**Westinghouse
Astronuclear
Laboratory**

WANL-TME-2722
SEPTEMBER 1970

DATA ITEM T-119
**THERMAL EXPANSION
CHARACTERISTICS
OF UNTHERMALIZED AND
THERMALIZED
REROLLED PYROFOIL
FINAL REPORT**

MASTER

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**Westinghouse
Astronuclear
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**Subcontract NP-1
CODE IDENT NO. 14683**

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APPROVED BY

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ABSTRACT

This report presents a comparison of the transverse thermal expansion characteristics of three forms of pyrofoil:

1. Unthermalized, PDS-30182-2.
2. Thermalized as rolled, PDS-30182-1.
3. Thermalized rerolled, PDS-30141-1.

The thermal expansion of a stack of pyrofoil pieces, under an argon gas purge, was measured for a number of test builds which included all three types of pyrofoil. Some builds were assembled with a petrolatum bond to obtain the apparent thermal expansion of the wrapper under conditions expected in reactor and test hardware builds. The thermal expansion, under 10 psi loading, was obtained as a function of temperature over the complete temperature range of reactor and test hardware operation.

The compaction pressure, at 4000°R, required to compress the stack to the room temperature dimension was measured as an aid to support the analysis of the core periphery wrapper cyclic strain test, 64DT-031.

The greatly reduced (factor of 10) thermal expansion of the thermalized rerolled pyrofoil resulted in its use in the core periphery tests, 64DT-211 and 64DT-212.

The comparative data support the use of pyrofoil as an impedance wrapper for the nuclear subsystem, NSS, core periphery. The stable thermal expansion of the thermalized rerolled pyrofoil material makes it the material having a minimum uncertainty range and, thus, most desirable for reactor application.

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1.0 INTRODUCTION

This report presents thermal expansion characteristics of Unthermalized, Thermalized As-Rolled, and Thermalized Rerolled Pyrofoil.

1.1 TEST IDENTIFICATION

1.1.1 Type Of Report

This report is a final report.

1.1.2 Applicable Scope of Test Document

64DE-310-1, July 23, 1969, Scope of Test for Thermal Expansion of R-1 Pyrofoil Wrapper Simulation.

1.1.3 Functional Category of Test

This is a development-type test and data generated will be used to support thermal and Stress Analysis needed to verify Paragraphs 3.1.1.1.1.3.1 and 3.1.1.1.1.2 of EC-677564.

1.1.4 Contractor

The Westinghouse Astronuclear Laboratory (WANL/14683), under Subcontract NP-1, CY'70 is the contractor.

1.1.5 Identification of Test Facility, Location and Dates of Test

Engineering Mechanics Laboratory, Furnace Room, Building 8; May 28, 1969 through December 23, 1969.

1.2 PURPOSE OF TEST

The objective of this series of tests is to determine the transverse thermal expansion characteristics of the pyrofoil wrapper material.

2.0 REFERENCES AND ASSUMPTIONS

2.1 REFERENCES

*EML DRM 52540	Test Plan for W. O. 00677, Component Tests TS:064DM-224
EML DRM 52541	Current Status Report of Test Program 64DE-310-1
Letter EM-7968	Test Specification 30141-1 - Report, N.P. Spofford, September 30, 1969
WANL-PDS-30182-2	Purchasing Department Specification for Graphite Tape
**WANL-PDS-30141-1	Purchasing Department Specification for Graphite Tape, Thermalized and Rerolled.
WANL-PDS-30182-1	Purchasing Department Specification for Graphite Tape Thermalized as Rolled

2.2 ASSUMPTIONS

The primary assumptions made in this test series are:

That the top and bottom blocks remain parallel to one another so that the compaction load is distributed evenly over the 1.00" x 1.25" cross-section of the test "build".

That as the top and bottom blocks move they remain parallel to one another so that the knife edges represent a true indication of the relative positions of the top and bottom layers of pyrofoil. It is further assumed that any deformation due to non-uniform thermal growth of the graphite top and bottom blocks themselves does not affect the parallelism of the knife-edges optical sighting surfaces of the blocks.

*The test procedure used in this test series is identical to that outlined in WANL DRM 52540 (test plan for Work Order 00677 tests conducted for WANL Quality Engineering.
**PDS 30141-1, Thermalized Rerolled Pyrofoil, replaced PDS 30182-1, Thermalized As-Rolled Pyrofoil, in the test program because of improved ductility characteristics and tighter thickness tolerance control.

