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Systematic Errors With Surface Mounted Heat Flux Transducers
And How To Live With Them

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SYSTEMATIC ERRORS WITH SURFACE-MOUNTED HEAT FLUX TRANSDUCERS
and how to live with them

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1. Introduction

Heat Flux Transducers (HFT's) are informative, cheap, and easy to use, but their behaviour is not simple. These valuable devices won't be reliable if used in a "catalogue engineering" manner - the selection must take account of a number of features of the item under test, and the environment it has to work in. Changes due to aging and environmental variations can be of great importance, and may not always be known exactly.

HFT's are so versatile that they can be discussed sensibly only within predefined limits, in this case to surface mounted HFT's applied to building heat flux measurement in steady or slowly varying state.

Previous literature (1, 2, 3) has offered much generalised advice on how HFT's should be used. But because the purposes of HFT installations vary so widely, and so do the constraints, any generalised advice may have to be tempered in some cases. This note gives such estimates of how significant a departure from this advice may be, and how to compensate for its effect.

Previous papers (1, 3) have discussed HFT faults (such as sensitivity to lateral temperature gradients, large edge/face area ratio, improper calibration, etc). This note deals exclusively with the behaviour of perfectly calibrated, ideal HFT's and is basically a tutorial on a parametric model first presented in reference (3).

2. Objectives and Definitions

The usual objective when using HFT's is to find the value of heat flux which would have occurred in the undisturbed state - i.e. with no HFT present. But disturbance to heat flux is intrinsic to the use of passive HFT's. It is only possible to avoid disturbance in special, restricted - and usually transient - conditions. Therefore some systematic error is inescapable. Typically these errors will change with time or conditions, which are as important to the final accuracy and reliability as is the quality of the HFT itself, or its calibration.

A perfectly calibrated HFT is taken here to mean one in which the heat flux through the HFT itself is exactly represented by the output. The systematic error is taken to mean the difference between the heat flux in totally undisturbed conditions, and that indicated by a perfectly calibrated HFT. This error may be either positive or negative, corresponding respectively with the HFT indicating either too low (the usual case) or too high.

These systematic errors can be estimated using a parametric model, defined in Figure 1, which offers a quantitative estimate of the systematic error E for perfectly calibrated, unguarded, surface-mounted HFT's. It uses three dimensionless parameters H, Emin, and Emax. The model was introduced and justified in reference 1 on the basis of computer modelling and compatibility with published measured data. It describes the systematic error E as a power-law function of H, unless constrained by the limiting error values Emin or Emax. The three parameters have both common and independent factors.

Suppose that for some case the parameter H were to be varied from very small to very large (e.g., by varying the size L of the HFT). The error would initially remain nearly constant at Emin as H increased. But when H becomes large enough, error E would increase with H according to a power law, until it approached Emax, where E would again level off. The three stages in this description were named in ref. 3 as:

"Insulation-controlled" - This corresponds to an arbitrarily large HFT. The error is simply the resistance ratio of the HFT to that of the total wall, and is denoted Emin.

"Power-Law regime" - This is dominated by edge leakage around the HFT perimeter. The error is a function of a dimensionless parameter "H", and is denoted Ep.

"Surface-controlled" - This corresponds to an HFT placed on a substrate of infinite lateral conductance, or to a zero breadth HFT. The error is equal to the ratio of the effective HFT resistance to the surface resistance, and is denoted Emax.

The value of this model is that it is comprehensive, and thus offers the designer a way to compromise between conflicting needs. The actual errors predicted by the model are themselves only approximations.

3. The Behaviour of a Surface-Mounted HFT Measuring System

It can be seen from Figure 1 that the behaviour of an HFT measurement system depends strongly on a dimensionless parameter "H". An accurate system requires that H be made small enough. This would be approached by making the HFT effective series resistance Rm small or the size L large, whilst the higher thermal resistance the test piece has, the better. There are several complications in manipulating the factors of "H". These will be discussed below.

The strongest single factor is the effective series resistance Rm, given by equation (1):-

$$Rm = Rh + Rc + (Rms - Rs) \tag{1}$$

Where:

Rh = series thermal resistance of the HFT alone
Rc = thermal contact resistance between HFT and substrate
Rms = total thermal surface resistance over HFT
Rs = total thermal surface resistance over surround area

The quantity Rm is not only the strongest single factor in determining the measurement quality, it is also the most complicated. Most users of HFT's are aware of the value in choosing a low HFT resistance Rh. It is not so widely appreciated that it is not Rh alone, but the composite value Rm which controls accuracy.

