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Reliability Testing of Active SDHW Components

Part II: Results of Collector Scaling Tests and the Effect on Thermal Performance from Scale Build-Up

Carl E. Bingham
Robert B. Farrington

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A Division of Midwest Research Institute

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MASTER

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PREFACE

Building space conditioning and water heating account for more than one-third of the nation's total energy consumption. Because solar energy can be efficiently captured at the low to moderate temperatures required for space conditioning and water heating, there is a good match among the resource, technology, and energy demand. In support of the Federal Government's goal to encourage the provision, both today and over the long term, of adequate, reliable, and reasonably priced energy supplies, DOE's Active Heating and Cooling (AHAC) Program supports research to develop the technology base that will allow the private sector to produce competitive active solar products and services.

The AHAC program consists of research on systems, components, and materials for solar cooling, heating, and domestic water applications. The technologies that are being pursued include heating, closed- and open-cycle absorption cooling, and liquid and solid desiccant cooling. The systems research associated with the AHAC program consists of analysis, experimental testing, and reliability testing and evaluation. The reliability research subelement is composed of identifying the causes and frequency of AHAC systems reliability problems and recommending appropriate research to improve the overall reliability of AHAC systems. Specific activities include laboratory testing of component reliability, outdoor exposure testing of materials and components, development of test standards for critical components, development of analysis techniques to estimate the effects of reliability on system performance and delivered energy cost, and evaluation of the performance of state-of-the-art AHAC systems. This report supports the AHAC reliability program by determining experimentally the degree of scale accumulation and analytically the effect of scaling on direct systems.

This report is one of three completed under the Component Reliability Program under the leadership of Charles Kutscher. The other reports are: Part 1: Test Results of Sensors Used in Control Systems, SERI/TR-253-2602, and Part 3: Development of a Fault Detection System, SERI/TR-253-2605. The U.S. Department of Energy, Office of Solar Heat Technology, provided the funding for this effort. This report was reviewed by Mary Linskens and Charles

Kutscher (SERI), Stanley W. Moore (Los Alamos National Laboratory), and Edward R. Durlak (the Naval Civil Engineering Laboratory).

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SUMMARY

The objective of this work was to determine how much scale, caused by repeated filling and draining, accumulates in a flat-plate collector.

Laboratory testing of solar domestic hot water system components in FY 1983 showed that a significant amount of scale accumulated on draindown (drainout) valves, air vents, vacuum breakers, check valves subject to periodic draining on one side (such as when used as an isolation valve), and tempering valves. In FY 1984, we tested a flat-plate collector to measure the degree of scale accumulation caused by evaporation of water.

Testing over a period of one year and 9733 cycles caused a 7% decrease in collector volume because of scale, which is equivalent to uniform scaling of 0.25 mm. A 1-mm scaling thickness would decrease the heat removal factor by 6% and increase the absorber plate temperature and overall heat loss factor U_L by 5°C and 2%, respectively. This would result in a 13% reduction in the amount of energy collected. Homeowners in geographical areas where the water has a high potential for scaling should not use direct solar energy systems that use conventional flat-plate collectors unless they treat the water before it enters the system.

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SECTION 1.0

INTRODUCTION

Farrington's (1984) tests on components for active solar energy systems using water as the transport medium reveal that a significant amount of scale (such as calcium carbonate) accumulated in air vents, vacuum breakers, check valves, draindown (drainout) valves, and tempering valves. Scale forms in pipes for one of two reasons. First, because the solubility of carbonates in water decreases with increasing temperature, carbonates will precipitate out of water in high temperatures, such as found in solar collectors. This could cause scale in tempering valves where the hot port serves as a heat source for the cold port. Argonne National Laboratory (1981) and Vitro Laboratories (1981) briefly reviewed scaling by precipitation, and Argonne (1979) discussed the prediction of calcium carbonate scaling in solar energy systems.

The second reason that scale forms is that minerals are deposited on the surface when water evaporates. As the water evaporates, the concentration of the minerals in the remaining water increases, eventually exceeding the saturation point in water, and the minerals precipitate out of the solution and onto nearby surfaces. This is the probable reason for scale accumulation in the other components mentioned.

