The number of turns in each coil is 190, and a ceramic-insulated nickel-clad copper wire (Hi-Temp, AWG 35, ca. 0.15 mmØ) is used for the coil. The transformer house (bobbin and outer case) is made of stainless steel SUS-304. Figure 3 shows photographs of the fabricated transformer.

3. Experiments.

3.1 Preliminary Tests with Iron and Ferromagnetic Stainless Steel Cores

A ferromagnetic stainless steel core is generally used for the differential transformer in measuring a long term fuel elongation in the reactor , because a ferromagnetic stainless steel such as martensitic stainless steel SUS-403 or SUS-410 has high corrosion resistance in high-temperature water environment and stable magnetic property in nuclear environment. In the case of NSRR, however, all measurements are carried out in a short time; and it is, therefore , not necessary to consider corrosion and radiation problems of the magnetic core.

From this point of view, it is suggested to use a mild iron steel or pure iron as the core material , since they may have better magnetic properties than those of ferromagnetic stainless steels. The question is then whether they still retain good magnetic properties under high-frequency excitations or not , because their lower electric resistances seem to produce much eddy-current loss , resulting in more degradation of the effective magnetic permeability.

In this connection , and also to examine a working property of the transformer, preliminary tests were carried out. The transformer was excited by a constant current of 10 kHz-50 mA , and each of the secondary voltages was measured with a rms-voltmeter for various core positions . The same experiments were performed for SUS-403 core and iron core having the same dimensions of desired linear range if the length is made sufficiently long. However, there is obviously limitation in the length due to space capacity inside the capsule ; and maximum acceptable length of the transformer body may be 100 mm when this space limitation and also the way of installing the transformers in the capsule are considered.

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differential; $(e_1 - e_2)$,

self-compensated; $(e_1 - e_2)/(e_1 + e_2)$,

where e_1 is the voltage in one of the secondary coils, and e_2 is in the other one. High sensitivities are thus obtainable with the SUS-403 core in both differential and self-compensated outputs.

The reason for choosing the excitation frequency of 10 kHz in the experiments is that the required response time of less than 1 msec may involve the excitation of 10 kHz at least. The excitation current of 50 mA and the dimensions of the cores were arbitrarily chosen considering current capacity of the coil wire and dimensions of the transformer respectively.

3.2 Core Length and Linear Range

Since the linear measuring range changes with length of the core even lengths of the coils are fixed, it is necessary to determine the length of the core to obtain a suitable linear measuring range for carrying out the experiments and tests . Simple experiments were thus carried out . The transformer was excited by the current of 10 kHz-50 mA , and " secondary voltage vs. core displacement " characteristics were then measured for several cores with different lengths. And, the differential outputs and self - compensated outputs were calculated. The results are shown in Figs.7 to 9. Refering to the results , the length of the core was determined to be 37 mm temporarily.

3.3 Obstruction of Eddy Current Path in Magnetic Core and Optimum Excitation Frequency

In the high-frequency differential transformer , reduction of the eddy currents is generally necessary to obtain the high sensitivity . In the case of the prototype differential transformer, however, reduction of the eddy currents may be very difficult, because the eddy currents is induced and flows mostly in the transformer body , and in the fuel cladding tube in the case of fuel stack elongation measurement, and the obstruction or reduction of these eddy current paths are impossible structurally. The obstruction and reduction is possible only in the magnetic core . This was attempted , and effectiveness was studied.

Seven types of the magnetic core, having the same length and diameter, were prepared as shown in Fig. 10. The eddy current paths could be obstructed by narrow ditches, the number of which increases from type 1 through 5; type 6 and 7 were used for testing tubular magnetic core . Each core was fixed in turns in the differential transformer or in the zircaloy tube , which was put through the differential transformer, so as to induce the maximum secondary voltage across one of the two secondary coils , and the secondary voltage in each case was measured at excitation of 50 mA and various frequencies. The minimum induction of secondary voltage was also measured by removing the magnetic core. The results are shown in Figs. 11 and 12. Type 5 is the best in giving the largest induction and that the tubular core with a ditch (i.e., type 7) gives approximately the same amount of induction as type 5 . Therefore , it is indicated that the magnetic core of type 5 or type 7 should be used.

On the other hand , the span voltages were calculated by subtracting the minimum secondary voltages from the maximum ones in Figs. 11 and 12 to find out the excitation frequencies at which the largest sensitivities were obtained . The results are shown in Figs. 13 and 14 . Since the larger span voltage gives the larger sensitivity , the excitation frequency which gives the maximum span voltage should be adopted to obtain the maximum sensitivity.

From Figs. 13 and 14, the followings are thus possible: the maximum span voltage is obtained at 10 kHz, when the magnetic core alone is set in the transformer, corresponding to the fuel clad elongation measurement; and, at 4 kHz when the magnetic core is set together with the zircaloy tube penetrating the transformer, corresponding to the fuel stack elongation measurement. It is inconvenient, however , to use two oscillators with different frequencies for exciting the respective transformers for the fuel clad and the fuel stack elongation measurements separately, in actual measurements and also in standardizing the measuring system. Therefore, the optimum excitation frequency was determined as 7 kHz by a compromise between the two measurements.

3.4 Effect of Zircaloy Tube

In fuel stack elongation measurement, the magnetic core is set in the fuel cladding tube of zircaloy as shown in Fig. 1. Therefore, It must be known how the eddy current induced in the tube influences the sensitivity and the measuring range.

Figure 15 shows the curve of " secondary voltage vs. excitation frequency " , reproduced from Figs. 11 and 12 . The effect of zircaloy tube is seen to be small below 1 kHz of excitation frequency but increase rapidly above 1 kHz.

When the magnetic core is set in the zircaloy tube , curves of the maximum and minimum secondary voltages crosses one another at about 30 kHz . The span voltage and hence, the sensitivity, becomes zero at this frequency ; unstable and abnormal characteristics of the transformer appear in the vicinity of and above 30 kHz.

Induced voltages across one of the secondary coils with and without the zircaloy tube were also measured, changing position of the magnetic core at excitation frequency of 7 kHz and current of 50 mA . The purpose of measurements was to see how the eddy current in the zircaloy tube influences the value of secondary voltage and also shape of the " secondary voltage vs. core displacement " curve. The results are shown in Fig. 16. It is seen that the shape of curve becomes flattened with the zircaloy tube, compared with that without the tube. The eddy current induced in the zircaloy tube thus has an effect equivalent to that when length of the coils is shortened and length of the magnetic core is made longer. Therefore, in the case of fuel stack elongation measurement where the magnetic core is set in the zircaloy tube, the same linear measuring range as that in the case of fuel clad elongation measurement cannot be expected. The linear measuring range in the former case may be shorter than that in the latter case, even though only length of the core is made short to the optimum length so as to give the maximum linear measuring range.

It is also seen that the effect of zircaloy tube becomes higher as the magnetic core moves toward the position where the secondary voltage becomes a maximum . For the reason , the magnetic fluxes which are attracted across the zircaloy tube to the magnetic core increase as the magnetic core moves toward the excitation coil and thus induction of eddy current in the zircaloy tube increases. Then, the increase of eddy current in the zircaloy tube lowers induction of the secondary voltage since the magnetic fluxes due to the eddy current have opposite phases to the original fluxes due to the excitation current.

3.5 Self-compensation Treatment and Its Effectiveness

Self-compensation treatment of the secondary voltages was proposed to compensate for sensitivity change due to the variations of excitation condition and ambient temperature, and its effectiveness was confirmed with a differential transformer excited by a frequency below 1 kHz$^{2)}$. The effectiveness of self-compensation treatment in the high-frequency differential transformer , however, may be reduced because of the eddy current induction, so experiments were carried out for investigating the phenomenon .

The secondary voltages of the prototype differential transformer with and without the zircaloy tube were measured under several excitation conditions around 7 kHz-50 mA , and the data were treated to give calibration curves of the differential outputs and self-compensated outputs. The results are shown in Figs. 17 to 20.

Then the sensitivity changes due to variations of excitation conditions were calculated from gradients of the calibration curves in the linear measuring range. On the other hand, the sensitivity changes due to variation of the ambient temperature were measured out in a furnace , changing the core position from -1 mm to +1 mm at temperatures between room temperature (about 20°C) and 300°C . The results are shown in Figs. 21 and 22, where the sensitivities are normalized to that for 7 kHz-50 mA and 20°C. It is seen that the perfect compensation cannot be achieved for sensitivity changes due to variations of excitation frequency and ambient temperature even when the self-compensation technique is used; the perfect compensation is possible only for the changes due to variation of excitation current . However , the self-compensation treatment is still effective , as compared with the differential treatment . Therefore , the best way of using the differential transformer under high-frequency excitation is to apply the self-compensation technique together with stabilization of the excitation frequency and calibration of the transformer at the temperatures where the transformer is used. This procedure is not of much trouble in actual usage.

3.6 Optimum Core Length

In order to obtain the value of optimum core length where the linear measuring range becomes a maximum , the secondary voltages were measured by changing the length of core under the excitation condition of 7 kHz-50 mA. Measurements were made for the two cases: i.e., only the core was set in the transformer , corresponding to the case of fuel clad elongation measurement ; and the zircaloy tube was also set, corresponding to the case of fuel stack elongation measurement. Then the measured results were treated to provide the self-compensation output and also differential output for references. The results of measurements and of data treatments are shown in Figs. 23 to 30.

From Figs. 25, 29 and 30 , the optimum lengths for the self-compensation treatment were obtained for both the cases as follows. When there is not the zircaloy tube in the transformer , it is about 37 mm where the linear measuring range is about 16 mm; and when there is the zircaloy tube, it is about 30 mm where the linear measuring range is about 10 mm.

In the former case , the difference between the obtained linear measuring range and the required one of 20 mm is only 4 mm. Therefore , slight modification of the transformer dimensions or allowance of a few per cent non-linearity may fulfills the requirement. In the latter case, however , the difference is so big that major modification may be necessary. One of the lightest but most effective modification may be to change the ratio of coil length between the primary and the secondary.

4. Discussion and Conclusion.

Experiments and tests with the prototype differential transformer produced several interesting results and suggestions for future works in developing the fuel elongation detectors for the high-temperature of excitation condition and ambient temperature, and its effectiveness was confirmed with a differential transformer excited by a frequency below 1 kHz[2]. The effectiveness of self-compensation treatment in the high-frequency differential transformer, however, may be reduced because of the eddy current induction, so experiments were carried out for investigating the phenomenon.

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4. Discussion and Conclusion.

Experiments and tests with the prototype differential transformer produced several interesting results and suggestions for future works in developing the fuel elongation detectors for the high-temperature water capsules of NSRR.

One problem for solving in the present experiment was how high the frequency could be in exciting the transformer without losing the sensitivity , for the desired response time was so fast that the excitation by a high frequency was inevitable. The experimental results indicated that the excitation by 7 kHz must be used for both the cases of fuel clad and fuel stack elongation measurements, because the excitation by over 7 kHz reduces sensitivity of the transformer rapidly in the latter case while it increases the sensitivity in the former case.