3.0 DESCRIPTION OF TEST ARTICLE

Twenty-six (26) pieces of Pyrofoil, 1.00" x 1.25", are carefully cut with the X-ACTO knife and stacked on top of one another with no petrolatum mixture. The stack thickness is measured to the nearest 0.0001 inch with a 1.00-inch hand micrometer, and the stack is then weighed on the Mettler Micro-Balance to the nearest 0.0001 gram. The twenty-six (26) layers are then taken apart and reassembled using the Petrolatum-in-Benzene bonding mixture to stick the layers together. The stack thickness and weight are again measured and recorded. Then the assembled stack is placed between the Upper and Lower Blocks and the Shaft is mounted over the Pin in the Upper Block, as shown in Figure 3-1. The assembly is then positioned in the EML 6 x 10 Furnace, and the furnace is closed and sealed. The vacuum pump is turned on and the furnace evacuated, backfilled, and purged with Argon gas. The RATIOTROL crosshead drive is started, and a constant load equivalent to the desired compaction pressure is applied to the Pyrofoil stack. This constant load may be varied throughout the run. While the furnace is still at room temperature prior to turning on furnace power, a light source is positioned behind the furnace so that it will shine through the rear sight ports and illuminate the test fixture and permit alignment of the Gaertner Cathetometer with the knife edges of the Upper Block and Lower Block. The crosshair reticle of the upper scope is centered on one of the knife edges, and the scope is focused to give a clear image. The vertical position of the cathetometer is set so as to provide sufficient up-and-down motion of the upper scope to permit viewing of both knife edges. Then the scope is adjusted until the crosshair reticle lines up with the knife edges of the Upper Block. A position reading is taken to the nearest 0.0001 inch on the vernier scale of the scope position drive screw. The scope is then lowered until the crosshair reticle lines up with the knife edge of the Lower Block, and a new position reading is taken. The difference of the two readings represents the distance between knife edges, and consequently, the thickness of the Pyrofoil stack under a compaction load of 10 psi. One similar set of readings is made at room temperature with just the dead weight of the upper block, shaft, and pin resting on the Pyrofoil stack prior to applying the pressure.

Figure 3-1 Exploded View of Fixturing for Transverse Pyrofoil Growth Test

Next, the light source is removed, and preparations are made for the elevated temperature heatup. Furnace power is turned on under the Argon gas purge while the compaction load is maintained constant. The fixture temperature is monitored with the optical pyrometer through the rear sight port of the furnace while the knife edges of the Upper Block and Lower Block are observed through the front sight port using the Gaertner Cathetometer. Once the fixturing has reached a temperature that is within the visible red range, the knife edges are in sharp contrast with the dark background of the opposite rear sight port, making it possible to take good, clear sightings.

Readings are taken every 500°R starting at 1000°R and continuing up to the peak temperature of 5000°R and then every 1000°R back down to room temperature following shutdown of furnace power. The entire cycle, including cooldown, requires about 6-8 hours to complete which limits the testing rate to one cycle per working day with single-shift operations. The subsequent cycles are run in the same manner as the first, and the test specimen is left in place in the furnace between cycles. The zero point (or the "L" at room temperature with 10 psi compaction load at the start of the first cycle) is used as the same reference point in both cycles. The data are presented in graphical plot form (see the actual sample two-cycle curve shown in Figures 4-2 thru 4-5 of this report) as well as in tabular form on the customary laboratory log book pages.

The curves on Figure 4-1 illustrate a variation of the standard testing procedure. In these tests, Builds No. 3 and 4 were assembled in the conventional manner (Build No. 3 without petrolatum and Build No. 4 with petrolatum) and then, subjected to only the 1.4 psi compaction load due to the "dead-weight" of the fixturing, optical measurements of the stack thickness were made. Each build was then heated to 4000°R and allowed to expand unrestrained. Once the system had reached equilibrium optical measurements were again made of the stack thickness incrementally, and the resulting reduction in thickness was measured. A curve of Compaction Pressure versus Reduction in Thickness was plotted for

each build, and these curves are presented in Figure 4-5. From these curves, it is possible to determine the compaction pressure necessary to restore the stack to its original room temperature thickness while its at temperatures of 2000°R, 3000°R, 4000°R and 5000°R as specified in Test Scope 64DE-310-0, although only the 4000°R data were obtained.