The series thermal resistance of HFT's ranges widely. Commercial HFT's have been reported as having resistances from about 0.002 $m^2 °C/W$ to 0.03 $m^2 °C/W$. Special purpose HFT's vary more widely, and values up to 0.1 $m^2 °C/W$ have been reported.

4. Examples

No step-by-step procedure for selecting HFT systems has yet been found, and so it is necessary to use interactive or trial-and error methods. In this paper we first take a typical example case to illustrate the use of Figure 1, and then in subsequent cases vary one factor at a time, to show how apparently simple variations can produce major changes in the quality of measurement. The complete calculation data for all examples is summarised in Table 1, so that calculation may be traced through. The results of those calculations are presented in Figure 2, to illustrate their relation to "H" and the three operating regimes.

EXAMPLE 1: A Base Case (Case 1 in Table 3)

A wall with 10 mm thick gypsum plaster-board lining (k = 0.16 W/m°C) has an overall thermal resistance expected to be about 2 $m^2 °C/W$. The surfaces are non-reflective, air is nominally still, and an HFT of 50 x 50 mm and series thermal resistance 0.01 $m^2 °C/W$ is to be used on the lining board. The surface is rough, so we allow a mean gap of 1 mm between HFT and plasterboard, and choose a filler paste of conductivity 1.0 $m^2 °C/W$. We also intend to make the infrared emittance of the HFT the same as the surrounding plasterboard. Surface resistances and other thermal properties can be found from standard handbooks, e.g. Ref (4).

Then:-

(a) HFT resistance Rh = 0.01
Contact resistance Rc = 0.001
0.011

Wind speed = 0, Rms = Rs = 0.09
Rm = 0.01 + 0.001 + (0.09 - 0.09) = 0.011

(b) Then we find H, as:-

$$H = \frac{(0.011)^2}{2*0.09} \left[\frac{0.16*0.01*0.09}{0.05*0.05} \right]^{0.5}$$

$$= 1.6*10^{-4}$$

(c) We then have to check the limit values Emin & Emax:-

Emin = 0.013 / (0.011 + 2) = 0.0055 or 0.55%
Emax = 0.013 / (0.011 + 0.09) = 0.109 10.9%

(d) From Figure 1 we then see that for H = $1.6*10^{-4}$, the error Ep from the power law effect is predicted as 3.6%.

(e) Finally, because neither limit Emin or Emax approaches Ep the final error E will be similar to the power-law error Ep.

We conclude that this selection would operate in the power-law regime, with a measurement error of about 4%. If the only in-service factors likely to change are the surface resistances, then the effect on H, and hence on systematic error, must remain very small. The predicted error of 4% should therefore be consistent, and may be used as a nearly constant correction to all heat flux data measured with this system.

EXAMPLE 2: Effect of Contact Resistance (Case 2 in Table 3)

For an HFT with no contact filler paste, we can expect the gap width between surface and HFT to be less than say 1 mm. It can be shown that for such small gaps the contact resistance will be dominated by air conduction, and will be about 0.04*b $m^2 °C/W$ (where b is gap width in mm), regardless of surface emittance or orientation. Where filler pastes are used, the contact resistance might range from 0.001*b for conductive pastes (k = 1.0) to 0.003*b for less conductive pastes (k = 0.3). If a filler paste is used, it is therefore more important that the paste does not shrink, embrittle, or crack, than what the paste conductivity might be when new. It can be better to use no paste than one at risk of shrinking or cracking.

Suppose our HFT of resistance 0.01 has 1 mm of a conductive but brittle paste, which later cracks and forms a 1/4 mm thick crack layer:-

Then Rm would change from 0.021 (see Table 3)
H would change from $1.6*10^{-4}$ to $5.9*10^{-4}$
Ep would change from 3.6% to about 6.7%

As in example 1 the limiting errors (1% and 19%) do not impinge on the result, and this case also operates in the power-law regime. The consequence of cracking would thus be that an initial error within 4% might suddenly double, but there would be no physical indication of such a change.