Scale accumulation is a potential problem in direct solar energy systems that use flat-plate collectors primarily because of reduced heat transfer rates resulting in a reduction in system performance.

This report discusses the construction of a scaling loop and the results of repeatedly filling and draining the loop. An analytical model of scaling in solar collectors is then discussed along with the potential effect of scaling on their thermal performance. Finally, conclusions and recommendations from the experimental and analytical results are presented.

SECTION 2.0

TESTING

The best method to determine how scale affects collector performance is to have a certified collector testing facility measure performance before and after scale buildup. However, shipping the collector after the scaling test would probably dislodge much of the scale. Also, the collector would have to accumulate a large amount of scale before much confidence could be put into the results. The change in efficiency caused by the scale would have to be larger than the uncertainty of the measurement process. Therefore, we measured the degree of scaling by the change in volume of the collector (rather than change in collector performance) and later by dismantling the absorber plate.

2.1 PROCEDURE

We designed a test to determine the amount of scale accumulation in a flat-plate collector resulting from repeated filling and draining, such as in a draindown (drainout) system. The laboratory setup is shown in Figure 2-1. The tests were run with Golden, Colorado, tap water. We measured the water quality periodically and recorded the temperature, flow, and cycles regularly. Using a titration process with a measurement uncertainty of ±5%, we determined the calcium hardness and total alkalinity.

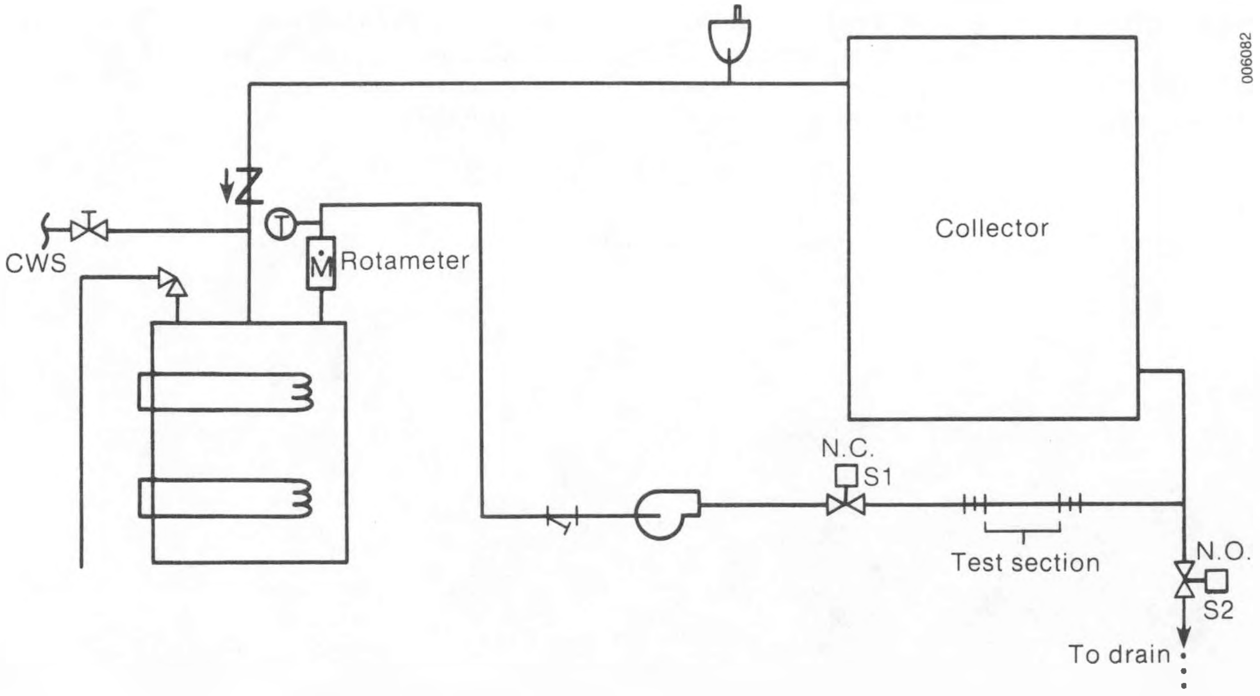

Figure 2-1. Laboratory Test Setup

We also measured the conductivity (±5%) and the pH (±2%) of the water. These measurements were necessary to determine the Langelier Saturation Index (see the appendix).