The following equipment and materials were used in this test series:

- 1) Gaertner Cathetometer (Optical Measuring Instrument)
- 2) "PYRO" Triple-Range Micro-Optical Pyrometer
- 3) ATJ Graphite Special Fixturing (see Figures A-1 and A-2, Appendix A)
- 4) Starrett 1.000-inch Hand Micrometer (for measuring pyrofoil thickness)
- 5) Mettler Micro-Balance (for weighing Pyrofoil specimens)
- 6) EML 6 x 10 Standard Furnace
- 7) X-ACTO Craft Knife (for cutting Pyrofoil specimens)
- 8) PDS 30141-1 (Thermalized Re-Rolled Pyrofoil)
- 9) Petrolatum (WANL-PDS-30189) cut with benzene (for bonding Pyrofoil layers together)
- 10) PDS 30182-2 (Unthermalized Pyrofoil)
- 11) PDS 30182-1 (Thermalized As-Rolled Pyrofoil)

4.0 SUMMARY OF TESTS

4.1 NARRATIVE

DRM 52541 (issued April 28, 1970) summarizes the various tests which were run and the reasons for the deviations from the Scope of Test document as issued.

4.2 TEST CONDITIONS

It should be noted that at the request of WANL Reactor Design several changes to the original test scope document were made by written and verbal agreement. The various assemblies and test conditions are listed below. The combinations of assemblies and test conditions which were tested are listed in Table A-1, summary of tests completed.

4.2.1 Test Builds (Also referred to as Test Coupons)

4.2.1.1 Unthermalized pyrofoil (PDS 30182-2) without petrolatum.

4.2.1.2 Unthermalized pyrofoil (PDS 30182-2) with petrolatum*.

4.2.1.3 Thermalized pyrofoil (PDS 30141-1) without petrolatum.

4.2.1.4 Thermalized pyrofoil (PDS 30141-1) with petrolatum*.

4.2.2 Temperature Ranges

**4.2.2.1 Room temperature (535°R) to 1000°R.

4.2.2.2 Room temperature (535°R) to 2000°R.

**4.2.2.3 Room temperature (535°R) to 2500°R.

4.2.2.4 Room temperature (535°R) to 3000°R.

**4.2.2.5 Room temperature (535°R) to 3500°R.

4.2.2.6 Room temperature (535°R) to 4000°R.

4.2.2.7 Room temperature (535°R) to 5000°R.

*A mixture of petrolatum (WANL PDS-30189-1) cut with benzene is spread between the various layers of pyrofoil and serves only as a bonding agent during assembly. This bonding agent volatilizes completely and disappears during the first heatup cycle leaving no perceptable residue.

**Represents additional test points not covered by the original test scope document. Refer to Table A for actual data.

4.2.3 Constant Internal Compaction Pressures

1.4 (due to dead-weight of fixturing only), 5, 10, 15, 30, and 60 psi.

4.2.4 Number of Repeated Successive Thermal Cycles

4.2.4.1 1 Cycle - Build No. 1, 2, 2-1, 3, 4, 21, 22, 23, 24, 25, 26, 27, 30, 32, 33, 34, 35, 36 and 37.

4.2.4.2 2 Cycles - Build No. 7, 28, 29, 31, 38, 39, 40, 41, 42 and 43.

4.2.4.3 3 Cycles - Build No. 5, 6, 8, 10, 12, 14, 15 and 18.

4.2.4.4 4 Cycles - Build No. 11.

4.2.4.5 6 Cycles - Build No. 9 and 13.

4.2.4.6 10 Cycles - Build No. 20.

4.2.4.7 11 Cycles - Build No. 19.

4.2.5 Other Parameters

Build No. 3 (26 layers of unthermalized pyrofoil without petrolatum) and Build No. 4 (26 layers of unthermalized pyrofoil with petrolatum) were allowed to heat up to 4000°R and expand unrestrained except for the 1.4 psi compaction force due to the dead weight of the top block and the shaft. The expansion was monitored with Gaertner Cathetometer, and once the temperature had reached 4000°R and both the temperature and thermal expansion of the pyrofoil stack had reached equilibrium, the compaction load was increased incrementally and the resulting incremental compaction measured and recorded. From a plot of these data, the compaction pressure required to restore the stack to its original unrestrained thickness at 4000°R could be determined. The results of these two tests are shown on the curve of Figure 4-1.

