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DIELECTRICS STUDY
FINAL REPORT

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Energy Sciences Inc.

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13. ABSTRACT

This dielectrics study was concerned with evaluating pulse signature effect upon the dielectric strength of deionized water. The "double resonance" HV generator used provided a prestressing of the dielectric before the major stress and the influence of this prestress was of interest.

The report describes the transformer generator and its characteristic in some detail and deals also with the overall experimental arrangements.

It is reported that, under normal design conditions, the prestress influence is insignificant and that breakdown stresses are close to those which would be predicted by the relationship $Ft^{1/3} A^{1/10} \simeq 0.3$, where F is breakdown field in MV/cm, t is effective stress time in microseconds, and A is electrode area in cm^2.

The report concludes that this generator form would be of considerable interest with pressurized dielectric conditions.

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Pressurized Water Dielectric						

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SUMMARY

This reports the findings of an experimental study to investigate the dielectric strength of deionized water when pulse stressed by a "double resonance" transformer.

The data provide evidence that the prestress conditions do not significantly affect the results. Additionally, it is suggested that the relationship for maximum stress as a function of time and electrode area can be applied for stress times of 5-10 microseconds.

The transformer generator is discussed in some detail. The conclusion is drawn that this generator form would be a sensible choice in a pulse system using pressurized water dielectric. High dielectric strengths are now claimed for this treatment with effective stress times of tens of microseconds - a range which is compatible with the transformer pulse signature.

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SECTION 1

INTRODUCTION

The role of deionized water as a dielectric medium for low impedance, pulse power systems has been well established and competent designs may be achieved by using time and area dependency relationships for breakdown stresses.

The pulse power technology which has evolved utilizes "fast" Marx generator designs for charging the water insulated, energy stores, taking advantage of the high energy densities which may be achieved via the shorter electrical stress times.

For the future, pulse power systems utilizing a water dielectric media are likely to increase in pulse energy and one can foresee that the provision of "fast" charging generators may well present technical and economic difficulties. From another viewpoint, unless higher energy densities are achievable in stores of contemporary dimensions, load discharge specification may be difficult to satisfy.

From either view it is desirable to increase the dielectric strength of water in the submicrosecond time scale and/or reduce the time dependency of breakdown stress such that high stresses may be sustained for as long as 1-10 microseconds.

This dielectrics study is intended as a first step in the re-evaluation of water as an energy storage medium. The ultimate goal is to achieve higher submicrosecond stresses and widen the options in charging generator designs via reduced time dependence of breakdown.

There are various influences, or combinations of influences, which may be explored towards improved dielectric performance:

(1) Physical and chemical treatments of the water.

(2) Treatments of the electrode surfaces.

(3) Charging generator pulse signatures.

Items (1) and (2) would involve studies of considerable duration and expense unless steering information was available. The effects of a particular pulse signature was selected for evaluation in this study - a pulse signature characteristic of the double resonance transformer which is not only a potentially useful generator but one which has a different utilization of the dielectric medium. The output voltage is periodic in the tens of microseconds range and maximum energy transfer via the transformer does not occur until the peak of the second half cycle (see Figure 1). The point of interest is that the first half cycle voltage, normally ~50% of the second half cycle peak, produces prestressing of the dielectric in opposite polarity to the main stresses of the second half cycle. According to Sletten,(1) dielectric strength improvements have been found for oil (clean) with an opposite polarity dc prestress.

The merits of prestressing were therefore to be evaluated under the conditions and time scales which are of concern to pulse power technology.

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(1) Ann. Rep. 1960, Conf. Elect. Insulation 67, (1961), Sletten, A.M.

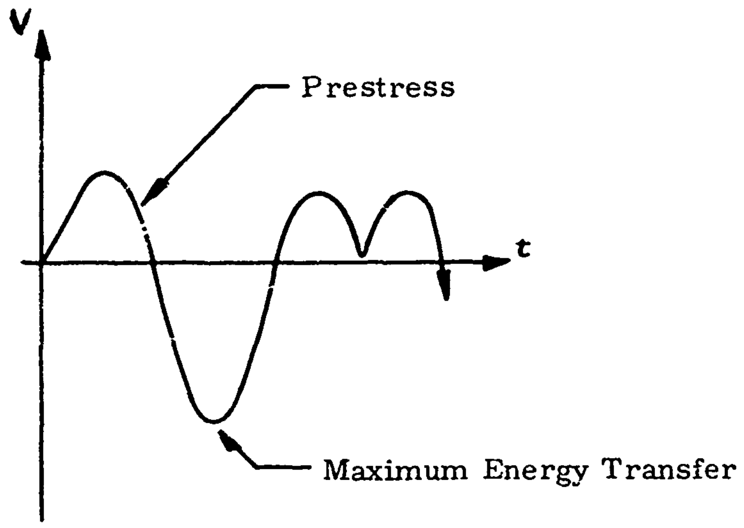

Figure 1 (a) Double Resonance Pulse

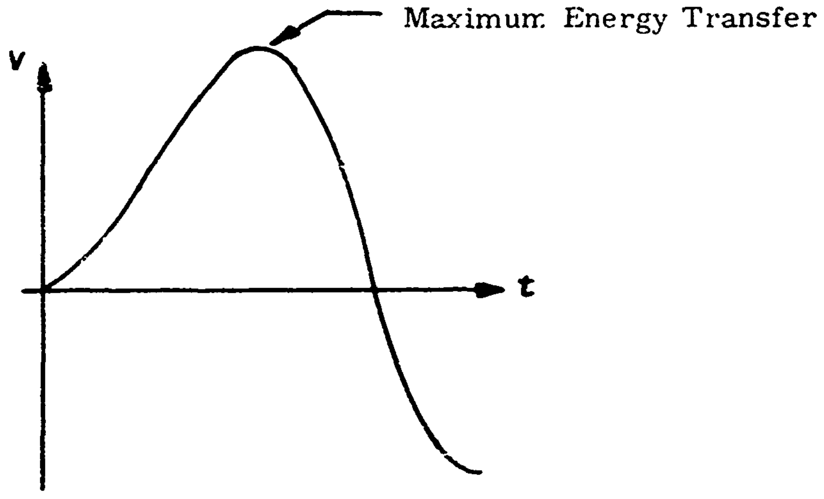

Figure 1 (b) Typical Marx Output Pulse

SECTION 2

THE "DOUBLE RESONANCE" PULSE TRANSFORMER

2.1 Voltage and Energy Transfer Relationships

The voltage pulse signature of concern in this study is characteristic of the "double resonance" transformer generator. It must be understood that the general effects of prestress in dielectrics could not be studied - only prestresses in the range 40-60% of the maximum applied voltage, which is the normal relationship for these transformers.

The argument for the "double resonance" form of pulse transformer is that it, theoretically, permits 100% energy transfer from primary to secondary circuit during the second half cycle of energy transport.