The collector used for this test was a single-glazed 3 m^2 (32 ft^2) unit with a copper fin and tube absorber. A list of significant events is given in Table 2-1. The test loop initially circulated water at 71°C (160°F) through the collectors at 3.8 L/m (1 gpm) for 15 min and then drained for 15 min. We detected very little scale accumulation after 874 cycles, so we changed the circulation time to 5 min and draining to 25 min to increase the scaling rate. After 3716 cycles and still very little scale deposits, we increased the storage tank temperature to 93°C (200°F) to further speed up the rate of scaling.

2.2 RESULTS

The change in volume of a flat-plate collector caused by uniform scaling is shown in Figure 2-2. Uniform scaling along the pipe walls of only 10% of the pipe radius will reduce the collector volume by 19% or 519 mL of a 2.73-L collector. However, if the scale thickness is 20% of the pipe radius, the collector volume will decrease 36% (which is simply because the volume is proportional to the square of the radius).

Table 2-2 is a record of the measurements of the collector volume. Notice the very small standard deviation of the measurements. The standard deviations are 0.27% of the mean for the first set of measurements, 0.40% of the mean for the second set of measurements, 0.73% of the mean for the third set of measurements, and 1.3% of the mean for the fourth set of measurements. The random error of the measurements is therefore very small. Since we were concerned with the change in volume and not the absolute volume of the collector, the systematic error of the measurement from inaccuracies in the

Table 2-1. Significant Scaling Loop Events

Date	Event	Cycles Temperature (°C)	Mean Tank Volume (mL)	Collector
4/26/84	Test began	0	71	2729.4
7/2/84	Moved experiment	864	--	--
8/16/84	Reduced circulation time to 5 min	874	71	2695.6
11/21/84	Increased tank temperature to 93°C	3716	93	2650.6
4/12/85	Test completed	9733	93	2535.2

graduated cylinder were not important as long as we used the same measurement procedure and equipment. Periodic inspection of the removable pipe section did not show any significant accumulation. Overall, the collector volume decreased by about 7.1%, which is equivalent to uniform scaling of 0.25 mm. After completion of the test, the absorber was dismantled and inspected. Visual inspection showed a trace of scaling in the absorber tubes, although the sections inspected appeared to have less than 0.25 mm scale.

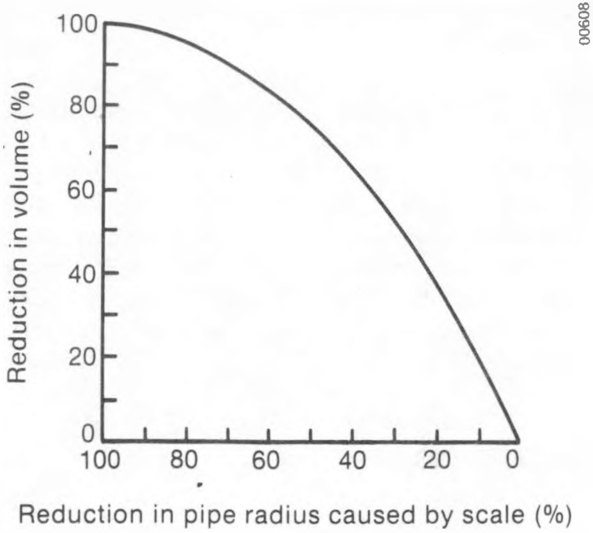

Figure 2-2. Change in Collector Volume Caused by Scale

The results of the water quality tests are shown in Table 2-3. In general, the water quality was fairly consistent. The Langelier Saturation Index (see the appendix), a qualitative measure of calcium carbonate saturation (when >0) or corrosion (when <0), was positive, which indicated a tendency to form scale from the precipitation of calcium carbonates. The Langelier Index does not predict the potential for scaling caused by evaporation, and it is very dependent on temperature; increasing the temperature from $10^{o}C$ to $80^{o}C$ increases the Langelier Saturation Index by about 1.2.