Build No. 22 and 23 were tested to slow heat-up rates described in Table A-1 (Pages A-2 through A-7) for one cycle only.

4.3 TEST RESULTS

4.3.1 Recorded Data

Table A-1 presents a tabular summary of the data obtained from Test Build No. 1 through 43. Figures 4-2 through 4-5 show typical two-cycle thickness change versus temperature plots.

4.3.2 Discussion of Data

Figures 4-2 thru 4-5 illustrate typical plots of the observed thickness-change measurements as a function of temperature under a constant 10 psi compaction pressure. It should be noted that the reference starting point 0.000 is taken as the as-assembled thickness of the 26-layer pyrofoil stack with petrolatum-benzene bonding solution (adding up to .006 inches to the total thickness in place). As the curves clearly illustrate, the shrinking effect of outgassing of the petrolatum-benzene mixture from between the layers of pyrofoil during the first cycle greatly overshadows that of the expansion of the individual layers to the extent that up to about 1000°R the net effect is a reduction in observed thickness at which time the stack begins to grow. Beyond the point of minimum thickness for unthermallyzed pyrofoil, (see Figures 4-2 and 4-3), the curves progress erratically up to peak temperatures approximating 3500°R to 4000°R where the bonding agents within the material matrix are completely volatilized. The material thickness then contracts until the end of the temperature range is reached. After a ten minute soak period, at which time the temperature is maintained nearly constant, the power is shut off and the build is allowed to furnace-cool in the protective helium atmosphere. Thickness readings are taken at regular intervals during the cooldown while the 10 psi compaction pressure is maintained constant. Once the entire furnace hot-zone has reached equilibrium at room temperature, a final

thickness reading is taken before the power is turned on to start the heatup ramp for the second thermal cycle. This time, since all the petrolatum has disappeared, the thermal expansion curve is nearly a straight-line function all the way to peak temperature. If the pyrofoil is thermally stable, the thickness readings at the beginning and end of the second cycle should be nearly identical.

Figure 4-4 and 4-5 show the minimum thickness point for thermalized rerolled pyrofoil to be under 1000°R during the first cycle as well. The curve proceeds in nearly a straight line function up to the peak temperature at the end of the temperature range like the unthermalized pyrofoil did during its second cycle. The cooldown and subsequent second heat up cycle for the thermalized rerolled pyrofoil are repeated the same as previously described for the unthermalized pyrofoil. To assure thickness stability at the beginning and end of subsequent cycles, PDS 30141-1 (Graphite Tape, Thermalized and Rerolled) states under paragraph 3.0 (Requirements):

"3.3.3 Transverse Growth: The thermalized and rerolled material shall exhibit no more than 1% permanent growth in the transverse direction after further cycling to 2500°C under a 10 psi compaction load."
(Note: 2500°C is equivalent to 4992°R)

Since the point of minimum thickness occurs during the first thermal cycle (as shown in Figures 4-2 thru 4-5) due to the outgassing of the petrolatum-benzene mixture, it is impossible to select a true "zero" point until the second thermal cycle. Only a comparison of initial and final thickness under the 10 psi compaction load for the cycle free of the effect of the petrolatum will give a true indication of the amount of residual permanent thermal growth. The only practical purpose served by the first of the two cycles is the volatilization of the petrolatum-benzene mixture, but it is impossible to extrapolate back to a "zero" reference point for this cycle.

The curves in Figure 4-1 show the amount of compaction pressure required to

restore two 26-layer builds of pyrofoil to their original room temperature thickness after being heated to 4000°R. It must be remembered that in the case of Build No. 4 the initial thickness, as measured, includes some 0.005-0.006 inch of petrolatum which volatilizes and "boils off" during heat-up. Consequently, the actual thickness of pyrofoil is 0.005-0.006 inch less than measured, which means that an even higher compaction pressure will be required to return the stack to its correct initial thickness without petrolatum.

