ANALYSIS OF A SCALING RATE METER
FOR GEOTHERMAL SYSTEMS

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SUMMARY

A research project was conducted to investigate an experimental technique for measuring the rate of formation of mineral scale and corrosion in geothermal systems. A literature review was performed first to identify and evaluate available techniques for measuring scale in heat transfer equipment. As a result of these evaluations, a conceptual design was proposed for a geothermal Scaling Rate Meter (SRM) that would combine features of certain techniques used (or proposed for use) in other applications. An analysis was performed to predict the steady-state performance and expected experimental uncertainty of the proposed SRM. Sample computations were then performed to illustrate the system performance for conditions typical of a geothermal scaling application. Based on these results, recommendations are made regarding prototype SRM construction and testing.

The review of available and proposed SRM concepts revealed none that appeared entirely suitable for use with geothermal systems. However, a concept proposed by the Lockheed Missiles and Space Company for the Ocean Thermal Energy Conversion program appeared very nearly suited when modified to reflect the special needs and hostile environment of geothermal applications.

The heart of the system that emerged from the discussions, evaluations, and analyses is a tube/block assembly. A "sample" tube of a selected material would be clamped between two (or possibly three) cylindrical blocks that would be precisely machined to fit the tube OD. Thermal contact between the tube and the block would be maximized with thermal grease and uniform pressure applied by the clamping bands. A coolant fluid (oil) would be passed through channels at the outer edge of the blocks to provide uniform cooling of the tube. Brine would be passed through the tube to produce corrosion and scaling under prototypic conditions.

The primary instrumentation would consist of a brine flowmeter and two sets of differential thermocouples. The inner thermocouple set would measure the temperature drop from the brine across the inside film including the tube wall. The outer set would measure the temperature drop across a measured

radial distance (and thus a known resistance) in the outer blocks. The outer set would provide a measurement of the rate of heat transfer from the brine. The inner set would provide a measure of the change in the inside resistance due to scale.

The brine could be extracted from the system and returned through the same fitting or it could be put into the reinjection line. The oil coolant loop would have an air-cooled primary heat rejection system. Water cooling could also be provided. However, in many geothermal applications, cooling water may not be readily available. If practical, all of the equipment should be mounted on a skid or trailer for easy portability.

The ratio of the two differential temperatures described above is the primary measured variable from which all other parameters would be computed. An analysis showed that differences in the values of this ratio at different brine flow rates and at different scaling conditions could be used to compute the values of several internal thermal resistances, including

- the inside heat transfer coefficient (or thermal resistance) due to convection for both clean and fouled conditions
- the fouling factor on the inside (or the effective fouling resistance)
- an estimate of the heat transfer enhancement due to roughness
- the effective thermal resistance and thickness of the scale
- an estimate of the initial contact resistance in the clean system.

The equations required to perform these computations are summarized in the text. The parameters are defined in the nomenclature provided.

In addition to the above "on line" measurements, the inner tube could be removed for direct measurement of scale quantity and distribution. The scaling experiment would have to be interrupted only long enough to change tubes. Tubes of different materials or with different surface treatments could be used in successive tests.

An example case computation was performed to illustrate the system performance. The required equations were used along with the HEATING5 conduction code to compute the temperature distributions and the resulting differential temperature ratios used in the example computations. For the case where scale would result in a 50% loss in heat transfer effectiveness, the computations show that the fouling factor could be measured to an estimated uncertainty of about $\pm 7\%$. The calculations indicate that the measured value of the actual effective scale resistance could be obtained at an estimated uncertainty of about $\pm 10\%$.

It was concluded that the proposed SRM could be a practical device for measuring scaling rate in geothermal applications where liquid phase brine can be extracted from the system. If direct two-phase scaling phenomena must be dealt with, some other approach will be required. However, the proposed technique appears sufficiently practical to justify a recommendation that the concept be studied further and that prototype scaling rate meters be built and tested in both the laboratory and the field.

CONTENTS

SUMMARY	iii
FIGURES	ix
TABLES	ix
NOMENCLATURE	xi
1.0 INTRODUCTION	1
2.0 BACKGROUND	3
2.1 SCALING PHENOMENA	3
2.2 SUMMARY OF DATA REQUIREMENTS	4
2.3 AVAILABLE TECHNIQUES FOR SCALE DETECTION AND MEASUREMENT	5
2.4 CONCEPTUAL DESIGN OF THE PROPOSED SCALING RATE METER	8
3.0 ANALYSIS OF THE PROPOSED SCALING RATE METER CONCEPT	15
3.1 COMPUTATION OF THE TOTAL FOULING RESISTANCE $R_{f\alpha}$	15
3.2 CALCULATION OF THE INSIDE CONVECTIVE RESISTANCE $R_{i\alpha}^*$ AND CONTACT RESISTANCE R_c^*	18
3.3 CALCULATION OF THE SCALED INSIDE RESISTANCE $R_{i\alpha}$	19
3.4 EVALUATION OF THE ROUGHENING ENHANCEMENT PARAMETER F	22
3.5 CALCULATION OF THE SCALE RESISTANCE R_s'	25
3.6 SUMMARY OF THE UNCERTAINTY ANALYSIS	26
4.0 CALCULATIONS OF SYSTEM PERFORMANCE AND ESTIMATED UNCERTAINTIES	31
4.1 SCALING RATE METER PERFORMANCE ANALYSIS	31
4.2 SENSITIVITY AND UNCERTAINTY ANALYSIS	36
5.0 DISCUSSION	39
5.1 CONCLUSIONS	39
5.2 RECOMMENDATIONS	42
REFERENCES	43

FIGURES

1	Schematic of the Scaling Rate Meter Block and Tube Geometry	9
2	Suggested Three-Block Scaling Rate Meter Configuration	10
3	Assembly Sketch for the Proposed Scaling Rate Meter	10
4	Schematic of Scaling Rate Meter Flow Loops and Instrumentation	13
5	Schematic of Probe Insertion System	14
6	Friction Factors for Commercial Piping	23
7	Effectiveness η for Turbulent Heat Transfer in Tubes	25
8	Calculated Differential Temperature Ratios for Copper and Stainless Steel Blocks	33
9	Computation of Scaling Rate Meter Response As a Function of Fouling Resistance	34
10	Calculation of Scaling Rate Meter Response As a Function of Velocity Ratio Γ	35

TABLES

1	Thermal Resistance Definitions	16
2	Summary of Equations for Experimentally Determined Resistance Parameters	26
3	Summary of Results of the Uncertainty Analysis	29
4	Summary of System Parameters and Estimated Uncertainties for Example Case	32
5	Summary of Thermal Resistance Values and Estimated Experimental Uncertainties for Example Case	37

NOMENCLATURE

a	estimated percent change in F_α between $\dot{m}_\alpha$ and $\dot{m}_\beta$
d	tube inside diameter
f	friction factor
F	roughening enhancement parameter
h	heat transfer coefficient
k	thermal conductivity
k^+	dynamic roughness
L	length of tube
m	limit of a summation
$\dot{m}$	mass flow rate of brine
n	limit of a summation
Nu	Nusselt number
Pr	Prandtl number
$\dot{Q}$	heat transfer rate
r	radial dimensions of system
R	thermal resistances
Re_d	Reynolds number based on U and d
t	tube wall thickness
T	temperature
U	bulk velocity in the tube
x, y, z	system coordinates
X, Y	general functions used in uncertainty analysis
θ_{ij}	temperature differential ($T_i - T_j$)
ϕ	differential temperature ratio
η	roughening enhancement effectiveness
Γ	mass flux ratio
δ	thickness of resistance elements
Δ	denotes uncertainty of various quantities
∂	denotes differentiation
Σ	denotes summation