The Palin Index was calculated at 12.5 using the average measurements and $76^{o}C$, the highest temperature given for the Palin Index Factors in the Argonne report (1979). This value is at the high end of the scale-forming category, which is consistent with the results from the Langelier Saturation Index.

Table 2-2. Collector Volume Measurements

Date	Number of Cycles	Measurement	Volume (mL)	Change in Volume (mL)	Change in Volume (%)
4/26/84	0	1	2726		
		2	2721		
		3	2726		
4/27/84	0	4	2739		
		5	2735		
		Mean	2729.4	0	0
		Std. dev.	7.4		
8/16/84	874	1	2694		
		2	2710		
		3	2694		
		4	2680		
		5	2700		
		Mean	2695.6	33.8	1.2
		Std. dev.	10.9		
11/21/84	3716	1	2679		
		2	2662		
		3	2635		
		4	2635		
		5	2642		
		Mean	2650.6	78.8	2.9
		Std. dev.	19.4		
4/12/85	9733	1	2497		
		2	2531		
		3	2527		
		4	2568		
		5	2594		
		6	2517		
		7	2523		
		8	2567		
		9	2493		
		Mean	2535.2	194.2	7.1
		Std. dev.	34.2		

Table 2-3. Water Quality Test Results

Date	Calcium Hardness (g/gal $CaCO_3$)	Total Hardness (g/gal $CaCO_3$)	Methyl Orange Alkalinity (g/gal $CaCO_3$)	Conductivity (μmhos/cm)	pH_s	pH	Temperature (^oF)	Langelier Index
04/27/84	11	--	10	580	6.6	8.0	165	1.4
05/07/84	10	--	10	540	6.7	7.7	165	1.0
05/08/84	11	--	11	470	6.6	8.1	165	1.5
05/10/84	11	--	10	440	6.6	8.0	165	1.4
05/11/84	11	--	10	480	6.7	8.0	165	1.3
05/14/84	11	--	11	540	6.6	8.0	165	1.4
05/23/84	10	--	10	500	6.8	7.9	165	1.1
05/29/84	10	--	11	360	6.7	8.0	165	1.3
06/05/84	10	--	11	490	6.6	7.8	165	1.2
06/11/84	10	--	10	490	6.7	7.9	165	1.2
06/18/84	8	--	9	450	6.8	7.9	165	1.1
11/20/84	12	18	14	600	6.4	7.8	165	1.4
11/21/84	12	17	13	700	6.4	8.2	165	1.8
11/27/84	13	18	14	680	6.4	7.8	165	1.4
11/28/84	12	18	13	720	6.4	7.6	165	1.2
11/29/84	12	17	13	630	6.4	7.8	165	1.4
12/20/84	12	16	13	510	6.3	7.9	195	1.6
12/27/84	12	17	13	550	6.3	7.9	195	1.6
01/04/85	11	15	12	500	6.3	7.8	195	1.5
01/08/85	12	16	13	630	6.3	7.9	195	1.6
01/15/85	11	15	13	530	6.3	7.9	195	1.6
02/26/85	10	13	10	580	6.5	7.9	195	1.4
03/06/85	10	14	10	580	6.5	8.2	195	1.7
03/14/85	9	13	11	560	6.5	7.9	195	1.4
03/21/85	10	12	10	610	6.5	7.5	195	1.0
03/28/85	10	14	10	620	6.5	7.9	195	1.4
04/05/85	9	13	10	600	6.6	7.8	195	1.2
04/11/85	9	12	9	540	6.6	7.9	195	1.3
$\bar{x}$	10.68	15.18	11.21	553	65.2	7.89		1.37
Std. dev.	1.19	±2.13	±1.55	±82	±0.15	±0.15		±0.20
Std. dev. (% of mean)	11	±14	±14	±15	±2	±2		±15

Multiply g/gal by 17.12 to obtain mg/L.