Figure 4-1. Deflection of Thermally-Expanded Pyrofoil Stack in Compression from Maximum Thickness Measured at Constant Temperature as a Function of Compaction Pressure

Figure 4-2 Typical Change-in-Thickness vs. Temperature Plot for Unthermalized Pyrofoil

Figure 4-3. Typical Percentage-Change-in-Thickness vs. Temperature for Unthermalized Pyrofoil

Figure 4-4. Typical Change-in-Thickness vs. Temperature Plot for Thermalized Pyrofoil

Figure 4-5. Typical Percentage-Change-in-Thickness vs Temperature for Thermalized Pyrofoil

5.0 ANALYSES

It was believed that thermal expansion of pyrofoil might have contributed to the breakage experienced in the 64DT-031 wrapper cyclic strain test. Data were obtained to ascertain whether this was true and to facilitate better wrapper design in future tests. These data are analyzed in this section to show the effects of thermal expansion on the 64DT-031 cyclic strain test.

From DRM 51543, the maximum thermal growth in the 64DT-031 cyclic strain test of the inner core, simulated elements, pyrotiles, and filler strips was determined to be 12 mils at Station 40, the station of maximum operating temperatures in the test rig. The lateral support plunger springs in the test build were shimmed to allow 30 mils nominal plunger gap clearance to assure compatibility between the expanded core assembly and the lateral support system. Thus, the allowable expansion envelope of the maximum temperature point for the 180 mils nominal thickness of the pyrofoil wrapper in the 64DT-031 test build was:

$$30 \text{ mils} - 12 \text{ mils} = 18 \text{ mils}$$

In terms of allowable percent expansion of the wrapper material thickness, this amounted to:

$$\frac{\Delta t}{t} = \frac{.018}{.180} = 10\%$$

From DRM 51473, the maximum average material temperature of the pyrofoil wrapper at Station 40 in the 64DT-031 test was calculated to be 2875°R. Based on the test results in Section 4.0, the percent expansion of a typical unthermalized (PDS 30182-2) pyrofoil wrapper assembly specimen (see Figure 4-2) at this temperature was determined to be:

Change in specimen thickness from R.T. to 2875°R, under 10 psi load, Δt = .0215 inches

Initial specimen thickness prior to startup of test assembly in Figure 4-3, t = .1444 inches

$$\text{Percent Expansion, } \frac{\Delta t}{t} = \frac{.0215}{.1444} = 15\%^*$$

This is 1.5 times the allowable percent expansion calculated for the test rig previously calculated showing that a probable interference condition was developed in the 031 test rig from the thermal expansion of the unthermalized pyrofoil.

If thermalized-rerolled (PDS 30141-1) pyrofoil wrapper material had been used in the test build and operated at the average material temperature of 2875°R, the percent expansion based on the test results plotted in Figure 4-4, would have been:

Change in specimen thickness from R.T. to 2875°R, under 10 psi load, Δt = - .0004 inches

Initial specimen thickness prior to startup of test assembly in Figure 4-4, t = .1480 inches

$$\text{Percent Compaction, } \frac{\Delta t}{t} = - \frac{.0004}{.1480} = - 0.27\%^{**}$$

The percent compaction condition at the above temperature for this typical specimen assembly existed after the petrolatum used as an assembly aid in stacking the pyrofoil layers was completely volatilized. Even with the uncertainties due to this volatilization, the thermal expansion of the thermalized-rerolled pyrofoil is seen to be a small fraction of the allowable expansion.

*Figure 4-3 represents the percent change in thickness of the specimen over the temperature range tested.

**Figure 4-5 represents the percent change in thickness of the specimen over the temperature range tested.

6.0 CONCLUSIONS

Based on the data and analysis presented earlier in the report, the thermal expansion, exclusive of the effects of decompression, of unthermalized (PDS 30182-2) pyrofoil is large enough to cause dimensional interference and breakage of seal segments and plunger retention caps at the higher temperature region as observed in the 64DT-031 cyclic strain test build. However, this mechanism would not account for the breakage at the cooler regions of the test rig.

If the thermalized-rerolled (PDS 30141-1) pyrofoil had been available for use in the 64DT-031 test build, its thermal expansion without decompression effects, would not have been a contributor to breakage of the same components in the test.

Based on these data, thermalized-rerolled (PDS 30141-1) pyrofoil wrapper material was selected for the 64DT-211 and 64DT-212 periphery corrosion tests and contributed to their operation without similar damage.

