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Design Calculations for Eddy-Current Displacement Sensors for Chalk River Nuclear Laboratories (AECL)

C. V. Dodd

OAK RIDGE NATIONAL LABORATORY
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SUMMARY

An analysis has been made of four different types of eddy-current sensors to measure the displacement of a fuel tube contained coaxially in a pressure tube. The first sensor consisted of a bifilar coil encircling the pressure tube. Its sensitivity was inadequate. The second sensor was a bifilar coil inside the pressure tube and encircling the fuel tube. This coil had adequate sensitivity to the swelling of the fuel cladding but could not measure its bowing. The third sensor consisted of an array of eight pancake coils spaced around the fuel cladding and inside the pressure tube. This sensor could measure both bowing and swelling of the cladding independently, but was subject to fairly large drifts. The fourth sensor used eight pancake coils that measured the distance to spring-loaded feelers that directly contacted the fuel cladding. This was the most sensitive device and exhibited the smallest drift.

None of the sensors could measure the temperature of the fuel cladding because the temperature was not a single valued function of the resistivity over the specified range of 20 to 1200°C.

INTRODUCTION

The design calculations were made by use of the eddy-current theory[1–3] and computer programs[4,5] developed at ORNL in the late 1960s

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[1] C. V. Dodd, W. E. Deeds, J. W. Luquire, and W. G. Spoeri, *Some Eddy-Current Problems and Their Integral Solutions,* ORNL-4384 (April 1969).

[2] C. C. Cheng, C. V. Dodd, and W. E. Deeds, "General Analysis of Probe Coils Near Stratified Conductors," *Int. J. Nondestru. Test.* 3(2): 109–30 (September 1971).

[3] C. V. Dodd, C. C. Cheng, and W. E. Deeds, "Induction Coils Coaxial with an Arbitrary Number of Cylindrical Conductors," *J. Appl. Phys.* 45(2): 638–47 (February 1974).

[4] C. V. Dodd, C. C. Cheng, W. A. Simpson, D. A. Deeds, and J. H. Smith, *The Analysis of Reflection Type Coils for Eddy-Current Testing,* ORNL-TM-4107 (April 1973).

[5] C. V. Dodd, C. C. Cheng, C. W. Nestor, Jr., and R. B. Hofstra, *Design of Induction Probes for Measurement of Level of Liquid Metals,* ORNL-TM-4175 (May 1973).

and early 1970s. This theory and the accompanying computer programs allow accurate calculation of the response of various types of eddy-current instrumentation to different types of inspection problems.

The problem as set forth in conversations with AECL personnel was:

1. to measure the diameter of the fuel cladding between 12.95 and 14.22 mm (0.510 and 0.560 in.) within ±0.13 mm (0.005 in.) and
2. to measure the temperature of the fuel cladding from 100 to 1200°C within ±50°C (by measuring the resistivity change with temperature).

The second measurement was not possible above about 400°C because the temperature was not a single-valued function of the resistivity (the curves supplied by AECL showed that the slope decreased above 400°C, became flat, and may bend back over). The various types of measurement techniques that were analyzed and the results of each are now discussed.

BIFILAR COIL ENCIRCLING THE PRESSURE TUBE

The first configuration considered was a bifilar coil encircling the pressure tube, as shown in Fig. 1. This configuration has the advantages that it operates from outside the pressure tube, will not influence the coolant flow, and requires no electrical connections through the pressure tube. The variations in the magnitude and phase as the fuel cladding expands from 12.95 to 14.22 mm (0.510 to 0.560 in.) are shown in Fig. 2. Neither the magnitude nor the phase change was large enough to permit a reliable measurement of the diameter of the fuel cladding, even if there were no changes in the properties of the pressure tube. Unless the pressure tube were considerably thinner in the region of interest, this sensor is not practical. The electrical circuit used for this sensor and the next one is shown in Fig. 3.