Excitation by such a high frequency, however, induces much eddy current in the transformer body , the magnetic core and other metal components around the transformer . Experimental results showed that the eddy current lowered not only the sensitivity but the linear measuring range, and also the efficiency of self-compensation. Longitudinal ditches along the magnetic core are useful in reducing the eddy current in the core and its effect.

Linear measuring range of the prototype transformer is small for fuel stack elongation measurement , as compared with the desired one. In the next stage of development, modification of the coil arrangement will, therefore, be made; that is, changing the ratio in coil length between the primary and secondary , setting up some space between the coils, and so on. For fuel clad elongation measurement, on the other hand, the linear measuring range obtained as 16 mm does not much differ from the required one of 20 mm , so only slight and simple modification may be necessary.

Experimental results showed also that the perfectness of self-compensation treatment for compensating sensitivity changes was reduced by the eddy current under high-frequency excitation condition. It has been confirmed, however , that the self-compensation treatment is still effective, as compared with the differential treatment. The most suitable way of achieving accurate measurement is self-compensation treatment of the secondary voltage with stabilization of the excitation condition and preparation of the calibration curves at the temperatures of the transformer usage.

Transient responses or step response times were not examined in the experiments, because the transient test equipment could not be prepared. However, the approximate estimates may be made from the excitation frequency.

Amplitude of secondary voltage in each half-cycle of the excitation varies directly with the position of the magnetic core at the respective time of each half-cycle. The differential transformer can, therefore, be considered as one of the sampling systems having the sampling period of 1/2f , where f is the excitation frequency. Therefore , the excitation by 7 kHz presents fourteen sampling during the required response time of 1 msec, and this seems to be sufficient for obtaining the response time of 1 msec with an acceptable measuring accuracy.

The effect of eddy current induction on the transient response is not known ; this will be studied in the future.

Acknowledgement.

The authors wish to thank Mr. M. Ishikawa, chief of the Reactivity Accident Laboratory, and Mr. T. Hoshi, senior research engineer of the Reactivity Accident Laboratory, and Mr. M. Hara , chief of the Reactor Instrumentation Laboratory, for their support of the present work.

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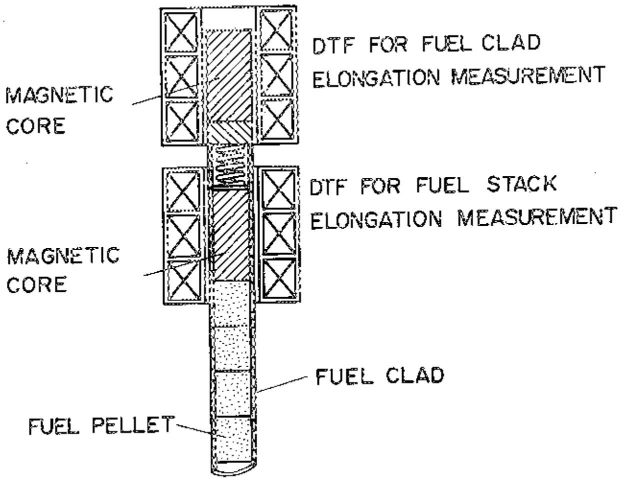


Fig.1 Setting-up of differential transformers for fuel elongation measurements in NSRR high-temperature water capsule.

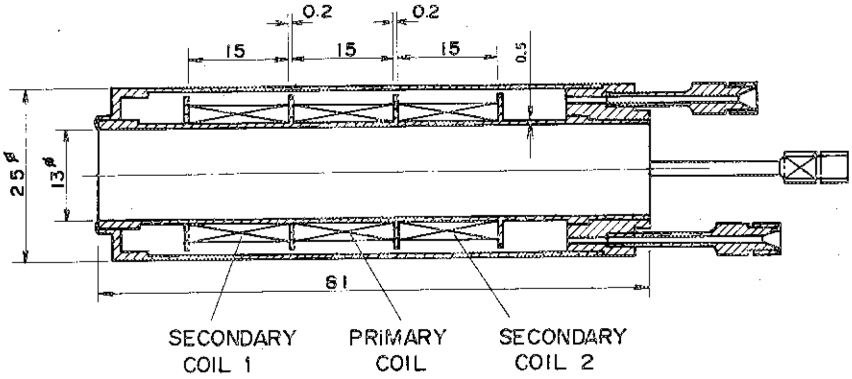


Fig.2 Cross section of prototype differential transformer with its dimensions.

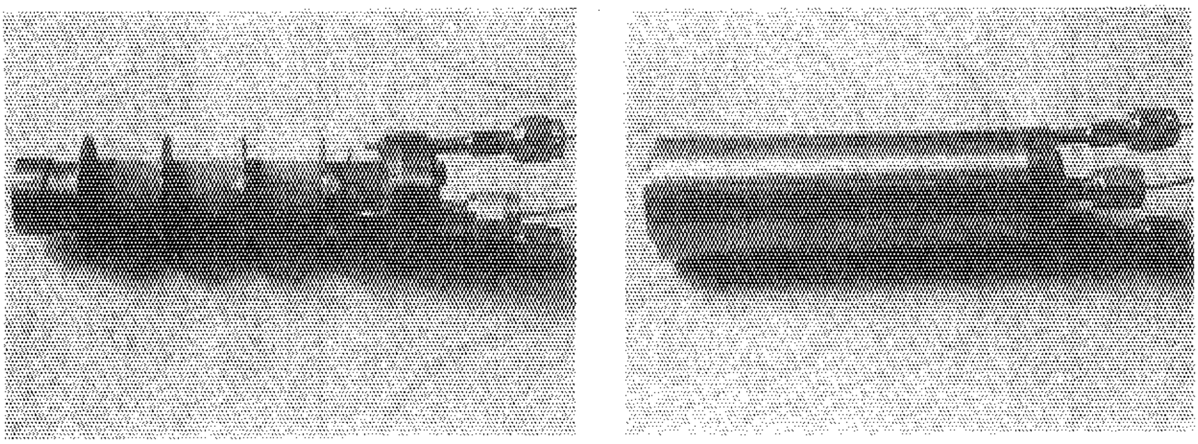


Fig.3 Photographs of prototype differential transformer.

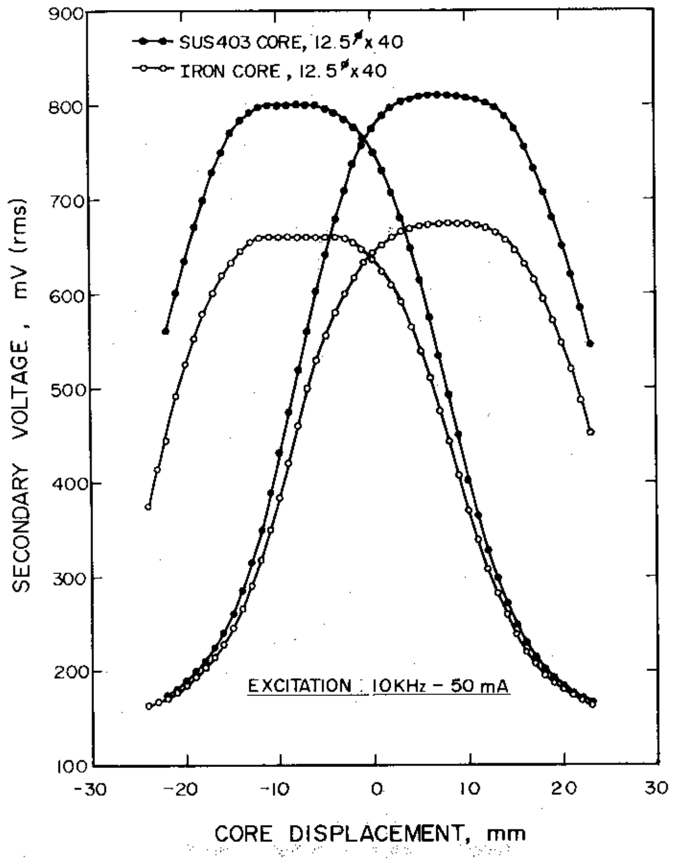


Fig.4 Secondary induced voltages for SUS403 and iron cores and their variations with core displacements.

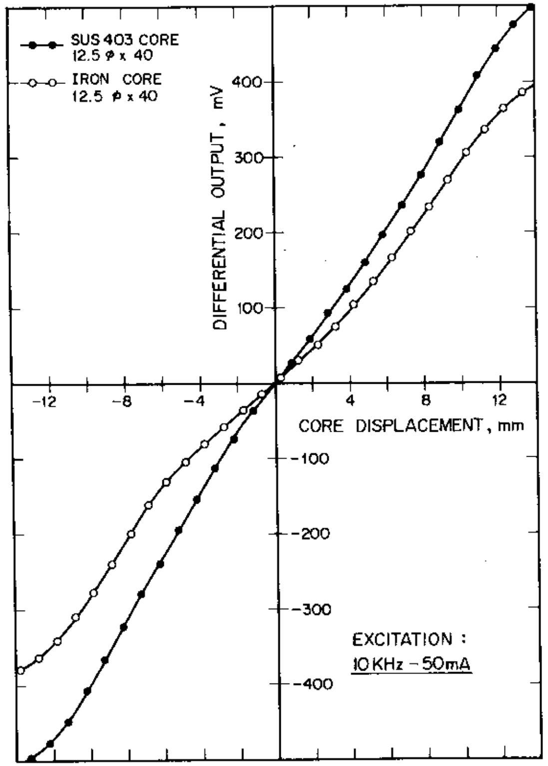


Fig.5 Secondary induced voltage for SUS403 and iron cores and their variations with core displacements.

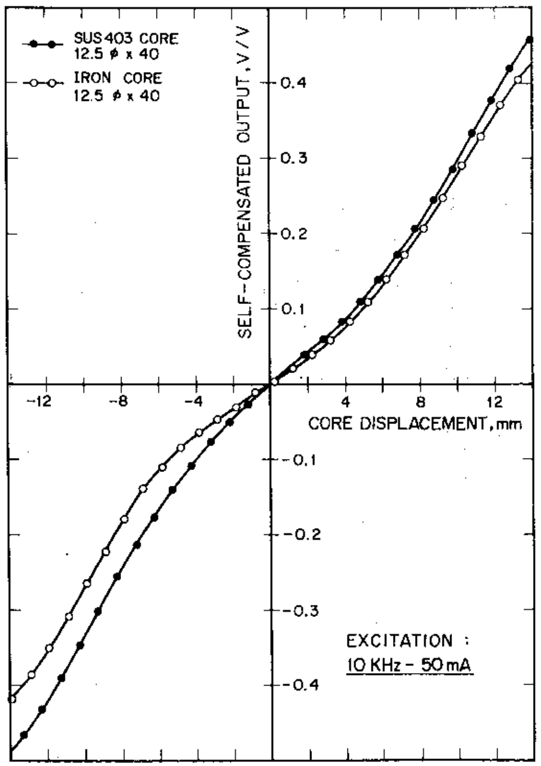


Fig.6 Self-compensated outputs for SUS403 and iron cores and their their variations with core displacements.