The unstable expansion characteristics of the unthermalized pyrofoil are not considered desirable, because a substitute such as the thermalized rerolled pyrofoil material is available. However, in the 75-minute R-1 reactor, either material could probably have been used without damage from the pyrofoil thermal expansion. The large diameter of the reactor relative to the TFFL test build makes the effect of the increased expansion of unthermalized pyrofoil produce only a small increment relative to the basic core thermal expansion. This incremental increase of expansion would readily be accommodated by the reflector lateral support system. The thermalized pyrofoil with increased dimensional stability promises a more predictable reactor.

APPENDIX A

SCOPE OF TEST DOCUMENTS - 64DE-310-0 AND 64DE-310-1

TABLE A-1

SUMMARY OF TESTS COMPLETED

Build No.	No. of Cycles Run	Type of Foil Used in Build	No. of Layers	Petrolatum Used In Ass'y	Maximum Test Temperature (°R.)	Compaction Pressure ▲ (PSI)	Remarks
1	1	Unthermalized Flat	26	No	4000	1.4	No Restraint
2	-	Unthermalized Flat	26	Yes	RT	1.4	No Restraint, Run Aborted (133 lbs. to compress back to .132 - 26 layers)
2-1	1	Unthermalized Flat	26	Yes	4000	1.4	238 lbs to compress back to .141, .012 expansion after load released.
3	1	Unthermalized Flat	26	No	4000	1.4	450 lbs to compress back to .133 at 4000°R.
4	1	Unthermalized Flat	26	Yes	4000	1.4	425 lbs. to compress back to .1392 at 4000°R.
5	3	Unthermalized Flat	26	Yes	No. 1 4000 No. 2 4000 No. 3 4000	1.4, 30 1.4, 30 1.4, 30	$\Delta = .0268$ at 3475°R. $\Delta = .0220$ at 3965°R. $\Delta = .0208$ at 3990°R.
6	3	Unthermalized Flat	26	Yes	No. 1 4000 No. 2 4000 No. 3 4000	1.4, 60 1.4, 60 1.4, 60	$\Delta = .0252$ at 3000°R. $\Delta = .0131$ at 4000°R. $\Delta = .0120$ at 4000°R.

▲ NOTE: The first figure in the "Compaction Pressure" column is that initial load due only to the "dead weight" of the loading block assembly. An initial stack thickness reading was taken under this condition for information purposes only.

TABLE A-1 (CONTINUED)

A-3	7	2	Unthermalized Flat	26	Yes	No. 1 4000	1.4, 15	$\Delta = .0258$ at 4000°R.
						No. 2 4000	1.4, 15	$\Delta = .0219$ at 4000°R.
	8	3	Unthermalized Flat	26	Yes	No. 1 4000	1.4, 15	$\Delta = .0030$ at 3500°R.
						No. 2 4000	1.4, 15	$\Delta = .0024$ at 4000°R.
						No. 3 4000	1.4, 15	$\Delta = .0025$ at 4000°R.
	9	6	Unthermalized Flat	26	Yes	No. 1 1000	5	$\Delta = .0030$ at 1000°R.
						No. 2 1000	5	$\Delta = .0034$ at 1000°R.
						No. 3 1000	5	$\Delta = .0035$ at 1000°R.
						No. 4 1000	5	$\Delta = .0038$ at 1000°R.
						No. 5 1000	5	$\Delta = .0038$ at 1000°R.
						No. 6 1000	5	$\Delta = .0039$ at 1000°R.
	10	3	Unthermalized Flat	26	Yes	No. 1 4800	1.4, 10	$\Delta = .0284$ at 4000°R.
						No. 2 4800	1.4, 10	$\Delta = .0195$ at 4800°R.
						No. 3 4800	10	$\Delta = .0185$ at 4800°R.
	11	4	Unthermalized Flat	26	Yes	No. 1 4000	1.4, 10	$\Delta = .0067$ at 4000°R.
						No. 2 4000	1.4, 10	$\Delta = .0068$ at 4000°R.
						No. 3 4000	10	$\Delta = .0070$ at 4000°R.
						No. 4 4000	1.4, 10	$\Delta = .0068$ at 4000°R.
	12	3	Unthermalized Flat	26	Yes	No. 1 4000	1.4, 10	$\Delta = .0262$ at 4000°R.
						No. 2 4000	10	$\Delta = .0235$ at 4000°R.
						No. 3 4000	1.4, 10	$\Delta = .0226$ at 4000°R.
	13	6	Unthermalized Flat	26	Yes	No. 1 2500	5	$\Delta = .0203$ at 2000°R.
						No. 2 2500	5	$\Delta = .0199$ at 2500°R.
						No. 3 2500	5	$\Delta = .0203$ at 2500°R.