Subscripts

0	tube centerline
1	tube ID
2	tube OD
3	location of inner probe thermocouple
4	location of outer probe thermocouple
b	block properties
c	contact zone
f	fouling layer
i	properties of inside convective film, also an index for summation
j	an index for summation
p	probe
s	scale properties
t	tube properties
α	properties evaluated at nominal brine flow rate $\dot{m}_{\alpha}$
β	properties evaluated at alternate brine flow rate $\dot{m}_{\beta}$

Superscripts

()*	denotes property of clean, unfouled system
R_s'	effective scale property
F	effective roughening enhancement parameter
$\overline{Nu}$	average Nusselt number based on tube diameter

ANALYSIS OF A SCALING RATE METER FOR GEOTHERMAL SYSTEMS

1.0 INTRODUCTION

The processes used to extract energy from geothermal brines inherently result in a reduction in temperature and, in flashing systems, a concurrent reduction in pressure and change of phase. Mineral scales occur in geothermal systems because the energy extraction processes cause certain of the mineral species present in the brine to exceed saturation, forming precipitants that either plate out on the internal surfaces or are carried through the system in bulk. Scale build-up in the system causes heat exchanger surface fouling, which can dramatically reduce heat exchanger effectiveness. In addition, the inside diameters of pipes and fittings can be reduced and, in some cases, blocked entirely in relatively short operating times. Friction losses can be increased and the operation of orifices, valves, flowmeters, and other fittings and instrumentation can be seriously impaired.

Scaling due to corrosion is also a frequent problem in geothermal systems. In some cases, the mass of corrosion products in the scale can exceed that of mineral scale precipitated from the brine. Corrosion scale can have all of the damaging effects of the mineral scales discussed above and more. Corrosive failure of heat exchangers, pipes, fittings, and instrumentation can result in severe maintenance problems and reduction of the system life.

These and other problems caused by scaling, once diagnosed, can usually be minimized by proper design of the fluid handling and energy extraction systems, variations in operating procedures, use of brine additives, and maintenance strategies. There is, thus, a need for a "scaling rate meter" (SRM), or the equivalent, that could be used to measure the scaling propensity of a given brine under operating conditions typical of a particular energy extraction system. Such an instrument would be useful for evaluating the relative

merits of various design alternatives that might be chosen to exploit a given geothermal resource. Alternatively, an SRM could be used to measure the scaling propensity of a brine stream extracted from any desired location in an operating geothermal system. An SRM would thus be a valuable tool for R&D work, for plant design, and for operation and maintenance functions.

The objectives of the work described in this report were, therefore, to assess the specific needs for an SRM in the geothermal energy field, to review and assess available techniques for measuring scaling rates as applicable to geothermal systems and, thereby, to make recommendations for instrumentation that might be suitable for geothermal applications in the field. This report describes the investigation, summarizes the results, and includes a specific recommendation for an SRM concept, a performance analysis, and an estimate of the expected experimental uncertainties.

2.0 BACKGROUND

This section briefly describes the primary scaling phenomena of interest in geothermal systems, summarizes the type of measurements needed, and reviews instrumentation employed or recommended by others for similar measurements in other fields. The review provided here is meant only to develop necessary background for discussion and is not intended to be either complete or comprehensive. More detailed treatment of the topics covered is contained in the references cited.

2.1 SCALING PHENOMENA

Geothermal brines that are not appreciably affected by surface water are in chemical equilibrium with, and thus saturated with respect to, the minerals present in the reservoir. Minerals that have "normal" solubility curves (increasing solubility with increasing temperature) will exceed saturation and begin to precipitate at the first point in the system where the brine experiences a temperature drop. Important examples of scales that form by this process are amorphous silica, quartz, and numerous silicates. The occurrence of flashing further concentrates the brine and proportionally accelerates the scaling rate of these species in the flashing region. Scales of "normal" solubility minerals tend to be most troublesome in high-temperature resources.

Minerals having reverse or retrograde solubility curves (decreasing solubility with increasing temperature) will not normally precipitate in geothermal energy systems if the brine is maintained in a compressed (liquid phase) state, because the temperature reduction accompanying the transfer of heat results in an increase in solubility. However, if flashing and the concurrent loss of dissolved CO_2 is allowed, the resultant rise in the pH of the brine and the concentration effect due to loss of vapor phase water can cause saturation conditions to be exceeded so that deposition will occur. An important example of a mineral of this type is CaCO_3 . In flashing systems, calcite scaling has frequently been observed to cause blockage of large pipes in a matter of hours. Because of its retrograde solubility, calcite scaling is

most severe in relatively low-temperature resources. Other carbonates and various other reverse solubility salts also occur frequently, but generally in smaller quantities.

The brines in geothermal systems are usually highly reduced (i.e., no appreciable dissolved oxygen) and H_2S is generally present. For carbon steel systems, the products of corrosion on the internal surfaces are primarily sulfides of iron and sulfide complexes involving iron and other species in the brine. Sulfide scaling can cause substantial losses in heat exchanger effectiveness but would not usually occur in sufficient quantities to appreciably alter inside diameters. If oxygen is introduced, additional and possibly more severe corrosive scaling could occur. There is evidence that the corrosion of carbon steel generally increases with increasing temperature and increasing pH (flashing, acid addition). Although use of exotic alloys can substantially reduce problems with corrosion, this is not generally practical for economic reasons.

2.2 SUMMARY OF DATA REQUIREMENTS

The primary scale characteristics that would be of interest in most geothermal systems include:

- scale composition
- mass of scale per unit area
- thickness of scale layer
- scale structure--hardness, porosity
- surface corrosion rate.

Where possible, these measurements would be needed as a function of time and location in the system of interest.

Of equal importance in actual applications are the effects of the scale on system performance, including:

- increased flow friction--friction factors, loss coefficients
- reduced heat transfer effectiveness--fouling factors, effective thermal conductivity.

Whereas the former parameters are local or point functions, the latter are averaged, overall effects of scale on system performance.

Ideally, it would be most desirable to develop the capability to obtain direct measurements of the above scale characteristics and effects in operating systems. However, this is not generally practical. Direct measurement of mass, thickness, composition, and structure of scale would normally require shutdown, disassembly, and, in many cases, destructive testing of the system in question.

Measurements of the overall system performance characteristics are comparatively easy to obtain. Pressure drop measurements can usually be obtained relatively easily in most systems. These measurements can be used to calculate the friction factor. Changes in friction factor relative to the clean (unscaled) conditions can sometimes be used to infer changes in roughness, but this determination would generally be primarily qualitative.

Similarly, changes in heat transfer effectiveness due to scaling can frequently be measured, although the measurements required are usually more extensive and more difficult than those required for pressure drop. Fouling factors can frequently be determined, incorporating in a lumped or average manner all of the effects due to scaling. The fouling factor can then be used to infer a lumped, effective thermal resistance of the scale. However, this determination is also primarily qualitative.

No indication of the type, quantity, structure, or distribution of the scale and corrosion is obtained from either the friction factor or fouling coefficient determination. Where such information is desired, the overall performance degradation data is useful but insufficient. In assessing the potential value of a resource, the detailed effect of scale, or in research and development programs, the point measurement capability is generally needed. This need is addressed in this study, and all discussion of instrumentation and measurement techniques herein will be directed toward this end.

