

Transient Heat Transfer in TCAP Coils

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by

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TRANSIENT HEAT TRANSFER IN TCAP COILS (U)

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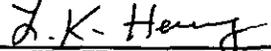
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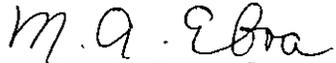
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ABSTRACT

The Thermal Cycling Absorption Process (TCAP) is used to separate isotopes of hydrogen. TCAP involves passing a stream of mixed hydrogen isotopes through palladium deposited on kieselguhr (Pd/k) while cycling the temperature of the Pd/k. Kieselguhr is a silica mineral also called diatomite. To aid in the design of a full scale facility, the Thermal Fluids Laboratory was asked by the Chemical and Hydrogen Technology Section to compare the heat transfer properties of three different configurations of stainless steel coils containing kieselguhr and helium. Testing of coils containing Pd/k and hydrogen isotopes would have been more prototypical but would have been too expensive.

Three stainless steel coils filled with kieselguhr were tested; one made from 2.0" diameter tubing, one made from 2.0" diameter tubing with foam copper embedded in the kieselguhr and one made from 1.25" diameter tubing. It was known prior to testing that increasing the tubing diameter from 1.25" to 2.0" would slow the rate of temperature change. The primary purpose of the testing was to measure to what extent the presence of copper foam in a 2.0" tubing coil would compensate for the effect of larger diameter. Each coil was connected to a pressure gage and the coil was evacuated and backfilled with helium gas. Helium was used instead of a mixture of hydrogen isotopes for reasons of safety. Each coil was quickly immersed in a stirred bath of ethylene glycol at a temperature of approximately 100°C. The coil pressure increased, reflecting the increase in average temperature of its contents. The pressure transient was recorded as a function of time after immersion.

The 2.0" coil with the added copper and the 1.25" coil both heated approximately 2.5 times as fast as the 2.0" coil. Therefore, adding copper foam compensates for the larger diameter. Thermal diffusivities were calculated for all runs. As expected, the thermal diffusivity of kieselguhr (no copper) was independent of tubing diameter. Thermal diffusivity, density and specific heat were used to calculate thermal conductivity. At one atmosphere of helium pressure the thermal diffusivity for kieselguhr (no copper) was 0.021 ± 0.002 ft²/hr.

Because the actual process will use Pd/k instead of kieselguhr, additional tests were run to determine the differences in thermal properties between the two materials. The method was to position a thermocouple at the center of a hollow sphere and pack the sphere with Pd/k. The sphere was sealed, quickly submerged in a bath of boiling water and the temperature transient was recorded. The sphere was then opened, the Pd/k was replaced with kieselguhr and the transient was repeated. The response was a factor of 1.4 faster for Pd/k than for kieselguhr, implying a thermal diffusivity approximately 40% higher than for kieselguhr. Another implication is that the transient tests with the coils would have proceeded faster if the coils had been filled with Pd/k rather than kieselguhr.

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1. INTRODUCTION

1.1 Background

The Thermal Cycling Absorption Process (TCAP) is used to separate isotopes of hydrogen [1]. TCAP involves passing a stream of mixed hydrogen isotopes through palladium absorbed on kieselguhr (Pd/k) while cycling the temperature of the Pd/k. Kieselguhr is a silica mineral also called diatomite. To aid in the design of a full scale facility, the Thermal Fluids Laboratory was asked by the Chemical and Hydrogen Technology Section to measure effective thermal conductivities and thermal diffusivities for three different configurations of stainless steel coils containing Pd/k. A Task Plan was prepared for this task [2].

1.2. Previous work

Suissa, et al. [3] measured the effective thermal conductivities of two metal hydrides as a function of hydrogen pressure. They found that increasing hydrogen pressure from 2 atm to 5 atm increased the effective thermal conductivity by 5%. They also concluded that the effective thermal conductivity consists of two terms in parallel; the thermal conductivity of the bulk solid and the thermal conductivity of the gas.