SECTION 3.0

ANALYTICAL MODEL

Scaling affects the performance of flat-plate collectors in several ways. One is the insulating effect of scale, which causes a higher plate temperature and greater heat losses to the cooler ambient air. We can determine this insulating effect by incorporating a fouling factor in the heat removal factor and heat loss coefficient. Severe scaling reduces the cross-sectional area of the collector passageways, leading to higher pressure drops in the system that cause lower flow rates, higher operating temperatures, and greater heat losses.

Baumeister (1967) gives information on fouling factors for heat exchangers. However, since fouling or scaling is generally not uniform, either dimensionally or with time, only average factors are given. This is a problem for our analysis since we want to understand how the varying thicknesses of scale affect collector performance.

The easiest way to approach this analytically is to determine the effect of scale accumulation on the heat removal factor F_R. Duffie and Beckman (1974) discuss in detail the important performance parameters of flat-plate collectors, including the development of all the major quantities used here.

The heat removal factor is defined as

$$F_R = P_1 \left[1 - \exp\left(-F'/P_1\right)\right] \quad , \tag{3-1}$$

where

$$P_1 = \frac{\text{collector mass flow rate } (\dot{m}) \times \text{collector fluid specific heat } (C_p)}{\text{collector area } (A_c) \times \text{collector overall heat loss factor } (U_L)}$$

F' = collector efficiency factor.

The collector efficiency factor is defined as

$$F' = \frac{1/U_L}{W\left\{\dfrac{1}{U_L[D + (W - D)F]} + \dfrac{1}{C_b} + \dfrac{1}{\pi D_i h_i}\right\}} \quad , \tag{3-2}$$

where

U_L = collector overall heat loss factor

C_b = bond conductance between the tube and the fin

h_i = convective heat transfer coefficient between the collector fluid and the tube inside wall

D_i = tube inside diameter

D = tube outside diameter

W = distance between centerlines of tubes

F = fin efficiency.

The fin efficiency for straight fins with a rectangular cross section is given by

$$F = \frac{\tanh[m(W - D)/2]}{m(W - D)/2} , \qquad (3\text{-}3)$$

where

$m = (U_L/k\delta)^{1/2}$

k = conductivity of the fin material

δ = fin thickness.

The denominator in Eq. 3-2 is the heat transfer resistance between the collector fluid and the ambient air. It is this factor that is modified to include the resistance from scaling. Each term of the denominator represents a separate thermal resistance. The denominator can be expressed as

$$1/U_o = W(1/C_a + 1/C_b + 1/C_f) , \qquad (3\text{-}4)$$

where

$1/U_o$ = heat transfer resistance between the fluid and the ambient air

$1/C_a$ = resistance between ambient air and the plate above the tube $(1/U_L[D + (W - D)F])$

$1/C_b$ = resistance caused by the tube/plate bond $1/C_b$

$1/C_f$ = resistance caused by the convective heat transfer from the tube to the fluid $(1/\pi D_i h_i)$.

In our analysis we changed C_f to represent the conductive heat transfer between the fluid and the scale by reducing the interior diameter of the tube by the thickness of the scale. We also added an additional term to account for the thermal resistance caused by the scale itself. Our underlying assumption is that the scale is smooth and of uniform thickness. This additional term is

$$1/C_s = \frac{\ln[D_i/(D_i - 2t)]}{2\pi k_s} , \qquad (3\text{-}5)$$

where

$1/C_s$ = thermal resistance caused by the conductivity of scale

k_s = thermal conductivity of scale

t = thickness of scale.

The collector efficiency factor, including the scaling factor, is then

$$F' = \frac{1/U_L}{W[1/U_L[D + (W-D)F] + 1/C_b + \{\ln[D_i/(D_i-2t)]/2\pi k_s\} + 1/\pi(D_i-2t)h_i]} . \tag{3-6}$$

If the conductivity of the scale was known, then we could calculate the effect of scale accumulation on F_R. However, this assumes that all of the parameters except t are independent of the scale accumulation, which is not completely accurate. The collector overall heat loss coefficient is a function of the absorber plate temperature, which increases with scale buildup.