EXAMPLE 3: Effect of mismatched Surface Resistance (cases 1,3,4,5 in Table 3)

Many authors, eg, Flanders (1985), have drawn attention to the effect of differing emittance between the HFT and the surface it is mounted on. Using the parametric model we can describe in some detail the effect of a mismatch. The effect comes about by the influence of the term (Rms - Rs) in Eq. 1 on Rm. This is dominated by any difference in emittance, although texture and edges can affect the convective heat transfer coefficients.

If both surfaces have the same emittance, the term (Rms - Rs) will always be zero or small. If an HFT surface is reflective and the surround is black, then (Rms - Rs) will be positive with a value of about 0.09 when there is no wind. The systematic error will increase since Rm will have risen from 0.011 to 0.101, but more importantly it will be strongly affected by any variation in wind strength. If the HFT were black and the surrounds reflective, then the (Rms - Rs) term will be negative, with a value of -0.09 at no wind. The value Rm, and hence measurement error may therefore become either positive or negative.

	wind = 0	
	black HFT	reflective HFT
	Error E%	
black surface	3.6%	28%
reflective surface	-19%	3.1%

Table 1. Effect of mismatched emittance, no wind

The results for this condition can be seen in Table 1. If the HFT surface and the surround surface both have similar surface emittance, whether high or low, then the calculated error E remains low. However if the surface emittances differ, the error can not only increase tenfold, but can be either positive (reading too low) or negative (reading too high). All cases are in the power-law regime, although case 5 is nearing the Emax limit.

EXAMPLE 4: Effect of Wind (Cases 6 - 9 in Table 3)

For this example we consider the same conditions as in EXAMPLE 3, except that the wind strength is set to 3m/s. This lowers all surface resistances, and also decreases the differences due to emittance. Consequently the effects of surface emittance in EXAMPLE 3 remain but are less marked in this example.

	wind = 3 m/s	
	black HFT	reflective HFT
	Error E%	
black surface	4.4%	8.0%
reflective surface	0.45%	4.2%

Table 2. Effect of mismatched emittance, 3 m/s wind

In the case of black HFT and reflective surround (case 8), wind has caused the calculated error E to reduce sharply, but has just failed to go negative - small changes to the surface resistances Rs or Rms may cause this to occur. Comparison of examples 3 and 4 show that the effect of changing wind speed is severe if the surface emittances are mismatched, but quite minor otherwise.

EXAMPLE 5: Effect of High Conductivity Substrates (Case 10 in Table 3)

If there is a highly conductive substrate layer such as metal or concrete under an HFT, then it might be expected that this would have an effect on the heat flow measurement. The parametric model predicts such an effect, by the effect of the k*t term in "H". The effect is especially strong if the HFT is small (ie, "L" is small), or sample resistance Rt is small.

Consider the case when the HFT from examples 1-3 is used to find heat flow from a machine hood, with a painted 1 mm aluminium skin, and insulation of 10 mm expanded polystyrene, ie, R-value about 0.3 m^2 °C/W. The surface resistance remains at 0.09 m^2 °C/W.

From Table 3 we see that the power-law error Ep would be 25%. However the value Emax is lower than 25%. This case therefore must operate in the "surface-controlled" region. The calculated error E will be close to Emax, 10.9%.

If this is explored further by considering a drop in the surface resistance - if air speed increases for instance - then we find that the actual error will increase sharply. If the air speed increases to 3 m/s, and the surface resistance therefore falls to 0.04, the H does not change greatly but the value Emax will rise to 22%, and the final error E will rise with it.

It is characteristic of the "surface-controlled" region that the measurement accuracy becomes dominated by the surface resistance Rs, with errors varying erratically with time in response to variations in wind speed.

EXAMPLE 6: Effect of large size, large R, HFT (Case 11 in Table 3)

If a large size HFT is required for some reason - say to span the framing pitch of a timber frame wall, then an HFT may not even need to have small thermal resistance. Consider EXAMPLE 1, but with a large HFT of say 500 x 500 mm, and a large HFT resistance of 0.1 m^2°C/W. Then the value H will increase from $1.6*10^{-4}$ to $13.6*10^{-4}$, and the predicted error E will increase to 9-10%. However as in EXAMPLE 1, this may also be seen to be a stable error which will not change significantly with air movement, and may equally be a usable option. In fact, such an option may be particularly resistant to change of contact resistance, since that factor can no longer have such a leverage on the value Rm. The change which caused EXAMPLE 2 to jump from 4% error to 9% error, would here be able only to increase the error from 9% to some 10%.

