MULTIPLE POLLUTANT REMOVAL USING THE CONDENSING HEAT EXCHANGER

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Task 3 Topical Report: Long Term Wear Test

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Principal Author

G. A. Kudlac

McDermott Technology, Inc.
1562 Beeson Street
Alliance, Ohio 44601

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Ralph T. Bailey

OCDO Grant Agreement:

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FAX: 330-829-7283

McDermott Technology, Inc. Contract: CRD 1337

Phone: 330-829-7353

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ABSTRACT

Long-term operation of a condensing heat exchanger under typical coal-fired flue gas conditions was investigated in Phase I, Task 3 of the "Multiple Pollutant Removal Using the Condensing Heat Exchanger" test program. The program was conducted under contract to the United States Department of Energy's Fossil Energy Technology Center (DOE-FETC) and was supported by the Ohio Coal Development Office (OCDO) within the Ohio Department of Development, Electric Power Research Institute's Environmental Control Technology Center (EPRI-ECTC) and Babcock and Wilcox - a McDermott Company (B&W).

The specific goal of this task was to determine the amount of wear, if any, on the Teflon®-covered heat transfer tubes in a condensing heat exchanger. A pilot-scale single-stage condensing heat exchanger (CHX®) was operated under typical coal-fired flue gas conditions on a continuous basis for a period of approximately 10 months. Operating conditions and particulate loadings for the test unit were monitored, Teflon® film thickness measurements were conducted, and surface replications (which duplicate the surface finish at the microscopic level) were taken at various times during the test.

Data from the test indicate that virtually no decrease in Teflon® thickness was observed for the coating on the first two rows of heat exchanger tubes, even at high inlet particulate loadings (400 mg/dscm [0.35 lb/10⁶ Btu]). Evidence of wear was present only at the microscopic level, and even then was very minor in severity. Operation at high inlet particulate loadings resulted in accumulated ash deposits within the heat exchanger. Installation of a modified (higher flow rate) wash nozzle manifold substantially reduced subsequent deposit formation.

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1.0 EXECUTIVE SUMMARY

This is the Task 3 Topical Report for "Multiple Pollutant Removal Using the Condensing Heat Exchanger," conducted by McDermott Technology Inc., Research & Development Division under contract to the United States Department of Energy, Fossil Energy Technology Center. The work was jointly sponsored by the Department of Energy's Fossil Energy Technology Center (DOE-FETC), the Ohio Coal Development Office (OCDO) within the Ohio Department of Development, the Electric Power Research Institute's Environmental Control Technology Center (EPRI-ECTC), and Babcock & Wilcox - a McDermott Company (B&W). The guidance and support of the project managers from the sponsoring organizations, Thomas J. Feeley III of DOE-FETC, Richard Chu of the OCDO, and Gerry B. Maybach of the EPRI-ECTC, is gratefully acknowledged.

The purpose of Phase I of this contract was to determine the pollutant removal performance and the anticipated wear life of an Integrated Flue Gas Treatment system using flue gas from coal combustion. Integrated Flue Gas Treatment uses two Condensing Heat Exchangers (CHXs®) to remove a variety of pollutants from combustion flue gas. The Teflon®-covered internals of the CHX® also permit heat recovery at temperatures below the acid dew point of the flue gas.

Condensing Heat Exchangers using Teflon®-covered heat exchanger tubes have long been used in the industrial market to recover energy from flue gas, thereby improving the overall thermal efficiency of the combustion process. More than 110 commercial units are in service, with operating lifetimes up to 14 years. These industrial installations have been exclusively gas and oil-fired installations. Prior to this work, only limited data existed on the pollutant removal efficiency of the IFGT process, and the effects of long-term exposure to abrasive flyash on the integrity of the Teflon®-covered heat exchanger tubes was unknown.

The objective of Task 3 was to demonstrate long-term operation of a condensing heat exchanger for coal-fired conditions. The specific goal of the task was to determine the amount of wear, if any, on the Teflon®-covered internals of the heat exchanger.

Task 3 Overview

Task 3 of this contract was conducted at the Electric Power Research Institute's Environmental Control Technology Center in Barker, New York. A single-stage CHX® unit was installed downstream of the ECTC electrostatic precipitator. The unit was operated as a heat recovery unit to determine the effects of long-term exposure to flyash under typical flue gas conditions.

Standard operating parameters (flue gas flows and temperatures, cooling water temperatures, etc.) were monitored and recorded by the ECTC data acquisition system over the course of the program. In addition, periodic visual inspections and Teflon® film thickness measurements were performed to determine the amount of wear. Finally, replications of the Teflon® film surface were made to both document the general physical condition of the Teflon® surface and allow for detection of wear at the microscopic level. Surface replications are made by moistening a strip of cellulosic film in acetone, laying the strip on the tube surface, and allowing to dry. The physical characteristics of the tube surface are thus exactly duplicated on the cellulosic film.

The wear test unit was operated for over 6,200 hours during the test program. A summary of the operating conditions is shown in Table 1.1.

Table 1.1 Summary of CHX® Operating Conditions at the ECTC

Time of Operation	6,240 hours
Inlet Gas Flow	1,275 scmh (750 scfm)
Inlet Gas Temperature	150°C (300°F)
Inlet Water Temperature	55 to 60°C (130 to 140°F)
Outlet Gas Temperature	82 to 93°C (180 to 200°F)
Outlet Water Temperature	76 to 80°C (170 to 175°F)
Inlet Particulate Loading (average)	25. mg/dscm (0.022 lb/10 ⁶ Btu) 2,060 hours 400. mg/dscm (0.35 lb/10 ⁶ Btu) 4,180 hours
Tube Wash Cycle	20 minutes every 8 hours

Five inspection trips were made over the course of the test program. During each trip, visual inspections, Teflon® thickness measurements and surface replications were performed.

No visible signs of wear were evident over the course of the test program. Minor amounts of fly ash deposition, not removed by the normal wash cycle, were detected after 5,000 hours of operation. These deposits were located several rows down from the top of the tube manifold and were attributed to inadequate wash water flowrates. A new wash nozzle manifold (3 nozzles vs. 1 nozzle) was installed following the 5,000 hour inspection. The end of test inspection revealed virtually no ash deposition.

Data from the Teflon® thickness measurements indicated no significant decrease in the tube film thickness. Measurements were made at several locations on each of the tubes in the top two rows of the tube bank. Over the course of the test program, the Teflon® film thickness increased approximately 7-10% (30.5 to 50.8 µm [1.2 to 2.0 mils] of a nominal 508 µm [20 mil] film) after roughly 2,000 hours of operation then showed no subsequent signs of decrease. This initial thickness increase has been attributed to a relaxation of surface stresses in the Teflon®. These surface stresses are a result of the manufacturing process, and stress relaxation occurs when the Teflon® film is heated. A graphical summary of the Teflon® thickness measurements is given in Figures 1.1 and 1.2.

Evaluation of the film surface replications revealed no significant wear damage to the Teflon® covering. Very minor wear damage was visible on tube 6, which was subject to the highest flue gas flow rate. This damage, however, was on the µm scale and is of the same magnitude as the surface striations created during manufacture and should pose no problems for extended operation.

Figure 1.1 Cumulative Change in Teflon® Film Thickness as a Function of Time for Tubes 1 through 6

Figure 1.2 Cumulative Change in Teflon® Film Thickness as a Function of Time for Tubes 7 through 12

Task 3 Conclusions and Recommendations

Based on the operational and inspection data collected over the course of the test program, the following conclusions and recommendations can be made:

- No significant wear was observed for any of the Teflon® tube coverings. Minor microscopic wear detected on some tubes is insignificant and should pose no problems for extended operation.
- Particulate deposition can be a problem, especially at higher particulate loadings and insufficient wash water flows. Increasing the wash water flow rate by modifying the wash nozzle manifold essentially eliminated particulate deposition.
- Teflon® life expectancy should be greater than 10 years. Tube replacement will more likely be required due to operational problems other than abrasive wear.

2.0 INTRODUCTION

The 1990 Clean Air Act Amendments address the need to reduce the quantity of pollutants released to the atmosphere. Some pollutants are currently regulated and additional species are targeted for control in the near future. The emission of SO₂ and particulate from electric utilities is currently regulated under the Phase I and Phase II requirements defined in Title IV. An additional 189 substances, classified as hazardous air pollutants, have been identified for regulation under Title III of the Clean Air Act Amendment. The Title III requirements will be imposed across approximately 750 source categories. Cluster rules are also being established to set emission standards for specific industries. Many state and local agencies are already imposing stringent regulations on hazardous pollutants, such as mercury. There is a need for equipment to remove the pollutants of concern in a cost-effective manner. Most of the commercial pollutant removal equipment suffer from three major drawbacks:

- Commercially available pollution removal equipment is parasitic, that is, they consume energy during operation. A typical coal-fired power plant will have a 2-4% or more reduction in power generation capacity when commercial SO₂ and particulate removal equipment is added for gas clean up.
- Commercially available flue gas clean up equipment generally treats only one pollutant at a time. Separate units are installed for each of the pollutants to be removed.
- Most of the commercial flue gas clean up equipment used in the electric utility industry can not be economically scaled down for industrial coal-fired applications. The capital cost and operating cost of these units are often prohibitive for the smaller energy producer.

