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**NEW FLOW BOILING HEAT  
TRANSFER CORRELATION FOR  
CFC-114 AND C<sub>4</sub>F<sub>10</sub>**

by

A. J. Szady  
Engineering Technology Division, ORNL

Uranium Enrichment Organization  
Lockheed Martin Utility Services, Inc.

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## New Flow Boiling Heat Transfer Correlation for CFC-114 and C<sub>4</sub>F<sub>10</sub>

A. J. Szady

August 1995

Prepared for the  
LOCKHEED MARTIN UTILITY SERVICES, INC.  
Oak Ridge, Tennessee 37830  
for the

UNITED STATES ENRICHMENT CORPORATION

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## ABSTRACT

The flow boiling tests being conducted at Cudo Technologies, Ltd. in Lexington, Kentucky are a part of The GDP Coolant Replacement Project. The tests are to be done with two alternates,  $C_4F_{10}$  and  $C_4F_8$ , as well as CFC-114. So far, tests were conducted with CFC-114 and  $C_4F_{10}$ . The CFC-114 data by Cudo shows better heat transfer performance than that predicted by the codes used in the numerical model which were based on a superposition model. The data was applied to an asymptotic model developed by Steiner and Taborek. The new correlation developed seems to fit better with the Cudo data as well as the Paducah cell test data. The model will be further investigated when  $C_4F_8$  data is available.

## **PREFACE**

This report was originally prepared as a feature article for a quarterly progress report that was never issued. It is being published now to be sure the work is not lost and is available for use by others.

## New Flow Boiling Heat Transfer Correlation for CFC-114 and $C_4F_{10}$

The flow boiling heat transfer tests conducted at CUDO Technologies (CUDO), on CFC-114 and  $C_4F_{10}$  has provided the necessary data to establish a new correlation for these fluids. The correlation is used in the gas cooler computer models to predict cooling water requirements under a variety of operating conditions and with different CFC replacement candidates. The existing correlation was developed by Jallouk<sup>(1)</sup> using CFC-114 test data, and was based on a superposition model first introduced by Chen<sup>(2)</sup>.

The CFC-114 test data from CUDO consistently has shown better heat transfer performance than that reported by Jallouk; consequently, the Jallouk correlation under predicts the CUDO data by as much as 100 percent. The recent Paducah cell test data with CFC-114 and  $C_4F_{10}$  has also shown better performance than predicted by the gas cooler computer model when the Jallouk correlation is used. Since the introduction of the Chen superposition model in 1966 several new models have been introduced. Therefore it was felt that since we are starting with new test data we should also proceed with the best type of correlation currently available.

The type of model chosen is called the asymptotic model as proposed by Steiner and Taborek<sup>(3)</sup>, and recommended by Webb and Gupte<sup>(4)</sup> as the best type of model available today. Like the superposition model, the asymptotic model relies on combining a forced convection component with a pool boiling component. However, the asymptotic model uses a power relationship as given by equation 1 in Fig. 1. The model is called asymptotic because the flow boiling coefficient  $h_{fb}$  always approaches the larger of convective coefficient  $h_c$  and the pool boiling coefficient  $h_{bp}$ . The maximum addition occurs when the two components are equal. In order to use this approach one must have experimentally determined values for the two components or use those published by Steiner and Taborek (determined from a 13,000 point data base covering a variety of fluids). We chose to use the experimental approach, and only used the convective multiplier, which accounts for enhancement due to the liquid-vapor mixture, given in the paper.

The forced convection component  $h_{fc}$  was determined experimentally at CUDO by running subcooled liquid through the tube for both CFC-114 and  $C_4F_{10}$ , and then correlating that data with a Dittus-Boelter type equation. The results are shown in Figs. 2 and 3.

Both fluids correlated quite well with the same equation. This is exactly what one would expect for forced convection since the equation is in terms of dimensionless numbers. The nucleate pool boiling term  $h_{nb}$  was also determined at CUDO by running very low flow in the tube and only using heat flux data from the bottom two zones. The results for both fluids are plotted in Figs. 4 and 5 using the Rohsenow dimensionless coordinates. The line used by Jallouk in his correlation is also shown for reference. Here again both fluids correlated the same, with an intercept value of 0.003826. It should be noted that on this coordinated system, the lower the line the higher the pool boiling coefficient. Now with dimensionless expressions for the two components in hand, and employing equations 1 and 4 from Fig. 1, one can make predictions for the flow boiling coefficient. The fact that the predictive correlation is the same for both fluids does not mean that the flow boiling heat transfer coefficient is the same. The difference in the physical properties of the fluids will result in different heat transfer coefficients for the same temperature level and heat flux.