2.3 AVAILABLE TECHNIQUES FOR SCALE DETECTION AND MEASUREMENT

Heat transfer surface fouling due to various causes is an important topic in a wide range of industrial applications.^(1,2) In particular, scaling

(or fouling in general) is expected to be a critical problem in several of the emerging alternative energy technologies, including Ocean Thermal Energy Conversion (OTEC),⁽³⁾ dry/wet cooling towers, and geothermal energy systems. A number of techniques for measuring fouling have been developed in R&D programs related to various of these technologies. The fundamentals of many of these techniques, including capabilities, limitations, and potential applications, are reviewed by Epstein⁽¹⁾ and Knudsen.⁽²⁾ Some of the techniques described are of the direct type that require disassembly and examination of the system in question. Others are of the indirect type in which scale is detected by its effect on heat transfer and friction. In most of these systems, scale is quantified in terms of an effective thermal resistance, as opposed to its actual mass or thickness.

The various techniques are classified by Epstein⁽¹⁾ and Knudsen⁽²⁾ according to the geometry of the detection apparatus or "probe" systems. The major categories are:

- inside or outside surfaces of tubes
- circular cylinders and wires
- spheres
- metal strips and plates
- porous plugs
- complex heat exchanger geometries.

Scale detection is typically accomplished by heating (or cooling) the probe element and detecting the net resistance due to fouling. The methods of heating (cooling) may be categorized as:

- sensible heating (cooling) with a fluid or gas
- evaporation or condensation of a fluid
- direct or indirect electric resistance heating
- thermoelectric cooling (or possibly heating).

Various combinations of these geometries and heating/cooling concepts have been employed with varying degrees of success in many different applications.

In principle, the most desirable approach to the localized measurement of scaling rate in geothermal systems would be a probe or equivalent device that could be inserted directly into the flowing brine at any chosen point.

Alternatively, the brine could be extracted from the system at the point of interest and passed through the "probe." This hypothetical probe should provide a direct (or indirect) measurement of the instantaneous mass of surface scale present per unit area. Average scaling rate could then be determined from measured scale accumulation in a specified time period. With several such devices in place, the rate of scale formation could then be determined as a function of location. With appropriate insertion or isolation devices, the probes could be periodically removed from the system (without affecting system operation) to determine the composition and structure of the scale and to compare indicated versus actual scale accumulation.

For such a probe to be effective, the surface mass transfer conditions should duplicate those on the prototype surfaces as closely as possible. The most important aspect of this problem is probably the need to match the dynamic character of the boundary layer on (or in) the probe to that in the prototype system. In addition, the surface temperature of the probe should match that of the prototype system. Assuming a similar boundary layer, the heat flux through the probe surface per unit area would then match that of the prototype. If all of these conditions are met, the scaling rate on the probe surfaces should be the same as on the prototype surfaces.

The relative importance of matching surface temperatures (and thus heat fluxes) is not clear at this time. The primary driving force for deposition is believed to be the degree of supersaturation in the bulk fluid. The deposition kinetics are assumed to be controlled by the mixing/diffusion characteristics of the boundary layer as modeled with accepted heat/mass transfer correlations. In this approach, surface-to-bulk temperature differences are important only insofar as they affect the most appropriate choice for evaluating fluid properties (i.e., property evaluation is normally at the mean or "film" temperature). However, certain surface effects and the combined gradients of temperature and concentration can result in significant coupling of heat and mass transfer processes. Thus, it is certainly desirable and possibly necessary to match the surface temperature as well as the boundary layer conditions.

The requirement for matching surface temperatures makes the geothermal application somewhat more difficult than some of the other applications because it requires cooling of the probe surface. It is generally much easier to electrically heat a wire, cylinder, or plate than it is to cool it. The relatively high temperatures and corrosive environments in geothermal systems also make this a difficult instrumentation problem.

The concept of a probe that could be inserted into the flowing brine at selected locations is very appealing. However, none of the existing instrumentation techniques appear to be adaptable to a cooled probe configuration suitable for geothermal applications. One of the primary problems is the establishment of a representative boundary layer on a miniaturized probe. The provision of cooling and subsequent detection of the change in surface thermal resistance are also extremely demanding requirements in a miniaturized insertable probe. Combining all of these requirements with the need for ruggedness appropriate for the severe conditions in a geothermal system has led to the conclusion that an insertable SRM probe is probably not feasible for geothermal applications.

The conclusion is that an external SRM, wherein brine would be extracted from the system and passed through the device, would be most practical for geothermal systems. The concept adopted is a cooled, thick-walled cylindrical tube with brine on the inside. The basic configuration is illustrated in Figure 1. This concept is similar to that proposed by Lockheed⁽⁴⁾ for the OTEC program. However, cooling would be provided by sensible heating of a fluid flowing through channels at the outer radius, as opposed to the use of thermoelectric coolers as proposed by Lockheed.⁽⁴⁾ The primary reason for this change is the lack of thermoelectric coolers operable in the temperature range of typical geothermal applications. Further discussion and a detailed analysis of this concept are provided in the next section.

2.4 CONCEPTUAL DESIGN OF THE PROPOSED SCALING RATE METER

The basic geometry of the proposed SRM is illustrated in Figures 1 and 2. The system would consist of a precision tube made from the desired test material (probably carbon steel) with copper "ballast" blocks in two or more

FIGURE 2. Suggested Three-Block Scaling Rate Meter Configuration

FIGURE 3. Proposed Scaling Rate Meter Assembly Sketch

measured using the inside and center thermocouples connected differentially. Using the calculated rate of heat transfer, $(T_0 - T_3)$ could then be used to calculate the sum of the inside thermal resistances. As scaling occurred, this resistance would change; from this change a fouling factor or scale resistance could be computed. If similar instrumentation is provided at different axial positions, the distribution of scale in the SRM could be determined.

The copper blocks could be made in two or possibly three pieces. The design proposed by Lockheed⁽⁴⁾ would use two blocks. Discussions with potential fabricators indicate that a design based on three blocks, such as that illustrated in Figure 2, might be preferred for both precision of fabrication and ease of assembly. Discussions on this design detail have not proceeded beyond this preliminary level.

The coolant channels at the outer extreme of the blocks could be bored directly in the blocks. However, for long blocks of the type envisioned, it would be extremely difficult to bore the holes with sufficiently precise alignment. Thus, it might be preferred to mill slots in the outer surface and surface-braze a cover plate as illustrated in Figure 2. At this time, information to justify a specific recommendation on this design feature is insufficient.

The coolant channels would be connected to manifolds at the inlet and outlet ends as illustrated in Figure 3. Balanced flow resistances could be used in each line to achieve uniform flow rates in all channels. The blocks would be clamped to the test tube by several bands equally torqued to achieve uniform pressure between the blocks and the tube. The number of bands required, material choice, and other details would have to be carefully considered in a final design. The entire assembly would have to be surrounded by insulation and properly housed to prevent damage. Thermocouple leads could be taken out through the sides or ends as convenient.

The mounting of the thermocouples in the blocks would be relatively straightforward. The greatest problem would probably be boring the wells and locating the junctions with sufficient precision. In addition, the choices of cement and insulation materials would have to be carefully considered.

The most difficult thermocouple to mount will be that which must be inserted through the tube wall into the brine. It is suggested that a small L-shaped probe (like a pitot tube) could be inserted through the tube wall downstream of the "instrumentation plane" so that the junction would extend upstream into the same plane as the other thermocouples. The temperature drop along the thermocouple probe axis for this configuration should be small even if the probe becomes scaled. The flow disturbance introduced by such a probe should be minimal. The insertion would have to be made at the point of intersection of two of the blocks. It would have to be small to minimize the resulting disturbance in the temperature distribution in the blocks.

The coolant fluid would probably have to be an oil. The temperatures likely to be used in the coolant will, at times, exceed the atmospheric boiling point of water, and it would be much more difficult to design for a pressurized coolant system. A schematic of the proposed system, including all the relevant flow loops, is shown in Figure 4. The primary coolant loop for the SRM would be oil. The oil could, in turn, be cooled by air or water, if available. For a typical geothermal field application, air cooling would probably be most appropriate. It might be advisable to design a system with both water and air cooling capabilities.