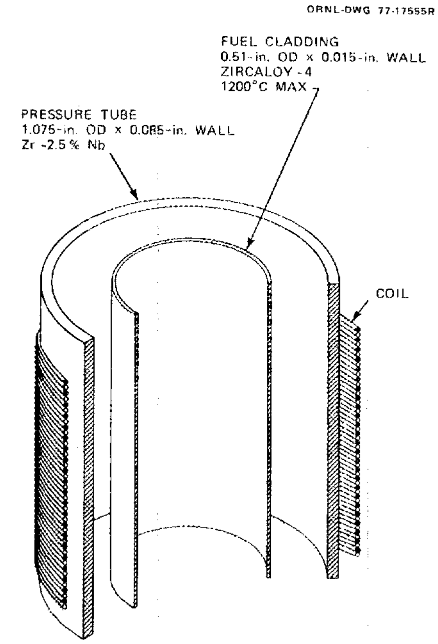

Fig. 1. Bifilar Coil Encircling the Pressure Tube. Pressure tube is 27.30 mm OD by 2.16 mm wall. Cladding is 13.0 mm OD by 0.38 mm wall.

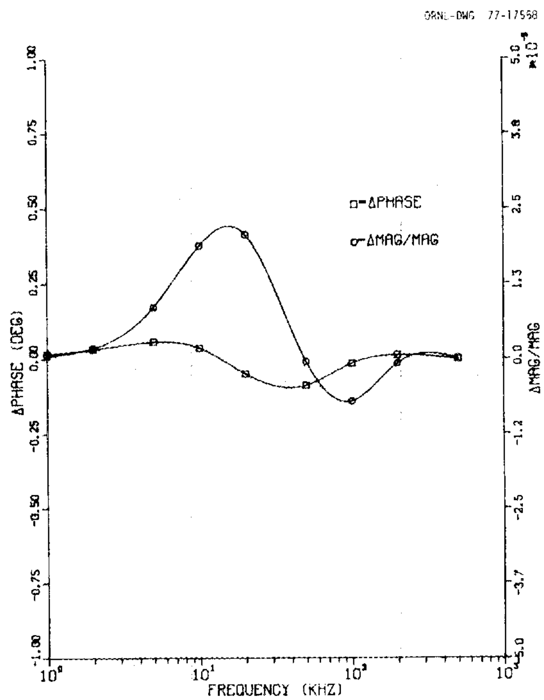

Fig. 2. Changes in the Magnitude and Phase of the Voltage from a Bifilar Coil Caused by Expansion of the Fuel Cladding from 12.95 to 14.22 mm (0.510 to 0.560 in.) Plotted Against Frequency.

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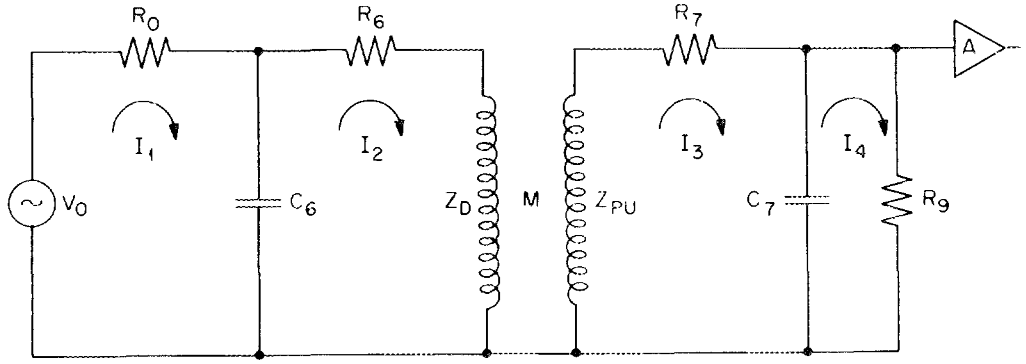

V_0 DRIVING VOLTAGE
R_0 SERIES RESISTANCE IN THE DRIVING CIRCUIT
C_6 SHUNT CAPACITANCE OF THE DRIVING CIRCUIT
R_6 D.C. RESISTANCE OF THE DRIVER COIL
Z_D IMPEDANCE OF THE DRIVER COIL
M MUTUAL IMPEDANCE BETWEEN THE DRIVER AND PICK-UP COIL
Z_{PU} IMPEDANCE OF THE PICK-UP COIL
R_7 D.C. RESISTANCE OF THE PICK-UP COIL
C_7 SHUNT CAPACITANCE OF THE PICK-UP CIRCUIT
R_9 AMPLIFIER INPUT IMPEDANCE
I LOOP CURRENT

Fig. 3. Electrical Circuit of Bifilar Coil Sensors.