The schematic for this circuit is shown in Figure 2. As the name implies, both the primary circuit, L_1C_1, and secondary circuit, L_2C_2, must be tuned to the same resonance frequency with the coupled network in "open circuit". This frequency is normally in the range of tens of kilohertz. For maximum circuit efficiency it is necessary that the secondary voltage reaches its maximum value at the peak of the second half cycle of discharge and this occurs over a narrow range of primary-secondary coupling factor.

The general equation for the transformer secondary voltage is·

$$V_2 = V_1\sqrt{\frac{L_2}{L_1}}\, e^{-\frac{t}{\tau}} \left\{ \mathrm{Sin}\ \frac{w}{2}\left(\frac{1}{\sqrt{1-k}} + \frac{1}{\sqrt{1+k}}\right) t \right.$$

$$\left. + \ \mathrm{Sin}\ \frac{w}{2}\left(\frac{1}{\sqrt{1-k}} - \frac{1}{\sqrt{1+k}}\right) t \right\}$$

where V_1 is the initial charge on C_1

w is the angular frequency of both circuits

k is the coupling factor

and τ is the damping time constant

$$= \frac{4}{w}\,\frac{Q_1Q_2}{Q_1+Q_2}\,(1-k^2)$$

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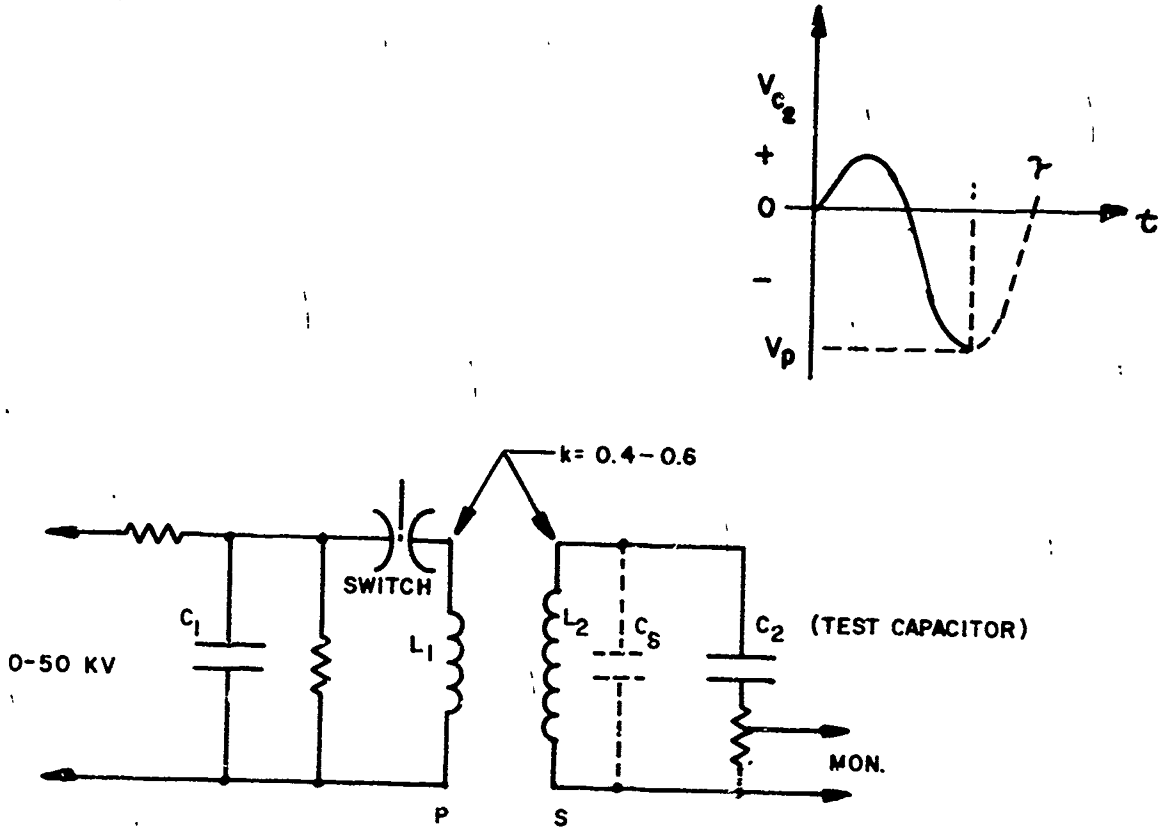


Figure 2 Dielectric Test Circuit

and Q_1, Q_2 are the circuit "quality factors defined as

$Q_1 = \frac{wL_1}{R_1}$; $Q_2 = \frac{wL_2}{R_2}$ where R_1 and R_2 are the effective series resistive elements in the primary and secondary circuits due to general energy losses.

From this expression it is shown that voltage maxima coincide with the peak of the "beat frequency" component for specific values of k and that for k = 0.6 the optimum condition is obtained - see Figure 3.

Now the energy transfer efficiency from primary store to secondary store is given by:

$$\eta = \frac{C_2 V_2{}^2 \max}{C_1 V_1{}^2}$$

This is ideally equal to unity but circuit losses, for which Q_1 and Q_2 are measures, reduce this efficiency to practical values in the range 0.7-0.9. Figure 4 illustrates this effect for assumed equal primary and secondary Q values and a range of coupling factors, k.

It must be emphasized that these voltage and energy relationships assume accurate double resonance and this will be the subject of further discussion. Designs should concentrate on obtaining the k = 0.6 value and achieving the highest possible circuit Q's. Obtainable values would seem to be $Q_1 \sim 20$, $Q_2 \sim 50$.

2.2 Physical Aspects of the Transformer Design

Although "double resonance" transformers have been designed in a variety of configurations, the usual models have a characteristic geometry - see Figure 5.

They are "air cored" devices with cylindrical secondary windings and coaxial primary windings of truncated cone geometry.