If we use the heat conduction equation for a multilayer cylinder (Chapman 1974),

$$q = \frac{2\pi L(T_1 - T_3)}{[\ln(r_2/r_1)]/k_s + [\ln(r_3/r_2)]/k_t} , \tag{3-7}$$

where

q = heat flow through cylinder (W)

L = length of cylinder (m)

T_1 = outer surface temperature, pipe (^oC)

T_3 = inner surface temperature, scale (^oC)

r_1 = outer radius of pipe (m)

r_2 = inner radius of pipe (m)

r_3 = inner radius of scale (m)

k_s = scale thermal conductivity (W/m ^oC)

k_t = tube thermal conductivity (W/m ^oC),

we can arrange the terms to determine the difference in temperature between the inner scale surface and the outer tube surface as a function of scale thickness ($r_2 - r_3$) as follows:

$$T_1 - T_3 = q\left\{\frac{[\ln(r_2/r_1)]/k_s + [\ln(r_3/r_2)]/k_t}{2\pi L}\right\} . \tag{3-8}$$

This analysis enables us to estimate the rise in plate temperature caused by the conductivity of the scale. From this rise in plate temperature we estimate the subsequent rise in U_L for a given case using the relationship between the absorber plate temperature and the top loss coefficient given in Duffie and Beckman (1974). The elevated U_L is used to calculate the new fin efficiency F, collector efficiency factor F', and the collector heat removal factor F_R.

SECTION 4.0

ANALYTICAL RESULTS

To put the analytical results in perspective we must first assess our assumptions. One assumption is that the scale is smooth and of uniform thickness. In reality, scale tends to build up locally and in varying thicknesses. Since it is difficult to predict the locations and local thicknesses of scaling we assume a smooth, uniform scaling for this analysis.

Another major assumption is that the increased pressure drop caused by scaling will not significantly lower the flow rate to a point where the elevated plate temperature (caused by the reduced flow rate) would affect the overall collector performance. The pressure drop across the collector is inversely proportional to the fifth power of the tube inner diameter (Crane Co. 1980). Reducing the inner diameter of the tubes by 2 mm to 5 mm increases the pressure drop fivefold. Note that if we reduce the flow rate in the collector significantly, the elevated plate temperature would reduce the collector heat removal factor F_R. However, our analysis did not include this effect.

Our analysis is based on a collector with the specifications listed in Table 4-1. The results presented here are primarily because of the increased resistance caused by the scaling, resulting in an increased plate temperature and higher heat loss.

If we take a case where we have a 1-m length of 9-mm (outside diameter) copper tube with a wall thickness of 1 mm, receiving 500 W/m^2, we can determine that the ΔT across the tube wall with no scale is less than 0.1°C. Assuming the scale consists of calcium carbonate ($CaCO_3$) with a thermal conductivity of

Table 4-1. Reference Collector Specifications

Flow rate $\dot{m}$	0.06 kg/s (1.0 gpm)
Aperture A	3.0 m^2(32.3 ft^2)
Back and edge heat loss coefficient U_{be}	1.5 W m^2 $^\circ$C (0.263 Btu/h ft^2 $^\circ$F)
Tube spacing W	10.7 cm (4.2 in.)
Tube inside diameter	7 mm (0.28 in.)
Tube thickness	1 mm (0.04 in.)
Bond conductance C_b	1000 W/m $^\circ$C (580 Btu/h ft $^\circ$F)
Fluid heat transfer coefficient h_i	300 W/m^2 $^\circ$C (52.8 Btu/h ft^2 $^\circ$F)
Fin thickness	0.5 mm (0.02 in.)
Plate emittance	0.10
Number of covers	1
Wind heat loss coefficient	5 W/m^2 $^\circ$C (0.88 Btu/h ft^2 $^\circ$F)

0.6 W/m^{o}C (Thermophysical Research Center 1970), we can determine the temperature drop across the tube wall and scale as a function of scale thickness. The results as portrayed in Figure 4-1 show that with severe scaling (a thickness of 2 mm) the ΔT across the tube and scale is about 12^{o}C. This increases the overall collector loss coefficient U_L.