BIFILAR COIL INSIDE THE PRESSURE TUBE

The second configuration consisted of a bifilar coil inside the pressure tube, as shown in Fig. 4. This sensor has the disadvantages that the coil connections must penetrate the pressure tube and the coil itself will restrict the coolant flow. However, as can be seen from the magnitude and phase plots in Fig. 5, the sensitivity is much greater, and either phase shift at 200 kHz or relative magnitude change at 1 MHz can be used to measure the expansion of the fuel cladding tube. Changes in the properties of the pressure tube have only a small effect on the measurements. However, this measurement will not detect bowing or ovality in the fuel cladding, and in recent tests[6] of similar fuel tubes the bowing and ovality were several times as great as the change in the average diameter.

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[6]D. O. Hobson, *Quarterly Progress Report on the Creepdown and Collapse of Zircaloy Fuel Cladding*, (to be published).

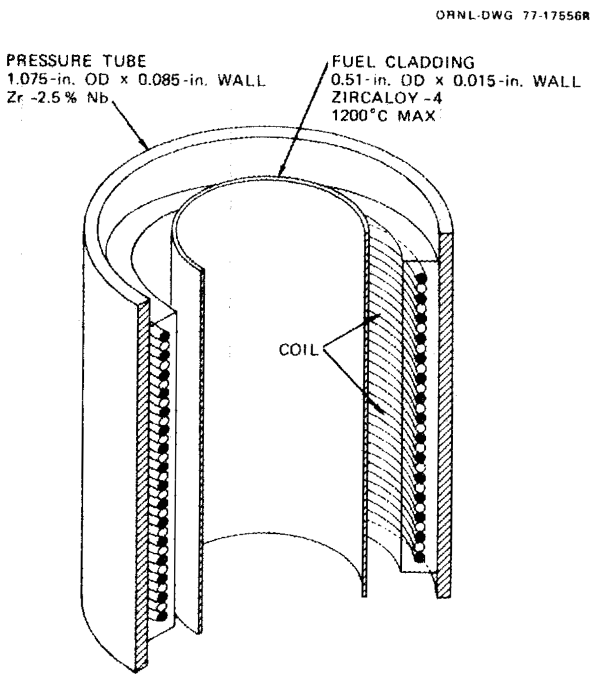

Fig. 4. Bifilar Coil Inside the Pressure Tube, Encircling the Fuel Cladding. Pressure tube is 27.30 mm OD by 2.16 mm wall. Cladding is 13.0 mm OD by 0.38 mm wall.

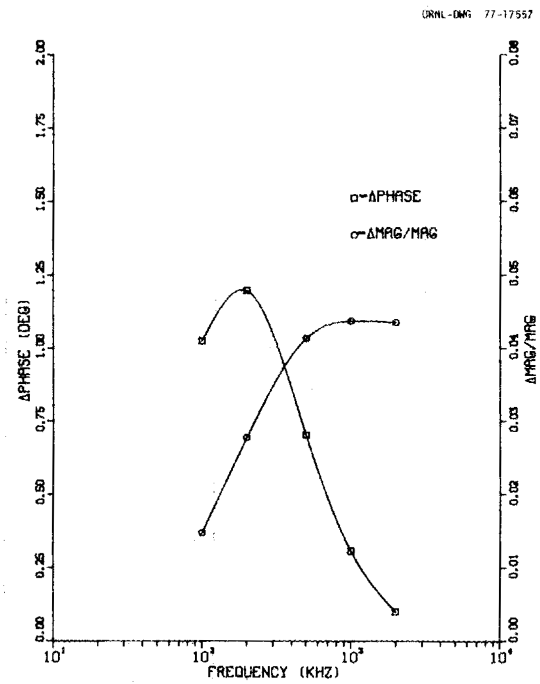

Fig. 5. Changes in the Magnitude and Phase of the Voltage from a Bifilar Coil Caused by Expansion of the Fuel Cladding from 12.95 to 14.22 mm (0.510 to 0.560 in.) Plotted Against Frequency.