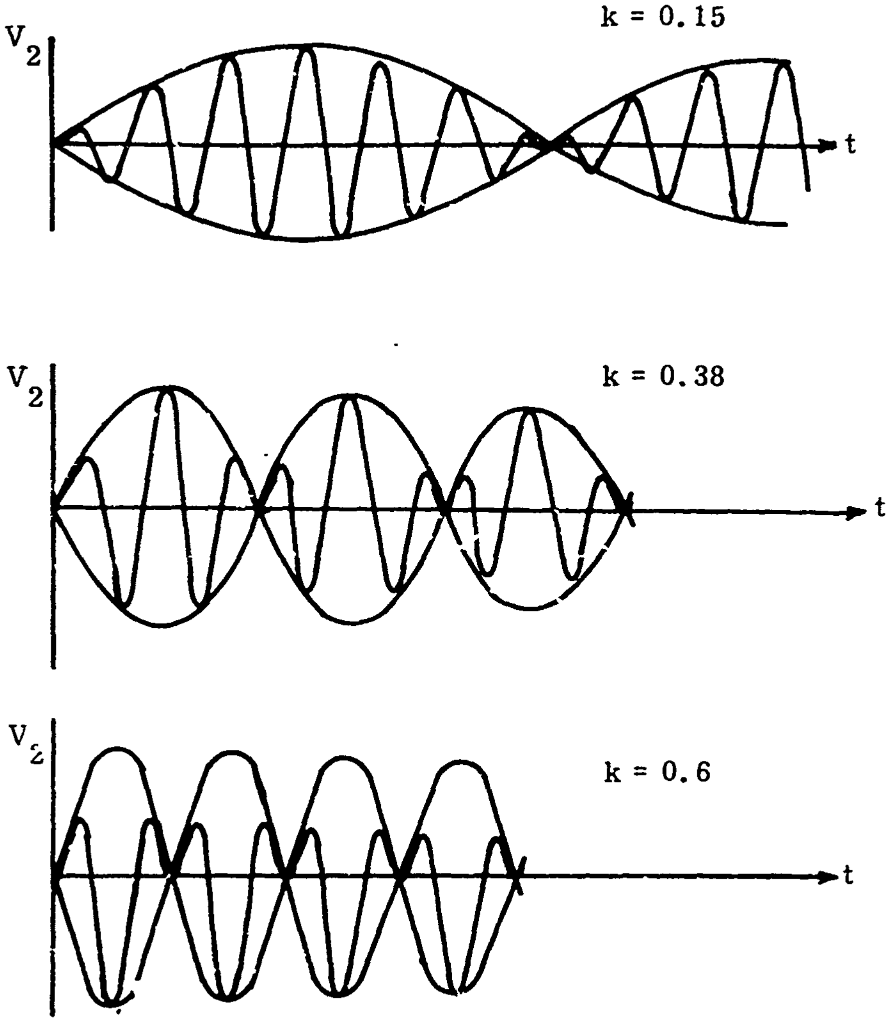


Figure 3 Secondary Voltage for Various Coupling Coefficients

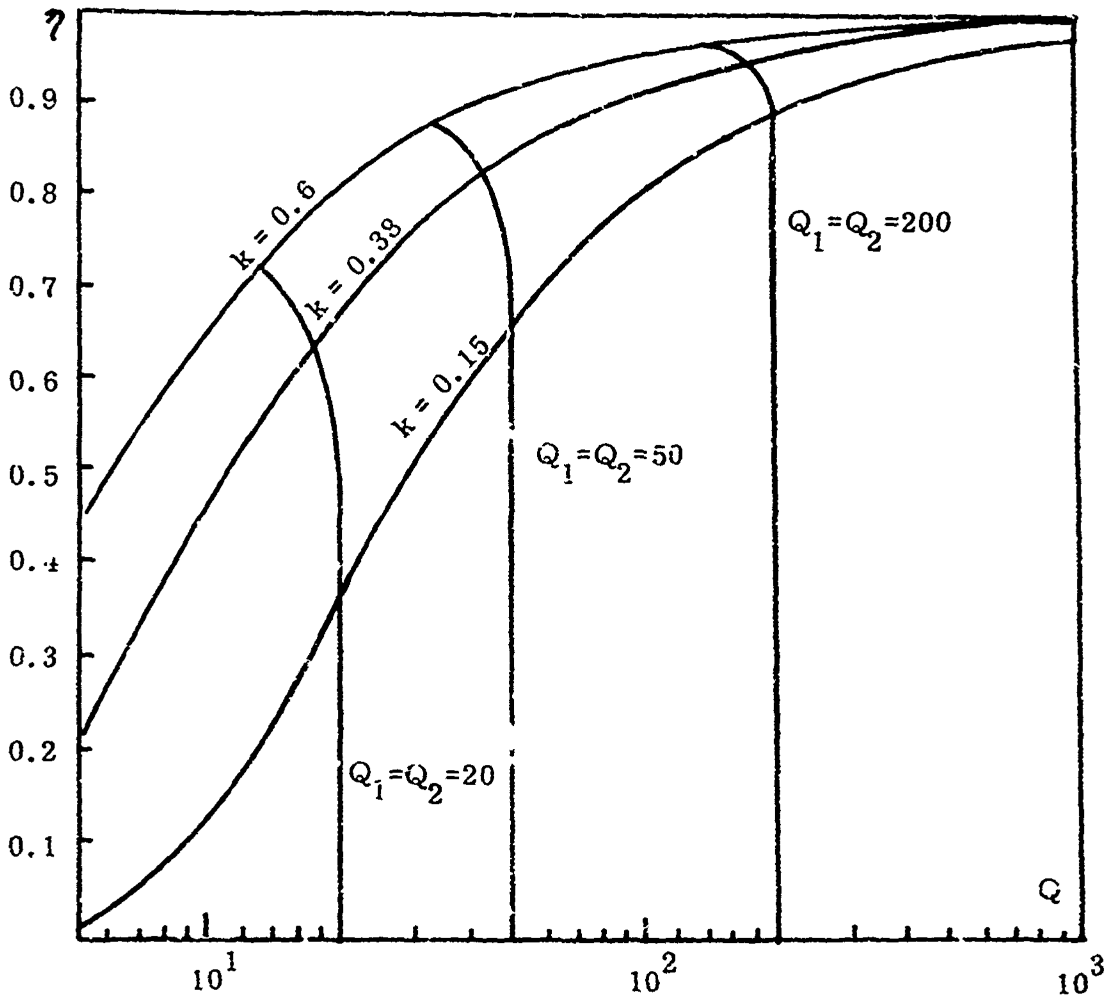


Figure 4 Energy Transfer Efficiently Under the Influence of Q

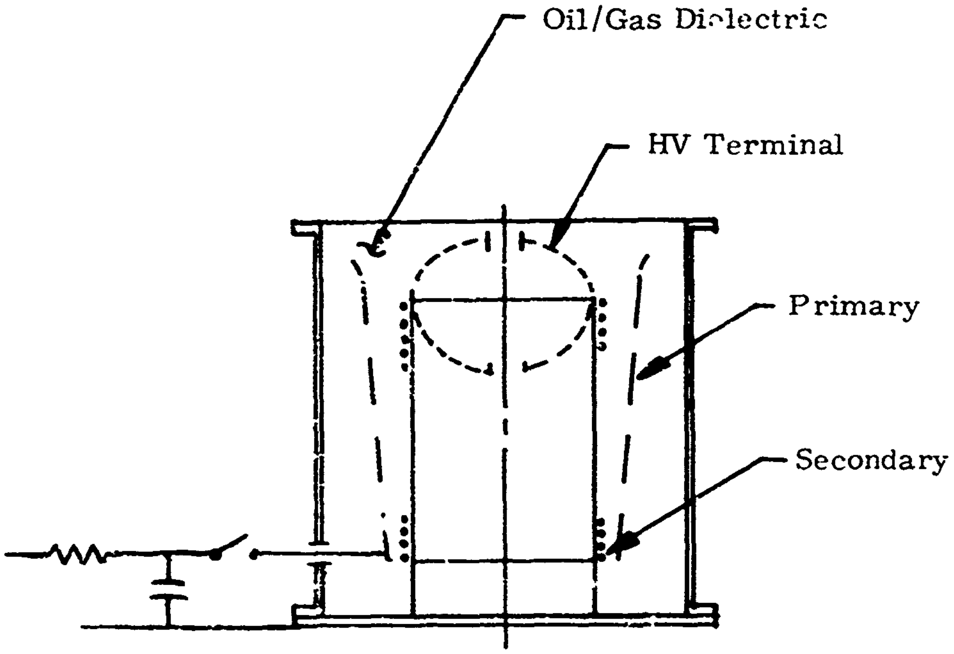


Figure 5 Transformer Geometry

The dimensions and winding details required for the transformer were influenced by the provisional experimental scope. We had decided to conduct the experiments using electrode areas which were comparable with the largest areas used in earlier tests, that is, in the range 400-1000 cm^2, and with comparable spacings of 2-5 cms. The secondary capacitance range was therefore defined, with a nominal 1500 pf taken for design purposes.