The temperature of the oil at the inlet to the SRM should be controlled with temperature-regulated heaters in the reservoir, the pumping system, or both. Flow meters should be used in all streams to facilitate control and to allow energy balance computations.

In the proposed concept the brine would be withdrawn and returned to the system using a probe insertion device such as that illustrated in Figure 5. A gate valve could be used as shown to isolate the probe for removal, cleaning, or inspection. A device of this general type has been built at PNL and is currently being used for other purposes. Although the brine is shown to be returned to the system through the probe, this is not an essential feature of the concept. However, in the configuration shown, fluctuations in system pressure or flow rate would have minimal effect on the SRM. This would be important in maintaining stable conditions in the SRM.

FIGURE 4. Schematic of Scaling Rate Meter Flow Loops and Instrumentation

The above description is only a conceptual design. If the decision is made to build such a device, each aspect of this concept will have to be carefully designed and optimized. Device performance would be affected by these design decisions in a manner that cannot be foreseen here. However, the overall operating characteristics can be estimated, based on a set of reasonable assumptions and approximations. This is the subject of the analysis in the next section.

FIGURE 5. Schematic of Probe Insertion System

3.0 ANALYSIS OF THE PROPOSED SCALING RATE METER CONCEPT

The basic geometry of the SRM is illustrated in Figure 1 and described in Section 2.4. The heart of the system is the tube/block assembly and associated temperature measurement instrumentation. The measurement technique requires accurate measurement of the brine flow rate and temperature, and differential measurements of temperature across the inside and probe resistances, respectively. The analysis that follows develops the required equations for extracting the fouling factor, the resistance of the scale, and other parameters of interest. In addition, an uncertainty analysis is included to estimate the expected experimental uncertainty for the proposed SRM technique.

3.1 COMPUTATION OF THE TOTAL FOULING RESISTANCE $R_{f\alpha}$

For steady-state one-dimensional heat transfer in the series cylindrical path illustrated in Figure 1, the rate of heat transfer per unit length of tube may be given by two alternative expressions:

$$\frac{Q}{L} = \frac{(T_3 - T_4)}{R_p} \quad (1)$$

$$= \frac{(T_0 - T_3)}{R_i + R_s + R_t + R_c} \quad (2)$$

Definitions of the thermal resistances are given in Table 1. Eliminating Q from these expressions gives an expression for the ratio of temperature differences ϕ :

$$\phi = \frac{(T_0 - T_3)}{(T_3 - T_4)} \quad (3)$$

$$= \frac{R_i + R_s + R_t + R_c}{R_p} \quad (4)$$

TABLE 1. Thermal Resistance Definitions

<u>Resistance Element</u>	<u>Symbol</u>	<u>Alternative Expressions or Approximations</u>
Inside Film Resistance		
Clean:	$R_i^* =$	$\frac{1}{2\pi r_1 h_1} = \frac{1}{\pi k Nu^*}$
Scaled:	$R_i =$	$\frac{1}{2\pi(r_1 - \delta_s)h_1} = \frac{1}{\pi k Nu}$
Scale Resistance	$R_s =$	$\frac{\ln \left \frac{r_1}{r_1 - \delta_s} \right }{2\pi k_s} \approx \frac{\delta_s}{2\pi r_1 k_s}$
Tube Wall Resistance	$R_t =$	$\frac{\ln \left \frac{r_2}{r_1} \right }{2\pi k_t} \approx \frac{t}{2\pi r_1 k_t}$
Contact Resistance	$R_c =$	$\frac{\ln \left \frac{r_2 + \delta_c}{r_2} \right }{2\pi k_c} \approx \frac{\delta_c}{2\pi r_2 k_c}$
Probe Resistance	$R_p =$	$\frac{\ln \left \frac{r_4}{r_3} \right }{2\pi k_b}$

For the initial, unscaled condition ($R_s = 0$), the temperature ratio is given by

$$\phi^* = \frac{(T_0 - T_3)^*}{(T_3 - T_4)^*} \quad (5)$$

$$= \frac{R_i^* + R_t + R_c^*}{R_p} \quad (6)$$

where the superscript ()^{*} denotes properties of the clean system. The scaled convective resistance R_i may differ from R_i^* because of effects of roughening, reduction in the tube ID due to scaling, and differences in flow rate between tests. The contact resistances R_c^* and R_c would, hopefully, be the same, but that cannot generally be assumed. The tube resistance R_t and probe resistance R_p would be constant.

Tube resistance R_t may be eliminated from Equations (4) and (6) by subtraction:

$$(\phi - \phi^*) = \frac{1}{R_p} \left[R_s + (R_i - R_i^*) + (R_c - R_c^*) \right] \quad (7)$$

Assuming ϕ and ϕ^* are measured at the same mass flow rate, the fouling resistance is defined by

$$R_f = R_s + (R_i - R_i^*) + (R_c - R_c^*) \quad (8)$$

such that R_f can be determined from Equation (7):

$$R_f = R_p (\phi - \phi^*) \quad (9)$$

If the change in contact resistance is negligible, the fouling resistance is merely the actual resistance of the scale plus the change in the convective resistance due to scaling.

The value of R_f is one of the prime quantities of interest; however, the actual resistance of the scale R_s is also desired. Unfortunately, changes in R_c cannot be distinguished from changes in R_s by the present technique. Thus, we may solve only for the apparent scale resistance,

$$R_s' = R_s + (R_c - R_c^*) \quad (10)$$

An expression for R_s' will be derived in a subsequent section. First, however, it is necessary to derive expressions for the inside convective resistances $R_{i\alpha}^*$ and $R_{i\beta}$ for unscaled and scaled conditions, respectively. In so doing, expressions are also derived for the contact resistance and the enhancement of heat transfer due to roughening of the inside.

3.2 CALCULATION OF INSIDE CONVECTIVE RESISTANCE $R_{i\alpha}^*$ AND CONTACT RESISTANCE R_c^*

Equation (6) may be solved for $R_{i\alpha}^*$ for brine flow rate in $\dot{m}_\alpha$ as:

$$R_{i\alpha}^* = R_p \phi_\alpha^* - R_c^* - R_t \quad (11)$$

Similarly, for a brine flow rate $\dot{m}_\beta$,

$$R_{i\beta}^* = R_p \phi_\beta^* - R_c^* - R_t \quad (12)$$

Subtracting these results eliminates R_c^* and R_t . The result is

$$R_{i\alpha}^* = \frac{R_p (\phi_\beta^* - \phi_\alpha^*)}{\left(\frac{R_{i\beta}^*}{R_{i\alpha}^*} - 1 \right)} \quad (13)$$

The ratio of thermal resistances in Equation (13) can be expressed in terms of Nusselt numbers as follows from Table 1:

$$\frac{R_{i\beta}^*}{R_{i\alpha}^*} = \frac{Nu_\alpha^*}{Nu_\beta^*} \quad (14)$$

For fully developed, turbulent flow in a tube at $10^4 \lesssim Re_d^* \lesssim 10^5$ and $Pr \approx 1$ (water), the Colburn analogy and Dittus Boelter equation⁽⁵⁾ both give the following correlation for Nu^* :

$$Nu^* = 0.023 (Re_d^*)^{0.8} \quad (15)$$

Defining a mass flux ratio Γ as

$$\Gamma = \frac{Re_\alpha^*}{Re_\beta^*} \quad (16)$$

Equation (13) can then be given by

$$R_{i\alpha}^* = \frac{R_p (\phi_\beta^* - \phi_\alpha^*)}{(\Gamma^{0.8} - 1)} \quad (17)$$

Equation (17) may now be used to solve for $R_{i\alpha}^*$ (and h_i^*) from data obtained in the clean SRM. In addition, Equations (11) and (13) may be solved for the contact resistance R_c^* . The result is

$$R_c^* = R_p \phi^* - R_{i\alpha}^* - R_t \quad (18)$$

Although theoretically possible, the computation of R_c^* will be subject to substantial uncertainty because it is a small quantity obtained by differencing two large quantities of similar magnitude. The actual degree of uncertainty is illustrated in the sample calculations.