Figure 1. New Flow Boiling Heat Transfer Correlation

$$h_{fb} = [h_c^3 + h_{nb}^3]^{1/3} \quad (1)$$

(Steiner & Taborek)

where the convective boiling heat transfer coefficient is defined by:

$$h_c = h_{fc} F \quad (2)$$

$$h_{fc} = 0.028 Pr_l^{0.4} Re_l^{0.8} \frac{k_l}{D} \quad (3)$$

(experimentally determined at CUDO)

where

$$F = [(1-x)^{1.5} + 1.9(x)^{0.6} \left( \frac{\rho_l}{\rho_v} \right)^{0.35} ]^{1.1} \quad (4)$$

(Steiner & Taborek)

and

$$h_{nb} = 78,245 \left( \frac{cp_l}{Pr^{1.7}} \right)^{2.02} \left( \frac{1}{h_v} \right)^{1.02} \mu_l \left( \frac{[\rho_l - \rho_v]}{\sigma} \right)^{0.5} (\Delta T)^{1.02} \quad (5)$$

The nucleate boiling heat transfer coefficient is defined by:

(experimentally determined at CUDO)

$h_b$  = flow boiling heat transfer coefficient  
 $Pr$  = Prandtl number of liquid  
 $Re$  = Reynolds number of liquid  
 $k_l$  = liquid thermal conductivity  
 $D$  = tube inside diameter

$x$  = quality  
 $\rho_l$  = liquid density  
 $\rho_v$  = vapor density  
 $cp_l$  = liquid specific heat  
 $h_v$  = latent heat of vaporization  
 $\mu_l$  = liquid viscosity  
 $\sigma$  = surface tension  
 $\Delta T$  = difference between fluid and tube wall temperatures