Next, the effective stress time was thought to be appropriate around 5.0 microseconds. This would be an order of magnitude above times previously used and comparable with times of possible future interest. For this purpose, the self-resonant frequencies were required to be approximately 30 kcs, setting the nominal secondary inductance at 20 mH.

The voltage capability of the transformer was required to be at least 1.0 MV because of the uncertainty of the dielectric performance under these pulse signature conditions. For convenience, the transformer was destined to operate under oil. Taking this into account, plus the necessity to operate with a solid dielectric barrier, or diaphram, between the oil of the generator and the water of the test bed, it was concluded that a transformer of similar radial dimension to a 2-3 MV pressurized gas unit would be required.

To assign a length to the secondary winding it was necessary to satisfy the inductance and the maximum voltage per turn requirements, taking into account the available candidate high voltage insulated wires. Since we had little experience with the overall geometrical effects of the transformer upon the primary-secondary coupling factor, k, it seemed sensible to stay fairly close to a proven winding length.

The major ransformer dimensions and details were therefore as follows:

(1)	Secondary form diameter -	24 in.
(2)	Primary winding major inner diameter -	36 in.
(3)	Primary winding minor inner diameter -	27 in.

(4) Secondary winding length - 30 in.

(5) Secondary turns - Nom. 250

Belden HV CRT Lead No. 8869

The working gain of the transformer was required to be in the range 35-40 and 5 turns were tentatively taken for the primary winding.

A full scale transformer model was made which included a mild steel cylinder to simulate the effects of the transformer tank upon coupling factor k, primary and secondary inductance and primary and secondary circuit Q factors.

This model confirmed the basic design details at low voltage. For the dimensions given:

(1) Normal resonant frequency - primary and secondary; 30 kcs

(2) Capacities - primary - 2.0 uf; secondary - 1500 pf

(3) Circuit Q's - primary - $\sim$20; secondary - $\sim$50

(4) Circuit gain - $\sim$40

(5) Coupling factor - $\sim$0.6

With this confirmation we proceeded with the final design and manufacture of the test bed generator.

2.3 Typical Generator Waveforms and Tuning Methods

Given a transformer structure with the recommended primary-secondary coupling factor of $k = 0.6$, the character of the pulse signature is primarily dependent upon the relative resonance frequencies of the primary and secondary circuits. Making allowances for the circuit decrement, the coincidence of circuit resonances provides the best pulse symetry. Departure from coincidence of tune results in a change of relative amplitudes of the third and fourth half cycles of the output waveform. Figure 6 a-c shows the three cases:

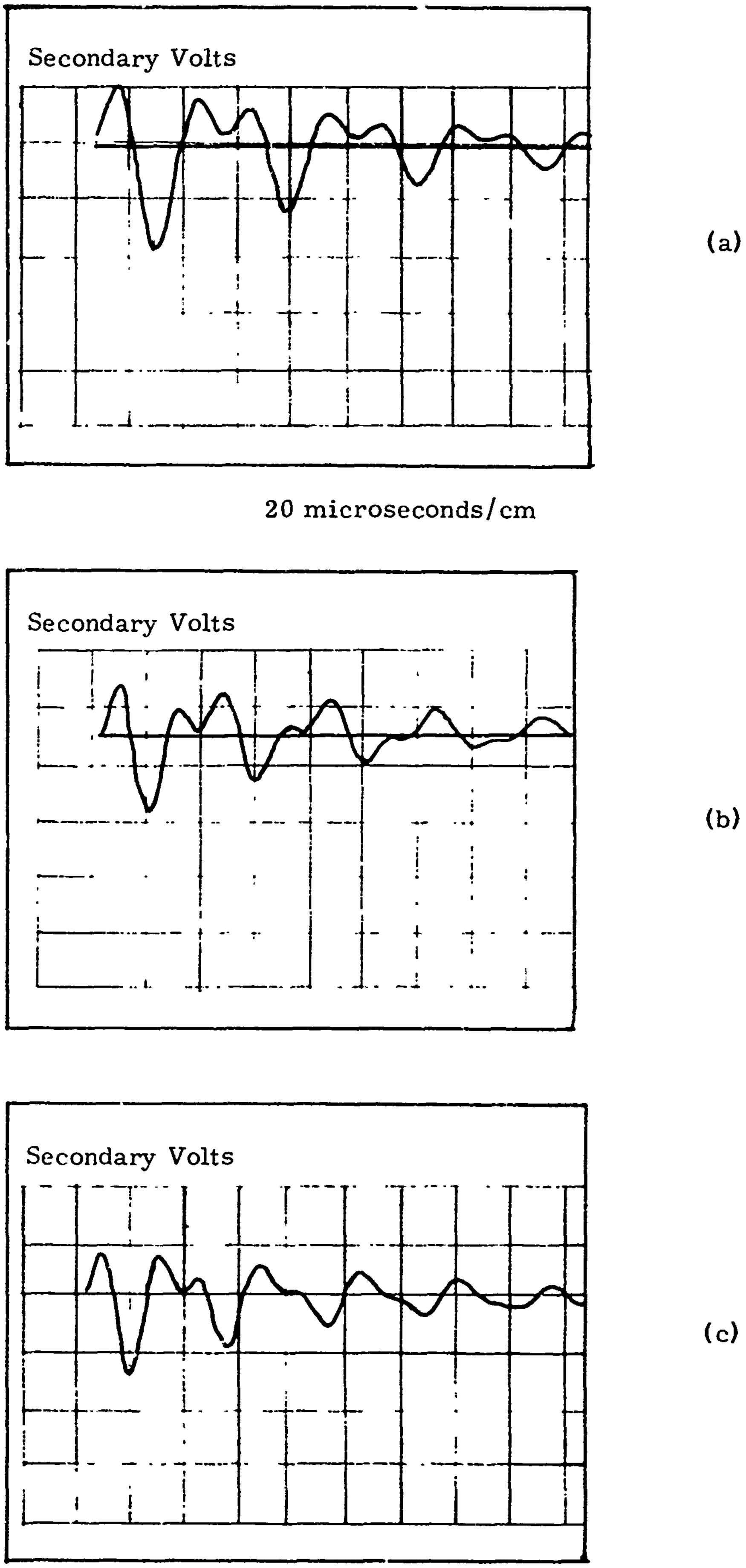


Figure 6 Typical Waveforms

(a) Primary and secondary circuits with coincident resonance frequencies.