3.3 CALCULATION OF THE SCALED INSIDE RESISTANCE $R_{i\alpha}$

The effect of surface roughening in determining the fouling resistance can be isolated by a differencing procedure similar to that performed in the preceding analysis. Evaluating Equation (8) for R_f at $\dot{m}_\alpha$ and $\dot{m}_\beta$ gives

$$R_{f\alpha} = R_s + (R_c - R_c^*) + (R_{i\alpha} - R_{i\alpha}^*) \quad (19)$$

$$R_{f\beta} = R_s + (R_c - R_c^*) + (R_{i\beta} - R_{i\beta}^*) \quad (20)$$

Subtracting eliminates R_s and R_c :

$$(R_{f\beta} - R_{f\alpha}) = (R_{i\beta} - R_{i\beta}^*) - (R_{i\alpha} - R_{i\alpha}^*) \quad (21)$$

$$= R_{i\beta}^* (F_\beta - 1) - R_{i\alpha}^* (F_\alpha - 1) \quad (22)$$

where the resistance ratios F_β and F_α are defined as

$$F_\beta = \frac{R_{i\beta}}{R_{i\beta}^*} = \frac{Nu_\beta^*}{Nu_\beta} \quad (23)$$

$$F_\alpha = \frac{R_{i\alpha}}{R_{i\alpha}^*} = \frac{Nu_\alpha^*}{Nu_\alpha} \quad (24)$$

The parameter F is a measure of the degree to which heat transfer is enhanced due to roughening.

For convenience, an effective value $\tilde{F}$ is defined as

$$(R_{i\beta}^* - R_{i\alpha}^*)(\tilde{F} - 1) = R_{i\beta}^* (F_\beta - 1) - R_{i\alpha}^* (F_\alpha - 1) \quad (25)$$

$$\tilde{F} = \frac{R_{i\beta}^* F_\beta - R_{i\alpha}^* F_\alpha}{(R_{i\beta}^* - R_{i\alpha}^*)} \quad (26)$$

Then Equation (22) can be written as

$$(R_{f\beta} - R_{f\alpha}) = (R_{i\beta}^* - R_{i\alpha}^*)(\tilde{F} - 1) \quad (27)$$

$$(\tilde{F} - 1) = \frac{(R_{f\beta} - R_{f\alpha})}{(R_{i\beta}^* - R_{i\alpha}^*)} \quad (28)$$

Equation (28) also follows directly from Equation (22) if F may be assumed constant (i.e., if $F_\alpha \approx F_\beta \approx \tilde{F}$). This will be identically true in the limit as $\dot{m}_\alpha \rightarrow \dot{m}_\beta$ as is shown by Equation (26).

Equation (28) may now be given in terms of ϕ . From Equations (9) and (13),

$$\tilde{F} = \frac{(\phi_\beta - \phi_\alpha)}{(\phi_\beta^* - \phi_\alpha^*)} \quad (29)$$

Theoretically, F_α could be obtained by a limiting process:

$$F_\alpha = \lim_{\dot{m}_\beta \rightarrow \dot{m}_\alpha} \left[\frac{\phi_\beta - \phi_\alpha}{\phi_\beta^* - \phi_\alpha^*} \right] \quad (30)$$

However, in the limit, the differences become small so that the uncertainties in this computation would become large.

Finally, from Equations (24) and (29) and assuming $F_\alpha \approx \tilde{F}$, $R_{i\alpha}$ may be given by

$$R_{i\alpha} = F_\alpha R_{i\alpha}^* \quad (31)$$

$$\approx R_p \left(\frac{\phi_\beta - \phi_\alpha}{\Gamma \cdot 8 - 1} \right) \quad (32)$$

If F varies slowly with $\dot{m}$ and if the range of $\dot{m}$ is small (i.e., Γ is close to 1.0), this result should be reasonably accurate. However, if Γ is too close

to 1.0, the uncertainty in the computation becomes large. The significance of these considerations is illustrated in example calculations presented in a subsequent section.

3.4 EVALUATION OF THE ROUGHENING ENHANCEMENT PARAMETER F

For turbulent flow in smooth tubes, the heat transfer coefficient may be given approximately in terms of the friction factor by use of the Colburn analogy:⁽⁵⁾

$$\bar{S}\psi^* \text{Pr}^{2/3} = \left(\frac{\overline{\text{Nu}}^*}{\text{Re}_d^* \text{Pr}} \right) \text{Pr}^{2/3} \quad (33)$$

$$= \frac{f^*}{8} \quad (34)$$

where f^* may be given for $10^4 < \text{Re}_d^* < 10^5$ by the Blasius equation⁽⁵⁾

$$f^* = 0.184 \left(\text{Re}_d \right)^{-0.2} \quad (35)$$

Thus, the Colburn analogy for $\text{Pr} = 1$ becomes

$$\frac{\overline{\text{Nu}}^*}{\text{Re}_d^*} = \frac{f^*}{8} \quad (36)$$

$$= 0.023 \left(\text{Re}_d^* \right)^{-0.2} \quad (37)$$

For turbulent flow in rough pipes, f is a function of both Re_d and the relative roughness e/d as given by the conventional Moody diagram⁽⁵⁾ illustrated in Figure 6. As a first-order approximation, it is adequate to assume that

FIGURE 6. Friction Factors for Commercial Piping

heat transfer in roughened tubes is given by Equation (37) with f determined from the Moody diagram. If this is true, the effectiveness of roughening for enhancement of heat transfer will be 1.0; i.e.,

$$\eta = \frac{Nu/Nu^*}{f/f^*} \approx 1.0 \quad \left\{ \begin{array}{l} \text{Colburn} \\ \text{Analogy} \end{array} \right. \quad (38)$$

For water at modest values of Re_d and e/d , this result overpredicts η by as much as a factor of two. Thus, a more generalized treatment is normally required.

Detailed experiments on the effects of roughening on heat transfer in tubes⁽⁶⁾ have shown that η can be given as a function of the dynamic relative roughness

$$k^+ = \frac{e}{d} Re_d \sqrt{\frac{f}{2}} \quad (39)$$

such that η is given by

$$\eta(R^+, Pr) = \frac{Nu/Nu^*}{f/f^*} \quad (40)$$

where f is determined from the Moody diagram at the appropriate Re_d and e/d . The empirical function η determined from experiments⁽⁶⁾ is shown in Figure 7. For $Pr \approx 1$ it can be seen that the Colburn analogy is good at low k^+ but decreases in accuracy at larger values of k^+ .

The results shown in Figures 6 and 7 have been used in this study to estimate the parameter F . Note that F_α may be given by

$$F_\alpha = \frac{Nu_\alpha^*}{Nu_\alpha} = \frac{f_\alpha^*}{\eta f_\alpha} \quad (41)$$

FIGURE 7. Effectiveness η for Turbulent Heat Transfer in Tubes

This result was used to estimate F_α and to check the assumption that F_α may be treated as a constant. These results are given in the example calculations in Section 4.1. For the conditions used there, it was found that $F_\alpha \approx 0.65$, which was constant over the range $5 < V < 9$ ft/sec to less than 5%. Thus, the assumption that F is constant appears to be adequate for these conditions.