SPECIAL CONDITIONS

Edge guards will clearly reduce edge leakage. In reference (3) the effect of edge guards was examined, and reported to vary as in Equation (2). As edge guard width increased from zero, the calculated error dropped from its initial value E, to the value Emin:

$$\frac{E(w) - Emin}{E(0) - Emin} = e^{-(c.w)} \qquad (2)$$

where w = width of edge guard, m
c = fitted constant
e = 2.718 ...

The value of c varied from about 12 to 50 in different cases. Typically the value of E(w) approached within 10% of Emin when the value of edge guard width w exceeded 50 - 150 mm width in the cases studied, in which the HFT width varied 20 - 50 mm. It is not known whether wider ranges occur. It should be noted that the error will not fall below the value Emin, even with perfect edge guarding.

A further special condition arises as in Equation (3). It is evident that if R_m can be reduced to zero, then there will be no systematic error. This condition can in principle be achieved by setting:-

$$Rm = 0 = Rh + Rc + (Rms - Rs)$$
$$\text{ie,} \quad Rms - Rs = Rh + Rc \qquad (3)$$

In our "base case" example, with (Rh + Rc) equal to 0.011, then we can achieve the no-error condition by choosing (Rms - Rs) to be also equal to 0.011, ie, Rms as 0.09 + 0.011, or 0.0101. This can quite readily be done by choosing the emittance of the surrounding surface to be just a little lower than the HFT, about 0.6 to 0.7 in this case.

Such a move is really one of cancelling the thermal imbalance created by the HFT, and could be regarded as being a method of edge guarding. However, such techniques are available only if one can have confidence that the surface coefficient (and hence wind speed) will remain at the design value, and thus would be feasible only in laboratory conditions.

CONCLUSIONS

- very high accuracy is not easily achieved. (To guarantee a 1% systematic error even in a "benign" case such as a well-insulated timber framed wall measured indoors, it may be necessary to use an HFT 500 mm square, resistance less than 0.009, and contact resistance which is not only less than 0.002 but also never changes significantly in use).

- it can be better to use systems having stable (and therefore correctable) error rather than those with very small error, if that error varies with conditions.

- errors may vary widely from time to time in some cases, namely:
    - where contact resistance between HFT and substrate changes
    - where emittance of HFT and surrounding surface do not match
    - where the HFT operates in the "surface controlled" regime.
- good reliability is greatly helped by using large HFT's. Size can be used to offset large HFT or contact resistance.
- no HFT can be correctly described as having a particular universal accuracy. The accuracy will vary widely according to the usage of that HFT.