Figure 2. Variation Of Nusselt number in forced flow field of  $C_4F_{10}$

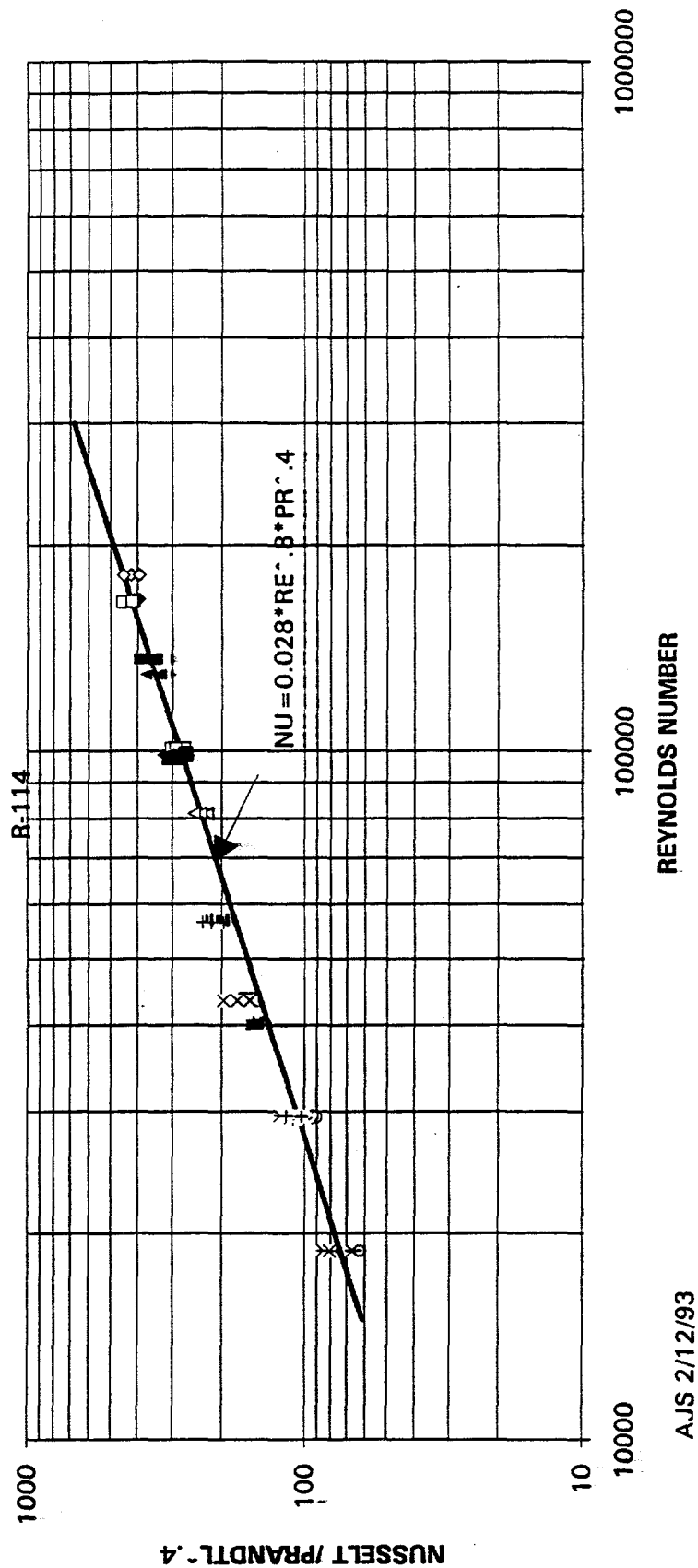
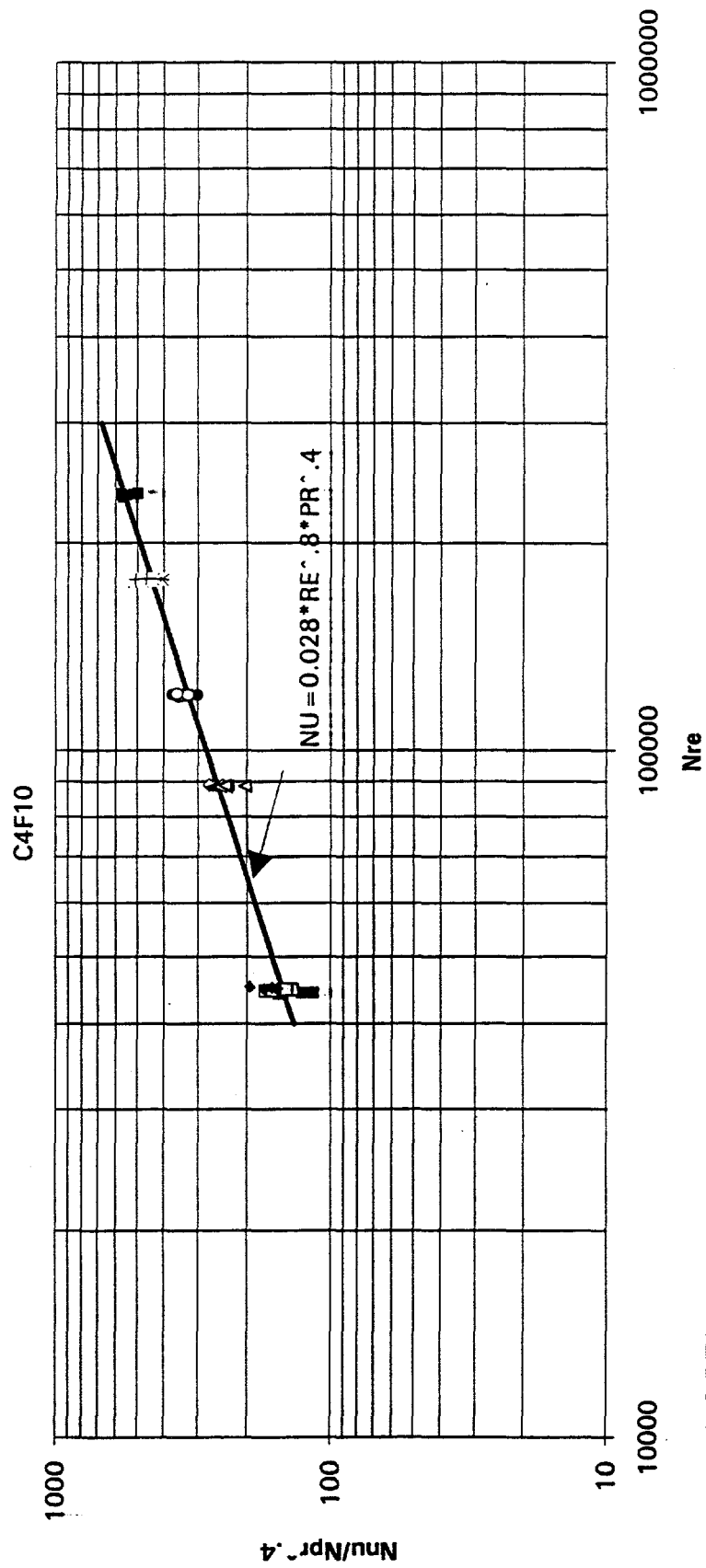


Figure 3. Variation of Nusselt number in forced flow field of C<sub>4</sub>F<sub>10</sub>



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Figure 4. Result of pool boiling test with CFC-114