(b) Primary circuit resonant at higher frequency (~20%) than secondary circuit.

(c) Secondary circuit resonant at higher frequency (~20%) than primary circuit.

This relative tune is of great practical importance because the transformer gain is tune dependent. Maximum gain is obtained for coincidence of tune. For reasonable Q factors, the gain can be reduced by approximately 50% for a 20% spread of circuit resonances. There are many methods which can be used to observe circuit resonances, only the method used in our work will be described.

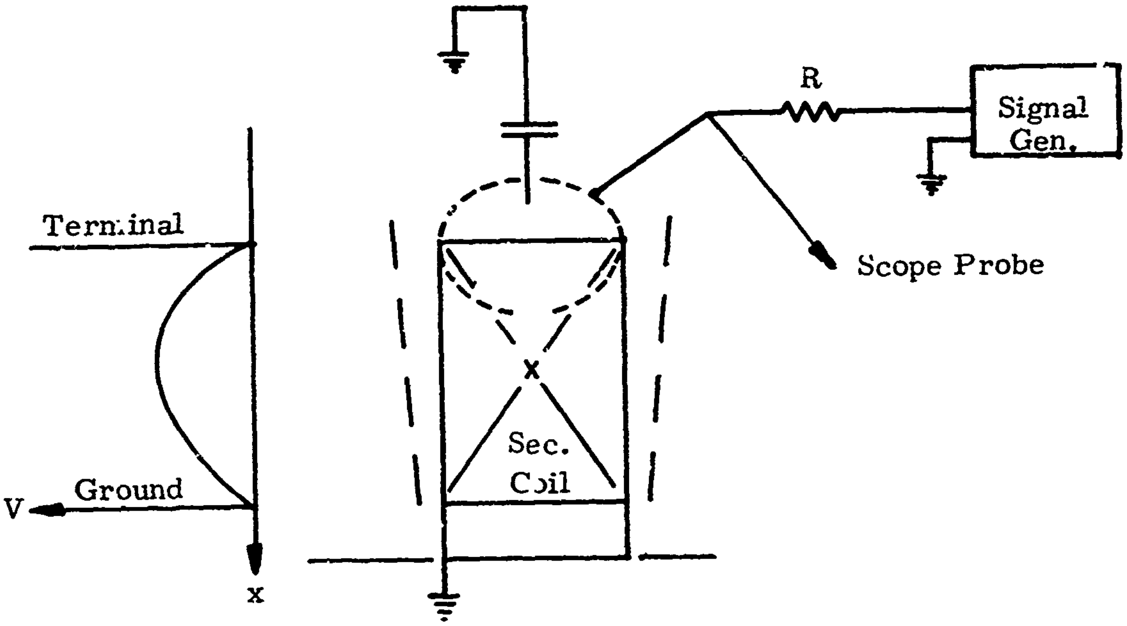
Before attempting to tune primary or secondary circuits to a required resonance frequency, it is essential that the opposite coupled circuit be "open" or resonant at a frequency far removed from the one of interest

If a parallel, L, C, R, circuit is driven by a high impedance, or constant current, source over an appropriate band of frequencies, the voltage across the circuit varies directly as its impedance over this frequency band. The impedance may be expressed as:

$$Z = \frac{L}{c} \quad \frac{1}{R + j\,(wL - \frac{1}{wC})} \qquad (1 - j\,\frac{R}{wL})$$

For circuits with a value of $Q > 10$, this impedance is a maximum at resonance, when, $wL = 1/wC$, and has a value equal to L/CR, which is called the dynamic circuit impedance at resonance.

The scheme used therefore was to couple a variable frequency generator to the circuit to be adjusted via a resistance of value higher than the anticipated magnitude of L/CR. The voltage at the junction of this resistor and the LCR circuit was then viewed via a high impedance probe. Figure 7a illustrates the method used, typical values for R were 100 kΩ for the secondary circuit and 1 kΩ for the primary.



Coil Voltage
Distribution 200 kcs

Figure (a) Method for Resonance Measurement

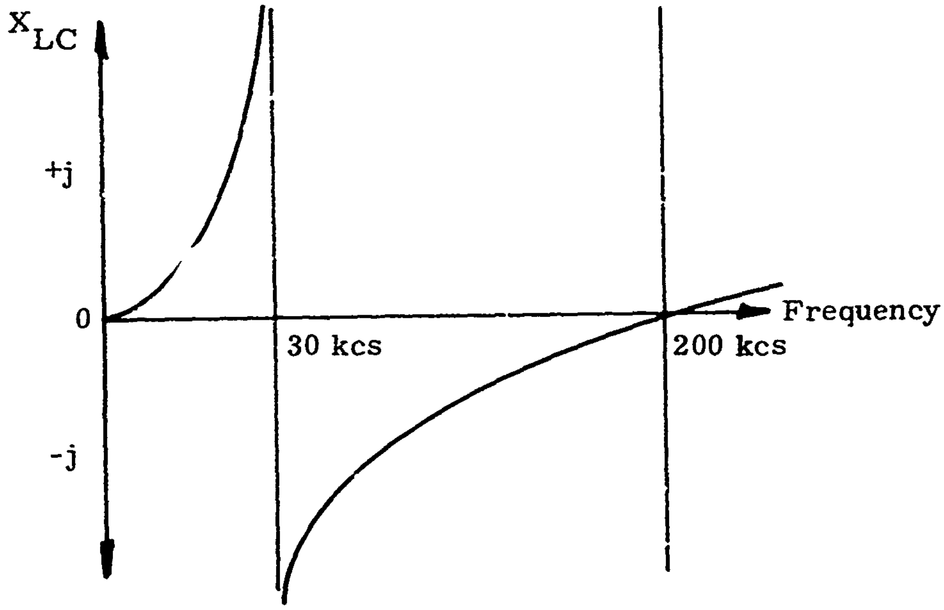


Figure 7 (b) Transformer Reactance Characteristic

2.4 Monitoring Methods

Because of the periodic nature of the transformer output pulse signature and the relatively low frequency components involved, an uncompensated resistive divider chain was found to be entirely adequate for evaluating the transformer performance and, eventually, viewing the incidence of breakdown in the dielectric test bed. The divider used was located on the axis of the transformer secondary, connected from the inner, stress relieving, output terminal to ground at the base of the transformer. The high voltage portion of the resistor was of $CuSo_4$ type in the form of a double helix; the low voltage portion was a ring of 2w composition resistors. The reduction ratio was 6700:1, calibrated against direct measurements at the output terminal for voltages approximately 500 V and against an accurate capacitance divider for approximately 80 kV.

It was noticed that direct viewing of the output terminal voltage at low levels demonstrated a waveform free of any transient or parasitic* components but viewing by the resistive divider, described above, exhibited additional frequency components. This provided a fortuitous insight to transient voltage excitations within the transformer structure.

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*The term "parasitic" is widely used in high power rf technology. A parasitic frequency is one associated with the resonance of stray reactances within the structure of an electrical circuit. In the case of the transformer, these reactances can be assigned to the transformer leakage inductance, winding self capacitances and interwinding capacitances. It is difficult to anticipate all these reactances in the design phase. The transient energies associated with these circuits result in peak voltage components which can augment the normal voltage modes to produce higher stresses than expected in the dielectric media.