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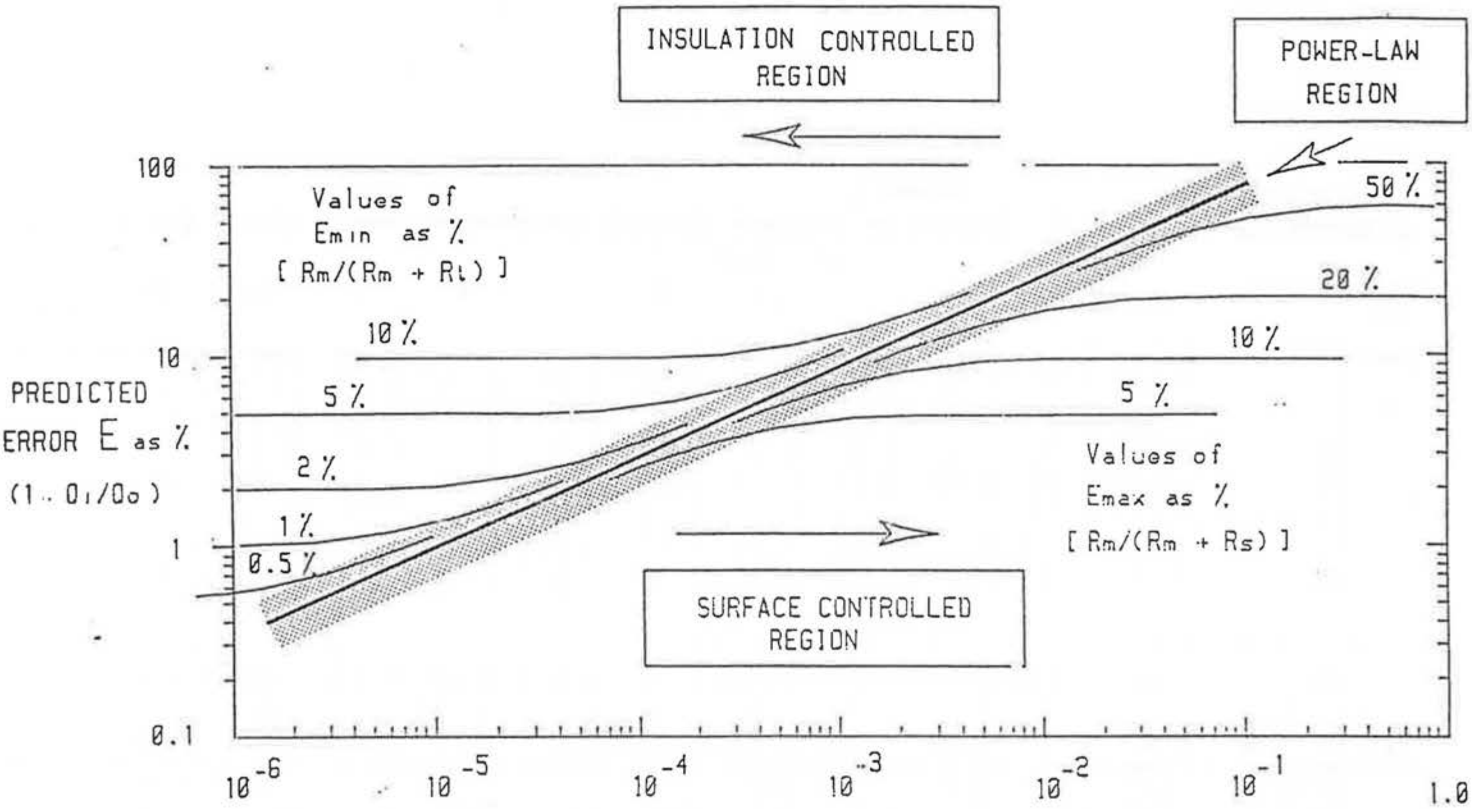
Physical quantity			EXAMPLE								
	1	2	3			4				5	6
	Case Number										
	1	2	3	4	5	6	7	8	9	10	11
k	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	150	0.16
t	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	.001	0.01
L	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.5
Rt	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.3	2.0
Rs	0.09	0.09	0.09	0.18	0.18	0.04	0.04	0.05	0.05	0.09	0.09
Rh	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.1
Rc	0.001	0.011	0.001	0.001	0.001	0.001	0.001	0.001	0.001	.001	.001
Rms	0.09	0.09	0.18	0.09	0.18	0.04	0.05	0.04	0.05	0.09	0.09
Rm	0.011	0.021	0.101	-.079	0.011	0.011	0.021	0.001	0.011	.011	0.101
$H*10^{-4}$	1.6	5.9	136	-59	1.1	2.4	8.8	0.018	2.0	104	13.6
Ep %	3.6	6.7	28.6	-19.4	3.1	4.4	8.0	0.45	4.2	25.3	9.8
Emin %	.55	1.0	4.8	-4.1	0.55	0.55	1.0	0.05	0.55	3.5	4.8
Emax %	10.9	18.9	53	-78	5.7	21.6	34.4	2.0	18	10.9	53
E%	3.6	6.7	25	-19.4	2.7	4.4	8.0	0.45	4.2	10.9	9.8

TABLE 3. SUMMARY OF CALCULATIONS FOR ALL CASES



$$H = \frac{(Rm)^2}{Rt.Rs} \cdot \sqrt{\frac{k.t.Rs}{L^2}}$$

where

E = 1 - Qi/Qo
Qi = indicated heat flux
Qo = undisturbed flux
Rh = HFT series resistance
Rc = Contact resistance
Rms = surface resistance over HFT
Rs = surface resistance over undisturbed structure
Rt = total thermal resistance of test structure
k = thermal conductivity of top substrate layer
t = thickness of top substrate layer
L = length or breadth of square HFT
= 2AB/(A + B) for rectangular HFT
s = sgn(m) (=±1, according to the sign of R_m)
c = fitted constant = 2.1136
n = fitted constant = 0.465

Rm = Rh + Rc + (Rms - Rs)
Ep = $s.c.H^n$
Emin = Rm/(Rm + Rt)
Emax = Rm/(Rm + Rs)

Figure 1. Parametric Model of Heat Flux Transducer Error (for surface mounted HFT without edge guards).