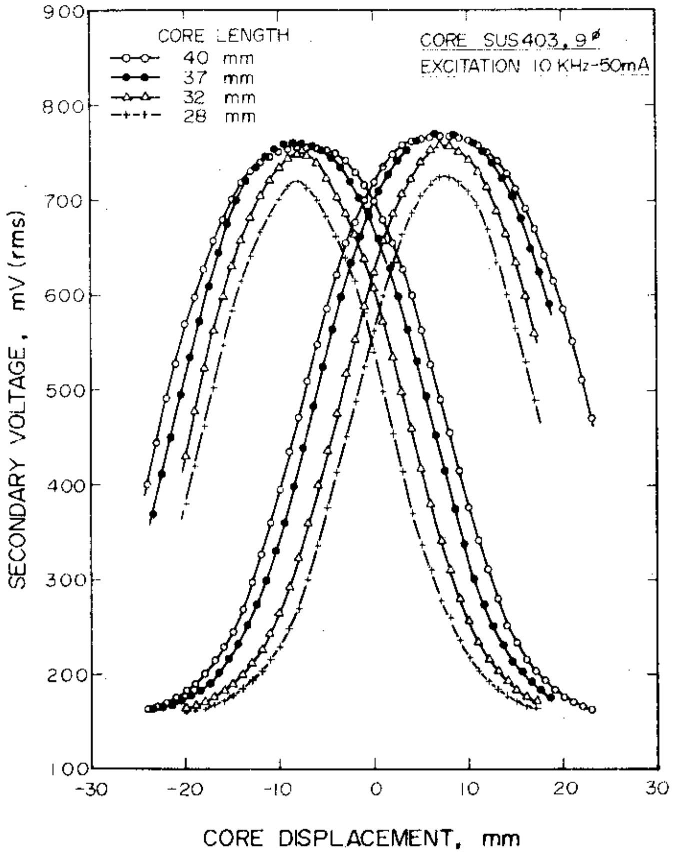


Fig.7 Secondary voltages for various core lengths and their variations with core displacements.

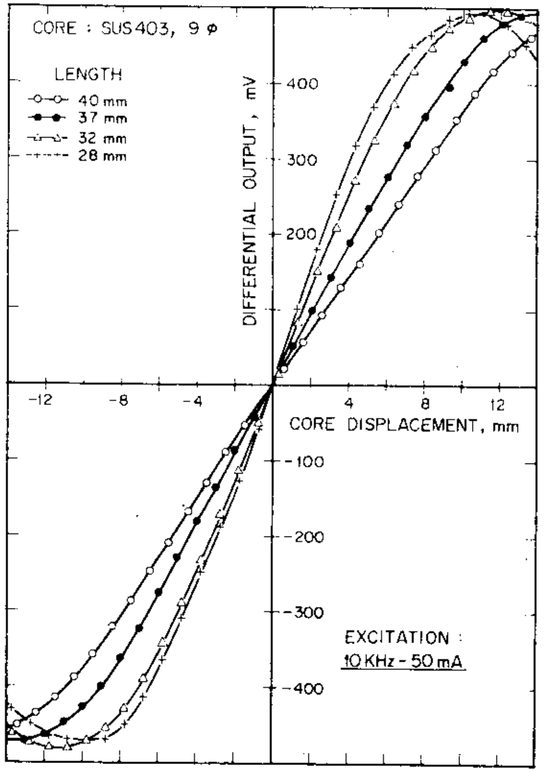


Fig.8 Differential outputs for various core lengths and their variations with core displacements.

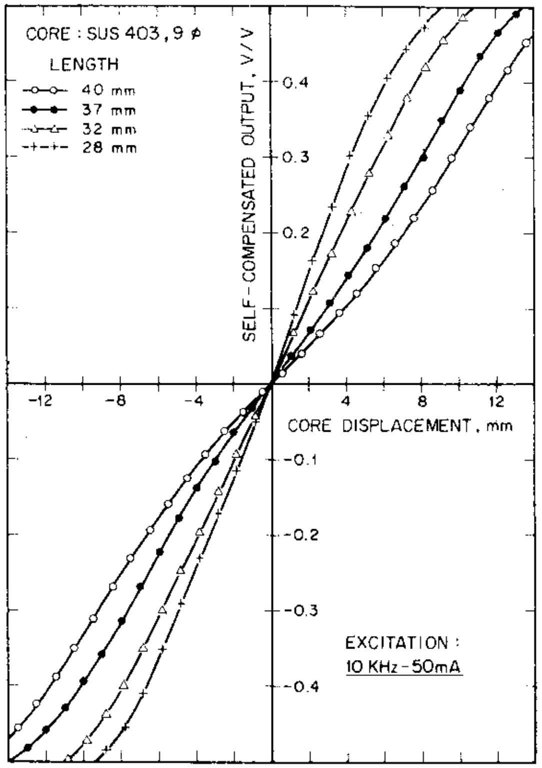


Fig.9 Self-compensated outputs for various core lengths and their variations with core displacements.

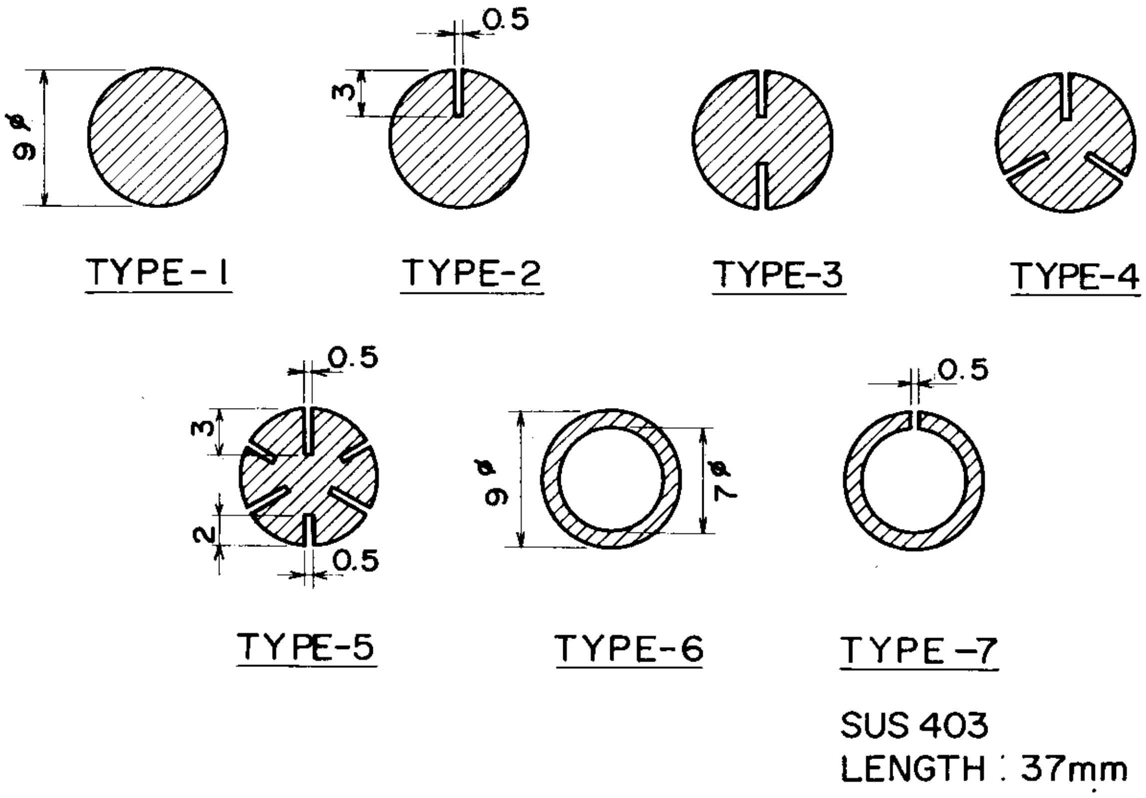


Fig.10 Types of magnetic core used in experiments on effects of reducing eddy current in the core.

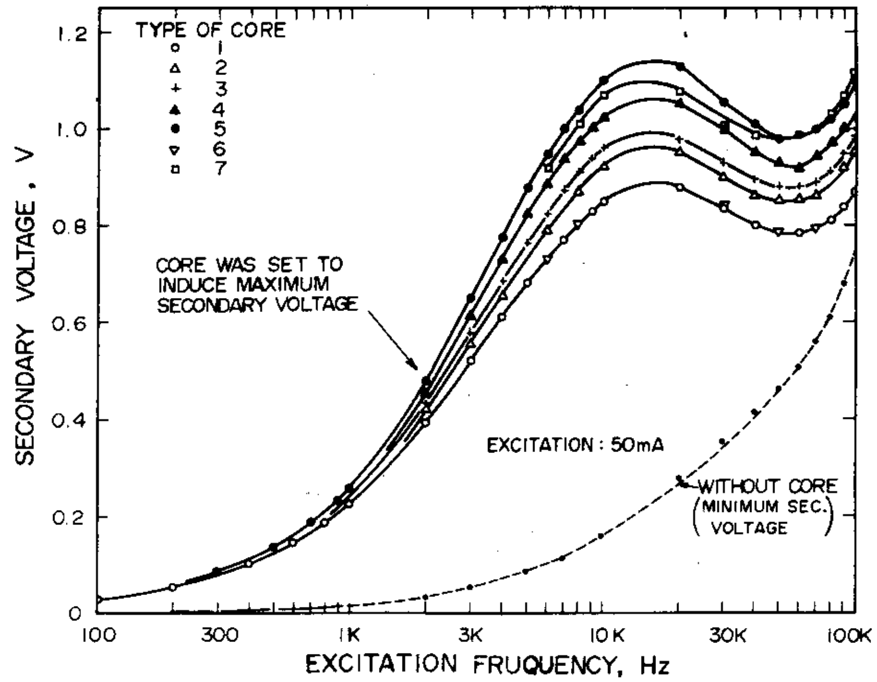


Fig.11 Frequency dependencies of maximum inductions of secondary voltages for various types of core, under the setting condition of transformer corresponding to the fuel clad elongation measurement (i.e., core was not in a zircaloy tube), in comparing with those of minimum ones.

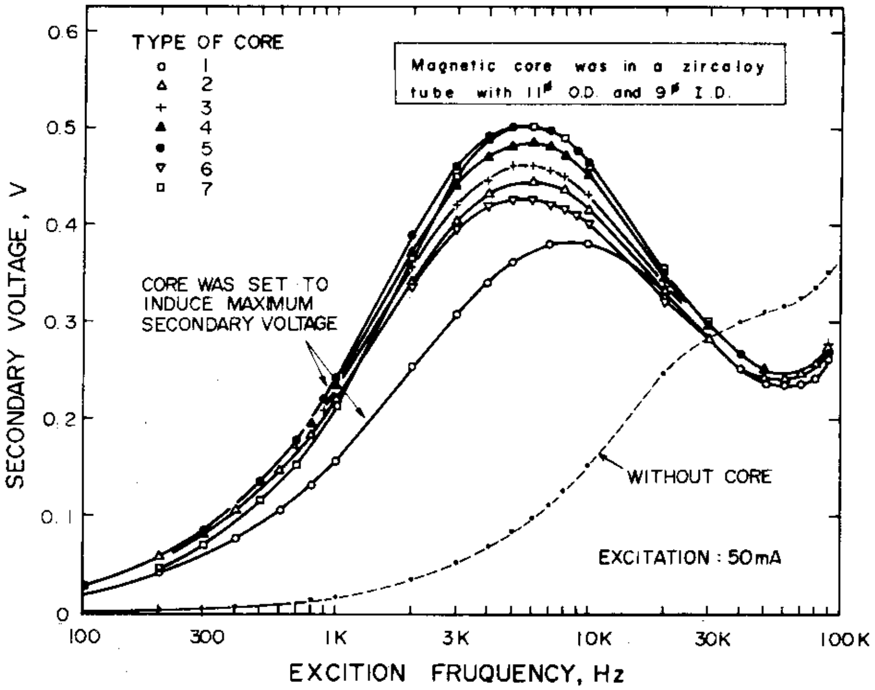


Fig.12 Frequency dependencies of maximum inductions of secondary voltages for various types of core, under the setting condition of transformer, corresponding to the fuel stack elongation measurement (i.e., core was in a zircaloy tube), in comparing with those of minimum ones.