EIGHT-COIL ARRAY INSIDE THE PRESSURE TUBE

The third coil and conductor configuration that was analyzed is shown in Fig. 6. This coil configuration allows the ovality and bowing of the fuel cladding to be measured by sensing the coil-to-conductor spacing at eight different locations around the tube. The electrical circuit used for this sensor and the next one is shown in Fig. 7. By use of both the magnitude and the phase, the resistivity and the lift-off can both be calculated. We used the following types of equations to determine these properties:

$$\text{Lift-off} = C_0 + C_1(\ln M) + C_2(\ln M)^2 + C_3(Ph) + C_4(Ph)^2 \ ,$$

$$\text{Resistivity} = A_0 + A_1(\ln M) + A_2(\ln M)^2 + A_3(Ph) + A_4(Ph)^2 + A_5(Ph)^3 \ .$$

We used a least squares fit to determine the coefficients at each frequency that we tested. The errors due to the lack of fit and the errors due to an instrument drift of 0.01° in the phase measurement (Ph) and 0.01% in the magnitude measurement (M) are summarized in Table 1. The types of equations used were determined by trial and error, and other combinations of the instrument readings might give a better fit. The three frequencies 500 kHz, 1 MHz, and 2 MHz seem to give the best results, so additional calculations were made at these frequencies. The instrument drifts represent the errors in the measurement of the magnitude and phase in the instrument itself and do not include the drift in these readings due to changes in the component values in the bridge circuit, as shown in Fig. 7. The coil and parts of the circuit are in a very hostile environment, and their values can vary considerably. While some of these variations will tend to be cancelled out because of the symmetry of the bridge, there will not be complete cancellation, and the component changes in the different legs of the bridge will not always match. The large amount of cable capacitance that results from long leads between the coil and the instrument can degrade the signal at the higher frequencies. In Table 2 we have summarized the major errors due to typical drifts in the bridge parameters.

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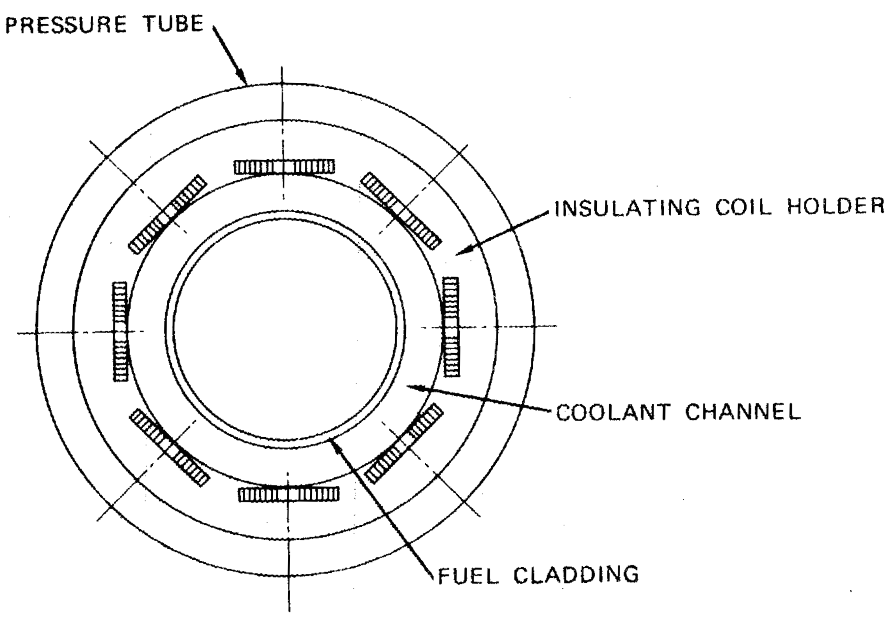

Fig. 6. Top View of an Array of Eight Pancake Coils Inside the Pressure Tube.