An untapped source of energy from coal-fired units is the waste heat in the flue gas released to the stack. The efficiency of a boiler can be significantly increased by decreasing the flue gas exit temperature. One means of lowering the exit temperature is to use a condensing heat exchanger to recover both sensible and latent heat from the flue gas. Condensing Heat Exchangers (CHX®) using Teflon®-covered internals are widely used to recover waste heat from flue gases. The Teflon® covering protects the heat exchanger components from corrosion as the temperature of the flue gas drops below the acid dew point. The most common applications to date are boilers firing oil or natural gas. Single-stage commercial condensing heat exchangers have provided satisfactory performance and lifetimes for more than one hundred industrial installations for the past fourteen years.

A recent innovation to the commercial condensing heat exchanger design, called the Integrated Flue Gas Treatment (IFGT) system, exhibits improved pollutant removal from the flue gas while recovering waste heat. The IFGT system is a two-stage condensing heat exchanger. Most of the sensible heat is removed from the gas in the first heat exchanger stage. The second heat exchanger stage can be operated in a condensing mode, recovering latent heat from the gas while removing pollutants. The top of the second heat exchanger stage is equipped with an alkali reagent spray system to enhance SO₂ and particulate removal. Pollutant removal mechanisms in

the IFGT include condensing (for water, some organic compounds, and some acid gases and trace metals), impaction (for particulates), and gas absorption (for removal of SO₂, and other acid gases). In an IFGT, several pollutants are treated using a single device - while recovering waste heat. Because of its modular design, it can be easily built for a wide range of size applications. An additional benefit realized by using the condensing heat exchanger is the proportional reduction in carbon dioxide released per MW of generated electricity because of the increase in plant efficiency.

One of the major questions that must be addressed before the IFGT can be considered viable for coal-fired applications is the expected material lifetime for the Teflon® covering on the tubes. Commercial condensing heat exchangers with Teflon®-covered parts have exhibited lifetimes of over 14 years, but these have been clean fuel (oil or natural gas) applications. Tests on coal-fired units have been limited in duration.

To address the material lifetime issue for coal-fired applications, a long-term wear test was included in Phase I of this project as Task 3 -- "Long-Term Wear Testing". The specific goal of this task was to determine the amount of wear, if any, on the Teflon®-covered internals of the heat exchanger. The location of maximum material wear in an IFGT will be at the inlet of the first heat exchanger stage. This is where the flue gas and Teflon® coverings are the hottest, the flue gas velocity and particulate loading the highest, and where the particulates first impact the Teflon®-covered tubes. It is expected that the top rows of tubes in an IFGT will experience the maximum wear due to fly ash abrasion. A single-stage condensing heat exchanger unit was used for the material lifetime demonstration since the inlet conditions will be the same as for an IFGT. Visual and physical examinations were performed on the top rows of tubes at periodic intervals during the one-year demonstration.

3.0 FACILITIES AND EQUIPMENT

The Environmental Control Technology Center (ECTC) was used to provide the flue gas to the wear test CHX® unit for this test program. The ECTC is a comprehensive test facility for evaluating advanced emissions control technologies applied to high sulfur coals. The test facility utilizes about one percent of the flue gas available from the 662 MW Kintigh Station, a pulverized coal boiler operated by the New York State Electric and Gas Corporation (NYSEG) in Barker, New York.

A flow schematic of the ECTC facility is shown in Figure 3.1. The facility is operated 24 hours a day, allowing long-term continuous tests to be performed. The pilot CHX® unit was installed in the mini-pilot wet scrubber sub-loop of the ECTC. This loop has a flue gas flow capacity of 2040-2550 acmh (1200-1500 acfm), sufficient to provide the "design" flue gas velocity of 12.2 m/sec (40 ft/sec) between the tubes at the inlet of the heat exchanger. To reproduce expected commercial conditions, the unit used a slipstream from the flue gas after it exits the electrostatic precipitator (ESP). The pilot CHX® test unit was located downstream of the ESP in place of the mini-pilot wet scrubber.

The CHX® unit used for the wear test is a skid-mounted, single-stage unit as shown in Figure 3.2. In addition to the heat exchanger, the unit is also equipped with a flue gas inlet control damper, water pump, and water circulation tank. Figure 3.3, is a top view drawing of the heat exchanger module of the CHX® pilot test unit. The internal dimensions of the heat exchanger are 30.87 cm by 36.51 cm (12 5/32 inches by 14 3/8 inches). There are six heat exchanger tubes in each row and 32 rows of tubes. The heat exchanger tube rows are staggered from each other (triangular pitch) so that there is no open line of sight from the top to the bottom of the heat exchanger. The CHX® pilot heat exchanger is operated with countercurrent flow, with the flue gas entering the top of the heat exchanger and exiting at the bottom, and the cooling water entering the bottom row of tubes and exiting the top row. The flue gas inlet plenum is removable, allowing access to the top of the heat exchanger for inspection of the Teflon® film on the top rows of tubes.

Data from the CHX® pilot test unit and ECTC equipment was collected and recorded by the ECTC data acquisition system. In addition, ECTC personnel maintained an hourly log of the major test parameters, including gas and water flows and temperatures, and ESP operating conditions. A list of the measured operating parameters and instruments used for the wear test is provided in Table 3.1.

Figure 3.1 Gas Flow Schematic of the ECTC Facility

Figure 3.2 CHX® Pilot Unit at the ECTC

Figure 3.3 Top View of the Pilot CHX® Unit Heat Exchanger

Table 3.1 CHX® Wear Test Instrumentation List

Measurement Parameter	Instrument	Provided By	Calibration Frequency	Measurement Frequency
Inlet water temperature	Type K Thermocouple	B&W	NA	Continuous DAS
Outlet water temperature	Type K Thermocouple	B&W	NA	Continuous DAS
Inlet gas temperature	Type K Thermocouple	B&W	NA	Continuous DAS
Outlet gas temperature	Type K Thermocouple	B&W	NA	Continuous DAS
Particle loading EPA Method 5		Parsons Power	NA	Periodic
Opacity	opacity meter	Parsons Power	weekly	Continuous DAS
Gas flow across orifice pressure diff. pressure temperature	pressure trans diff pressure trans Type K TC	Parsons Power	semi-annually semi-annually NA	Continuous DAS
Pressure at CHX® inlet	pressure transmitter	Parsons Power	semi-annually	Continuous DAS
Pressure drop across CHX®	differential pressure transmitter	Parsons Power	semi-annually	Continuous DAS
CHX® exposure time	clock	Parsons Power	NA	Continuous
Teflon® wear tube dimension surface profile thickness	micrometer profilometer eddy current	B&W	annually NA during use	Periodic
Sulfur dioxide	SO ₂ analyzer	Parsons Power	daily	Continuous DAS
Oxygen	O ₂ analyzer	Parsons Power	daily	Continuous DAS

4.0 TEST DESCRIPTION

4.1 Unit Operation

The ECTC pilot facility and the condensing heat exchanger were operated so that the wear test was conducted under conditions representative of commercial operation at the flue gas inlet of an IFGT condensing heat exchanger. Specifically, this required:

- A flue gas with a representative particulate loading, temperature, and flow for a commercial coal-fired application. For example, the inlet particulate loading was to be maintained at 34 mg/dscm (0.03 lbs/10⁶ Btu) or greater during the test period.
- Controlling the temperature and flow rate of the cooling water for the condensing heat exchanger to provide the Teflon® film temperature expected at the flue gas inlet of a full-scale IFGT unit.
- Operation of the CHX® unit on a continuous basis, whenever possible, to maximize the Teflon® exposure to flue gas.

The design operating conditions used as a basis for operation of the CHX® pilot unit are shown in Table 4.1. All major operating parameters (see Table 3.1) were monitored by ECTC personnel (and recorded by the ECTC data acquisition system) to ensure that the CHX® test unit was operating within the desired conditions.

Table 4.1 Design Operating Conditions for the CHX® Pilot Unit -- One Year Wear Test

Parameter	Nominal Value	Range
Inlet Flue Gas Temperature	160 °C (320 °F)	+/- 17 °C (30 °F)
Outlet Water Temperature	77 °C (170 °F)	+/- 11 °C (20 °F)
Cooling Water Supply	11.4 lpm {3.0 gpm (est.)}	---
Flue Gas Velocity, between tubes	12.2 m/sec (40 ft/sec)	+/- 1.5 m/sec (5 ft/sec)
Inlet Flue Gas Flow	1,275 scmh (750 scfm)	+85 -0 scmh (+50 -0 scfm)
Inlet Particulate Loading	representative of poor to good particulate cleanup from a commercial cleanup device.	34 to 340 mg/dscm (0.03 to 0.3 lbs/10 ⁶ Btu)

To achieve the desired particulate loading (~34 mg/dscm [0.03 lbs/10⁶ Btu] or greater) at the inlet to the condensing heat exchanger, the test unit was located downstream of the ECTC ESP. An opacity meter was used to monitor the flue gas particulate loading downstream of the ESP. In addition to the opacity meter, an Environmental Systems P-5A *in-situ* particulate monitor was used as a qualitative indicator for the particulate loading level to aid ECTC personnel in

maintaining a steady particulate loading. Finally, EPA Method 5 particulate loading measurements were made at various times during the test to confirm the opacity readings and the particulate loading to the unit.