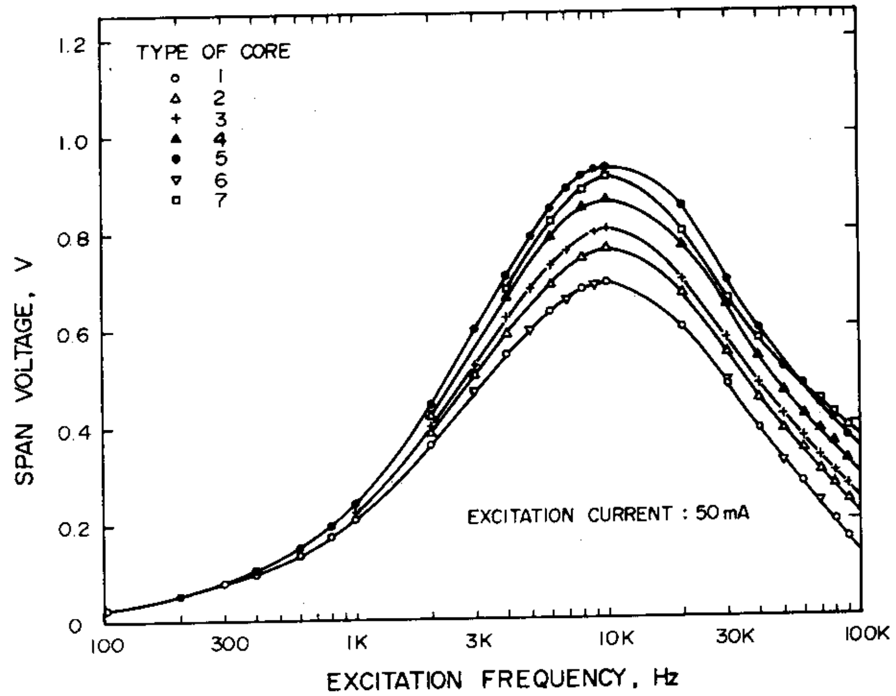


Fig.13 Span voltages for various types of core under the setting condition of transformer, corresponding to the fuel clad elongation measurement.

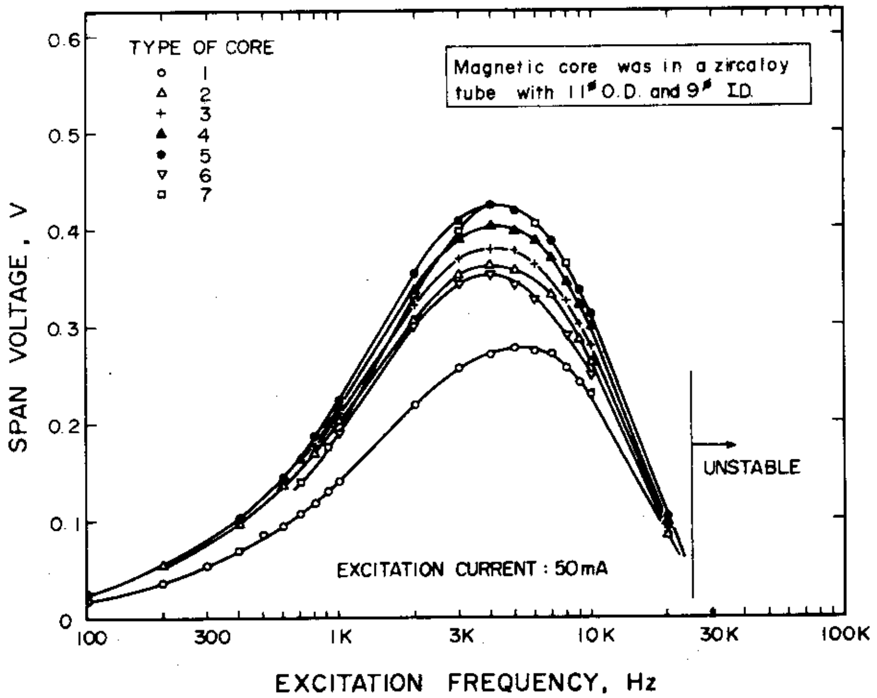


Fig.14 Span voltages for various types of core under the setting condition of transformer, corresponding to the fuel stack elongation measurement.

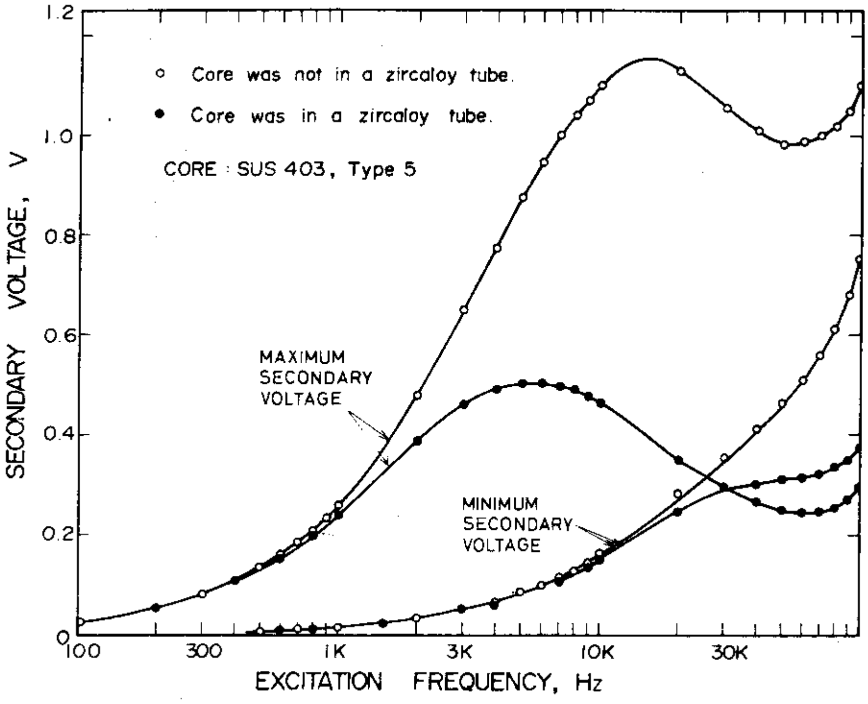


Fig.15 Effect of zircaloy tube on the maximum and minimum secondary voltages as a function of excitation frequency.

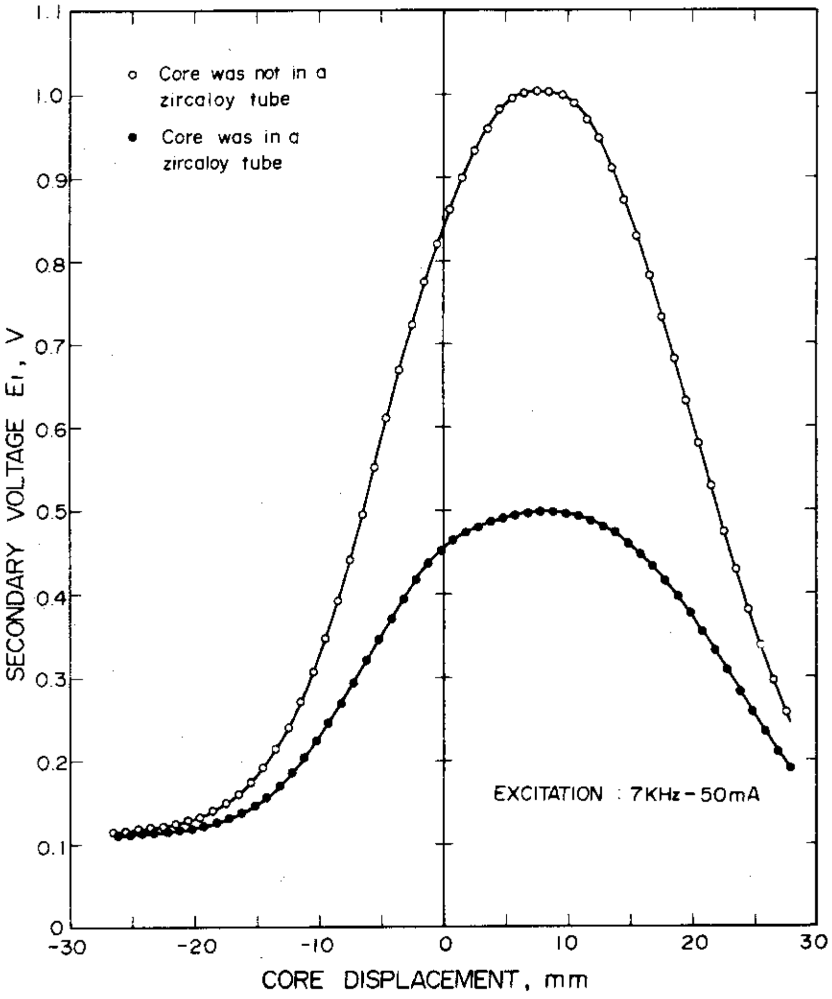


Fig.16

Effect of zircaloy tube on the shape of "secondary voltages vs. core displacement" curve.