Lin, Watson and Fisher [4] measured the thermal conductivity of iron-titanium alloy powders. They found that packing the powder in the pores of aluminum foam with a void fraction of 92% increased the thermal conductivity 40% over that measured for powder alone.

2. EXPERIMENTAL WORK

2.1 Description of Coils and Sphere

Three coils were made from stainless steel tubing with a wall thickness of 0.065". Coil #1, the base case, was made from 2" OD tubing bent into a coil having 2.4 turns and an outer diameter of 16". A 2" diameter stainless steel disk was welded to each end of the coil and a pipe nipple was welded to one of the disks. Kieselguhr was poured into the coil through the nipple. A tee and two valves were attached to the nipple so that the coil could be independently connected to a pressure gage and to either a vacuum pump or a cylinder of helium gas. Coil #2 was like Coil #1 except that it also contained foam copper, it had 1.1 turns and the outer diameter was 21.5". The foam copper is 93.2% void and has an average pore diameter of 0.050". Coil #3 contained only kieselguhr, had a tubing OD of 1.25", 1.75 turns and an outer diameter of 11". The following table lists material properties. Pd/k is 50 wt % palladium on kieselguhr.

Table 1 Properties of Materials

material	kieselguhr in air	kieselguhr in He	Pd/k in He	copper	stainless steel	aluminum
density, lb/ft ³	28	28	43	558	488	169
thermal conductivity, btu/ft hr F	0.021 - 0.042	0.13*	0.17*	218	9.4	119
specific heat, btu/lb F	0.21	0.21	0.13	0.091	0.11	0.208
thermal diffusivity, ft ² /hr	0.0036 - 0.0072	0.022	0.031* * estimated	4.29	0.175	3.38

The properties of metals are from Kreith [5]. Thermal conductivities for kieselguhr in air were found in References 5, 6 and 7 and its specific heat was found in Reference 6. The specific heat listed for Pd/k is the mass weighted average of the specific heats for kieselguhr and palladium. The densities of kieselguhr and Pd/k were measured in the TFL by weighing a volume of powder measured in a volumetric cylinder. The estimation of the thermal conductivity and thermal diffusivity for kieselguhr in helium and Pd/k will be discussed in Sections 3.3 and 3.4 of this report.

The actual TCAP process would use palladium absorbed on kieselguhr, Pd/k. The tests reported here were conducted with kieselguhr only because insufficient Pd/k was available to fill a coil. A smaller scale test was conducted to allow a comparison of the thermal response of kieselguhr and Pd/k. Three holes were drilled into a hollow stainless steel sphere with an outer diameter of 2.56" and a wall thickness of 0.016". A 0.032" diameter thermocouple was silver soldered in one hole so that its tip was at the center of the sphere. A 3/16" outside diameter tube was silver soldered to the second hole of the sphere. The sphere was filled with Pd/k using the third hole and the hole was sealed with a disk of stainless steel and epoxy. The sphere was weighed before and after filling so that the mass of Pd/k could be calculated. A Tygon tube was used to connect the 3/16" stainless steel tube to a vacuum pump and a vacuum was pulled on the sphere overnight. Then the sphere was backfilled with helium at 1.0 atmosphere. The sphere was sealed by pinching the Tygon tube. Two thermal transient tests were conducted with this configuration. Later, the disk was removed, the Pd/k was replaced with kieselguhr and the process was repeated.

The tests were conducted with helium gas instead of hydrogen isotopes for safety reasons. The thermal conductivities of helium, hydrogen and deuterium at 120°F are 0.091, 0.114 and 0.086 btu/ft hr F [6]. Using linear extrapolation for hydrogen isotopes, the thermal conductivity of tritium is expected to be 0.058 btu/ft hr F. Therefore, helium is a reasonable substitute for a mixture of hydrogen isotopes.