4.2 Inspection Measurements

In order to determine the amount of wear, if any, on the Teflon® covered internals of the heat exchanger, and specifically the tubes, three types of measurements, in addition to a visual inspection, were performed during each of the five inspection trips conducted during the course of the test program. These measurements included:

- Vertical and horizontal tube dimensions
- Eddy current Teflon® film thickness determination
- Teflon® film surface replications

A fourth type of surface measurement utilizing a surface profilometer, which was originally specified as a test program measurement, was not used due to damage to the Teflon® film caused by the profilometer probe during use.

Each measurement was performed at several locations on the top two rows of tubes. A graphical representation of the measurement locations is shown in Figure 4.1. Tubes 1 through 6 are located in the top row of the heat exchanger and tubes 7 through 12 in the second row. Flue gas

Figure 4.1 Location of Film Thickness and Surface Replication Measurements

flow with respect to the diagram is from the left and then into the page. Each of the dimensional measurements (horizontal, vertical, and film thickness) were performed in triplicate at each location and the values averaged. These location values were then averaged to obtain an average

tube value. Single surface replications were made at each of the indicated locations. Three replications were performed on tube 6 since the greatest potential for abrasive wear was expected on this tube. Descriptive summaries of each of the three measurement techniques may be found in the following paragraphs:

Tube Dimensions: Micrometers were used to measure the top-to-bottom and side-to-side dimensions of the top row of tubes at each of the locations shown in Figure 4.1 (locations labeled "Film Thickness" on tubes 1 through 6). A digital caliper micrometer was used for the horizontal diameter measurements and a standard micrometer was used for the vertical diameter measurements. The overall accuracy of the horizontal diameter measurement was $25.4\text{ }\mu\text{m}$ (0.001 inches) and the overall accuracy of the vertical diameter measurement was $12.7\text{ }\mu\text{m}$ (0.0005 inches). After two sets of dimensional measurements were obtained, it was discovered that the Teflon® tube surfaces were being damaged by the micrometers. This was most likely due to the tight tube spacing, which complicated the insertion and removal of the calipers. Evaluation of the two sets of measurements indicated that any change in film thickness would be more evident from the eddy current measurements, so this procedure was dropped from subsequent inspection trips.

Film Thickness: An Elcometer 300 Coating Thickness Gage, which uses an eddy current measurement principle, was used to make the film thickness measurements. The instrument has a range of 25.4 to $1,016\text{ }\mu\text{m}$ {0.001 to 0.040 inches (1 to 40 mils)} and an accuracy of $\pm 1\%$ of its reading. Teflon® thickness measurements were made for the top surface of the first and second row of heat exchanger tubes. Thickness measurements were also made at specified angles from vertical ($0 + 45$ and $0 - 45$ degrees) for the top row of tubes. In relation to the diagram in Figure 4.1, "vertical" may be thought of as a line coming straight out of the paper, "+45" angled towards tube 1 and "-45" angled towards tube 6. Thickness measurements could not be made for these angles for the second row of tubes because of the staggered array (overlap of the tubes for adjacent rows) of the tubes. Measurements were made at the locations indicated in Figure 4.1. As mentioned above, these measurements were made in triplicate at each location and angle and then averaged. These location average values were then averaged for each tube to obtain a tube average. Each data set was then normalized based on 1) the calibration data for that particular set, and 2) the film thickness data from a "reference" tube measured at the same time using the same calibration as the inspection.

Surface Roughness: A cellulosic film surface replication technique was used to obtain a physical replicate of the Teflon® tube surfaces. The goal of making the surface replications was to record and observe any microscopic changes to the Teflon® tube surface. The replications were made during each inspection trip at the locations indicated in Figure 4.1. After cleaning the Teflon® tube surfaces, a strip of cellulosic film tape was moistened with acetone and laid on the surface of the tube. Upon drying, the tape was lifted from the tube and mounted on a glass slide, replicate side up. This procedure was then repeated for the remaining sample locations. The tapes were then viewed under a microscope and photographed at magnifications of 25X and 200X for comparison with the replications made prior to exposing the heat exchanger to flue gas.

5.0 RESULTS AND DISCUSSION

5.1 Operation Summary and Discussion

Over the course of Task 3, the CHX® pilot test unit was operated "at conditions" for 6,240 hours. During this time, all major design conditions operating ranges were met and maintained. A summary of the major operating conditions and the actual operating ranges is given in Table 5.1.

Table 5.1 Summary of CHX® Operating Conditions at the ECTC

Operating Parameter	Range or Value
Inlet Gas Flow	1275 scmh (750 scfm)
Inlet Gas Temperature	150°C (300°F)
Inlet Water Temperature	55 to 60°C (130 to 140°F)
Outlet Gas Temperature	82 to 93°C (180 to 200°F)
Outlet Water Temperature	76 to 80°C (170 to 175°F)
Inlet Particulate Loading (EPA M5 average)	25. mg/dscm (0.022 lb/10 ⁶ Btu) 2,060 hours 400. mg/dscm (0.35 lb/10 ⁶ Btu) 4,180 hours
Tube Wash Cycle	20 minutes every 8 hours

The particulate loading to the inlet of the CHX® test unit is reported as an average unit because the loading was increased partway through the test. The above value represents an average of the measured values after the change in particulate loading. A graphical summary of the CHX® inlet particulate loading over the course of the test program is shown in Figure 5.1. The particulate loading data presented in Figure 5.1 was obtained using an Environmental Systems P-5A *in situ* particulate monitor. The P-5A monitor was operated on a continuous basis and served as a qualitative indicator for the particulate loading level to aid ECTC personnel in maintaining a steady particulate loading to the CHX®. EPA Method 5 particulate sample trains were performed periodically to confirm the particulate loading. Particulate loadings from the EPA Method 5 sample trains are considered to be the official particulate loading data for Task 3.

Figure 5.1 P-5A Measurements of Particle Concentration During the One Year Test

Visual inspections of the top surface of the CHX® heat exchanger were made both before and after scheduled tube washings during each inspection trip. In every case, the "dirty" inspection revealed a uniform coating of fly ash on each tube with no apparent bias from one tube to another. This coating covered the top (leading) half of each tube. Minimal fly ash was found on the bottom (trailing) half. After washing, the "clean" inspection revealed essentially complete removal of the fly ash coating, with only isolated areas (<5% total visible surface area) retaining some of the fly ash. Photographs of typical "dirty" and "clean" tubes may be found in Figures 5.2 and 5.3, respectively. The clean area in the center of Figure 5.2 is due to inadvertent contact with the tube surface prior to being photographed.

Figure 5.2 Top of CHX® Heat Exchanger Prior to Washing

Figure 5.3 Top of CHX® Heat Exchanger After Washing

After approximately 5,000 hours of operation, several fly ash deposits were found in the heat exchanger which were unaffected by the wash cycle. These deposits began approximately halfway down the heat exchanger, on the tubes closest to the walls, and continued to the bottom of the heat exchanger. These deposits can be seen in Figure 5.4. The most likely cause for these

**Figure 5.4 Flyash Deposits on the Tubes
of the CHX Heat Exchanger**

deposits is inadequate wash water flow rate. The initial wash water setup consisted of one (1) spray nozzle with a nominal flow rate of 3.8 lpm (1 gpm) which operated for 20 minutes every 8 hours. This is the standard wash cycle for oil-fired applications. While the top few rows of tubes were effectively cleaned, being subjected to the most energetic cleaning, the tubes further down in the heat exchanger were essentially cleaned by wash water dripping from the tubes above. Any deposits which were not removed, but only wetted, then served as sites for additional fly ash deposition. Based on these findings, a new wash nozzle manifold, consisting of three (3) equally spaced 3.8 lpm (1 gpm) nozzles, was installed for the remainder of the test. This new manifold was also operated for 20 minutes, effectively tripling the wash water flow rate.

The effect of the modified wash water manifold can be seen in Figures 5.5 and 5.6. In Figure 5.5, the percent solids of the wash water effluent is shown for the two manifold setups. For the original setup (1 nozzle), it can be seen that the percent solids concentration levels off at the end of the wash cycle, indicating that less than complete solids removal is occurring. With the modified manifold (3 nozzles), not only is the percent solids concentration continually decreasing, the initial and final concentrations are higher (and lower, respectively), indicating more complete solids removal.

Figure 5.5 Wash Water Solids Concentration

In Figure 5.6, the heat exchanger differential pressure drop is shown as a function of time for the last four extended operating periods. The first three periods were conducted with one wash nozzle in service, the last with the three-nozzle manifold. In each of the first three operating periods, the differential pressure drop increased by approximately 100 Pa (0.4 in. H₂O) and was increasing, while the pressure drop increase for the last period was approximately 50 Pa (0.2 in. H₂O) and essentially steady.