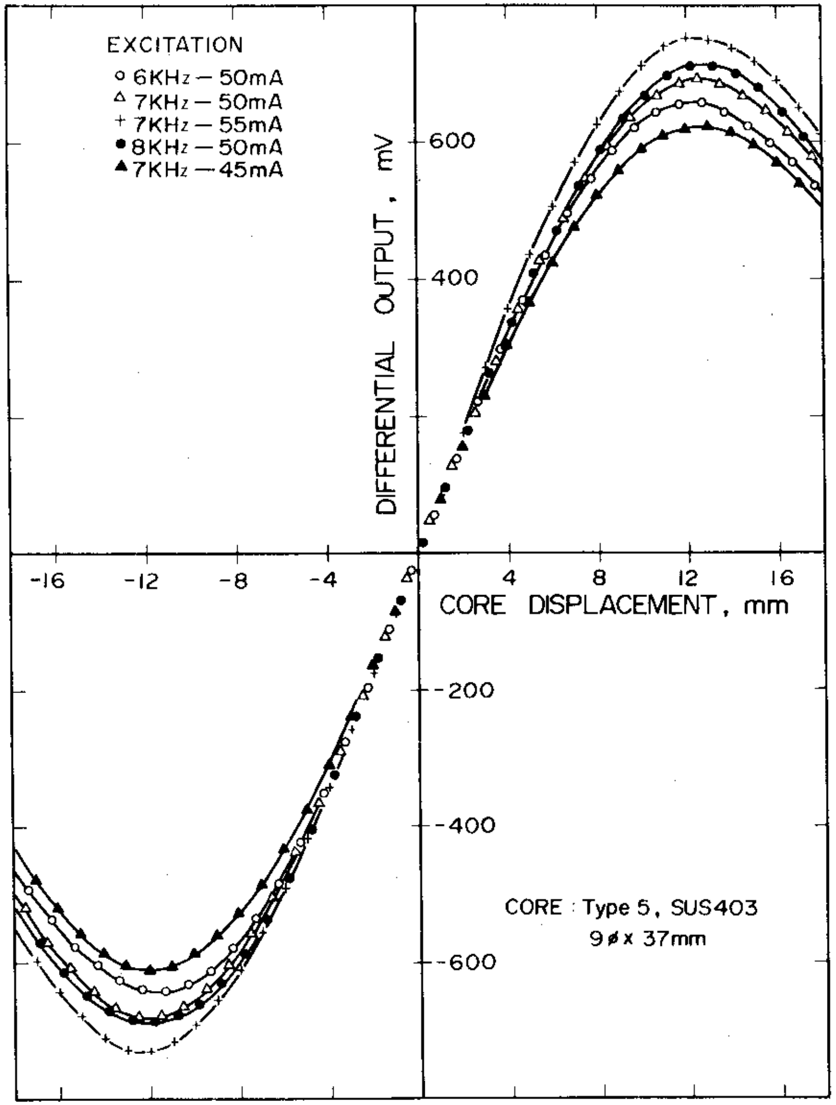


Fig.17 Calibration curves of differential outputs for various excitation conditions, in case that core was not in a zircaloy tube.

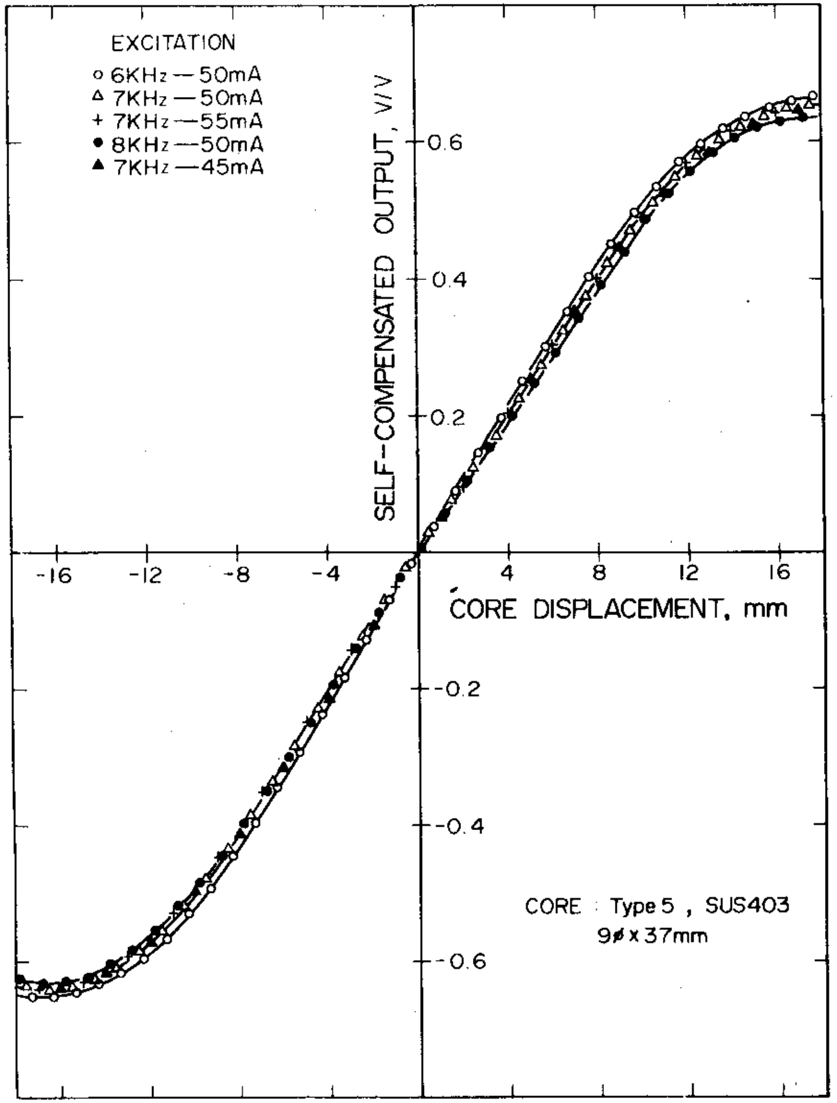


Fig.18 Calibration curves of self-compensated outputs for various excitation conditions, in case that core was not in a zircaloy tube.

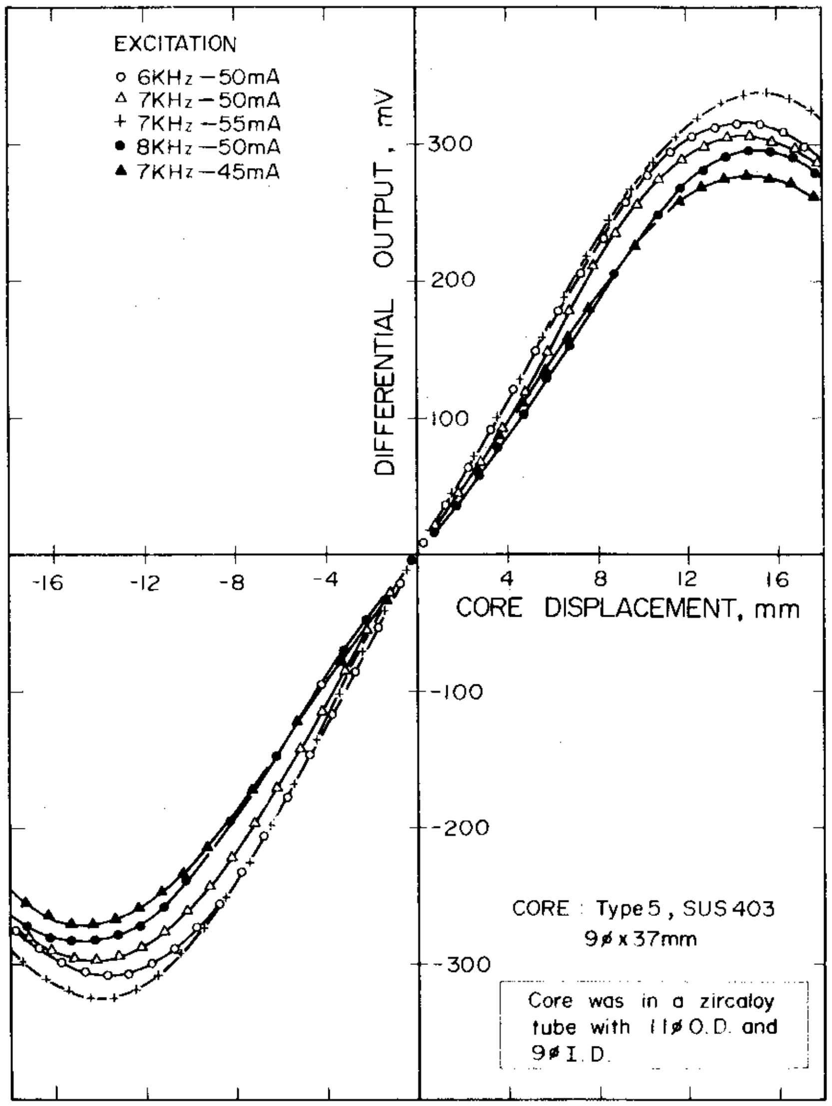


Fig.19 Calibration curves of differential outputs for various excitation conditions, in case that core was in a zircaloy tube.