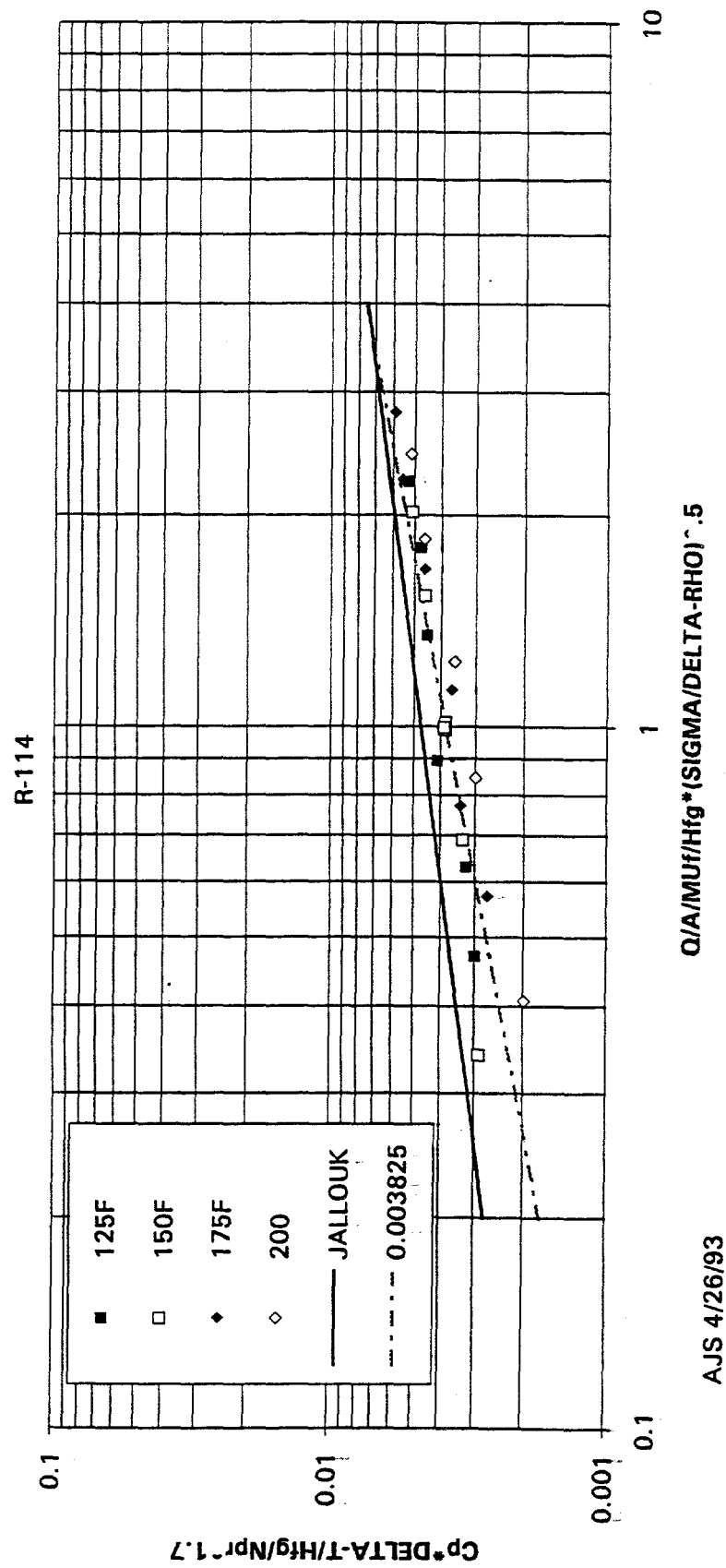
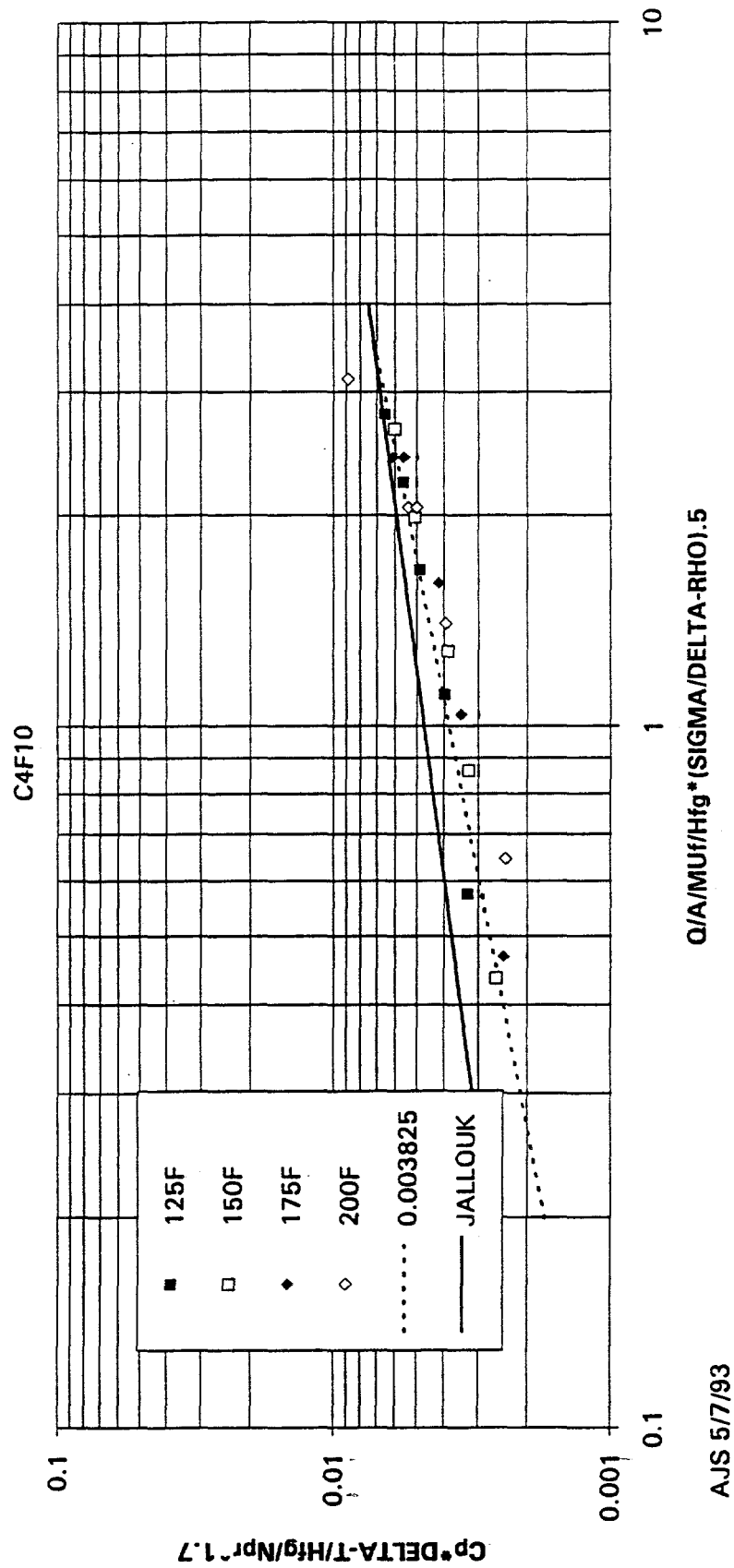