Figure 5.6 Differential Pressure Across the CHX® Unit as a Function of Time

5.2 Wear Performance Discussion

The primary goal of Task 3 was to determine the amount of wear, if any, incurred by the Teflon® internals of the CHX® pilot unit's heat exchanger (specifically the heat exchanger tube surfaces), while operating under typical flue gas conditions. As mentioned in Section 4.2, three measurement techniques were employed in an effort to determine the amount and type of wear. This section will focus on the results from two of the techniques (eddy current film thickness and surface replication). The third technique (vertical and horizontal tube dimensions) is not included in this discussion for the reasons outlined in Section 4.2.

5.2.1 Teflon® Film Thickness Measurements

Six complete sets (including measurements taken prior to flue gas exposure) of film thickness measurements were obtained during the course of the test program. Each set consists of 90 data points for the top row of tubes (3 angles * 6 tubes * 5 locations) and 30 data points for the second row of tubes (1 angle * 6 tubes * 5 locations). Tabular summaries of each of the data sets are located in Appendix A through F. All film thickness data presented in graphical and tabular form have been normalized.

Results of the film thickness measurements indicated that no significant reduction in tube film thickness occurred during the course of the test program. Figures 5.7 and 5.8 illustrate this finding. The data presented in Figures 5.7 and 5.8 represent the average tube values for measurements taken in the vertical position for tubes 1 through 6 and tubes 7 through 12, respectively.

Figure 5.7 Cumulative Change in Teflon® Film Thickness as a Function of Operating Hours for Tubes 1 through 6

Figure 5.8 Cumulative Change in Teflon® Film Thickness as a Function of Operating Hours for Tubes 7 through 12

As illustrated in the two figures, after an initial increase in film thickness, no significant decrease was observed on any of the tubes measured. The increase in film thickness observed during the first two inspection trips is most likely due to the relaxation of surface stresses in the Teflon® film. These surface stresses result from the manufacturing process, and stress relaxation occurs when the Teflon® film is heated. The amount of increase ranged from 30.5 to 50.8 μm (1.2 to 2.0 mils), representing a 7 to 10% increase for a nominal 508 micron (20 mil) film.

As mentioned in Section 4.2, thickness measurements were also obtained for angles of $+45^\circ$ and -45° from the vertical at each of the measurement locations. These off-angle measurements were conducted to expand the amount of film surface being inspected and thus offer a more complete picture of any potential wear patterns and tendencies. In addition, the flue gas velocity at these locations was higher, creating the potential for greater abrasive wear than on the top surface of the tubes. In Figures 5.9 and 5.10, film thickness data is plotted as a function of both time and measurement angle for tubes 1 and 5, respectively. Due to the flue gas flow pattern from the inlet plenum to the first row of tubes, tubes 1 and 5, respectively, were chosen as representative of minimal and maximal potential wear sites. Tube 6, having the greatest potential for wear in the top row, was not chosen for this comparison due to instrument positioning problems during inspection, resulting in greater measurement variation. Plots for the other 4 tubes from the top row may be found in Appendix G.

Figure 5.9 Cumulative Change in Teflon® Film Thickness as a Function Of Operating Hours and Angular Position -- Tube 1

Figure 5.10 Cumulative Change in Teflon® Film Thickness as a Function of Operating Hours and Angular Position -- Tube 5

In each of the figures it can be seen that there were no significant differences in film thickness changes as a function of angular position, suggesting that high flue gas velocity areas, such as those between tubes, do not incur increased amounts of abrasive wear. Similar results were observed for the other 4 tubes in the top row of the heat exchanger. Although there appears to be a slight (10.2 µm [0.4 mil]) decrease in film thickness for tube 5, this amount is within the absolute accuracy range (+/- 1% of reading) of the thickness gage for a nominal 508 µm (20 mil) film.

5.2.2 Teflon® Surface Replications

Six sets (including replications made prior to flue gas exposure) of film surface replications were obtained during the course of the test program. Each set consists of 5 film replications made in the locations shown in Figure 4.1. The goal of making the surface replications was to record and observe any microscopic changes to the Teflon® tube surface which may not be evident to the naked eye or detected with the eddy current film thickness technique. As mentioned in Section 4.2, each replication was inspected under a microscope and then photographed at two different magnifications (25X and 200X). Comparisons were then made between the pre-test, intermediate and post-test replications to determine the location and amount of microscopic surface wear. Representative examples of the surface replications are shown in Figures 5.11 through 5.13. Figure 5.11 represents a typical tube surface prior to exposure to flue gas, Figure 5.12 shows the surface of tube 1, and Figure 5.13 the surface of tube 6, both at the conclusion of

Figure 5.12 Microphotograph of Tube 1 -- End of Test

Figure 5.13 Microphotograph of Tube 6 -- End of Test

6.0 CONCLUSIONS AND RECOMMENDATIONS

The objective of Task 3 was to demonstrate long-term operation of a condensing heat exchanger for coal-fired conditions. The specific goal of the task was to determine the amount of wear, if any, on the Teflon®-covered internals of the heat exchanger. A single-stage pilot CHX® unit was installed at the ECTC and operated at typical flue gas conditions for over 6,200 hours. Visual inspections, film thickness measurements, and film surface replications were performed at various times during the test program. No significant wear was detected on any of the tube surfaces. Specific conclusions and recommendations include the following:

- Particulate Deposition: At higher particulate loadings, deposition can be a problem, particularly if inadequate wash water flow rates are used. Wetted ash surfaces which are not removed during washing become sites for additional ash deposition, resulting in increases in heat exchanger pressure drop. Installation of the modified, 3-nozzle manifold (and subsequent increase in flow rate) seemed to alleviate this problem. For oil applications, the "design" wash schedule is 40.75 lpm/m² (1 gpm/ft²) for 10 minutes. Based on the results from this test program, this rate will need to be increased for higher particulate loadings such as coal-fired utility applications.
- Film Thickness: No significant decrease in film thickness was detected during the course of the test program. After an initial increase in film thickness resulting from surface stress relaxation during heating, film thicknesses remained essentially constant. Some locations exhibited a slight decrease (0.4 mils) in thickness, but this amount is within the absolute accuracy range (+/- 1% of reading) of the thickness gage. Measurements at various angular positions around the circumference of the tubes also showed no significant wear, even in areas of high flue gas velocity.
- Film Surface: Surface replications taken during the course of the test program revealed only minor, microscopic wear damage to the surface of the Teflon® film, and only on tubes subjected to the highest flue gas flow rates. The wear damage appeared to be on the µm level and was very fine and uniform, resembling round depressions in the film surface. At this scale, this type of wear damage should pose no problems for long-term operation of a large-scale unit.
- Predicted Teflon® Film Life: Based on the measurement data, the Teflon® covering on the heat exchanger tubes should have a life expectancy of greater than 10 years. If the 0.4 mil decrease observed for some tube locations is correct, 10 years of operation would yield an approximate decrease in film thickness of 4 mils from a nominal film thickness of 20 mils. It would be more probable that any tube replacement would be due to other operational problems (e.g., scale buildup, temperature excursions due to cooling water failure, etc.). For comparison, operation at a particulate loading of 400 mg/dscm (0.35 lb/10⁶ Btu) for 6 months is equivalent to 10 years at 20 mg/dscm (0.017 lb/10⁶ Btu).

Appendix A: Tabulated Data - Teflon® Film Thickness Measurements
Data Set 1 - 3/12/96

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top of Tube), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.508	0.506	0.467	0.479	0.557	0.513
	2	0.513	0.496	0.455	0.481	0.554	0.510
	3	0.515	0.510	0.459	0.481	0.554	0.508
	Average	0.512	0.504	0.460	0.480	0.555	0.510
B	1	0.501	0.523	0.518	0.552	0.557	0.525
	2	0.518	0.523	0.493	0.508	0.554	0.525
	3	0.508	0.523	0.523	0.491	0.554	0.523
	Average	0.509	0.523	0.511	0.517	0.555	0.524
C	1	0.489	0.481	0.489	0.510	0.535	0.515
	2	0.493	0.472	0.484	0.476	0.547	0.523
	3	0.491	0.469	0.503	0.486	0.537	0.520
	Average	0.491	0.474	0.492	0.491	0.540	0.519
D	1	0.518	0.501	0.459	0.469	0.523	0.527
	2	0.498	0.510	0.459	0.467	0.518	0.520
	3	0.508	0.510	0.464	0.464	0.520	0.525
	Average	0.508	0.507	0.461	0.467	0.520	0.524
E	1	0.496	0.518	0.459	0.489	0.530	0.518
	2	0.498	0.513	0.472	0.498	0.540	0.554
	3	0.496	0.513	0.469	0.496	0.549	0.535
	Average	0.497	0.514	0.467	0.494	0.540	0.536
Tube Average		0.503	0.504	0.478	0.490	0.542	0.523
Hrs. Operation: 0 Temperature: 51 F Date: 3/12/96 Recorded by: KHS							
25.4 mm = 1 inch							