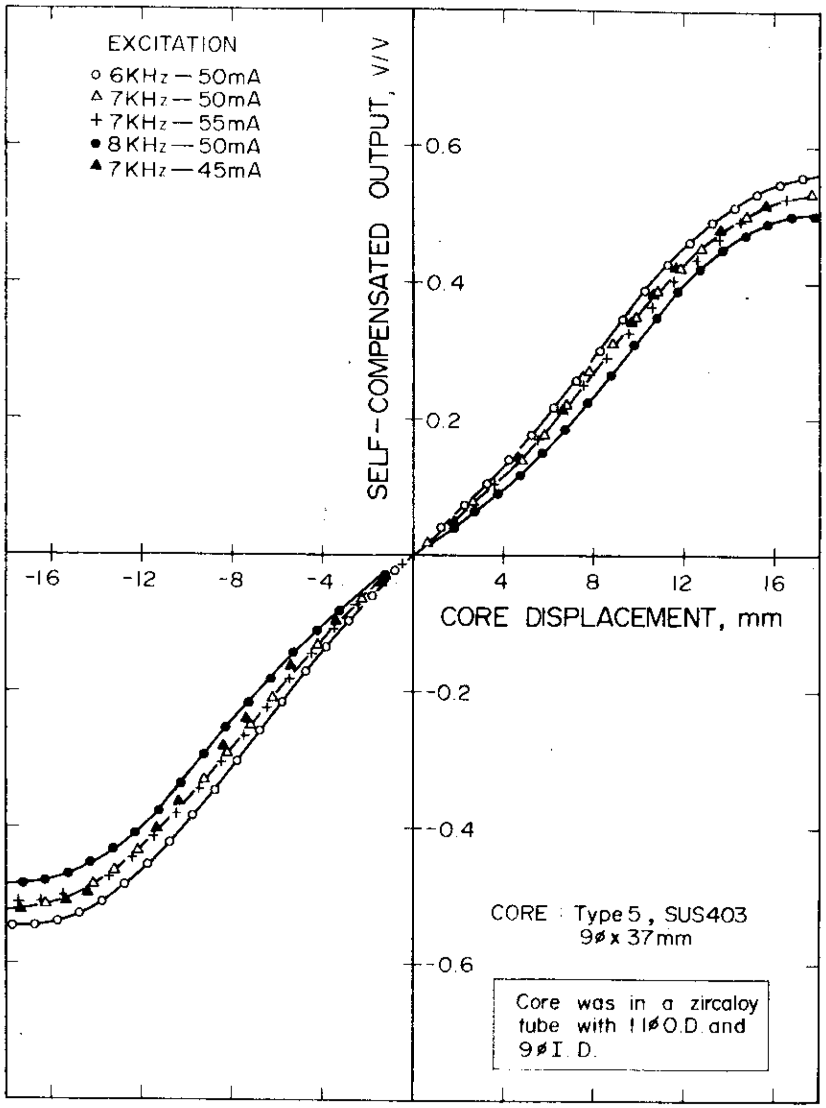
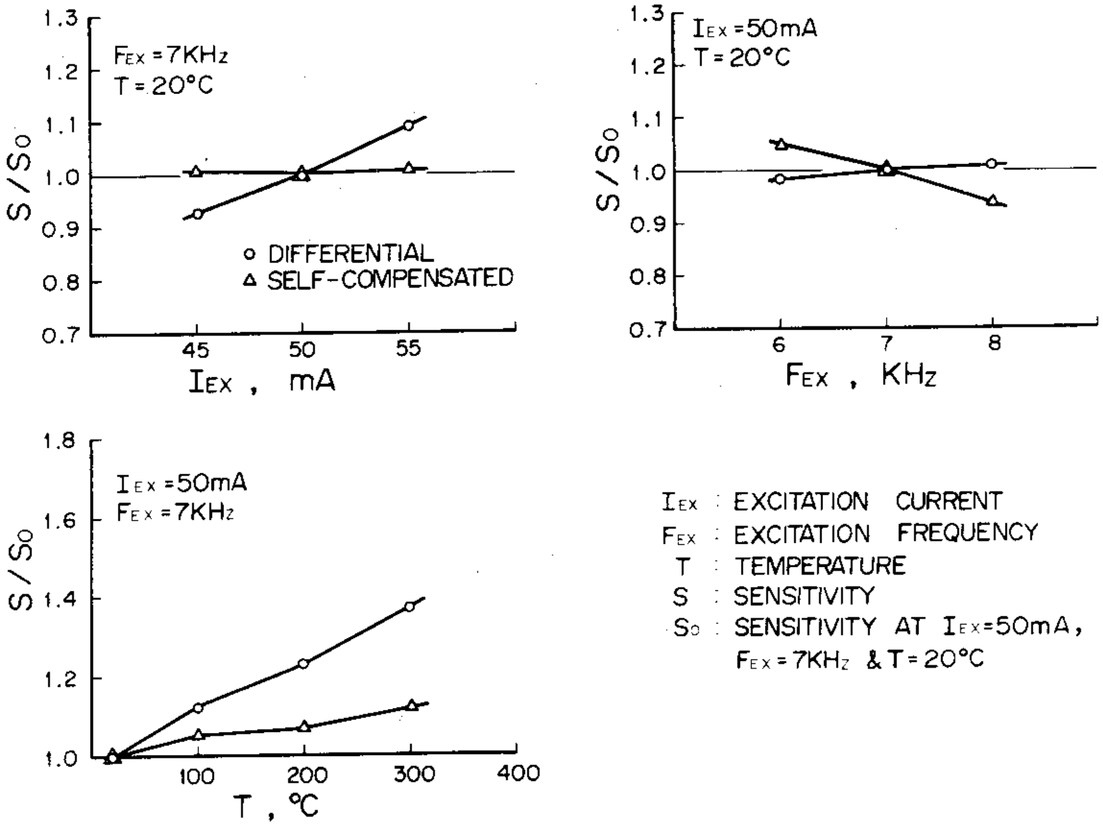
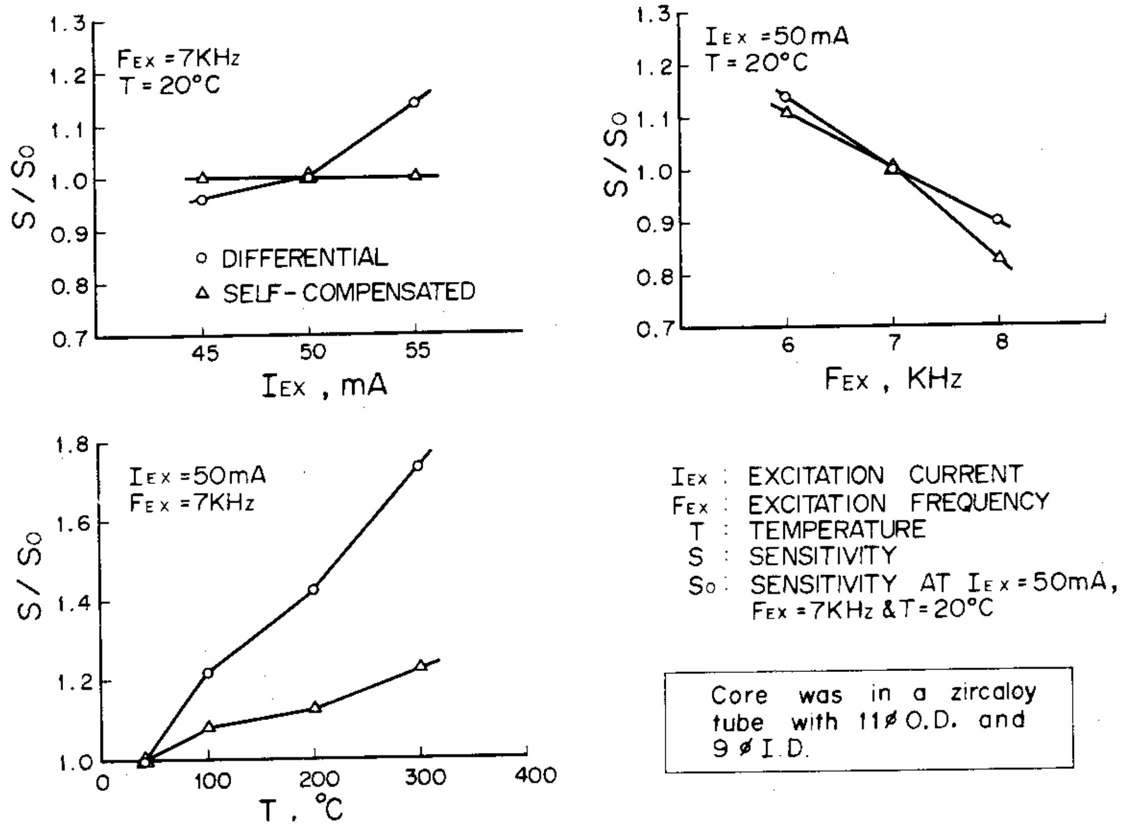


Fig.20 Calibration curves of self-compensated outputs for various excitation conditions, in case that core was in a zircaloy tube.



IEX : EXCITATION CURRENT
FEX : EXCITATION FREQUENCY
T : TEMPERATURE
S : SENSITIVITY
So : SENSITIVITY AT IEX=50mA, FEX=7KHz & T=20°C

Fig.21 Comparisons between sensitivity changes in differential treatment and self-compensation one, in case that core was not in a zircaloy tube.



IEX : EXCITATION CURRENT
FEX : EXCITATION FREQUENCY
T : TEMPERATURE
S : SENSITIVITY
So : SENSITIVITY AT IEX = 50mA, FEX = 7KHz & T = 20°C

Core was in a zircaloy tube with 11ø O.D. and 9ø I.D.

Fig.22 Comparisons between sensitivity changes in differential treatment and self-conpensation one, in case that core was in a zircaloy tube.

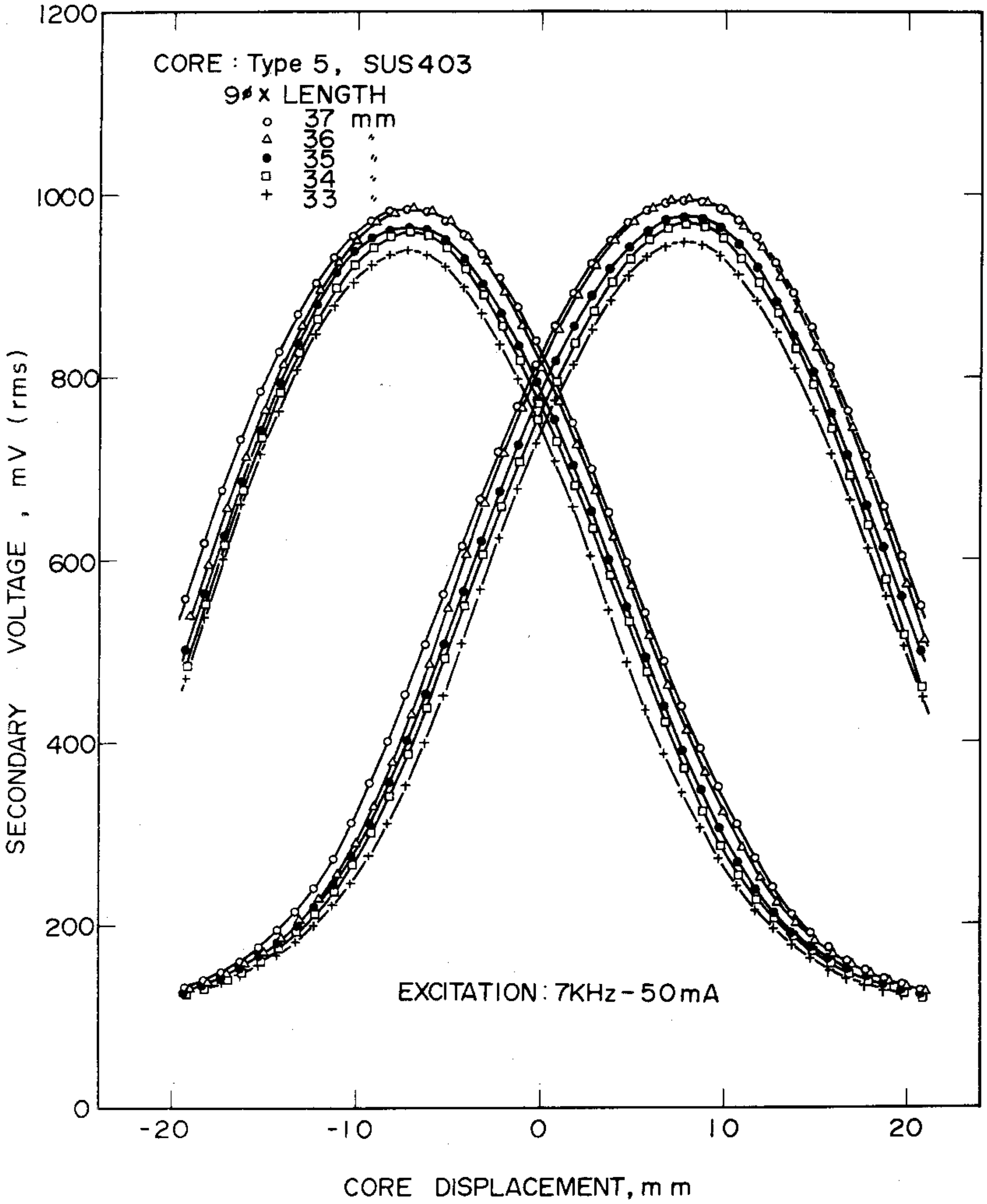


Fig.23 Secondary voltages vs. core displacements for various lengths of core, in case that the core was not in a zircaloy tube.