2.2 Description of Test Facility and Instrumentation

The test facility for testing the three stainless steel coils is shown in Figure 1 and consisted of an insulated stainless steel tank, an agitator, an electric hoist, two 1000 watt electric heaters, instrumentation and a data acquisition system. The tank had a diameter of 30" and a height of 31". The agitator had a three bladed impeller with a diameter of 11" which was rotated at 1800 rpm by a motor mounted on the tank cover. The coil to be tested was suspended 18" below the tank cover and 4" above the impeller.

The coil was connected to one of two pressure gages using 1/4" tubing. Pressure transducer TR-3553 was used to measure pressures for the runs that began at pressures of 1 atm and 5 atm. Transducer TR-2180-2 was used for the runs that began at 5 torr. Four temperatures inside the tank were measured with Type J thermocouples; TR-3123, TR-1322, TR-1335, TR-1233, TR-1055. The thermocouples were accurate to within $\pm 2^\circ\text{C}$. Ambient temperature was measured using thermocouple TR-1055 or thermometer TR-2896. The data acquisition software was Labview V5.0. Tank temperature was controlled using an E type thermocouple connected to an Omega CN9000A controller.

Two 12" long aluminum bars with diameters of 2.00" and 1.50" were prepared to allow the measurement of heat transfer coefficient in the stirred tank. Both bars had a hole drilled down the axis to the center. A type J thermocouple was inserted into each hole to the center and sealed with Scotchcast resin.

2.3 Abbreviated Test Procedure

Testing was conducted using a written procedure [8]. The coil to be tested was connected to a vacuum pump and a pressure gage and placed in an oven maintained at 100°C. Coils #1 and #3 were kept in the oven for about three days to bake moisture out of the kieselguhr. It should be noted that the coils were still evolving water vapor at the end of several days. For example, the pressure inside Coil #1 was 2 torr after three days in the oven while being evacuated with a vacuum pump. When the valve between the coil and the vacuum pump was closed the pressure on the vacuum pump side of the valve decreased to 0.5 torr. A leak check was performed to eliminate a leak as the reason that the pressure was higher when the coil was connected to the pressure gage and vacuum pump. Coil #2 was not placed in the oven because it was too large. However, it was maintained at a vacuum for a longer period than the other coils. After being disconnected from the vacuum pump it maintained a pressure of 1 torr.

Heaters #1 and #2 were used to heat the ethylene glycol to the operating temperature of approximately 100°C. To perform a test run, heater #2 and its controller were used to maintain the temperature. The tank cover / agitator assembly was raised using the hoist and a lightweight insulating cover was placed over the tank to reduce heat loss. The coil to be tested was mounted below the tank cover and a 1/4" stainless steel tube was used to connect it to a pressure gage. The coil was again connected to a vacuum pump. After evacuation, the coil was backfilled with helium at the desired pressure; either 5 torr, 1 atm or 5 atm. Note that helium was used instead of hydrogen for safety reasons, because of the residual water vapor, the contents of the coils were a mixture of helium and water vapor. Water vapor formed a negligible fraction of the total gas at 1 atm and 5 atm but roughly half of the total gas at 5 torr. Data logging was begun on the DAS, the lightweight cover was removed, the tank cover / agitator assembly was lowered into the ethylene glycol and the agitator was energized. Data logging continued until the rate of pressure increase was small. For some runs data logging was performed at a high rate at the start of the run and at a lower rate when the rate of pressure changes became smaller. No tank agitation was used for the very last run to allow an estimate of the effect of tank agitation. A total of thirty transients were run with the three coils, although two of the transients were not usable. Laboratory Notebook SRT-ETF-980032 was used for this task. Data logs were identified in the notebook by date and time.

Heat transfer coefficient was measured in the following way. The coil was removed from the tank cover / agitator assembly and replaced with both aluminum bars. The thermocouples were connected to data acquisition system and a log was started. The assembly with the two aluminum bars was quickly lowered into the bath and the agitator was energized. Temperature transients were measured for both thermocouples. The log was stopped when the rate of temperature change became very slow. The aluminum bars were exposed to the same tank location and conditions of agitation as the coils were. Therefore, the heat transfer coefficients measured using the bars was the same as the coils were exposed to.