Figure 5. Result of pool boiling test with  $C_4F_{10}$



Figures 5 and 6 show the boiling data taken at CUDO for CFC-114 at 150°F and 200°F, for heat fluxes of 10,000, 15,000, 20,000, and 25,000 BTU/HR/FT<sup>2</sup>. An exact match would follow the solid line. Deviation lines of plus or minus 15 percent are shown for reference. This same information for C<sub>4</sub>F<sub>10</sub> is shown in Figs. 8 and 9. Here the heat fluxes range from 5,000 to 20,000 BTU/HR/FT<sup>2</sup>. For both fluids the flow rate was varied from 1 to 5 GPM. In Jallouk's correlation the data scatter was plus or minus 30 percent. The 150°F figure covers coolers at high horsepower (3000), and the upper temperature covers low horsepower. All the figures clearly show that the predicted coefficient is largely unaffected by changes in coolant flow rate and axial position (local quality) along the length of the tube. However, some of the horizontal spread shown in the curves must be attributed to experimental error.

It should be noted that the prediction correlation has not been adjusted based on the actual flow boiling test data from CUDO. Only the forced convection and in-tube pool boiling data have been used. However, there remains a question in the literature as to whether or not a suppression factor should be used with the pool boiling term in equation 1. We do have the data to back out such a suppression factor. The early indications are that some pool boiling suppression does indeed take place. We intend to further pursue that correction, and therefore the predictive correlation will better agree with the flow boiling test data. However, before doing so we must have a better understanding of the experimental variation expected down the length of the tube so that not all discrepancies are put into the suppression factor. The correlation analysis described above will be repeated when the C<sub>4</sub>F<sub>10</sub> testing begins at CUDO.

Figure 6. Comparison of heat transfer coefficients with CFC-114 at 200°F saturation temp