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top of Tube), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		7	8	9	10	11	12
A	1	0.527	0.569	0.498	0.513	0.527	0.518
	2	0.527	0.569	0.486	0.513	0.527	0.513
	3	0.527	0.569	0.486	0.515	0.525	0.513
	Average	0.527	0.569	0.490	0.514	0.527	0.514
B	1	0.527	0.559	0.503	0.518	0.520	0.506
	2	0.515	0.564	0.506	0.515	0.525	0.501
	3	0.515	0.564	0.506	0.515	0.523	0.501
	Average	0.519	0.562	0.505	0.516	0.523	0.502
C	1	0.510	0.540	0.479	0.520	0.523	0.506
	2	0.518	0.547	0.476	0.520	0.525	0.498
	3	0.520	0.549	0.472	0.520	0.523	0.498
	Average	0.516	0.545	0.476	0.520	0.523	0.501
D	1	0.523	0.532	0.476	0.518	0.525	0.506
	2	0.527	0.535	0.476	0.520	0.525	0.506
	3	0.520	0.537	0.476	0.523	0.518	0.506
	Average	0.523	0.535	0.476	0.520	0.523	0.506
E	1	0.523	0.542	0.523	0.513	0.518	0.513
	2	0.523	0.537	0.520	0.510	0.518	0.513
	3	0.523	0.532	0.523	0.510	0.518	0.513
	Average	0.523	0.537	0.522	0.511	0.518	0.513
Tube Average		0.522	0.550	0.494	0.516	0.523	0.507
Hrs. Operation: 0 Temperature: 51 F Date: 3/12/96 Recorded by: KHS							
25.4 mm = 1 inch							

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top + 45°), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.552	0.525	0.510	0.513	0.574	0.566
	2	0.542	0.508	0.554	0.544	0.574	0.569
	3	0.537	0.535	0.557	0.518	0.566	0.554
	Average	0.544	0.523	0.540	0.525	0.571	0.563
B	1	#N/A	0.510	0.540	0.525	0.561	0.569
	2	#N/A	0.508	0.578	0.506	0.581	0.569
	3	#N/A	0.506	0.542	0.513	0.549	0.574
	Average	#N/A	0.508	0.553	0.514	0.564	0.570
C	1	0.547	0.501	0.510	0.508	0.530	0.564
	2	0.535	0.498	0.515	0.510	0.530	0.574
	3	0.544	0.493	0.513	0.508	0.535	0.574
	Average	0.542	0.497	0.513	0.509	0.531	0.570
D	1	0.540	0.506	0.506	0.510	0.530	0.557
	2	0.552	0.506	0.506	0.506	0.530	0.564
	3	0.544	0.503	0.503	0.508	0.540	0.569
	Average	0.545	0.505	0.505	0.508	0.533	0.563
E	1	0.549	0.530	0.508	0.549	0.537	0.537
	2	0.549	0.530	0.508	0.554	0.537	0.540
	3	0.559	0.527	0.510	0.561	0.542	0.520
	Average	0.553	0.529	0.509	0.555	0.539	0.532
Tube Average		0.546	0.512	0.524	0.522	0.548	0.560
Hrs. Operation: 0 Temperature: 51 F Date: 3/12/96 Recorded by: KHS							
25.4 mm = 1 inch							

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top - 45°), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.527	0.547	0.474	0.527	0.569	0.530
	2	0.520	0.547	0.469	0.491	0.566	0.496
	3	0.518	0.544	0.469	0.489	0.566	0.532
	Average	0.522	0.546	0.471	0.502	0.567	0.519
B	1	0.506	0.544	0.481	0.489	0.571	0.484
	2	0.508	0.549	0.491	0.496	0.564	0.506
	3	0.506	0.552	0.484	0.496	0.566	0.481
	Average	0.506	0.548	0.485	0.493	0.567	0.490
C	1	0.518	0.537	0.491	0.489	0.559	0.501
	2	0.506	0.542	0.503	0.496	0.564	0.474
	3	0.510	0.540	0.501	0.496	0.564	0.474
	Average	0.511	0.540	0.498	0.493	0.562	0.483
D	1	0.535	0.554	0.484	0.486	0.564	0.476
	2	0.535	0.554	0.489	0.498	0.559	0.503
	3	0.532	0.554	0.486	0.496	0.559	0.491
	Average	0.534	0.554	0.486	0.493	0.561	0.490
E	1	0.513	0.566	0.474	0.510	0.569	0.508
	2	0.513	0.554	0.472	0.508	0.566	0.476
	3	0.513	0.569	0.472	0.506	0.569	0.481
	Average	0.513	0.563	0.472	0.508	0.568	0.489
Tube Average		0.517	0.550	0.483	0.498	0.565	0.494
Hrs. Operation: 0 Temperature: 51 F Date: 3/12/96 Recorded by: KHS							
25.4 mm = 1 inch							

**Appendix B: Tabulated Data - Teflon® Film Thickness Measurements
Data Set 2 - 4/29/96**

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top of Tube), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.548	0.523	0.484	0.503	0.584	0.538
	2	0.550	0.523	0.484	0.513	0.587	0.543
	3	0.540	0.526	0.496	0.508	0.582	0.545
	Average	0.546	0.524	0.488	0.508	0.584	0.542
B	1	0.543	0.523	0.506	0.503	0.570	0.555
	2	0.530	0.523	0.511	0.513	0.584	0.575
	3	0.540	0.530	0.508	0.503	0.584	0.555
	Average	0.538	0.526	0.508	0.507	0.580	0.562
C	1	0.540	0.503	0.511	0.499	0.555	0.545
	2	0.526	0.499	0.501	0.503	0.550	0.550
	3	0.540	0.503	0.506	0.501	0.555	0.550
	Average	0.535	0.502	0.506	0.501	0.553	0.548
D	1	0.540	0.526	0.491	0.503	0.555	0.562
	2	0.545	0.548	0.503	0.499	0.550	0.553
	3	0.550	0.526	0.503	0.496	0.548	0.557
	Average	0.545	0.533	0.499	0.499	0.551	0.557
E	1	0.543	0.548	0.494	0.518	0.565	0.557
	2	0.540	0.545	0.494	0.513	0.565	0.557
	3	0.535	0.545	0.491	0.521	0.570	0.557
	Average	0.539	0.546	0.493	0.517	0.566	0.557
	Tube Average	0.541	0.526	0.499	0.507	0.567	0.553

Hrs. Operation: 834

Temperature: 62 F

Date: 4/29/96

Recorded by: KHS

25.4 mm = 1 inch

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top of Tube), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		7	8	9	10	11	12
A	1	0.560	0.604	0.516	0.545	0.560	0.548
	2	0.557	0.597	0.511	0.540	0.555	0.550
	3	0.557	0.594	0.513	0.543	0.557	0.548
	Average	0.558	0.598	0.513	0.543	0.557	0.548
B	1	0.553	0.594	0.526	0.548	0.555	0.535
	2	0.548	0.584	0.530	0.540	0.555	0.528
	3	0.553	0.584	0.528	0.543	0.553	0.528
	Average	0.551	0.588	0.528	0.544	0.554	0.530
C	1	0.548	0.587	0.506	0.565	0.565	0.526
	2	0.543	0.587	0.501	0.550	0.555	0.533
	3	0.550	0.577	0.503	0.553	0.557	0.533
	Average	0.547	0.584	0.503	0.556	0.559	0.530
D	1	0.565	0.577	0.506	0.555	0.555	0.543
	2	0.560	0.577	0.506	0.553	0.550	0.545
	3	0.560	0.577	0.506	0.555	0.555	0.548
	Average	0.562	0.577	0.506	0.554	0.553	0.545
E	1	0.557	0.567	0.555	0.548	0.562	0.545
	2	0.560	0.580	0.550	0.548	0.560	0.555
	3	0.555	0.580	0.553	0.545	0.553	0.557
	Average	0.557	0.575	0.553	0.547	0.558	0.553
Tube Average		0.555	0.584	0.521	0.549	0.556	0.541
Hrs. Operation: 834 25.4 mm = 1 inch Temperature: 62 F Date: 4/29/96 Recorded by: KHS							

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top + 45°), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.584	0.535	0.518	0.528	0.604	0.580
	2	0.567	0.538	0.533	0.557	0.597	0.575
	3	0.570	0.530	0.521	0.533	0.599	0.580
	Average	0.574	0.535	0.524	0.539	0.600	0.578
B	1	0.562	0.530	0.533	0.550	0.584	0.580
	2	0.570	0.540	0.548	0.535	0.589	0.577
	3	0.570	0.543	0.545	0.535	0.582	0.575
	Average	0.567	0.538	0.542	0.540	0.585	0.577
C	1	0.577	0.540	0.538	0.540	0.557	0.589
	2	0.580	0.533	0.540	0.538	0.557	0.604
	3	0.584	0.543	0.543	0.540	0.553	0.589
	Average	0.580	0.539	0.540	0.539	0.556	0.594
D	1	0.584	0.533	0.545	0.550	0.560	0.580
	2	0.577	0.533	0.538	0.538	0.562	0.584
	3	0.575	0.530	0.540	0.545	0.562	0.572
	Average	0.579	0.532	0.541	0.544	0.562	0.579
E	1	0.572	0.567	0.550	0.543	0.582	0.577
	2	0.570	0.562	0.548	0.545	0.580	0.550
	3	0.575	0.567	0.540	0.553	0.575	0.557
	Average	0.572	0.566	0.546	0.547	0.579	0.562
Tube Average		0.576	0.542	0.539	0.542	0.576	0.578
Hrs. Operation: 834 25.4 mm = 1 inch Temperature: 62 F Date: 4/29/96 Recorded by: KHS							