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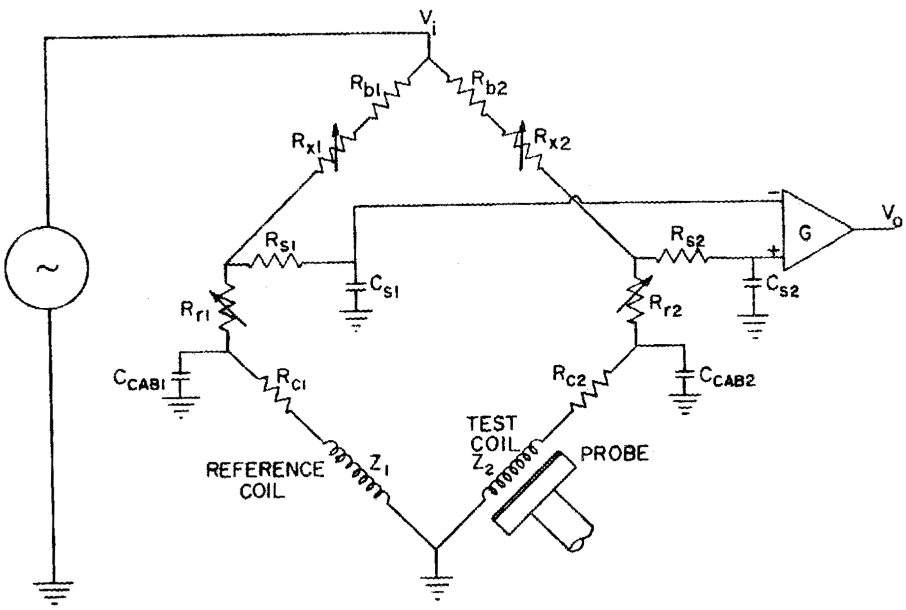

Fig. 7. Electrical Circuit for Eddy-Current Bridge.

Table 1. Errors Due to Lack of Fit and Instrument Drift

Frequency (kHz)	Lift-Off, μm (mils)		Resistivity, nΩ m	
	Fit Error	Drift Error	Fit Error	Drift Error
100	44.7(1.76)	27.9(1.10)	39	20
200	40.9(1.61)	12.7(0.50)	43	14
500	38.6(1.52)	6.9(0.27)	42	14
1000	35.8(1.41)	5.1(0.20)	40	18
2000	34.3(1.35)	5.8(0.23)	48	39

Table 2. Errors in Lift-Off and Resistivity Due to Typical Variations in Key Bridge Components

Variation		Lift-Off		Error at 500 kHz			Error at 1 MHz			Error at 2 MHz		
(%)	Component[a]	(mm)	(mils)	Lift-Off (μm)	Lift-Off (mils)	ρ (μΩ m)	Lift-Off (μm)	Lift-Off (mils)	ρ (μΩ m)	Lift-Off (μm)	Lift-Off (mils)	ρ (μΩ m)
1	R_{c_1} or R_{c_2}	1.0	40	560	22	1.50	112	4.4	0.56	48	1.9	0.29
		2.5	100	1040	41	4.29	232	9.3	1.84	165	6.5	0.97
10	R_{c_1} and R_{c_2}	1.0	40	180	7	0.32	64	2.5	0.19	230	9.0	0.40
		2.5	100	860	34	1.00	409	16.1	0.60	1170	46	1.17
1	R_{s_1} or R_{s_2}	1.0	40	2.5	0.1	0.008	5	0.2	0.02	8	0.3	0.07
		2.5	100	23	0.9	0.02	28	1.1	0.09	38	1.5	0.28
10	R_{s_1} and R_{s_2}	1.0	40	18	0.7	0.05	30	1.2	0.13	51	2.0	0.46
		2.5	100	86	3.4	0.16	10.4	4.1	0.49	269	10.6	1.66
1	C_{cab_1} or C_{cab_2}	1.0	40	36	1.4	0.07	33	1.3	0.07	640	25	2.13
		2.5	100	107	4.2	0.36	2.5	0.1	0.41	530	21	6.84
10	C_{cab_1} and C_{cab_2}	1.0	40	430	17	0.45	224	8.8	0.45	5436	214	21.91
		2.5	100	690	27	2.82	10.4	4.1	2.65	2750	187	67.9
1	C_{s_1} or C_{s_2}	1.0	40	5	0.2	0.01	2.5	0.1	0.01	2.5	0.1	0.03
		2.5	100	25	1	0.04	18	0.7	0.04	8	0.3	0.15
10	C_{s_1} and C_{s_2}	1.0	40	25	1	0.06	56	2.2	0.20	22.9	9.0	1.65
		2.5	100	114	4.5	0.25	114	4.5	0.87	422	16.6	6.27

[a]Identified on Fig. 7.

The errors are shown for $\rho = 0.65\ \mu\Omega$ m, although they are about same over the entire resistivity range. The 500-kHz frequency calculations were made with $C_{cab} = 3500$ pF, and the 1 MHz and 2 MHz calculations for $C_{cab} = 900$ pF. The errors in both the lift-off and resistivity measurements exceed the stated limits. The lift-off error increases as the lift-off increases and as the resistivity increases. The large initial lift-off, which is necessary for the coolant flow, can be eliminated by using the next coil configuration.