The spheres were tested in the following way. Three thermocouples were connected to a data acquisition system. One was the thermocouple in the sphere, another thermocouple was placed in a bath of boiling water and the third thermocouple was held outside the bath. A log was started and the sphere and the third thermocouple were simultaneously submerged in the bath. The third thermocouple served to time stamp the moment of immersion in the log. The sphere and thermocouple were kept in the bath until rate of temperature change in the sphere was very small. Then the sphere was removed from the bath and allowed to cool to room temperature. Two transients were conducted for both Pd/k and kieselguhr.

3. RESULTS OF TRANSIENT TESTS

3.1 Transient Aluminum Bar Test

The purpose of this test was to measure the heat transfer coefficient in the agitated tank. Figures 2 and 3 [9] show that the calculated surface and centerline temperatures for transient heat conduction in a long cylinder are functions of Fourier number, $\alpha t/R^2$, with Biot number, hR/k , as a parameter. The Fourier number is a normalized time. The Biot number can be thought of as the ratio of external to internal heat transfer. The terms T_0 , T_a , α , t , R , h and k are initial temperature of the cylinder, imposed ambient temperature, thermal diffusivity, time, radius, heat transfer coefficient and thermal conductivity, respectively. Thermal diffusivity is defined as

$$\alpha = k / (\rho C_p) \quad (1)$$

where ρ and C_p are density and specific heat, respectively. Figure 4 shows the measured temperature transients for the centerline temperatures of the two aluminum cylinders, as well as the average bath temperature. The same data were replotted in Figure 5 in dimensionless form. Thermal conductivity, thermal diffusivity, and radius, are known for the aluminum cylinders, see Table 1. Four of the parametric curves from Figure 3 were also plotted in Figure 5. The aluminum bar transient data fall between the parametric curves for Biot numbers of 0.1 and 0.4. The Biot numbers for the aluminum bar transients for diameters of 1.5" and 2" are estimated from Figure 5 to be 0.15 ± 0.04 and 0.2 ± 0.05 , respectively. Using the definition of Biot number and a thermal conductivity for aluminum of 119 btu/ft hr F gives an external heat transfer coefficient of 300 ± 75 btu/ft² F hr for both cylinders. Therefore, the three coils containing kieselguhr were also exposed to that heat transfer coefficient.

3.2 Transient Coil Tests

The pressure inside the coil reflects the average temperature of the contents. If the gas inside the coil can be considered to be an ideal gas, then there is exact proportionality between gas pressure and average temperature inside the coil. Any water vapor being evolved from the kieselguhr is a complication because the partial pressure of water vapor does not obey the Ideal Gas Law. The effect of evolved water vapor was significant for the 5 torr transients and negligible for the 1 atm and 5 atm transients. Therefore, the transients for 5 torr were more variable than the transients at 1 atm and 5 atm. Figures 6 through 14 show that plots of pressure versus time were approximately exponential decays. Transient pressure data were fitted to exponential form in the least squares sense. Time constant is the time required to make 63% of the total pressure change. Measured time constants for the runs follow. The letters "nu" mean that the data were not usable.

Table 3 Time Constants for TCAP Transient Tests

	Coil #1		
	5 torr	1 atm	5 atm
	490 sec	127 sec	99 sec
	700 sec	122 sec	101 sec
	500 sec	124 sec	105 sec
averages	560 sec	124 sec	102 sec

Coil #2			
	<u>5 torr</u>	<u>1 atm</u>	<u>5 atm</u>
nu	57 sec	36 sec	
nu	58 sec	39 sec	
258 sec	55 sec	39 sec	
292 sec	61 sec		
averages	275 sec	58 sec	38 sec

Coil #3			
	<u>5 torr</u>	<u>1 atm</u>	<u>5 atm</u>
260 sec	55 sec	38 sec	
268 sec	54 sec	39 sec	
258 sec	52 sec	40 sec	
averages	262 sec	54 sec	39 sec