If we assume an initial plate temperature of 60^{o}C and an ambient temperature of 10^{o}C, we can use the graphs in Duffie and Beckman (1974) to estimate the collector top loss coefficient U_t. Using the relationship

$$U_L = U_t + U_{be} , \tag{4-1}$$

where U_{be} is the collector back and edge loss coefficient, we may determine a new U_L to calculate the fin efficiency F using Eq. 3-3, the collector efficiency factor F' using Eq. 3-5, and the collector heat removal factor F_R using Eq. 3-1.

The results of this analysis are shown in Figure 4-2. The 0.25-mm and 1-mm scale in our reference collector should result in a 1% and 6% reduction in the collector efficiency factor F', respectively. Similar results for the collector heat removal factor F_R are shown in Figure 4-2.

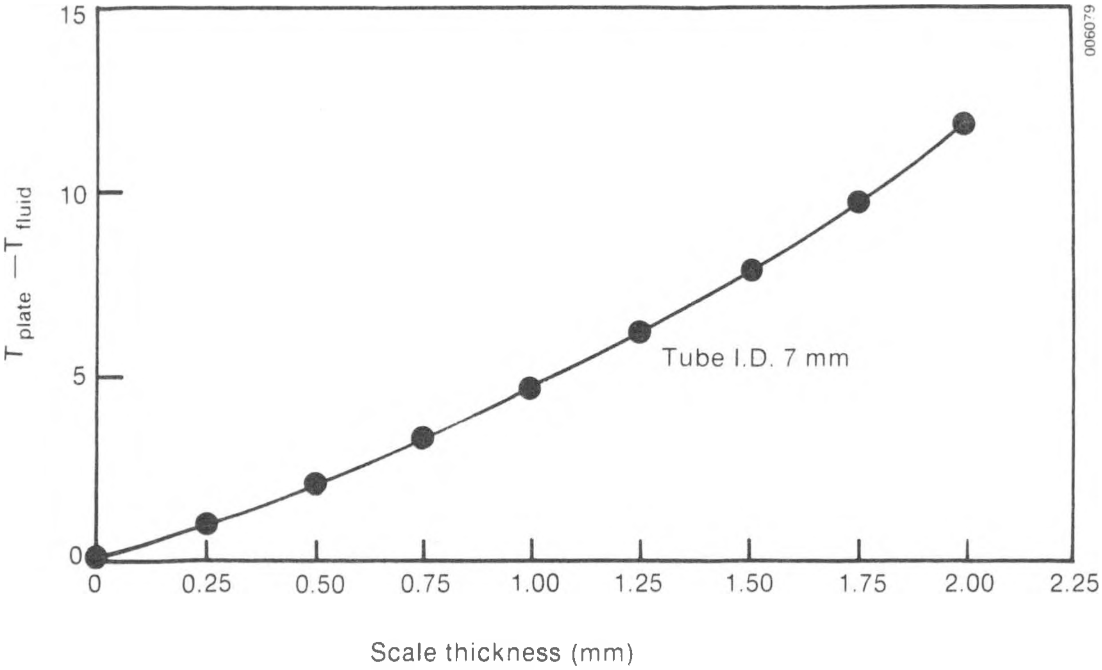

Figure 4-1. Scale Thickness versus Plate Temperature

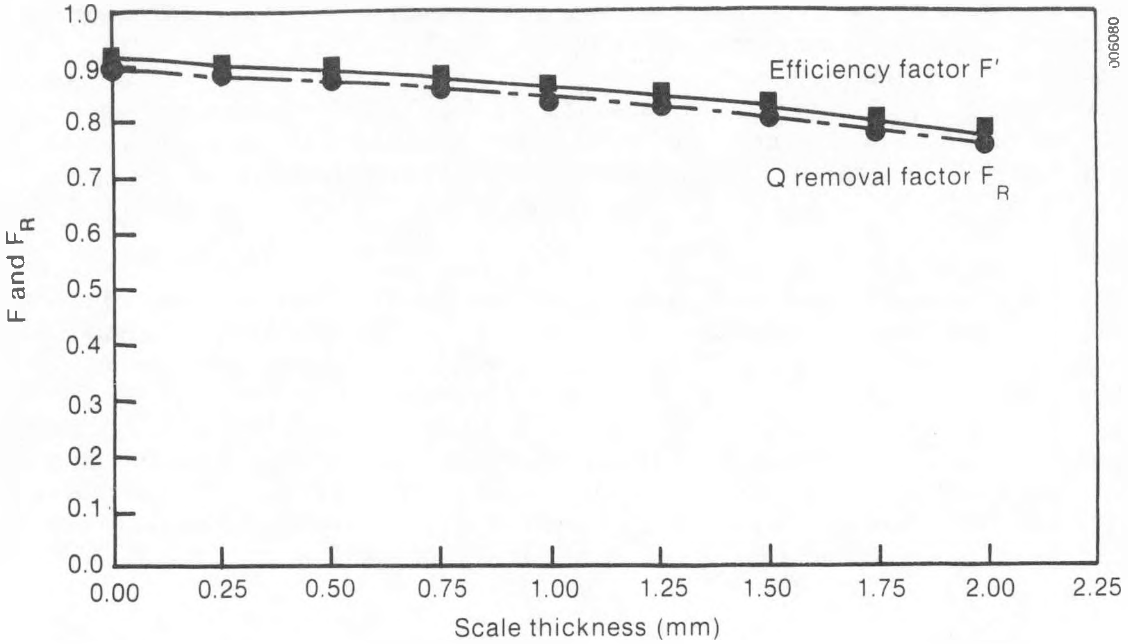

Figure 4-2. Scale Thickness versus Efficiency and Removal Factors

SECTION 5.0

CONCLUSIONS AND RECOMMENDATIONS

Our test results show some scale accumulation from repeated wetting and drying of the collector. However, scale buildup from evaporation does not appear to be a significant problem. We are now operating a collector loop to determine the accumulation of scale from precipitation when the collector is a heat source.

Our analytical results show that even scale accumulation as thin as 1 mm can significantly reduce system performance (by 13%). Clearly, users in geographical areas that have water with a high potential for scaling or a history of a scale buildup should consider using treated water in their solar systems or consider using indirect systems with heat exchangers easily accessible for clearing or replacement.

SECTION 6.0

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APPENDIX

LANGELIER SATURATION INDEX*