2.5 Transformer Parasitic Frequency Modes and Damping Methods

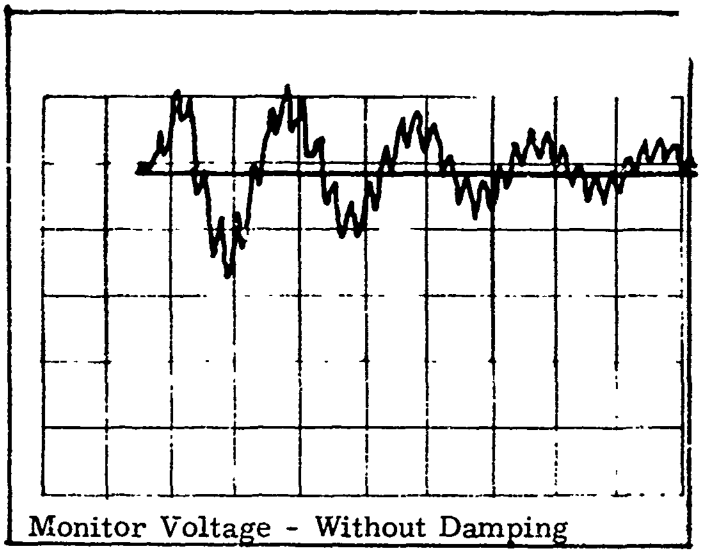
For the geometry and winding configuration of the transformer this parasitic component had a frequency of approximately 200 kcs (cf 30 kcs fundamental component). This was found to be a fundamental characteristic of the transformer and not of our monitoring arrangement. The monitoring components were coupled to the magnetic field of a transformer secondary parasitic mode. All distributed L-C circuits, of which coils and chokes form a class, have multiple parallel and series resonant modes. The first, or fundamental mode, occurs at the lowest frequency for which the secondary inductance and load capacitance undergo a parallel resonance. For this, the voltage distribution on the secondary winding is near linear, zero at one end of the winding and maximum at the other. This lowest resonance frequency condition is often referred to as the quarter-wave ($\lambda / 4$) mode. For increasingly higher frequencies, under the influence of stray capacities, the winding or structure will undergo an alternating pattern of series and parallel resonances, the effectiveness of which is only limited by circuit losses.

For this transformer type, the first series resonance was found to be the prime parasitic excitation mode, specifically here at 200 kcs. Figure 7 (a) and (b) shows the transformer secondary reactance characteristic with frequency and the method used to determine the resonance points.

It is important to note that for the series resonant mode the 200 kcs voltage component is zero at both ends of the winding and therefore may not be detected by direct potentiometer methods. If not treated, the additive effect of the fundamental (30 kc) and parasitic (200 kcs) voltage components is to produce higher resultant turn-turn voltages than normal in the lower half winding region.

In order to produce differential damping of the 200 kc component, a series L-C-R circuit, tuned to 200 kcs, was coupled to the lower turns of the secondary winding, the region of maximum circulating current at this frequency.

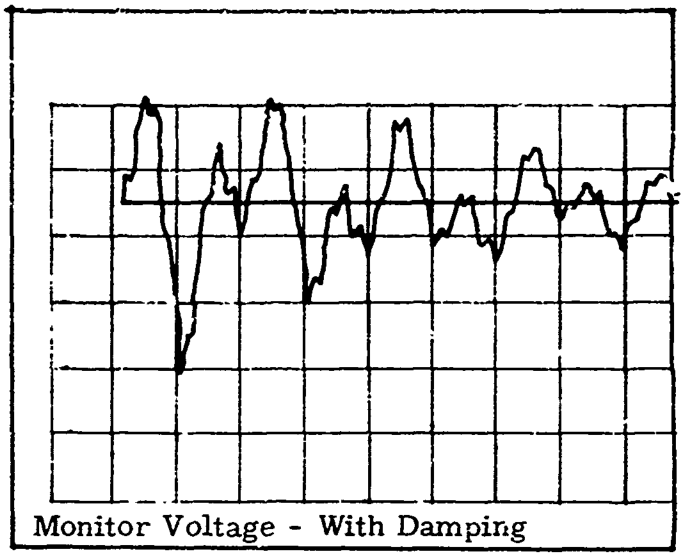
Figure 8 a-c illustrates the voltage monitor output before damping and after damping together with a typical waveform, used during the experimentation, obtained by interposing a tuned Wein bridge between the monitor output and the viewing oscilloscope.



Monitor Voltage - Without Damping

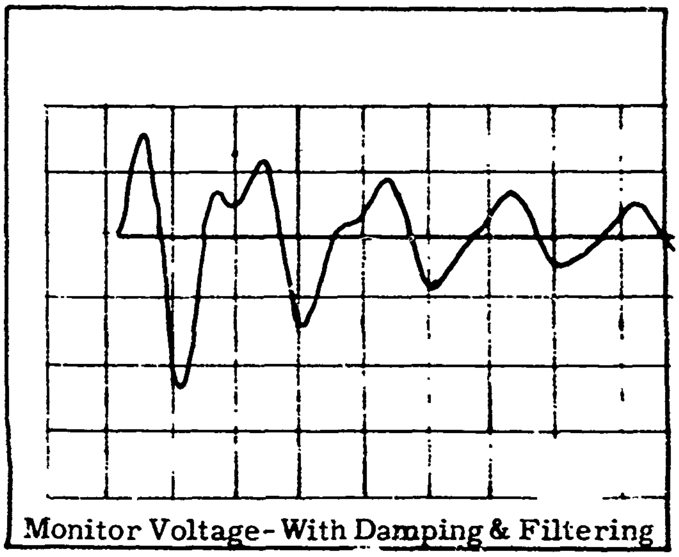
(a)

20 microseconds/cm



Monitor Voltage - With Damping

(b)



Monitor Voltage- With Damping & Filtering

(c)

Figure 8 Parasitic Frequency Damping

SECTION 3

THE DIELECTRIC STUDY TEST BED

3.1 General Arrangement

The volume of water which contained the test electrode structure was mounted atop the transformer vessel. The containing, treated, fiberglass housing formed a dielectric barrier between the two liquid media. Figure 9 shows the general test bed arrangement.

The fixed lower electrode was coupled to the transformer generator via a parallel L-R network which provided critical damping for the discharge of the generator stray capacity at electrode breakdown, affording some protection to the transformer secondary windings.

The upper, adjustable electrode structure was mounted off the top cover plate and continuity of the transformer vessel was provided around the fiberglass vessel by removable aluminum panels to which the upper electrode was referenced. Provisions were made for continuous processing and recirculation of the water with both flow and wiping actions available for removing air and debris from the interelectrode volume.

3.2 The Electrode System

Provisions were made for two sets of test electrodes, 350 cm^2 and 1000 cm^2. They were constructed of stainless steel with profiles machined such that breakdowns between the electrodes were near equally probable from the edges or from the flat portions. For all practical purposes, with the electrode spacings used, uniform field conditions were assumed.