3.5 CALCULATION OF THE SCALE RESISTANCE R_s'

Finally, we may now solve for the apparent resistance of the scale. From Equations (8), (10), and (24) we obtain

$$R_s' = R_{f\alpha} + R_{i\alpha}^* (1 - F_\alpha) \quad (42)$$

where $R_{f\alpha}$, $R_{i\alpha}^*$ and $F_\alpha \approx \tilde{F}$ are computed from the experimental data using Equations (9), (13), and (29), respectively. Note that R_s' contains changes in the contact resistance (if any) relative to the unscaled condition.

The results of the analysis in this section are summarized in Table 2. The use of these equations for computing the scale resistance from data obtained with the SRM is illustrated in Section 4. First, however, a summary of an uncertainty analysis will be provided, for use in calculating the expected uncertainty in computations derived from the experiments.

TABLE 2. Summary of Equations for Experimentally Determined Resistance Parameters

<u>Resistance Element</u>	<u>Resistance Equation</u>
Inside Convective Film Resistance (Clean)	$R_{i\alpha}^* = R_p \frac{(\phi_\beta^* - \phi_\alpha^*)}{(\Gamma^{.8} - 1)}$
Roughening Effectiveness	$\tilde{F} = \frac{(\phi_\beta - \phi_\alpha)}{(\phi_\beta^* - \phi_\alpha^*)}$
Inside Convective Film Resistance (Scaled)	$R_{i\alpha} = R_{i\alpha}^* F_\alpha$ $\approx R_p \frac{(\phi_\beta - \phi_\alpha)}{(\Gamma^{.8} - 1)}$
Total Effective Fouling Resistance	$R_{f\alpha} = R_p (\phi_\alpha - \phi_\alpha^*)$
Apparent Scale Resistance	$R'_{s\alpha} = R_{f\alpha} + R_{i\alpha}^* (1 - F_\alpha)$
Contact Resistance (Clean)	$R_c^* = R_p \phi^* - R_{i\alpha}^* - R_t$

3.6 SUMMARY OF THE UNCERTAINTY ANALYSIS

An estimate of the expected uncertainty in the computed quantities derived from measurements in the SRM may be computed by one of several accepted techniques.⁽⁷⁾ The method used here may be summarized as follows.

For this analysis, a computed quantity Y will be assumed to be derived from a sum (or difference) of a finite number of terms X_i in the form

$$Y = \sum_{i=1}^n X_i(z_j) \quad (43)$$

where the functions X_i are assumed to be dependent on a finite set of primary variables z_j . The uncertainty in Y may be given in terms of the uncertainties in the individual elements of the sum by

$$(\Delta Y)^2 = \sum_{i=1}^n (\Delta X_i)^2 \quad (44)$$

The uncertainty in each of the elements of the above sum $(\Delta X_i)^2$ may, in turn, be computed as

$$(\Delta X_i)^2 = \sum_{j=1}^m \left(\frac{\partial X_i}{\partial z_j} \right)^2 (\Delta z_j)^2 \quad (45)$$

where Δz_j are the estimated uncertainties in the primary variables. Thus, the uncertainty in Y may be given by

$$(\Delta Y)^2 = \sum_{i=1}^n \sum_{j=1}^m \left(\frac{\partial X_i}{\partial z_j} \right)^2 (\Delta z_j)^2 \quad (46)$$

There are various alternative but equivalent means for performing the computations in Equation (46). The approach used here will be demonstrated by computation of the uncertainty in the calculated tube wall resistance R_t .

From Table 1, R_t may be given by

$$R_t = \frac{\ln|r_2|}{2\pi R_t} - \frac{\ln|r_1|}{2\pi R_t} \quad (47)$$

Thus, from Equation (45), ΔR_t^2 may be given by

$$(\Delta R_t)^2 = \left(\frac{1}{2\pi R_t}\right)^2 \left[\left(\frac{\Delta r_2}{r_2}\right)^2 + \left(\frac{\Delta r_1}{r_1}\right)^2 \right] \quad (48)$$

Assuming $\Delta r_1 = \Delta r_2 = \Delta r$ and dividing by R_t^2 gives

$$\left(\frac{\Delta R_t}{R_t}\right)^2 = \left[\frac{1 + \left(\frac{r_2}{r_1}\right)^2}{\left(\ln \left|\frac{r_2}{r_1}\right|\right)^2} \right] \left(\frac{\Delta r_2}{r_2}\right)^2 \quad (49)$$

In this and all other results, the uncertainties in physical properties are neglected.

Similar computations were performed for the other variables and the results are summarized in Table 3. Where appropriate, each of the uncertainties is given as a relative uncertainty. In the case of the scale resistance, the uncertainty is divided by the fouling resistance $R_{f\alpha}$. The uncertainty in contact resistance R_c is given only as a magnitude. The term a^2 in the equation for $(\Delta F_\alpha)^2$ is an estimate of the difference between the actual value of F_α and the computed value $\tilde{F}$, which is subsequently used for F_α .

TABLE 3. Summary of Results of the Uncertainty Analysis

Resistance Parameter	Uncertainty Expression
Tube Wall Resistance	$\left(\frac{\Delta R_t}{R_t}\right)^2 = \left[\frac{1 + \left(\frac{r_2}{r_1}\right)^2}{\left(\ln \left \frac{r_2}{r_1} \right \right)^2} \right] \left(\frac{\Delta r_2}{r_2}\right)^2$
Probe Resistance	$\left(\frac{\Delta R_p}{R_p}\right)^2 = \left[\frac{1 + \left(\frac{r_4}{r_3}\right)^2}{\left(\ln \left \frac{r_4}{r_3} \right \right)^2} \right] \left(\frac{\Delta r_4}{r_4}\right)^2$
Diff. Temp. Ratios (ϕ_α , ϕ_α^* , ϕ_β or ϕ_β^*)	$(\Delta \phi)^2 = \left[1 + \phi^2 \right] \left(\frac{\Delta \phi}{\phi} \right)^2$
Velocity Ratio	$\left(\frac{\Delta U}{U}\right)^2 = (1 + r^2) \left(\frac{\Delta U}{U} \right)^2$
Roughening Factor	$\left(\frac{\Delta F}{F}\right)^2 = \left\{ \frac{(\Delta \phi_\beta^*)^2 + (\Delta \phi_\alpha^*)^2 + \frac{1}{F^2} [(\Delta \phi_\beta)^2 + (\Delta \phi_\alpha)^2]}{(\phi_\beta^* - \phi_\alpha^*)^2} \right\} + a^2$
Fouling Resistance	$\left(\frac{\Delta R_{f\alpha}}{R_{f\alpha}}\right)^2 = \left(\frac{\Delta R_p}{R_p}\right)^2 + \left[\frac{(\Delta \phi_\alpha)^2 + (\Delta \phi_\alpha^*)^2}{(\phi_\alpha - \phi_\alpha^*)^2} \right]$
Inside Film Resistance (Clean)	$\left(\frac{\Delta R_{i\alpha}^*}{R_{i\alpha}^*}\right)^2 = \left(\frac{\Delta R_p}{R_p}\right)^2 + \left[\frac{(\Delta \phi_\alpha^*)^2 + (\Delta \phi_\beta^*)^2}{(\phi_\beta^* - \phi_\alpha^*)^2} \right] + \left[\frac{.8}{1 - \left(\frac{1}{F}\right) \cdot .8} \right]^2 \left(\frac{\Delta F}{F}\right)^2$
Inside Film Resistance (Fouled)	$\left(\frac{\Delta R_{i\alpha}}{R_{i\alpha}}\right)^2 = \left(\frac{\Delta R_{i\alpha}^*}{R_{i\alpha}^*}\right)^2 + \left(\frac{\Delta F}{F}\right)^2$
Scale Resistance	$\left(\frac{\Delta R_s}{R_{f\alpha}}\right)^2 = \left(\frac{\Delta R_{f\alpha}}{R_{f\alpha}}\right)^2 + \left(\frac{R_{i\alpha}^*}{R_{f\alpha}}\right)^2 \left[(1 - F_\alpha)^2 \left(\frac{\Delta R_{i\alpha}^*}{R_{i\alpha}^*}\right)^2 + \Delta F_\alpha^2 \right]$
Contact Resistance	$(\Delta R_c)^2 = (\phi_\alpha^*)^2 (\Delta R_p)^2 + R_p^2 (\Delta \phi_\alpha^*)^2 + (\Delta R_{i\alpha}^*)^2 + (\Delta R_t)^2$