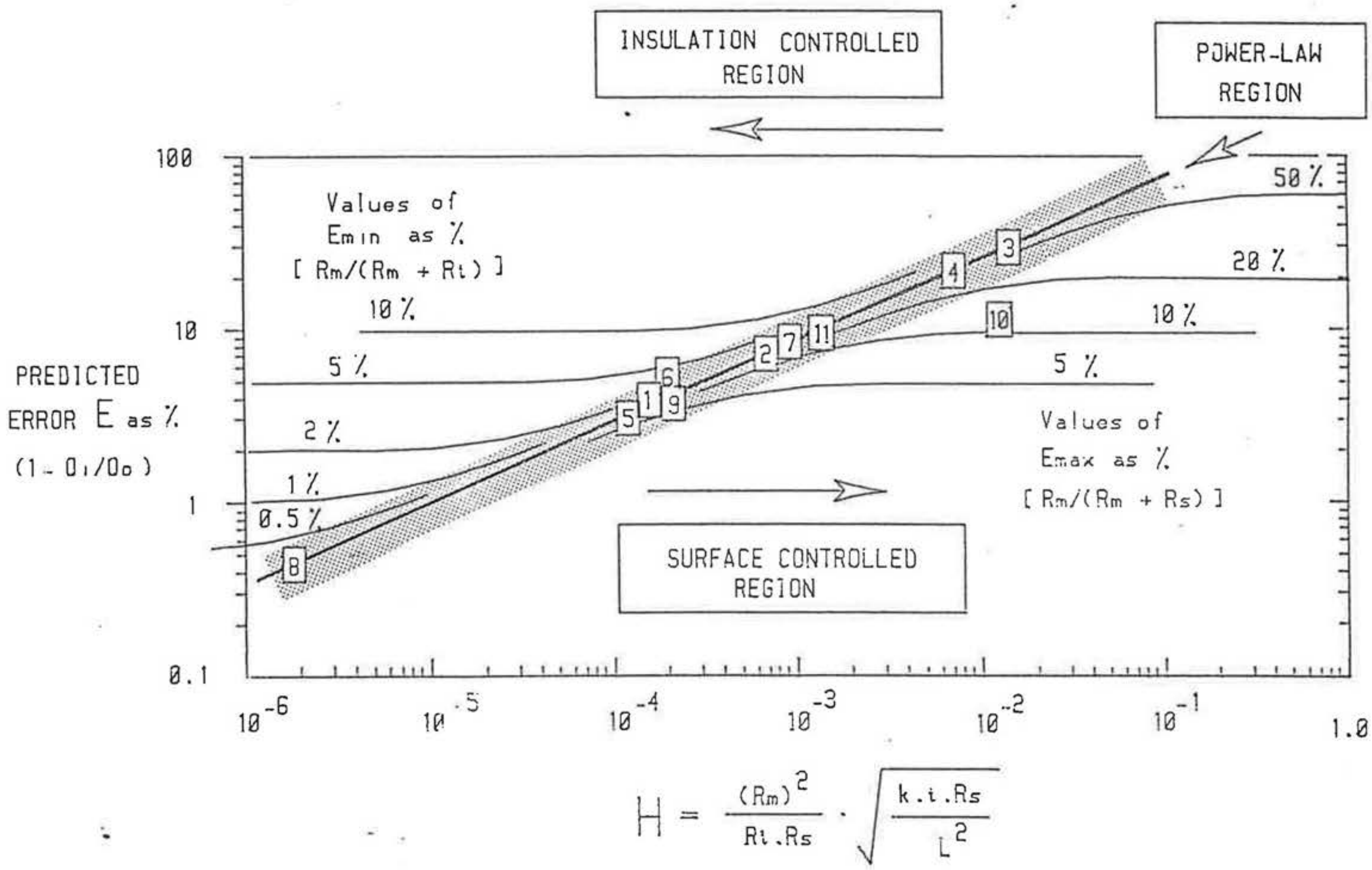


Figure 2. Showing Locations of Example Cases from Table 3, on parametric Correlation Diagram

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