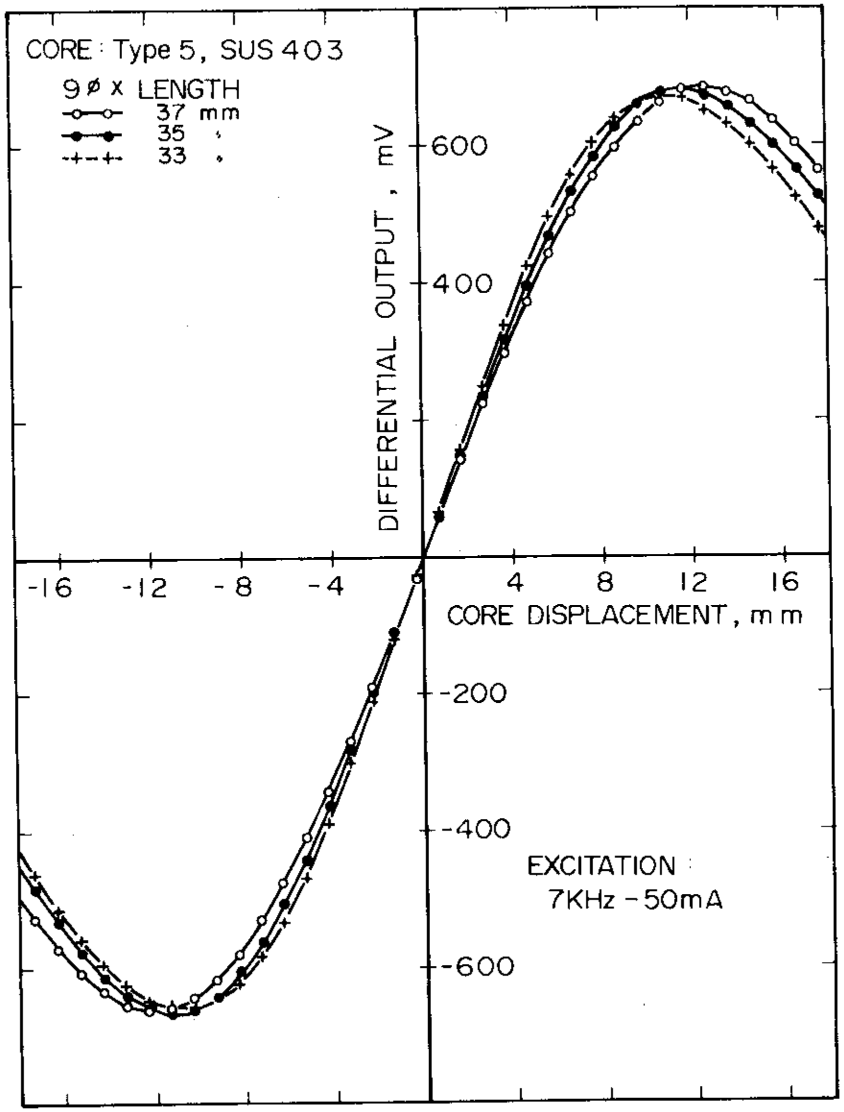


Fig.24 Calibration curves of differential outputs for various lengths of core, in case that the core was not in a zircaloy tube.

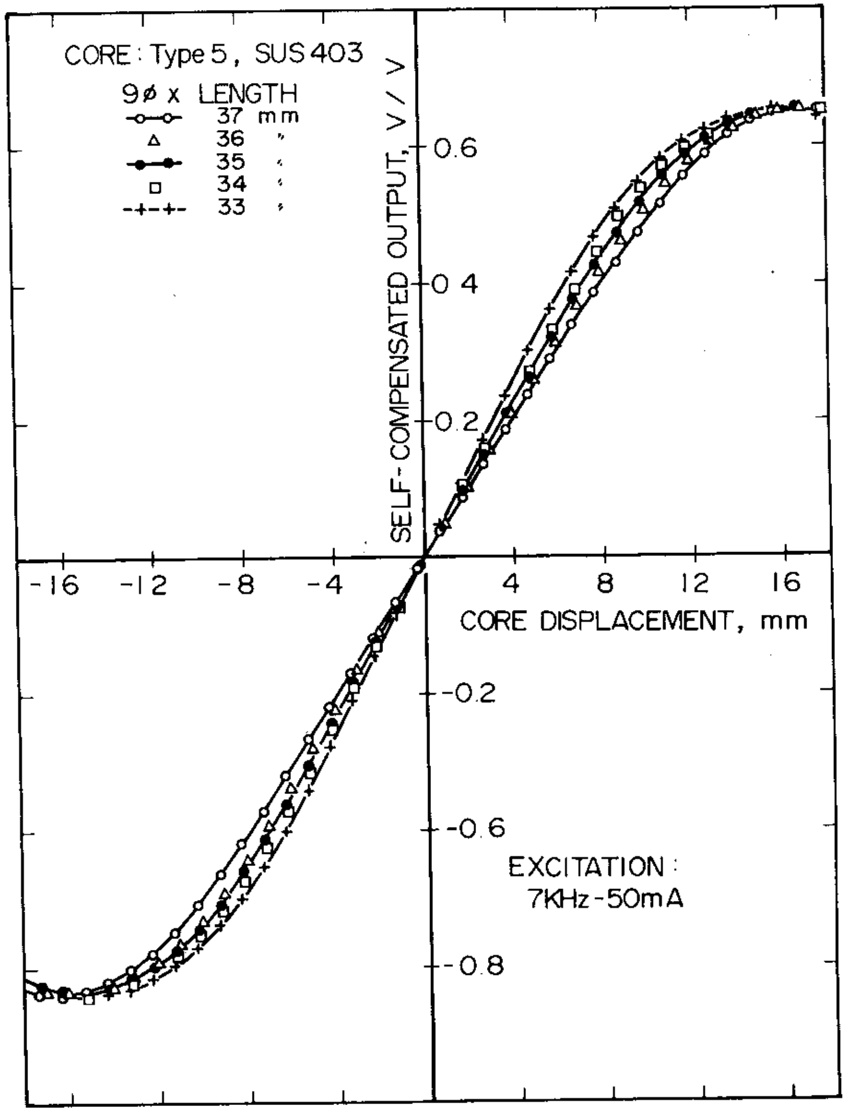


Fig.25 Calibration curves of self-compensated outputs for various lengths of core, in case that core was not in a zircaloy tube.

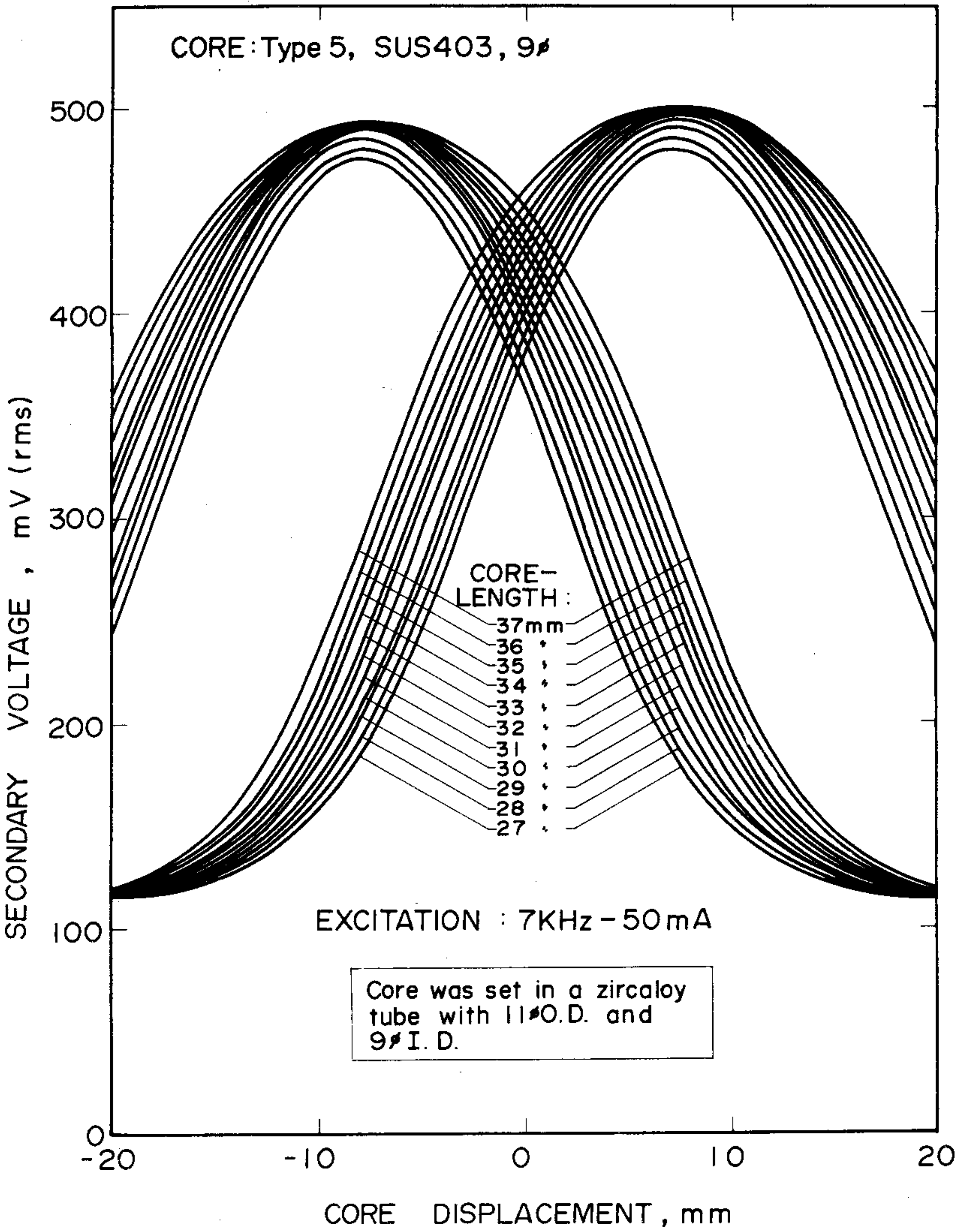


Fig.26 Secondary voltages vs. core displacements for various lengths of core, in case that the core was in a zircaloy tube.