4.0 CALCULATIONS OF SYSTEM PERFORMANCE AND ESTIMATED UNCERTAINTIES

Computations of temperature distributions and heat fluxes were made for the geometry shown in Figure 1 for representative values of physical properties and scaling conditions. The calculations were performed with HEATING5,⁽⁸⁾ a three-dimensional finite difference heat transfer code. The code allows the user to specify the geometry (r- θ -z or x-y-z coordinates), a material property map, and boundary conditions. Computations can be made for steady-state or transient conditions. In the current case, cylindrical coordinates were used and only steady-state computations were performed. The geometry, material map, and boundary conditions were set up to model the system illustrated in Figure 1. The relevant design and operational data are given in Table 4.

4.1 SCALING RATE METER PERFORMANCE ANALYSIS

The SRM design analyzed was based on a 1.0-in. OD tube with a 0.05-in. wall assumed to be carbon steel. The contact was assumed to be sealed with thermal grease with an effective thickness of 10^{-4} in. and conductivity of 0.5 (Btu/hr ft⁰F). The ballast block was assumed to be copper or stainless steel. Thermocouples were assumed to be set at $r = 0$ (center of tube), $r_3 = 0.500$ in. and $r_4 = 2.75$ in. The nominal fluid bulk velocity in the brine was 5 (ft/sec) for all cases.

Computations of ϕ were performed for values of fouling resistance given as (R_f/R_i^*) between 0 and 1.0. These results are shown in Figure 8. Computations of $(\phi_{\alpha}^* - \phi_{\beta}^*)$ versus Γ were performed for $0 < \Gamma < 2$. These results are shown in Figure 9. Both graphs were used in the subsequent analysis.

The results show that use of a copper block results in better sensitivity to scale. This is so because, for any given scale condition, the resistance of the scale represents a much larger fraction of the total when using the copper block. Thus, a given change in scale results in a larger temperature difference and thus better sensitivity. This result is illustrated in both Figure 9 and Figure 10.

TABLE 4. Summary of System Parameters and Estimated Uncertainties for Example Case

Parameter	Symbol	Units	Value	Absolute Uncertainty $\pm$ (abs)	Relative Uncertainty $\pm$ (%)	Comments
Probe outer radius	r_4	in.	2.750	0.005	0.18	Assumed accuracy to which the thermocouple junctions can be located or to which assumed dimensional tolerance of tube OD and ID
Probe inner radius	r_3	in.	0.500	0.005	1.0	
Tube outer radius	r_2	in.	0.500	0.001	0.20	
Tube inner radius	r_1	in.	0.450	0.001	0.22	
Probe temp. diff.	θ_{34}	$^{\circ}\text{F}$	10.0	0.25	2.5	Assumes thermopiles selected for uniformity and calibrated
Inside temp. diff.	θ_{03}	$^{\circ}\text{F}$	variable	0.25	--	
Nominal brine velocity	U_{α}	ft/sec	5.00	0.250	5.0	Assumed flowmeter accuracy property variations neglected
Reynolds number in tube	Re_{α}^*		1.88×10^5	9.4×10^{-3}	5.0	
Alternate brine velocity	U_{β}	ft/sec	9.00	0.450	5.0	Possible effect of scale on flowmeter not accounted for
Velocity ratio			0.56	0.032	5.7	
Roughness parameter	F_{α}		0.65	0.37	5.7	Estimated
DTR, (a) nominal, clean	ϕ_{α}^*		2.19	6.02×10^{-2}	2.7	Differential Temperature Ratios (DTRs) for clean and fouled tubes at nominal and alternate brine flow rates
DTR, (a) alternate, clean	ϕ_{β}^*		1.56	4.63×10^{-2}	3.0	
DTR, (a) nominal, fouled	ϕ_{α}		3.87	9.99×10^{-2}	2.6	
DTR, (a) alternate, fouled	ϕ_{β}		2.61	6.99×10^{-2}	2.7	
Scale thickness	δ_s	in.	3.99×10^{-3}	0.33×10^{-3}	8.3	Calculated using computed R's and $k_s = 0.5 [\text{Btu/ft hr}^{\circ}\text{F}]$ δ_c value assumed, $k_c \approx 0.5 [\text{Btu/ft hr}^{\circ}\text{F}]$
Contact thickness	δ_c	in.	1.0×10^{-4}	2.73×10^{-4}	273	

(a) DTR = Differential Temperature Ratio

FIGURE 8. Calculated Differential Temperature Ratios for Copper and Stainless Steel Blocks

FIGURE 9. Calculation of Scaling Rate Meter Response As a Function of Velocity Ratio

FIGURE 10. Computation of Scaling Rate Meter Response As a Function of Fouling Resistance

It is important to point out that the curves in Figures 8, 9 and 10 are similarity solutions. These curves do not depend on temperature level or overall temperature difference (i.e., heat flux). However, the expected uncertainty does depend on the temperature difference (or heat flux). In practice it will be desirable to maintain approximately the same heat flux as is obtained in the prototype to maintain similar mass transfer conditions. This is discussed in a previous section.

4.2 SENSITIVITY AND UNCERTAINTY ANALYSIS

To evaluate the system performance and expected experimental uncertainty, a calculation was performed for a selected operating condition. The calculations were done for a copper block in the geometry described above and specified in Table 4. For these computations, the probe temperature difference was arbitrarily taken as 10°F (probably representative of an expected operating condition). The resistance of the scale was assumed to be such that the fouling resistance was equal to that of the convective film in the clean tube, $R_{f\alpha}/R_{i\alpha}^* = 1.0$. This would correspond to an actual condition in a heat exchanger where overall performance degradation due to scale would be about 50%. The nominal brine velocity was assumed to be 5.0 ft/sec and the alternative velocity was taken as 9.0 ft/sec or $\Gamma = 0.556$. The value of F_{α} was estimated using $e/d = 0.01$ and Figures 6 and 7 as described in Section 3.4. The other input and computed parameters are summarized in Tables 4 and 5, including the expected experimental uncertainties.