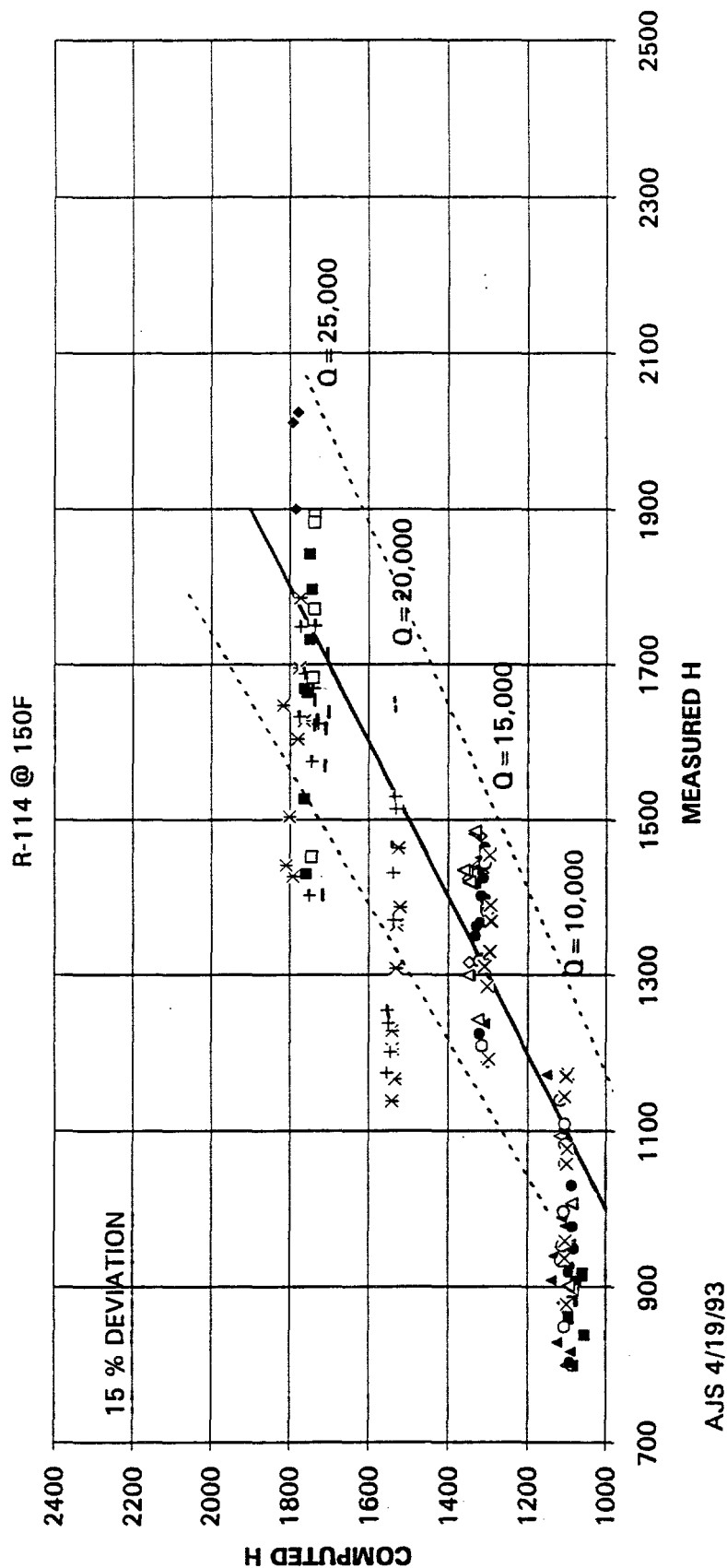


Figure 7. Comparison of heat transfer coefficients with CFC-114 with 150°F saturation temp