It was evident at the higher voltages used in the experiments that flashovers were occurring across the water surface. To prevent this perturbation, which could cause premature gap breakdown, a guard ring at ground potential was supported around and several inches above the upper electrode. This guard ring reduced the potential gradients on the water surface, eliminating flashover.

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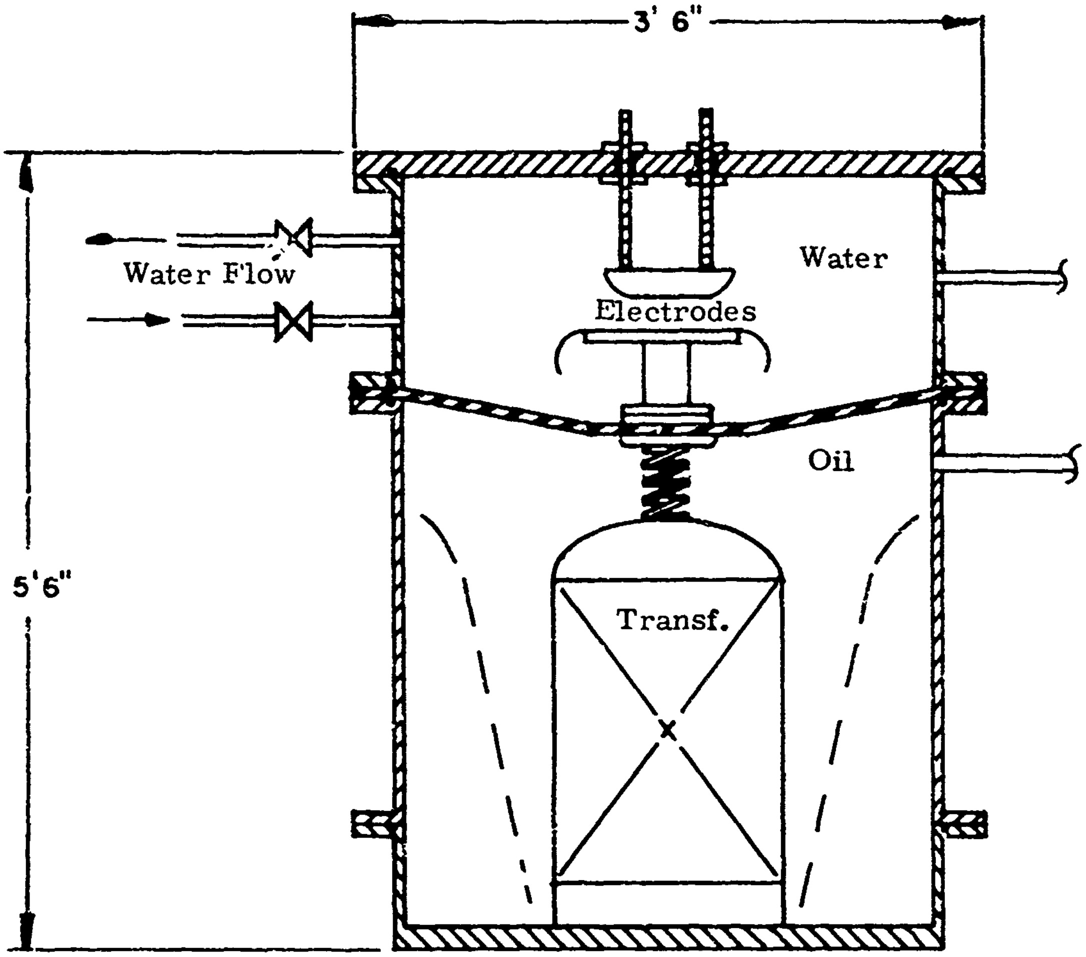

Figure 9 Pressurized Water Test Bed

3.3 Water Treatment

The volume of water used in the test bed was in the order of 100 gallons. This water was processed continuously via a Millipore Super-Q™ system capable of maintaining a maximum water resistivity of 18 MΩ-cm at a flow rate of 4 gpm. Under these conditions, the water resistivity in the test bed could be maintained in the range 5-15 MΩ-cm, provided that the water temperature was held in the range 20-25°C. To ensure this temperature range, the circulating system contained a simple heat exchanger coil.

The majority of our experimental data were taken under these water conditions and owing to the simplicity of the test bed and the available experimental time, no attempts were made to relate the data to water temperature or resistivity.

SECTION 4

EXPERIMENTAL RESULTS

In all, fourteen (14) test series were completed. The first ten (10) series, using both 350 cm^2 and 1000 cm^2 electrodes, were concerned with improving the conditions of the generator and test bed and, by various means, ensuring that the diagnostics were accurate to within a few percent.

Contrary to the experience of workers using submicrosecond "effective stress" times, we found that the presence of submillimeter diameter air bubbles and foreign matter between, or on, the electrodes, had a deleterious effect on breakdown strength in the 3.0 - 5.0 usec. stress times. As a consequence of this our precautions were rigorous and our trial runs numerous.

Table I gives our final data for the large 1000 cm^2 and smaller 350 cm^2 electrodes. For the latter we also provide data for breakdown at the peak of the first half cycle of generator voltage.

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TABLE I

DIELECTRIC PERFORMANCE OF DEIONIZED WATER WITH PRESTRESS

A) Second Half Cycle Breakdown Data-Large, Parallel Plate Electrodes (1000 cm^2)

d cm	Prestress kV/cm	V MV	F MV/cm	t usec	A cm^2	Ft$^{1/3}$
6.35	42.5	0.658	0.105	4.0	1000	0.168
6.35	55.5	0.516	0.081	4.0	1000	0.130
6.35	50.0	0.47	0.074	4.0	1000	0.120
6.35	54.4	0.585	0.092	6.0	1000	0.166
6.35	55.5	0.54	0.085	6.5	1000	0.157
6.35	54.4	0.527	0.083	4.0	1000	0.133
6.35	52.6	0.585	0.092	3.0	1000	0.134
6.35	61.0	0.59	0.093	3.0	1000	0.135
6.35	66.0	0.656	0.106	4.0	1000	0.168
					mean -	0.145
					S. D. -	approx. 13%

B) Second Half Cycle Breakdown Data-Small, Parallel Plate Electrodes (350 cm^2)

d	Prestress	V	F	t	A	Ft$^{1/3}$
5.0	72.0	0.535	0.107	4.0	350	0.17
5.0	74.0	0.535	0.107	4.0	350	0.17
5.0	74.0	0.530	0.106	4.0	350	0.17
5.0	67.0	0.487	0.097	3.0	350	0.14
5.0	67.0	0.500	0.100	5.0	350	0.17
5.0	70.0	0.534	0.107	6.0	350	0.19
5.0	70.0	0.517	0.103	5.0	350	0.17
5.0	70.0	0.505	0.101	4.0	350	0.16
3.8	65.0	0.352	0.093	3.0	350	0.13
3.8	62.0	0.375	0.099	3.5	350	0.15
					mean -	0.16
					S.D.	11%

C) First Half Cycle Breakdown Data-Small, Parallel Plate Electrodes (350 cm^2)

d	V	F	t	A	$Ft^{1/3}$
2.54	0.312	0.123	4.0	350	0.197
2.54	0.250	0.10	3.5	350	0.147
2.79	0.35	0.125	4.0	350	0.20
2.79	0.31	0.111	4.0	350	0.178
2.54	0.288	0.113	4.0	350	0.18
2.54	0.305	0.120	4.0	350	0.19
				mean -	0.18
				S.D. -	10.7%

SECTION 5

COMMENTS ON THE EXPERIMENTS AND EXPERIMENTAL RESULTS

5.1 Experimental Results

For both electrode areas there was a very reasonable agreement with current predictions (i.e., $Ft^{1/3} A^{1/10} \hat{=} 0.3$) in the longer time scale. The standard deviations of the results were higher but this was understandable in view of the impeccable test bed conditions required with the pulse signature.