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top - 45°), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.560	0.584	0.511	0.528	0.611	0.533
	2	0.562	0.582	0.501	0.523	0.609	0.523
	3	0.557	0.589	0.501	0.526	0.614	0.523
	Average	0.560	0.585	0.504	0.526	0.610	0.526
B	1	0.543	0.584	0.523	0.528	0.602	0.518
	2	0.543	0.589	0.523	0.526	0.604	0.508
	3	0.538	0.589	0.526	0.526	0.604	0.501
	Average	0.541	0.588	0.524	0.526	0.603	0.509
C	1	0.543	0.584	0.513	0.526	0.582	0.511
	2	0.550	0.580	0.526	0.511	0.582	0.511
	3	0.550	0.580	0.530	0.513	0.577	0.513
	Average	0.548	0.581	0.523	0.517	0.580	0.512
D	1	0.575	0.587	0.508	0.516	0.584	0.533
	2	0.577	0.589	0.516	0.508	0.582	0.518
	3	0.577	0.589	0.518	0.511	0.584	0.518
	Average	0.576	0.589	0.514	0.512	0.584	0.523
E	1	0.540	0.597	0.506	0.535	0.587	0.521
	2	0.545	0.597	0.496	0.530	0.587	0.503
	3	0.550	0.602	0.501	0.530	0.594	0.526
	Average	0.545	0.598	0.501	0.532	0.589	0.517
	Tube Average	0.554	0.588	0.513	0.522	0.594	0.517

Hrs. Operation: 834

Temperature: 62 F

Date: 4/29/96

Recorded by: KHS

25.4 mm = 1 inch

Appendix C: Tabulated Data - Teflon® Film Thickness Measurements
Data Set 3 - 7/9/96

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top of Tube), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		7	8	9	10	11	12
A	1	0.584	0.625	0.525	0.563	0.579	0.568
	2	0.579	0.628	0.527	0.558	0.576	0.563
	3	0.579	0.622	0.527	0.561	0.574	0.563
	Average	0.580	0.625	0.526	0.561	0.576	0.563
B	1	0.574	0.617	0.553	0.566	0.581	0.550
	2	0.576	0.620	0.550	0.566	0.574	0.543
	3	0.563	0.620	0.550	0.576	0.571	0.548
	Average	0.571	0.619	0.551	0.569	0.575	0.547
C	1	0.563	0.599	0.517	0.576	0.579	0.545
	2	0.563	0.602	0.517	0.576	0.579	0.548
	3	0.556	0.592	0.514	0.574	0.579	0.548
	Average	0.561	0.598	0.516	0.575	0.579	0.547
D	1	0.571	0.594	0.525	0.566	0.566	0.556
	2	0.571	0.579	0.520	0.568	0.566	0.558
	3	0.568	0.581	0.520	0.566	0.566	0.558
	Average	0.570	0.585	0.521	0.567	0.566	0.557
E	1	0.584	0.581	0.581	0.561	0.571	0.566
	2	0.574	0.584	0.574	0.561	0.568	0.566
	3	0.574	0.584	0.574	0.561	0.571	0.566
	Average	0.577	0.583	0.576	0.561	0.570	0.566
Tube Average		0.572	0.602	0.538	0.567	0.573	0.556
Hrs. Operation: 2082 Temperature: 73 F Date: 7/9/96 Recorded by: KHS							

25.4 mm = 1 inch

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top + 45°), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.602	0.540	0.532	0.556	0.622	0.589
	2	0.586	0.550	0.538	0.553	0.622	0.592
	3	0.586	0.540	0.532	0.553	0.620	0.589
	Average	0.592	0.544	0.534	0.554	0.622	0.590
B	1	0.581	0.548	0.558	0.550	0.607	0.607
	2	0.581	0.548	0.553	0.550	0.625	0.607
	3	0.584	0.540	0.553	0.556	0.604	0.610
	Average	0.582	0.545	0.555	0.552	0.612	0.608
C	1	0.586	0.548	0.556	0.566	0.561	0.592
	2	0.589	0.543	0.553	0.538	0.566	0.610
	3	0.589	0.543	0.548	0.548	0.566	0.607
	Average	0.588	0.544	0.552	0.550	0.564	0.603
D	1	0.594	0.548	0.556	0.556	0.581	0.615
	2	0.586	0.540	0.550	0.553	0.576	0.594
	3	0.584	0.543	0.548	0.550	0.574	0.612
	Average	0.588	0.544	0.551	0.553	0.577	0.607
E	1	0.592	0.586	0.553	0.561	0.607	0.574
	2	0.594	0.586	0.550	0.574	0.602	0.574
	3	0.594	0.576	0.550	0.576	0.604	0.574
	Average	0.593	0.583	0.551	0.570	0.604	0.574
Tube Average		0.590	0.552	0.549	0.556	0.596	0.596
Hrs. Operation: 2082 Temperature: 73 F Date: 7/9/96 Recorded by: KHS							

25.4 mm = 1 inch

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top - 45°), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.589	0.597	0.558	0.535	0.622	0.540
	2	0.568	0.607	0.514	0.530	0.622	0.545
	3	0.568	0.599	0.509	0.532	0.630	0.538
	Average	0.575	0.601	0.527	0.532	0.625	0.541
B	1	0.540	0.602	0.522	0.540	0.625	0.535
	2	0.545	0.599	0.522	0.548	0.630	0.517
	3	0.540	0.599	0.522	0.540	0.622	0.530
	Average	0.542	0.600	0.522	0.543	0.626	0.527
C	1	0.563	0.592	0.530	0.527	0.610	0.512
	2	0.558	0.599	0.522	0.525	0.594	0.522
	3	0.556	0.592	0.522	0.525	0.594	0.525
	Average	0.559	0.594	0.525	0.526	0.599	0.520
D	1	0.581	0.607	0.527	0.525	0.607	0.520
	2	0.581	0.617	0.525	0.530	0.604	0.514
	3	0.576	0.610	0.525	0.530	0.615	0.517
	Average	0.580	0.611	0.526	0.528	0.609	0.517
E	1	0.553	0.612	0.504	0.558	0.617	0.499
	2	0.556	0.610	0.504	0.545	0.617	0.504
	3	0.550	0.610	0.504	0.543	0.615	0.504
	Average	0.553	0.610	0.504	0.549	0.616	0.502
Tube Average		0.562	0.603	0.521	0.535	0.615	0.521
Hrs. Operation: 2082 Temperature: 73 F Date: 7/9/96 Recorded by: KHS							

25.4 mm = 1 inch

**Appendix D: Tabulated Data - Teflon® Film Thickness Measurements
Data Set 4 - 9/12/96**

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top of Tube), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.551	0.531	0.501	0.516	0.599	0.546
	2	0.541	0.531	0.496	0.511	0.607	0.551
	3	0.541	0.529	0.493	0.511	0.604	0.546
	Average	0.545	0.530	0.497	0.513	0.603	0.548
B	1	0.541	0.554	0.521	0.511	0.584	0.564
	2	0.539	0.546	0.521	0.524	0.581	0.564
	3	0.539	0.546	0.508	0.516	0.584	0.564
	Average	0.539	0.549	0.517	0.517	0.583	0.564
C	1	0.529	0.508	0.508	0.503	0.561	0.554
	2	0.526	0.511	0.508	0.506	0.561	0.556
	3	0.529	0.508	0.508	0.506	0.561	0.561
	Average	0.528	0.509	0.508	0.505	0.561	0.557
D	1	0.544	0.549	0.501	0.503	0.566	0.566
	2	0.534	0.546	0.496	0.503	0.561	0.566
	3	0.534	0.546	0.503	0.503	0.566	0.569
	Average	0.537	0.547	0.500	0.503	0.565	0.567
E	1	0.539	0.551	0.503	0.526	0.581	0.564
	2	0.536	0.561	0.496	0.524	0.574	0.566
	3	0.536	0.554	0.493	0.521	0.576	0.564
	Average	0.537	0.555	0.498	0.524	0.577	0.565
	Tube Average	0.537	0.538	0.504	0.512	0.578	0.560
Hrs. Operation: 2970 Temperature: 78 F Date: 9/12/96 Recorded by: GAK							