EIGHT-COIL ARRAY USING A SPRING-LOADED FEELER

The final configuration analyzed consisted of an array of eight pancake coils as shown in Fig. 8. The coils sense the distance to the feelers, which are spring loaded against the fuel cladding. This configuration decreases the measurement range by about 40%. The top of the feeler can be plated with copper, which is a much better conductor than Zr–2.5% Nb.

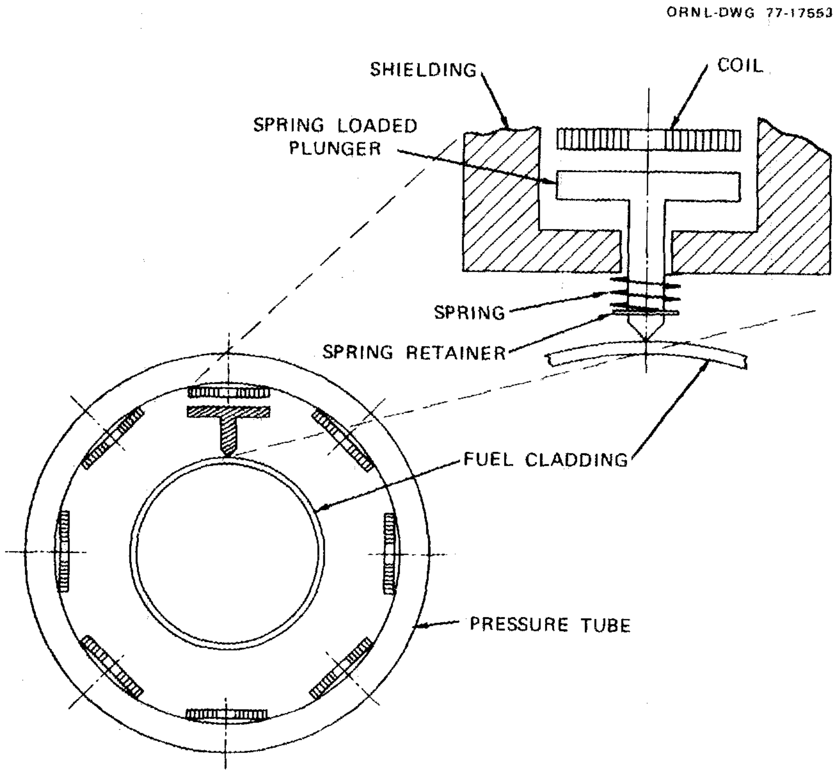

Fig. 8. Top View of an Eight-Coil Array with Spring-Loaded Feelers to Sense the Fuel Cladding.

These design changes considerably increase the sensitivity and correspondingly reduce the errors. The lift-off can be calculated by the equation:

$$\text{Lift-Off} = C_0 + C_1(\ln M) + C_2(\ln M)^2 \ .$$

The error in fit is about 5 μm (0.2 mils) for a range of 0 to 1.5 mm (60 mils). The errors due to the variation in the bridge parameters and some other test parameters are summarized in Table 3. This configuration and the accompanying instrumentation has been tested up to 17 MPa (2300 psi) and 370°C, but not in a reactor.[7] The error due to a ±100°C temperature variation was about ±25 μm (1.0 mil), and even this error could be eliminated by the use of one reference coil and three "standard" coils. This technique is quite accurate, but it still cannot measure the temperature.

INSTRUMENTATION

Instrumentation that will drive either the bifilar coils or the array of pancake coils has been constructed and tested at ORNL. The circuit diagrams and printed circuit lay-outs are available on request from the Industrial Cooperation Office at ORNL.

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[7]D. O. Hobson and C. V. Dodd, *Interim Report on the Creepdown of Zircaloy Fuel Cladding*, ORNL/NUREG/TM-103 (May 1977).