The results in Tables 4 and 5 illustrate the primary sources of uncertainty that can be expected in the experiments. The measurement of flow rate is expected to be difficult and a major source of uncertainty. The measurements of differential temperature ratios are individually subject to modest uncertainty, but, in sum they are important because several ratios and differences are involved in many of the computations. From Table 5, it is found that the expected uncertainty in measurement of the fouling resistance $R_{f\alpha}$ is about $\pm 6.9\%$. The uncertainty in the scale resistance extracted from R_s'

TABLE 5. Summary of Thermal Resistance Values and Estimated Experimental Uncertainties for Example Case

Parameter	Symbol	Computed Value $\left(\frac{\text{Btu}}{\text{ft} \cdot \text{hr}^\circ\text{F}}\right)^{-1} \times 10^{-3}$	Absolute Uncertainty $\pm \left(\frac{\text{Btu}}{\text{ft} \cdot \text{hr}^\circ\text{F}}\right)^{-1} \times 10^{-3}$	Relative Uncertainty $\pm(\%)$	Comments
Tube wall resistance	R_t	9.671	0.0019	2.8	Calculated from known dimensions and conductivity.
Probe resistance	R_p	1.292	0.008	0.6	
Inside resistance, clean	$R_{i\alpha}^*$	2.092	0.153	7.3	An independent measure of $R_{i\alpha}^*$ and $R_{i\alpha}$ can be obtained by heat balance techniques.
Inside resistance, fouled	$R_{i\alpha}$	3.218	0.299	9.3	
Fouling resistance	$R_{f\alpha}$	2.092	0.144	6.9	Note that $R_{f\alpha}$ can actually be measured to better accuracy than $R_{i\alpha}^*$!
Scale resistance	R_s'	2.824	0.234	8.3	Equivalent to δ_s 0.004 in. if $k_s = 0.5[\text{Btu/hr ft}^\circ\text{F}]$
Contact resistance	R_c	0.0637	0.174	273	The limit of detectability for R_c is apparently about $0.20[\text{Btu/ft hr}^\circ\text{F}]^{-1}$.

was found to be about $\pm 8.3\%$. The thickness of scale (assuming $k_s \approx 0.5 \text{ Btu/ft hr}^\circ\text{F}$) was computed to be only 4×10^{-3} in. for the assumed scale resistance. However, the uncertainty in this value should probably be higher because the change in contact resistance was neglected. An estimated uncertainty of $\pm 10\%$ in detecting the true resistance of the scale is probably reasonable. For smaller amounts of scale, the relative uncertainty will go up; for larger amounts it will go down.

5.0 DISCUSSION

The overall performance characteristics of the SRM have been dealt with in the analysis. However, a number of design features impact its usefulness in ways that are not immediately apparent. It is important to point out some of the unique characteristics, advantages, and deficiencies of this concept as currently perceived so that a balanced evaluation of its potential can be obtained. The discussion provided here is meant to at least partially fulfill this objective. First, however, a brief summary will be given of the primary results and conclusions of the analysis.

5.1 CONCLUSIONS

The results of the analysis presented in this report are sufficiently encouraging to conclude that an SRM of the type described here could probably be useful for many geothermal applications. For single-phase flow in the case where fouling is assumed to result in an approximately 50% reduction in heat transfer effectiveness, the calculations indicate that the scale resistance could be detected to about $\pm 10\%$ accuracy. Because very little scale is required for a 50% reduction in effectiveness, this is a meaningful result. For larger amounts of scale, the uncertainty would be even smaller. For very small amounts of scale, the differencing technique would result in large uncertainties. However, because small amounts of scale often result in small problems (if any), this lack of "low end" sensitivity should not be a major problem in most applications.

One potentially important feature of the proposed SRM is that it does not interfere with the operation of the prototype system. Measurement of the scaling rate could be made indirectly in essentially "real time" from the thermal decay curve. In addition, the actual scale quantity, average deposition rate, distribution, composition, and structure could be determined at chosen time intervals by disassembling and examining the SRM. To do so, the experiment would have to be interrupted only long enough to remove the tube and replace it with a new one. The redundancy provided by the subsequent

detailed tests (by sectioning, weighing, microscopic examination, etc.) may in time "prove out" the technique to where only the thermal decay measurements would be required.

The SRM could find extensive use in various maintenance operations. Potential cleaning solutions or scale inhibitors could easily be tested with the SRM in place. Alternatively, a scaled tube could be subjected to various cleaning solutions while separated from the prototype without endangering or interfering with prototype system operation. If SRMs were used at several locations in the system, the location of most severe scaling could be pinpointed. Acid injection for scale removal or inhibition could then be localized and the most severe corrosion effects might thus be restricted to the treated areas only. Other maintenance functions might also arise after SRMs have been used for a while.

The construction of the SRM in two or more blocks that are clamped to the tube to be tested has several advantages, some of which are alluded to in the above discussion. An alternative technique would be to construct the entire SRM from a single piece of the tube material of interest. However, this would make examination of internal scale distribution much more difficult than would be the case where only the tube would have to be sectioned. Furthermore, the higher sensitivity to scale obtained with the copper block would be lost.

To study different materials, the entire system, including thermocouples, would have to be reproduced using the appropriate material. Some materials of interest as compared to copper would be too expensive, difficult to machine, and otherwise poorly suited for the SRM. By using demountable blocks on a separate tube, the expense of materials, machining, and thermocouple installation would be incurred only once. Because the same blocks could be used repeatedly, the system characteristics and response would remain constant, thus giving better repeatability in subsequent experiments.

The proposed SRM requires that fluid be withdrawn from the system being tested. In the case of a heat exchanger, this is relatively straightforward. However, the fluid line from the extraction point to the SRM should be as short as possible and well-insulated, to minimize scale deposition in the

lines. Scale deposited in the lines could subsequently be collected, weighed, and accounted for, but it would be preferable to minimize the relative amount of scale collected in this manner.

If brine is to be collected from a two-phase stream, some means for separating phases would be required so that only the liquid phase would be passed through the SRM. The system would then function in the same way as for the single-phase application. In many cases it may be sufficient to examine the scaling propensity of just the brine.

If measurements of scaling due to flow of an actual two-phase mixture are required, the problem becomes much more complex, primarily because another variable, the steam quality, must be accounted for. In this case all measurements of both scaled and unscaled operation would have to be performed with quality as an additional measured parameter. This would normally be a very difficult set of measurements to obtain, even in a "clean" system. The detection of scale by the technique described here would require matching all of the flow conditions in the scaled condition to the clean calibration conditions (including the same quality) and differencing, as described previously. This would be an extremely difficult (if not impossible) task under most practical conditions. Thus, direct two-phase applications of the SRM are not foreseen at this time.

The biggest potential problem foreseen in development and use of the SRM is related to the contact resistance between the blocks and the tube. The analysis showed that the magnitude of the contact resistance is essentially irrelevant to the operation of the system. However, changes in the contact resistance are indistinguishable from changes in scale resistance. Thus, it is important that the system be designed and assembled such that the contact resistance would remain constant. By using a suitable thermal grease and by careful attention to proper application of the clamping bands, it may be possible to obtain a stable contact. Alternatively, it might be possible to furnace-solder the tube to the blocks, but this would make assembly and disassembly difficult.

There is a potential solution to the problem with contact resistance. A thermocouple could be mounted in the tube wall below the tube/block contact. The temperature difference ($T_0 - T_3$) in the ratio ϕ could then be replaced with ($T_0 - T_2'$) where T_2' would be the temperature in the tube wall at r_2' , the location of the thermocouple junction. This would require a thicker tube wall, and assembly/disassembly would be much more difficult. The analysis would be essentially unchanged, and the performance would be essentially identical to that described here.

5.2 RECOMMENDATIONS

This analysis indicates that the proposed concept has potential for geothermal systems applications. It is recommended that a prototype SRM be designed, built, and tested in the laboratory and then in the field to establish the practicality of this concept for field applications.

Before proceeding to a final design, more detailed analyses are also required. The present analysis was for steady state; transient performance analyses should also be performed to study the system response to transients that could be expected in the field. No optimization was provided here, only a comparison of performance for two block materials--copper and stainless steel. Some degree of system optimization is needed before the detailed design phase.

The potential problem with contact resistance should be studied to see what effects this could have on performance. The use of a solder contact might be given serious consideration. Alternatively, the use of a thermocouple in the tube wall may have to be considered.

Finally, no means for extending this concept to flowing two-phase conditions have been identified in this work. Some means for altering the design or data analysis techniques might be found to extend this technique to the important area of flashing flow simulation.

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