One can say that, in this time regime, provided the prestress level remained below the approximate value of $55\ Kv/cm^2$, the double resonance pulse signature and the single capacitive discharge signature (Marx) will yield similar breakdown strengths for deionized water under similar effective stress time conditions. Further to the prestress level, the threshold of its effects was found to be quite pronounced. The range of stress levels which, on the one hand, allowed complete and consistent oscillating discharge without breakdown and, on the other, consistent early breakdown during the second half cycle of discharge was narrow, ~ 10 → 15 Kv/cm. The general inference was that one could operate a system most reliably with peak stresses (2nd half cycle) very close to breakdown stresses predicted by: $Ft^{1/3} A^{1/10} \hat{=} 0.3$. This attribute of reliability was intriguing and prompted the question whether raising the 1st half cycle threshold - say by pressurization of the dielectric - would demonstrate a superior combination of pulse signature and dielectric treatments.

Separate experimental runs were made in an attempt to demonstrate the influence of prestress level upon dielectric performance during the second half cycle of the discharge pulse. These results are combined in Fig. 10 to show the operational precipice and did not accrue from experiments reported in Table 1.

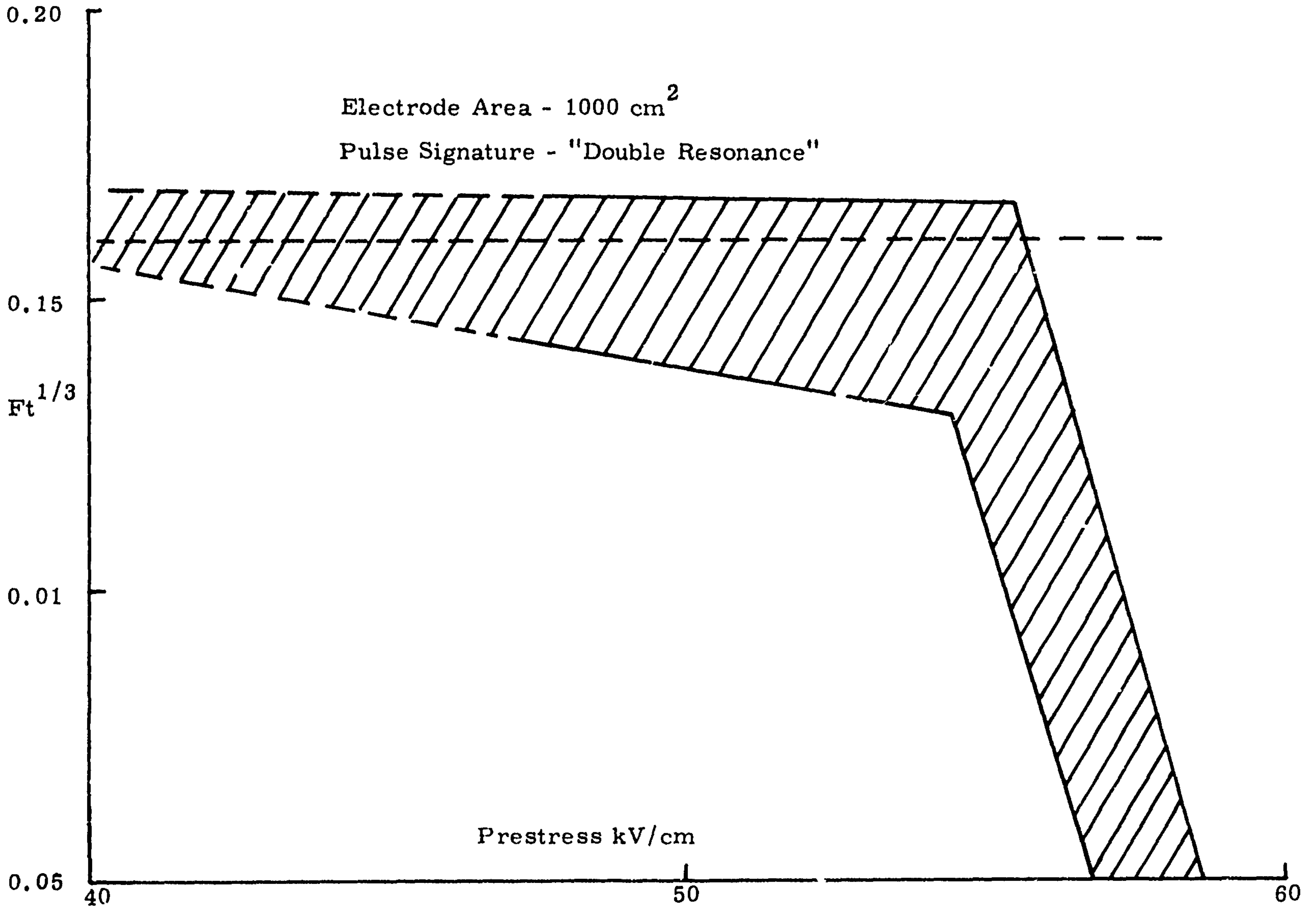

Figure 10 Effect of Prestress Level Upon the Dielectric Strength of Water

5.2 The Transformer Generator

This generator has proved to be a simple, reliable device. Foremost of its characteristics was the extreme reproducibility of output pulse, both in the short and long term.

The ease with which all damaging modes of operation may be diagnosed and treated provides a sharp contrast to other H.V. generator forms.

5.3 Implications for Pulse Power Systems

It is clear that under U.S. accepted methods of designing pulse systems with water dielectric, generators which provide 5 usec. effective dielectric stress times are not economically or technically interesting.

The apparent interest of other workers in simple generators of this time scale and signature is now known to be due to the advantages of water pressurization.

From the scant information that we have(2) it seems that for hydrostatic pressures of a few hundred psi the time dependence of water breakdown reduces from the third power $(t^{1/3})$ to the fifth $(t^{1/5})$. If this can be confirmed, then the higher energy densities claimed are achievable with "slower", pressure compatible generators such as the double resonance pulse transformer.

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(2) "The Development of Electrical Discharge in Water", Doklady, 15 No. 10, pp. 959-961, April 1971, Alkhimov, et al.