TABLE A-1 (CONTINUED)

14	3	Unthermalized Flat	26	Yes	No. 1	1700	1.4, 15	$\Delta = .0084$ at 1700°R
					No. 2	4000	15	$\Delta = .0262$ at 4000°R
					No. 3	4000	15	$\Delta = .0236$ at 4000°R
15	3	Unthermalized Flat	26	Yes	No. 1	4000	5	$\Delta = .0339$ at 3500°R
					No. 2	4000	5	$\Delta = .0294$ at 4000°R
					No. 3	4000	5	$\Delta = .0283$ at 4000°R
16	THIS BUILD WAS NOT RUN.							
17	THIS BUILD WAS NOT RUN.							
18	3	Unthermalized Flat	26	Yes	No. 1	4000	1.4	$\Delta = .0494$ at 4000°R
					No. 2	4000	1.4	$\Delta = .0462$ at 4000°R
					No. 3	4000	1.4	$\Delta = .0442$ at 4000°R
19	11	Unthermalized Flat	26	Yes	No. 1	4000	1.4	$\Delta = .0388$ at 4000°R
					No. 2	4000	1.4	$\Delta = .0354$ at 4000°R
					No. 3	4000	1.4	$\Delta = .0336$ at 4000°R
					No. 4	4000	1.4	$\Delta = .0332$ at 4000°R
					No. 5	2900	1.4	Run aborted, change filters
					No. 6	4000	1.4	$\Delta = .0312$ at 4000°R
					No. 7	4000	1.4	$\Delta = .0315$ at 4000°R
					No. 8	4000	1.4	$\Delta = .0295$ at 4000°R
					No. 9	4000	1.4	$\Delta = .0284$ at 4000°R
					No. 10	4000	1.4	$\Delta = .0276$ at 4000°R
					No. 11	4000	1.4	$\Delta = .0272$ at 4000°R

TABLE A-1 (CONTINUED)

A-5	20	10	Unthermalized Flat	26	Yes	No. 1	4000	1.4	$\Delta = .0101$ at 4000°R
						No. 2	4000	1.4	$\Delta = .0090$ at 4000°R
						No. 3	4000	1.4	$\Delta = .0097$ at 3500°R
						No. 4	4000	1.4	$\Delta = .0102$ at 4000°R
						No. 5	4000	1.4	$\Delta = .0089$ at 4000°R
						No. 6	4000	1.4	$\Delta = .0092$ at 4000°R
						No. 7	4000	1.4	$\Delta = .0087$ at 3500°R
						No. 8	4000	1.4	$\Delta = .0087$ at 4000°R
						No. 9	4000	1.4	$\Delta = .0086$ at 3500°R
						No. 10	4000	1.4	$\Delta = .0086$ at 4000°R
	21	1	Unthermalized Flat	26	Yes	No. 1	5000	1.6, 10	$\Delta = .0213$ at 3250°R ($12^{\circ}/\text{min.}$ to 5000°R)
	22	1	Unthermalized Flat	26	Yes	No. 1	4000	1.6, 10	$\Delta = .0202$ at 3500°R ($12^{\circ}/\text{min.}$ to 2500°R , then $6^{\circ}/\text{min.}$ $2500^{\circ}\text{R} - 4000^{\circ}\text{R}$)
	23	1	Unthermalized Flat	26	Yes	No. 1	3500	1.6, 10	$\Delta = .0204$ at 3250°R ($5^{\circ}/\text{min.}$ to 3500°R)
	24	1	Unthermalized Flat	26	Yes	No. 1	5000	10	$\Delta = .0259$ at 3500°R
	25	1	Unthermalized Flat	26	Yes	No. 1	5000	10	$\Delta = .0248$ at 3500°R
	26	1	Unthermalized Flat	26	Yes	No. 1	5000	10	$\Delta = .0050$ at 3750°R
	27	1	Unthermalized Flat	26	Yes	No. 1	5000	1.6, 10	$\Delta = .0085$ at 3750°R
	28	2	Thermalized Flat	26	Yes	No. 1	5000	1.6, 10	$\Delta = .0064$ at 5000°R
						No. 2	5000	1.6, 10	$\Delta = .0064$ at 5000°R
	29	2	Thermalized, Re-rolled Flat	26	Yes	No. 1	5000	1.6, 10	$\Delta = .0056$ at 4500°R