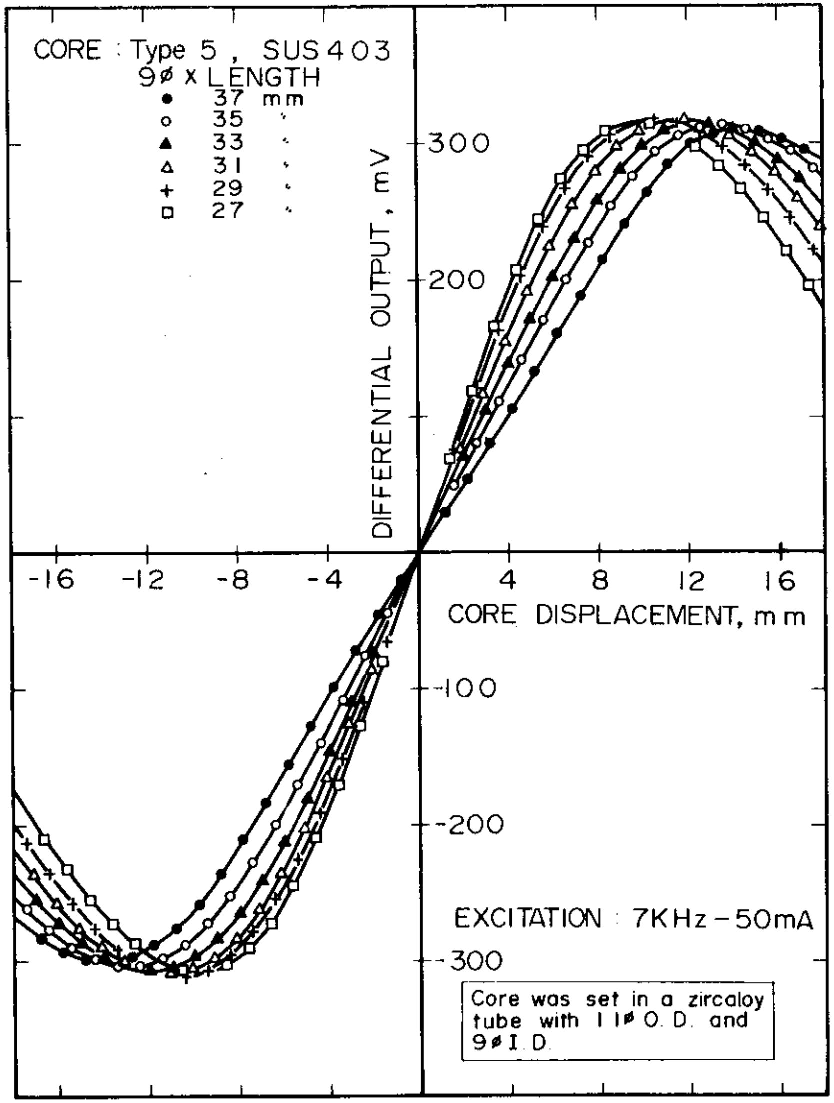


Fig.27 Calibration curves of differential outputs for various length of core, in case that the core was in a zircaloy tube; (1).

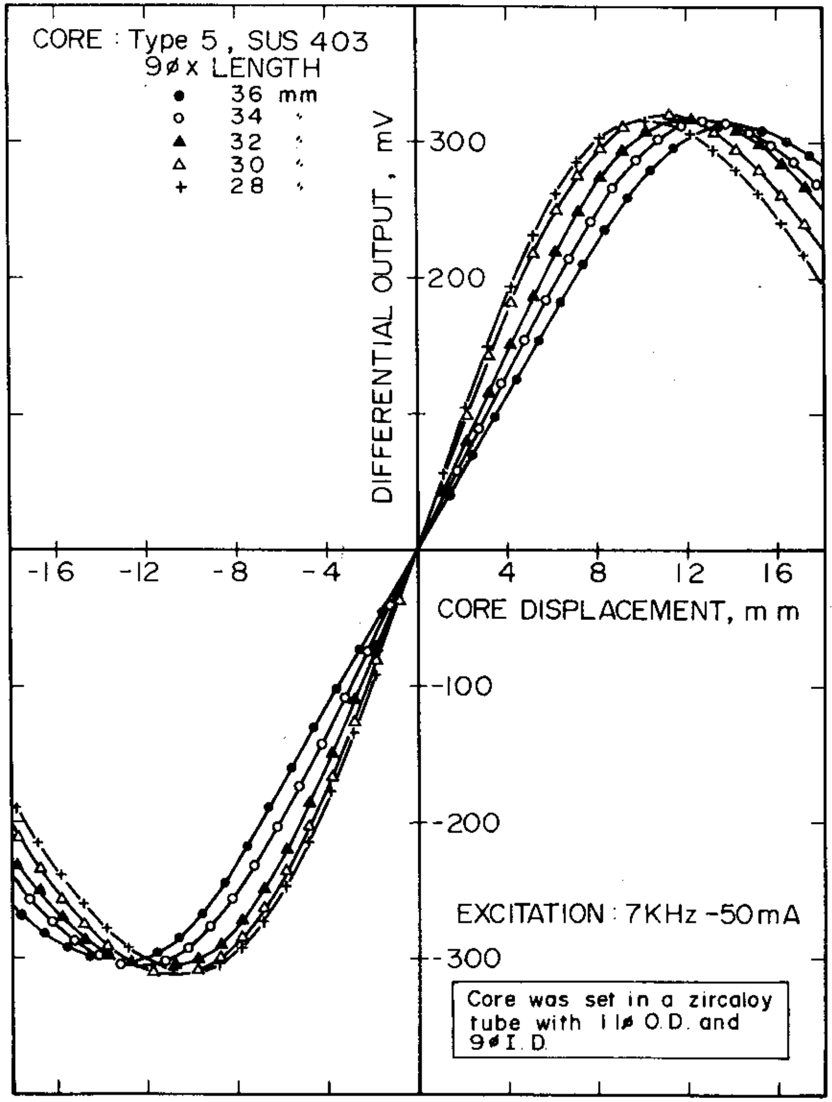


Fig.28 Calibration curves of differential outputs for various lengths of core, in case that the core was in a zircaloy tube; (2).

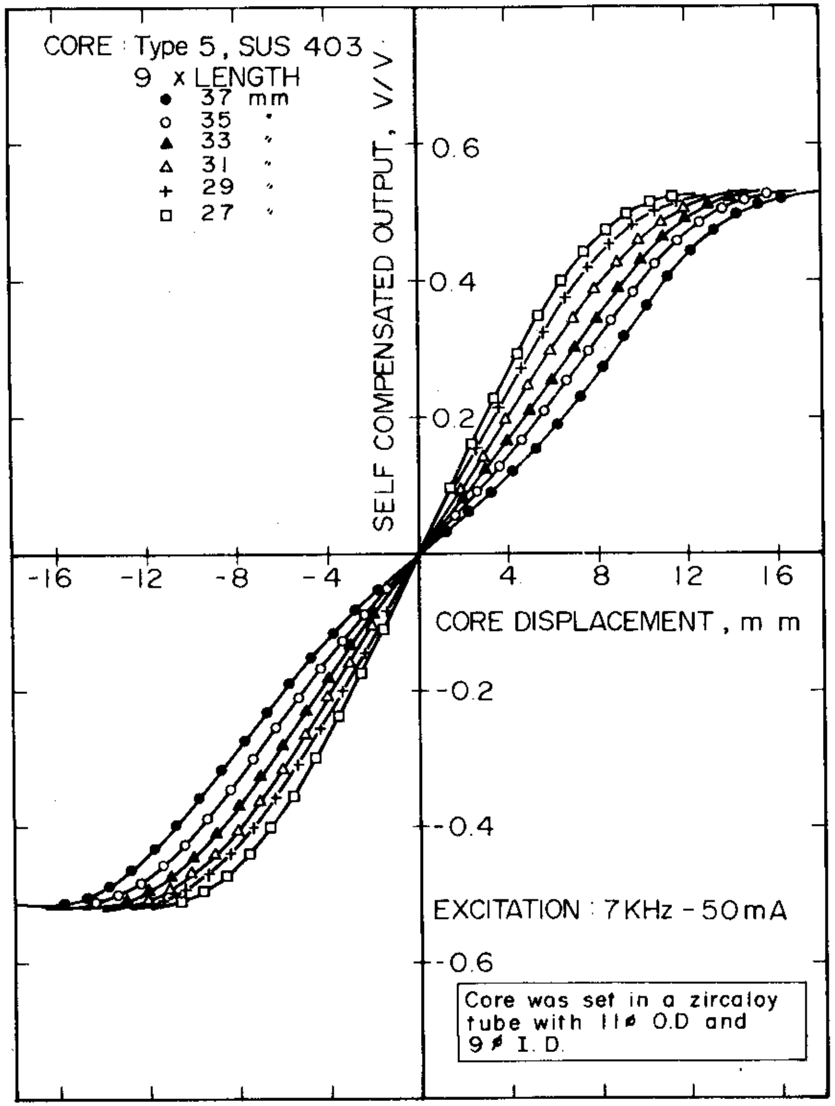


Fig.29 Calibration curves of self-compensated outputs for various lengths of core, in case that the core was in a zircaloy tube; (1).

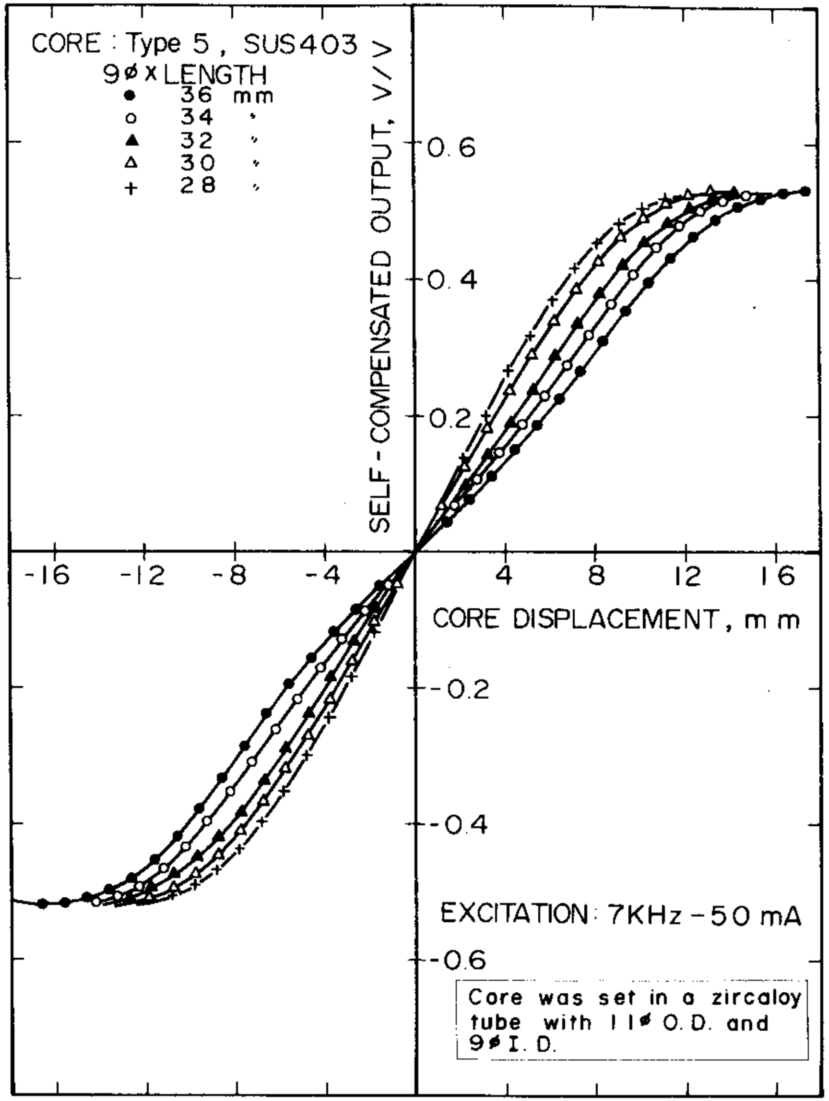


Fig.30 Calibration curves of self-compensated outputs for various lengths of core, in case that the core was in a zircaloy tube; (2).