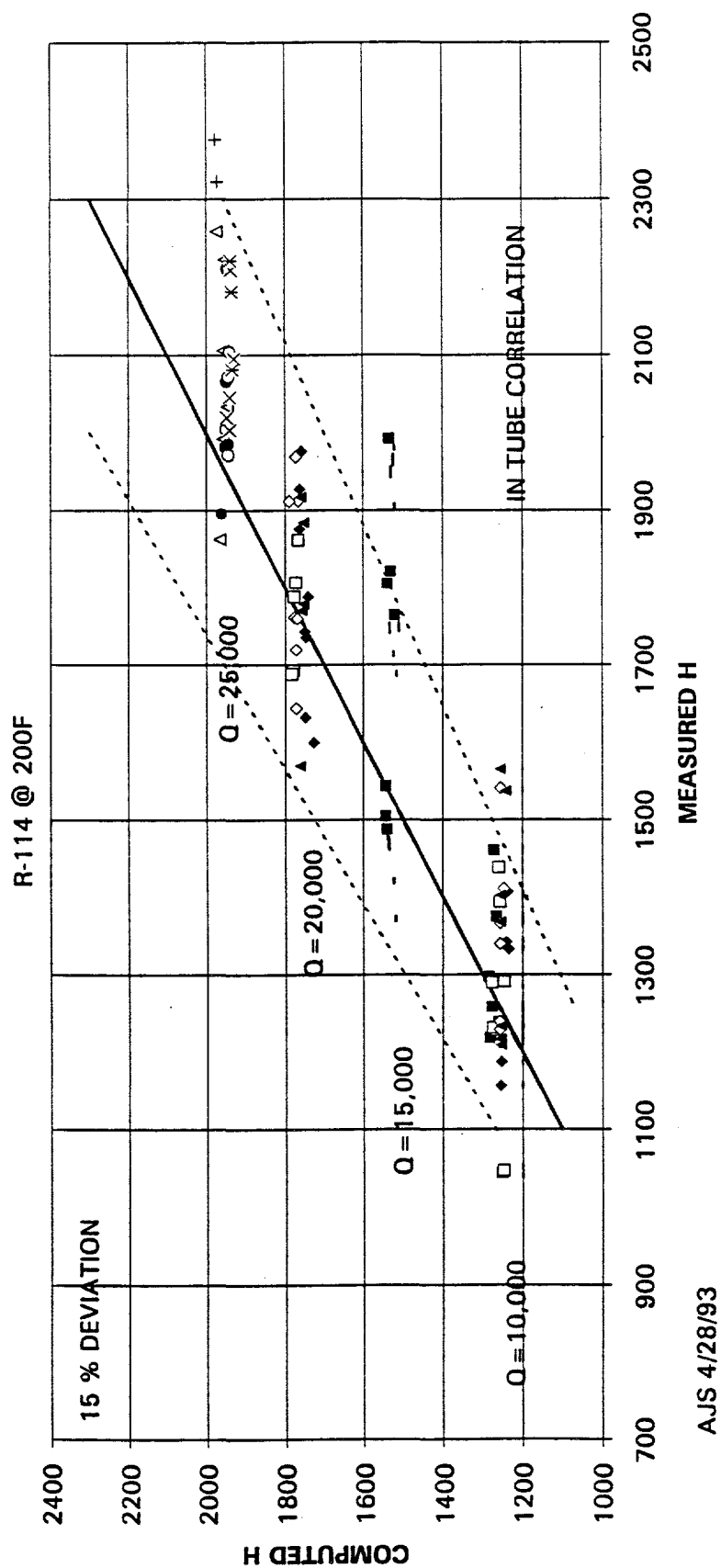




Figure 8. Comparison of heat transfer coefficients with  $C_1 F_{10}$  at 150°F saturation temp