TABLE A-1 (CONTINUED)

30	1	Thermalized, Re-Rolled Flat	26	Yes	No. 1	5000	1.6, 10	$\Delta = .0103$ at 5000°R
31	2	Thermalized, Re-Rolled Flat	26	No	No. 1 No. 2	5000 5000	1.6, 10 1.6, 10	$\Delta = .0088$ at 5000°R $\Delta = .0090$ at 5000°R
32	1	Thermalized, Re-Rolled Flat	26	No	No. 1	5000	1.6, 10	$\Delta = .0099$ at 5000°R
* 33	1	Special Test Material (TFL)	26	Yes	No. 1	5000	1.6, 10	$\Delta = .0070$ at 5000°R
34	1	Thermalized, Re-Rolled Flat (Q.C.)	26	No	No. 1	5000	1.8, 10	$\Delta = .0107$ at 5000°R
* 35	1	Thermalized, Re-Rolled Flat (Q.C.)	26	No	No. 1	5000	1.8, 10	$\Delta = .0104$ at 5000°R
* 36	1	Thermalized, Re-Rolled Flat (Q.C.)	26	No	No. 1	5000	1.8, 10	$\Delta = .0087$ at 5000°R
* 37	1	Thermalized, Re-Rolled Flat (Materials)	26	No	No. 1	5000	1.8, 10	$\Delta = .0085$ at 5000°R
* 38	2	Thermalized, Re-Rolled Flat (Materials)	26	Yes	No. 1 No. 2	5000 5000	1.6, 10 1.6, 10	$\Delta = .0050$ at 5000°R $\Delta = .0054$ at 5000°R
39	2	Thermalized, Re-Rolled Flat	26	Yes	No. 1 No. 2	5000 5000	1.8, 10 1.8, 10	$\Delta = .0076$ at 5000°R $\Delta = .0074$ at 5000°R

*Indicates a special test build run for another WANL Department but under the scope of 64DE-310.

TABLE A-1 (CONTINUED)

40	2	Thermalized, Re-Rolled Flat	26	Yes	No. 1	5000	1.8, 10	$\Delta = .0062 \text{ at } 5000^{\circ}\text{R}$
					No. 2	5000	1.8, 10	$\Delta = .0056 \text{ at } 5000^{\circ}\text{R}$
41	2	Thermalized, Re-Rolled Flat	26	Yes	No. 1	5000	1.8, 10	$\Delta = .0069 \text{ at } 5000^{\circ}\text{R}$
					No. 2	5000	1.8, 10	$\Delta = .0069 \text{ at } 5000^{\circ}\text{R}$
42	2	Thermalized, Re-Rolled Flat	26	Yes	No. 1	5000	1.8, 10	$\Delta = .0060 \text{ at } 5000^{\circ}\text{R}$
					No. 2	5000	1.8, 10	$\Delta = .0057 \text{ at } 5000^{\circ}\text{R}$
43	2	Thermalized Flat	26	Yes	No. 1	5000	1.6, 10	$\Delta = .0024 \text{ at } 5000^{\circ}\text{R}$
					No. 2	5000	1.6, 10	$\Delta = .0020 \text{ at } 5000^{\circ}\text{R}$

Figure A-1 Pyrofoil Compression Assembly (Exploded View)

Figure A-2 Pyrofoil Compression Assembly (Front View)

Figure A-3 Pyrofoil Compression Assembly (Right-Side View)

Figure A-4 Taking Optical Sighting on Upper & Lower Block Targets

TITLE Thermal Expansion Characteristics of Unthermalized and Thermalized Rerolled Pyrofoil	
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ABSTRACT A series of tests were performed to compare the transverse thermal expansion characteristics of unthermalized (PDS 30182-2) pyrofoil and thermalized rerolled (PDS 30141-1) pyrofoil. The unthermalized pyrofoil exhibited thermal expansion up to ten (10) times that of thermalized rerolled pyrofoil over the same temperature range up to the temperature of thermalization.			
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