The Langelier Saturation Index (LI), a measure of a solution's ability to dissolve or deposit calcium carbonate, often is used as an indicator of the corrosiveness of water. The index is not related directly to corrosion but is related to the deposition of a calcium carbonate film or scale that can insulate pipes, boilers, and other components of a system from contact with water. When no protective scale is formed, water is considered to be aggressive and corrosion can occur. Highly corrosive water can cause system failures or result in health problems from dissolved lead and other heavy metals. On the other hand, an excess of scale can damage water systems, necessitating repair or replacement.

The Langelier Index is defined as the difference between actual pH (measured) and calculated pH_s (the pH at which water is saturated with calcium carbonate). The magnitude and sign of the LI value show a water's tendency to form or dissolve scale and thus inhibit or encourage corrosion.

Although information obtained from the LI is not quantitative, it can be useful in estimating water treatment requirements for low pressure boilers, cooling towers, and water treatment plants and in serving as a general indicator of the corrosiveness of water.

The index is a gauge of whether water will precipitate or dissolve calcium carbonate. If the pH_s is equal to the actual pH, the water is considered "balanced." This means that calcium carbonate will not be dissolved or precipitated. If the pH_s is less than the actual pH (the LI is a positive number), the water tends to deposit calcium carbonate and is scale-forming (nonaggressive). If the pH_s is greater than the actual pH (the LI is a negative number), the water is not saturated and will dissolve calcium carbonate (aggressive).

Remember, **the LI value is not a quantitative measure** of calcium carbonate saturation or corrosion.

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*Taken from Hach Analytical Procedure Publication 8073 "Langelier and Aggressive Indices."

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