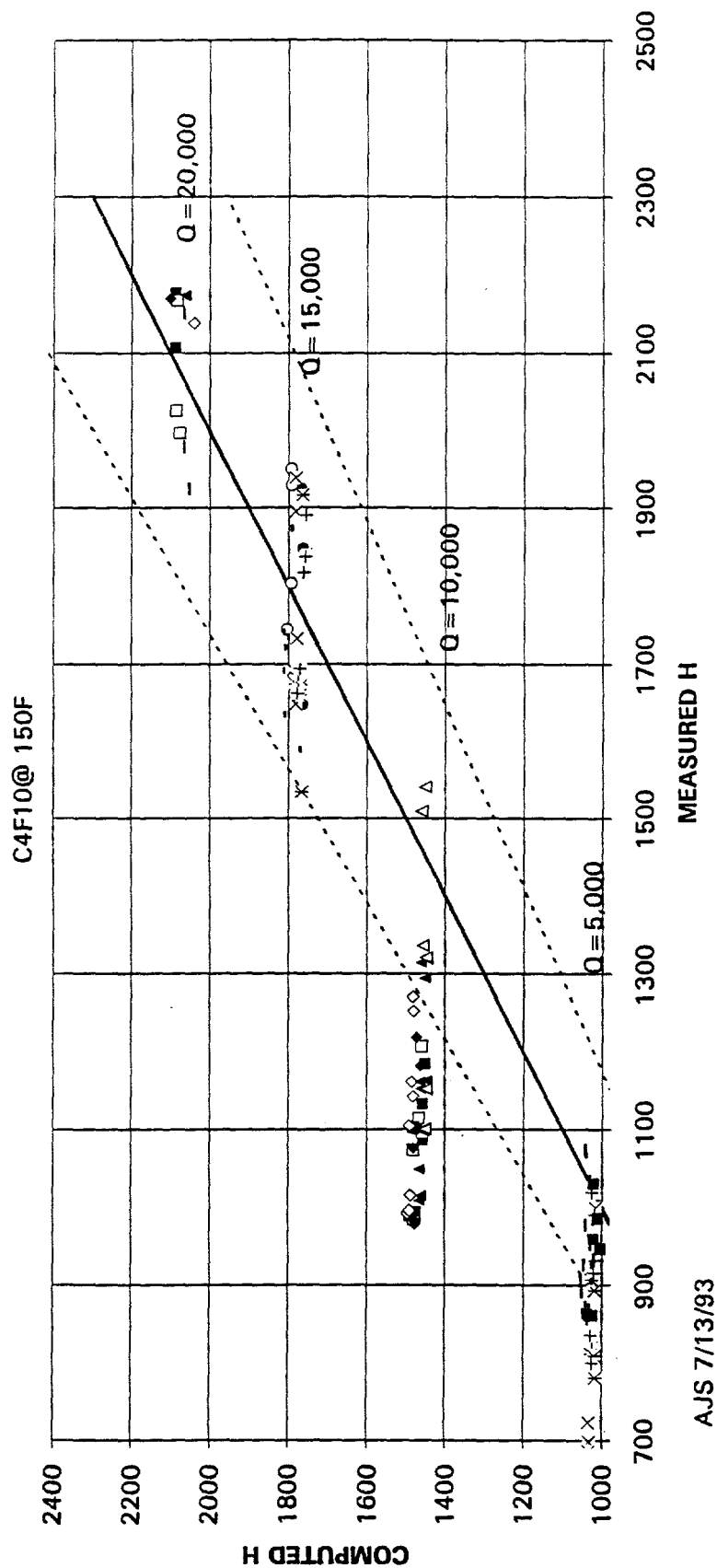
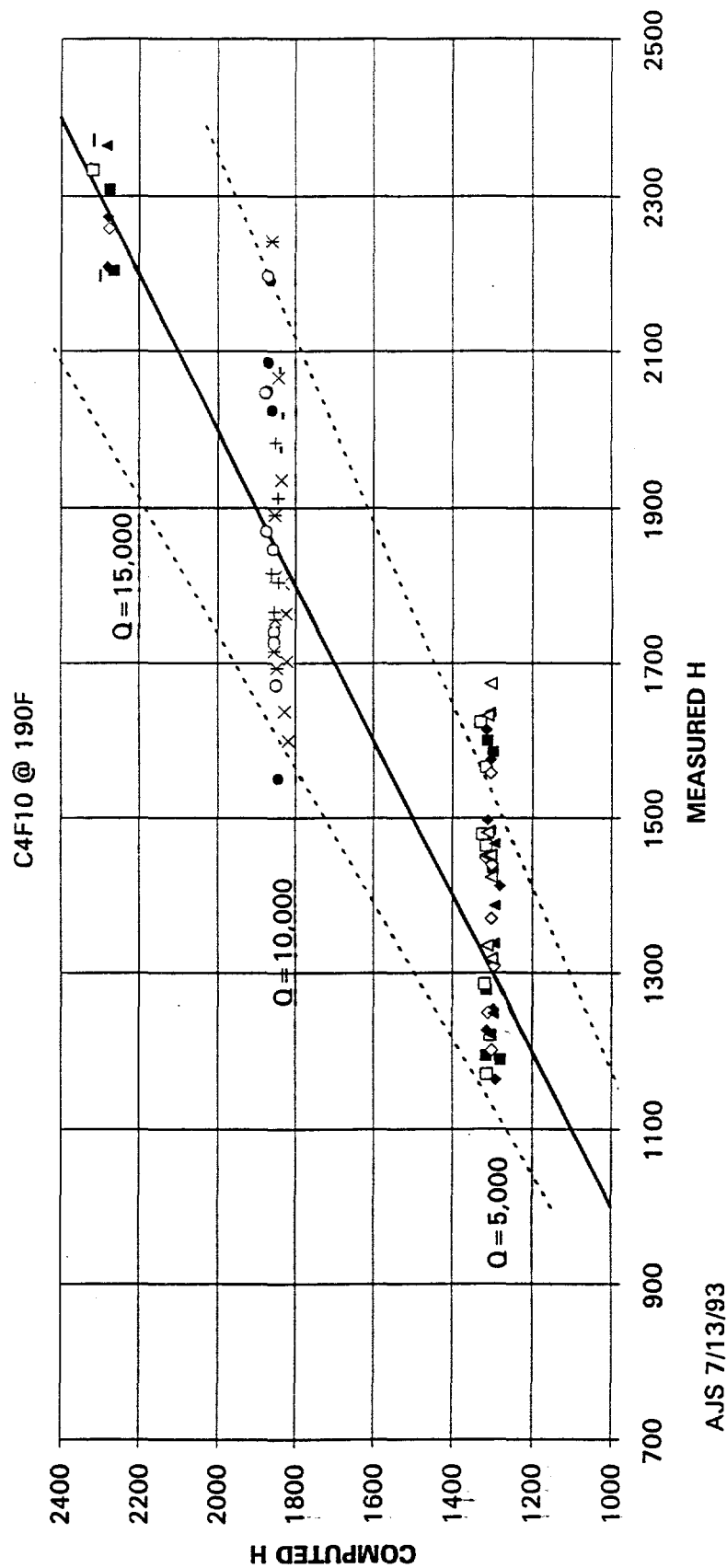


Figure 9. Comparison of heat transfer coefficients with CFC-114 at 200°F saturation temp



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