Table 3. Error in Lift-Off Due to Variation of Test Parameters

Parameter Variation[a]	Frequency (MHz)	Capacitance (pF)	Error, μm (mils) for Each Lift-Off in mm (mils): 0.25 (10)	0.51 (20)	0.76 (30)	1.02 (40)	1.27 (50)
ρ from 17.32 to 30.8 nΩm, R_{c1} from 3.0 to 3.3Ω	2	830	14.1(0.56)	12.7(0.50)	11.4(0.45)	10.0(0.39)	8.9(0.35)
	2	3500	69.9(2.75)	68.2(2.69)	62.3(2.45)	52.8(2.08)	38.9(1.53)
	1	3500	19.4(0.76)	17.6(0.69)	15.7(0.62)	13.9(0.55)	11.7(0.46)
R_{c1} from 3.00 to 3.03Ω	2	830	0.6(0.02)	0.7(0.03)	0.7(0.03)	0.7(0.03)	0.4(0.02)
	2	3500	4.4(0.17)	4.1(0.16)	3.7(0.15)	3.1(0.12)	2.0(0.08)
	1	3500	1.2(0.05)	1.4(0.06)	1.4(0.06)	1.1(0.04)	1.1(0.04)
R_{s1} from 65.00 to 65.65Ω	2	830	0.7(0.03)	1.0(0.04)	1.3(0.05)	1.9(0.07)	3.0(0.12)
	2	3500	0.0(0.00)	0.2(0.01)	−0.4(−0.02)	−0.7(−0.03)	−1.1(−0.04)
	1	3500	0.7(0.03)	0.9(0.04)	1.3(0.05)	2.0(0.08)	3.0(0.12)
R_{s1} and R_{s2} from 65.00 to 71.5Ω	2	830	0.5(0.02)	0.5(0.02)	0.4(0.02)	0.4(0.02)	0.3(0.01)
	2	3500	0.9(0.04)	0.8(0.03)	0.7(0.03)	0.6(0.02)	0.4(0.02)
	1	3500	0.1(0.00)	0.1(0.00)	0.1(0.00)	0.1(0.00)	0.1(0.00)
C_{cab1} increased 1%	2	830	−2.6(−0.10)	−3.8(−0.15)	−5.5(−0.22)	−8.2(−0.32)	−12.8(−0.50)
	2	3500	−11.4(−0.45)	−17.5(−0.69)	−25.5(−1.00)	−36.1(−1.42)	−49.7(−1.96)
	1	3500	−1.3(−0.05)	−1.9(−0.07)	−2.9(−0.11)	−4.4(−0.17)	−7.3(−0.29)
C_{cab1} and C_{cab2} both increase 10%	2	830	−18.7(−0.74)	−18.8(−0.74)	−18.1(−0.71)	−16.7(−0.66)	−14.6(−0.57)
	2	3500	−58.6(−2.31)	−57.0(−2.24)	−50.5(−1.99)	−40.5(−1.59)	−28.4(−1.12)
	1	3500	−17.3(−0.68)	−17.5(−0.69)	−16.9(−0.67)	−15.7(−0.62)	−13.8(−0.54)
C_{s1} from 90 pF to 90.9 pF	2	830	0.5(0.02)	0.7(0.03)	1.0(0.04)	1.4(0.06)	2.1(0.08)
	2	3500	−0.3(−0.01)	−0.6(−0.02)	−1.1(−0.04)	−1.6(−0.06)	−2.4(−0.09)
	1	3500	0.7(0.03)	1.0(0.04)	1.4(0.06)	2.1(0.08)	3.2(0.13)
C_{s1} and C_{s2} both from 90 to 99 pF	2	830	−1.2(−0.05)	−1.3(−0.05)	−1.2(−0.05)	−1.2(−0.05)	−1.0(−0.04)
	2	3500	−0.3(−0.01)	−0.4(−0.02)	−0.3(−0.01)	−0.2(−0.01)	−0.1(−0.00)
	1	3500	−0.3(−0.01)	−0.3(−0.01)	−0.3(−0.01)	−0.3(−0.01)	−0.2(−0.01)
V_o increased 0.1%	2	830	−0.6(−0.02)	−0.6(−0.02)	−0.5(−0.02)	−0.5(−0.02)	−0.4(−0.02)
	2	3500	−0.8(−0.03)	−0.7(−0.03)	−0.6(−0.02)	−0.5(−0.02)	−0.4(−0.02)
	1	3500	−0.6(−0.02)	−0.6(−0.02)	−0.5(−0.02)	−0.5(−0.02)	−0.4(−0.02)

[a]Circuit components identified in Fig. 7.

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