25.4 mm = 1 inch

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top of Tube), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		7	8	9	10	11	12
A	1	0.574	0.617	0.524	0.556	0.566	0.556
	2	0.569	0.619	0.524	0.554	0.566	0.556
	3	0.566	0.614	0.526	0.556	0.569	0.556
	Average	0.570	0.617	0.524	0.555	0.567	0.556
B	1	0.579	0.617	0.551	0.566	0.574	0.561
	2	0.576	0.617	0.549	0.569	0.574	0.556
	3	0.576	0.617	0.549	0.569	0.571	0.556
	Average	0.577	0.617	0.550	0.568	0.573	0.558
C	1	0.554	0.591	0.511	0.564	0.571	0.536
	2	0.556	0.586	0.508	0.564	0.566	0.536
	3	0.554	0.591	0.508	0.564	0.566	0.536
	Average	0.555	0.590	0.509	0.564	0.568	0.536
D	1	0.561	0.576	0.513	0.559	0.559	0.554
	2	0.564	0.579	0.511	0.559	0.559	0.551
	3	0.561	0.571	0.511	0.561	0.559	0.549
	Average	0.562	0.576	0.512	0.560	0.559	0.551
E	1	0.566	0.581	0.576	0.564	0.571	0.571
	2	0.571	0.581	0.566	0.561	0.571	0.566
	3	0.571	0.576	0.574	0.561	0.571	0.569
	Average	0.570	0.580	0.572	0.562	0.571	0.569
Tube Average		0.567	0.596	0.533	0.562	0.568	0.554
Hrs. Operation: 2970 Temperature: 78 F Date: 9/12/96 Recorded by: GAK							

25.4 mm = 1 inch

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top + 45°), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.576	0.544	0.534	0.551	0.614	0.589
	2	0.576	0.541	0.534	0.551	0.617	0.586
	3	0.576	0.541	0.531	0.551	0.614	0.586
	Average	0.576	0.542	0.533	0.551	0.615	0.587
B	1	0.581	0.539	0.536	0.536	0.589	0.604
	2	0.584	0.536	0.539	0.534	0.589	0.607
	3	0.581	0.534	0.541	0.536	0.591	0.607
	Average	0.582	0.536	0.539	0.535	0.590	0.606
C	1	0.586	0.529	0.549	0.551	0.556	0.591
	2	0.586	0.531	0.549	0.554	0.551	0.594
	3	0.591	0.529	0.549	0.549	0.551	0.591
	Average	0.588	0.529	0.549	0.551	0.553	0.592
D	1	0.581	0.541	0.539	0.561	0.581	0.584
	2	0.584	0.541	0.544	0.559	0.569	0.581
	3	0.584	0.541	0.544	0.559	0.576	0.589
	Average	0.583	0.541	0.542	0.560	0.576	0.585
E	1	0.586	0.579	0.556	0.554	0.594	0.561
	2	0.584	0.576	0.551	0.554	0.594	0.561
	3	0.581	0.571	0.551	0.564	0.589	0.556
	Average	0.584	0.576	0.553	0.557	0.592	0.560
Tube Average		0.583	0.545	0.543	0.551	0.585	0.586
Hrs. Operation: 2970 Temperature: 78 F Date: 9/12/96 Recorded by: GAK							

25.4 mm = 1 inch

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top - 45°), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.561	0.594	0.506	0.529	0.619	0.531
	2	0.569	0.599	0.508	0.526	0.619	0.524
	3	0.571	0.599	0.511	0.526	0.622	0.524
	Average	0.567	0.597	0.508	0.527	0.620	0.526
B	1	0.536	0.591	0.513	0.519	0.604	0.521
	2	0.539	0.594	0.516	0.521	0.604	0.519
	3	0.536	0.594	0.513	0.519	0.604	0.516
	Average	0.537	0.593	0.514	0.519	0.604	0.519
C	1	0.551	0.597	0.524	0.526	0.591	0.526
	2	0.549	0.597	0.526	0.521	0.602	0.513
	3	0.551	0.591	0.529	0.524	0.602	0.526
	Average	0.550	0.595	0.526	0.524	0.598	0.522
D	1	0.574	0.609	0.511	0.526	0.594	0.511
	2	0.576	0.604	0.513	0.534	0.599	0.513
	3	0.579	0.599	0.516	0.529	0.597	0.516
	Average	0.576	0.604	0.513	0.529	0.597	0.513
E	1	0.546	0.607	0.506	0.539	0.604	0.539
	2	0.549	0.604	0.506	0.536	0.607	0.524
	3	0.549	0.604	0.508	0.539	0.609	0.536
	Average	0.548	0.605	0.507	0.538	0.607	0.533
	Tube Average	0.556	0.599	0.514	0.527	0.605	0.523
Hrs. Operation: 2970 Temperature: 78 F Date: 9/12/96 Recorded by: GAK							

25.4 mm = 1 inch

Appendix E: Tabulated Data - Teflon® Film Thickness Measurements
Data Set 5 - 1/20/97

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top of Tube), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.557	0.549	0.504	0.517	0.614	0.560
	2	0.555	0.547	0.506	0.520	0.611	0.560
	3	0.557	0.547	0.504	0.520	0.611	0.563
	Average	0.556	0.547	0.505	0.519	0.612	0.561
B	1	0.547	0.549	0.514	0.517	0.595	0.571
	2	0.547	0.549	0.517	0.517	0.595	0.576
	3	0.549	0.552	0.520	0.517	0.595	0.579
	Average	0.547	0.550	0.517	0.517	0.595	0.575
C	1	0.533	0.514	0.517	0.509	0.565	0.560
	2	0.538	0.517	0.517	0.506	0.565	0.565
	3	0.536	0.517	0.517	0.506	0.565	0.563
	Average	0.536	0.516	0.517	0.507	0.565	0.563
D	1	0.541	0.552	0.501	0.504	0.568	0.576
	2	0.544	0.555	0.501	0.506	0.568	0.576
	3	0.544	0.552	0.501	0.506	0.568	0.576
	Average	0.543	0.553	0.501	0.505	0.568	0.576
E	1	0.547	0.571	0.498	0.528	0.587	0.576
	2	0.544	0.568	0.498	0.528	0.581	0.576
	3	0.544	0.568	0.498	0.528	0.581	0.576
	Average	0.545	0.569	0.498	0.528	0.583	0.576
Tube Average		0.545	0.547	0.508	0.515	0.585	0.570
Hrs. Operation: 5160 Temperature: Date: 1/20/97 Recorded by: GAK							

25.4 mm = 1 inch

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top of Tube), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		7	8	9	10	11	12
A	1	0.581	0.624	0.530	0.565	0.576	0.565
	2	0.584	0.627	0.533	0.565	0.579	0.568
	3	0.581	0.624	0.530	0.563	0.579	0.565
	Average	0.582	0.625	0.531	0.564	0.578	0.566
B	1	0.571	0.614	0.547	0.563	0.571	0.549
	2	0.568	0.614	0.544	0.563	0.568	0.547
	3	0.571	0.616	0.547	0.560	0.571	0.544
	Average	0.570	0.614	0.546	0.562	0.570	0.547
C	1	0.563	0.597	0.512	0.568	0.571	0.544
	2	0.563	0.595	0.512	0.568	0.571	0.541
	3	0.563	0.595	0.512	0.568	0.571	0.541
	Average	0.563	0.596	0.512	0.568	0.571	0.542
D	1	0.568	0.581	0.517	0.565	0.565	0.560
	2	0.568	0.587	0.514	0.565	0.568	0.565
	3	0.568	0.587	0.517	0.565	0.568	0.563
	Average	0.568	0.585	0.516	0.565	0.567	0.563
E	1	0.576	0.587	0.571	0.557	0.571	0.581
	2	0.576	0.587	0.576	0.557	0.568	0.576
	3	0.576	0.587	0.573	0.565	0.571	0.576
	Average	0.576	0.587	0.573	0.560	0.570	0.578
	Tube Average	0.572	0.601	0.536	0.564	0.571	0.559
Hrs. Operation: 5160 Temperature: Date: 1/20/97 Recorded by: GAK							
25.4 mm = 1 inch							

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top + 45°), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.600	0.547	0.536	0.544	0.616	0.605
	2	0.600	0.549	0.536	0.547	0.624	0.603
	3	0.597	0.549	0.533	0.552	0.627	0.605
	Average	0.599	0.548	0.535	0.547	0.622	0.605
B	1	0.605	0.541	0.557	0.541	0.603	0.592
	2	0.603	0.544	0.557	0.541	0.597	0.595
	3	0.603	0.541	0.557	0.544	0.600	0.592
	Average	0.604	0.542	0.557	0.542	0.600	0.593
C	1	0.595	0.538	0.552	0.538	0.560	0.597
	2	0.597	0.538	0.552	0.538	0.560	0.600
	3	0.597	0.538	0.555	0.538	0.563	0.605
	Average	0.597	0.538	0.553	0.538	0.561	0.601
D	1	0.595	0.544	0.547	0.544	0.571	0.595
	2	0.584	0.547	0.549	0.544	0.571	0.597
	3	0.587	0.547	0.549	0.544	0.573	0.595
	Average	0.589	0.546	0.548	0.544	0.572	0.596
E	1	0.603	0.576	0.547	0.552	0.589	0.584
	2	0.597	0.576	0.547	0.552	0.589	0.584
	3	0.595	0.576	0.547	0.555	0.592	0.584
	Average	0.598	0.576	0.547	0.553	0.590	0.584
	Tube Average	0.596	0.550	0.548	0.545	0.589	0.596
Hrs. Operation: 5160 Temperature: Date: 1/20/97 Recorded by: GAK							
25.4 mm = 1 inch							

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top - 45°), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.573	0.603	0.509	0.528	0.627	0.517
	2	0.571	0.605	0.509	0.525	0.627	0.520
	3	0.571	0.605	0.509	0.525	0.624	0.522
	Average	0.572	0.605	0.509	0.526	0.626	0.520
B	1	0.538	0.597	0.517	0.530	0.619	0.501
	2	0.541	0.597	0.520	0.530	0.619	0.504
	3	0.538	0.597	0.520	0.533	0.619	0.504
	Average	0.539	0.597	0.519	0.531	0.619	0.503
C	1	0.549	0.589	0.522	0.512	0.595	0.506
	2	0.552	0.589	0.525	0.512	0.595	0.504
	3	0.552	0.589	0.522	0.512	0.595	0.504
	Average	0.551	0.589	0.523	0.512	0.595	0.505
D	1	0.576	0.603	0.514	0.514	0.597	0.506
	2	0.579	0.605	0.514	0.514	0.597	0.509
	3	0.581	0.605	0.514	0.514	0.597	0.512
	Average	0.579	0.605	0.514	0.514	0.597	0.509
E	1	0.563	0.632	0.504	0.552	0.611	0.512
	2	0.568	0.632	0.506	0.552	0.614	0.509
	3	0.565	0.630	0.506	0.552	0.616	0.514
	Average	0.565	0.631	0.505	0.552	0.614	0.512
	Tube Average	0.561	0.605	0.514	0.527	0.610	0.510
Hrs. Operation: 5160 Temperature: Date: 1/20/97 Recorded by: GAK							

25.4 mm = 1 inch

**Appendix F: Tabulated Data - Teflon® Film Thickness Measurements
Data Set 6 - 3/21/97**

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top of Tube), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.546	0.530	0.492	0.510	0.595	0.548
	2	0.543	0.530	0.489	0.510	0.595	0.546
	3	0.538	0.530	0.489	0.510	0.595	0.546
	Average	0.542	0.530	0.490	0.510	0.595	0.547
B	1	0.538	0.533	0.507	0.510	0.587	0.566
	2	0.538	0.533	0.507	0.510	0.587	0.566
	3	0.538	0.530	0.507	0.510	0.587	0.566
	Average	0.538	0.532	0.507	0.510	0.587	0.566
C	1	0.530	0.510	0.513	0.505	0.559	0.556
	2	0.530	0.507	0.513	0.505	0.559	0.556
	3	0.530	0.507	0.510	0.505	0.559	0.556
	Average	0.530	0.508	0.512	0.505	0.559	0.556
D	1	0.536	0.536	0.495	0.502	0.561	0.566
	2	0.536	0.538	0.495	0.502	0.561	0.566
	3	0.536	0.538	0.495	0.502	0.559	0.566
	Average	0.536	0.537	0.495	0.502	0.560	0.566
E	1	0.538	0.559	0.497	0.525	0.577	0.569
	2	0.538	0.559	0.495	0.525	0.577	0.566
	3	0.538	0.559	0.495	0.525	0.577	0.566
	Average	0.538	0.559	0.495	0.525	0.577	0.567
	Tube Average	0.537	0.533	0.500	0.510	0.575	0.561
Hrs. Operation: 6240 end of test 25.4 mm = 1 inch Temperature: Date: 3/21/97 Recorded by: GAK							

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top of Tube), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		7	8	9	10	11	12
A	1	0.566	0.607	0.525	0.556	0.577	0.564
	2	0.566	0.610	0.525	0.556	0.571	0.564
	3	0.566	0.607	0.525	0.554	0.574	0.564
	Average	0.566	0.608	0.525	0.555	0.574	0.564
B	1	0.559	0.607	0.543	0.556	0.569	0.543
	2	0.561	0.605	0.543	0.556	0.569	0.543
	3	0.559	0.607	0.543	0.556	0.566	0.541
	Average	0.559	0.606	0.543	0.556	0.568	0.542
C	1	0.556	0.589	0.513	0.566	0.569	0.543
	2	0.556	0.589	0.513	0.566	0.569	0.543
	3	0.556	0.589	0.515	0.566	0.571	0.543
	Average	0.556	0.589	0.513	0.566	0.570	0.543
D	1	0.566	0.577	0.515	0.561	0.561	0.551
	2	0.566	0.577	0.515	0.561	0.561	0.551
	3	0.564	0.577	0.515	0.561	0.564	0.551
	Average	0.565	0.577	0.515	0.561	0.562	0.551
E	1	0.569	0.579	0.569	0.554	0.561	0.566
	2	0.569	0.579	0.571	0.554	0.561	0.566
	3	0.571	0.579	0.571	0.556	0.561	0.566
	Average	0.570	0.579	0.571	0.554	0.561	0.566
	Tube Average	0.563	0.592	0.534	0.559	0.567	0.553
Hrs. Operation: 6240 end of test 25.4 mm = 1 inch Temperature: Date: 3/21/97 Recorded by: GAK							

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top + 45°), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.597	0.538	0.528	0.538	0.610	0.587
	2	0.595	0.538	0.528	0.538	0.610	0.587
	3	0.589	0.538	0.525	0.538	0.607	0.584
	Average	0.594	0.538	0.527	0.538	0.609	0.586
B	1	0.587	0.541	0.551	0.538	0.584	0.589
	2	0.579	0.541	0.551	0.538	0.584	0.587
	3	0.587	0.541	0.548	0.538	0.584	0.587
	Average	0.584	0.541	0.550	0.538	0.584	0.588
C	1	0.587	0.533	0.551	0.538	0.556	0.592
	2	0.592	0.533	0.548	0.538	0.556	0.592
	3	0.587	0.533	0.548	0.538	0.556	0.592
	Average	0.589	0.533	0.549	0.538	0.556	0.592
D	1	0.595	0.541	0.546	0.543	0.571	0.597
	2	0.597	0.541	0.546	0.543	0.571	0.595
	3	0.592	0.541	0.546	0.543	0.571	0.597
	Average	0.595	0.541	0.546	0.543	0.571	0.596
E	1	0.595	0.577	0.546	0.554	0.589	0.574
	2	0.597	0.574	0.546	0.554	0.589	0.577
	3	0.595	0.574	0.546	0.554	0.589	0.574
	Average	0.595	0.575	0.546	0.554	0.589	0.575
	Tube Average	0.593	0.545	0.544	0.542	0.582	0.587
Hrs. Operation: 6240 end of test 25.4 mm = 1 inch Temperature: Date: 3/21/97 Recorded by: GAK							

Project No. 43456-300

One Year CHX Life Test at the ECTC

MEASUREMENT: Teflon Thickness (Top - 45°), millimeters							
Tube Location	Measurement Number	TUBE NUMBER					
		1	2	3	4	5	6
A	1	0.569	0.605	0.510	0.530	0.620	0.528
	2	0.569	0.605	0.510	0.530	0.620	0.528
	3	0.569	0.605	0.510	0.530	0.620	0.528
	Average	0.569	0.605	0.510	0.530	0.620	0.528
B	1	0.541	0.597	0.518	0.528	0.610	0.505
	2	0.541	0.597	0.518	0.528	0.610	0.505
	3	0.543	0.597	0.518	0.525	0.610	0.502
	Average	0.542	0.597	0.518	0.527	0.610	0.504
C	1	0.548	0.584	0.518	0.513	0.589	0.507
	2	0.548	0.584	0.518	0.513	0.589	0.507
	3	0.548	0.584	0.520	0.513	0.589	0.507
	Average	0.548	0.584	0.518	0.513	0.589	0.507
D	1	0.571	0.600	0.513	0.515	0.592	0.507
	2	0.571	0.597	0.513	0.515	0.592	0.507
	3	0.571	0.597	0.513	0.513	0.592	0.507
	Average	0.571	0.598	0.513	0.514	0.592	0.507
E	1	0.554	0.610	0.500	0.536	0.602	0.502
	2	0.554	0.607	0.500	0.536	0.602	0.502
	3	0.554	0.607	0.502	0.536	0.602	0.502
	Average	0.554	0.608	0.501	0.536	0.602	0.502
Tube Average		0.557	0.598	0.512	0.524	0.603	0.510
Hrs. Operation: 6240 end of test 25.4 mm = 1 inch Temperature: Date: 3/21/97 Recorded by: GAK							

Appendix G: Graphical Data - Change in Teflon® Film Thickness as a Function of Time

Figure G.1 Cumulative Change in Teflon® Film Thickness as a Function of Operating Time and Angular Position -- Tube 2

Figure G.2 Cumulative Change in Teflon® Film Thickness as a Function of Operating Time and Angular Position -- Tube 3

Figure G.3 Cumulative Change in Teflon® Film Thickness as a Function Of Operating Time and Angular Position -- Tube 4

Figure G.4 Cumulative Change in Teflon® Film Thickness as a Function of Operating Time and Angular Position -- Tube 6