Coil #3, no bath agitation	
	<u>1 atm</u>
	59 sec

3.3 Analysis of Transient Coil Test Data

The results of the transient tests allow analysis of three effects; the effect of changing tube diameter, the effect of changing helium pressure in the tubes and the effect of replacing some of the kieselguhr with copper foam. The effect of changing diameter was analyzed in the following way. Figure 3 was used in Section 3.1 to determine the heat transfer coefficient outside the coils. Note that the curves for Biot numbers of 10 and 1000 are nearly the same. The conclusion is that transient conduction becomes nearly insensitive to Biot number for Biot numbers greater than 10. An estimate of the thermal conductivity of kieselguhr is needed to calculate the Biot number. The International Critical Tables [7] state that the thermal conductivity of kieselguhr in air is 0.021 btu/ft hr F. For an external heat transfer coefficient of 300 btu/ft² hr F and a radius of 1.0" the Biot number is 1200. Therefore, transient heat conduction in the tubes is insensitive to changes in Biot number. This is a great simplification in the analysis of the results. Anticipation of this simplification is one of the reasons that the external heat transfer coefficient was measured.

By inspection of Figure 2 and a Biot number of 1200, the temperature of the outer surface of the cylinder reaches 95% of the temperature of the bath for a Fourier number of 0.001. Using the definition of Fourier number, a thermal diffusivity for kieselguhr of 0.0061 ft²/hr from Table 1 and a radius of 1.0 inch gives a time of 4 seconds, which is short compared to the length of the transient. Figure 15 shows transient radial temperature profiles for transient heat conduction in a solid cylinder when the surface of the cylinder instantaneously changes to a new temperature [10] which is a good approximation here. Normalized temperature is a function of radial position with Fourier number as a parameter. The data were numerically integrated over the radius of the cylinder using the following equation.

$$\bar{T} = \frac{1}{\pi R^2} \int_0^R 2\pi r T(r) dr \quad (2)$$

The resulting volume weighted average temperature is plotted in Figure 16 as function of Fourier number only. One time constant is equivalent to a 63% change in average temperature. Figure 16 shows that a 63% change in average temperature requires a Fourier number of 0.111. Knowing this relationship allows one to determine the effect of reducing diameter.

$$Fo = \alpha t / R^2 = 0.111 \quad (3)$$

Rearranging equation 3 gives

$$t = 0.111 R^2 / \alpha \quad (4)$$

Therefore, holding thermal diffusivity constant and reducing the radius from 1.00" to 0.625" reduces time by a factor of $(0.625/1.00)^2$ or 0.39. This prediction was compared with the experimental results listed in Table 3. For pressures of 5 torr, 1 atm and 5 atm the time constants for Coil #3 (1.25" diameter tubing) were 47%, 44% and 38%, respectively, as large as the time constants for Coil #1 (2.00" diameter tubing). These percentages are in reasonable agreement with the theoretical prediction of 39%.

The thermal diffusivities of the three coils were calculated using equation 3, the diameters and measured time constants with the following results.

Table 4 **Coil Thermal Diffusivity in ft²/hr**

Coil #	5 torr	1 atm	5 atm
1	0.005	0.022	0.027
2	0.010	0.048	0.073
3	0.004	0.020	0.028

Effective thermal conductivities were calculated by multiplying the thermal diffusivities in Table 4 by density and specific heat. For Coil #2 a weighted average was used for the product of density and specific heat for copper and kieselguhr. It should be noted that the thermal conductivities in Table 5 are more uncertain than the thermal diffusivities in Table 4 because they are products of three measured quantities, each having an uncertainty.

Table 5 Effective Coil Thermal Conductivity in btu/ft hr F

Coil #	5 torr	1 atm	5 atm
1	0.03	0.13	0.16
2	0.09	0.43	0.65
3	0.02	0.12	0.16

Coils #1 and #3 contain only kieselguhr and helium and have nearly the same thermal diffusivities. For comparison, the International Critical Tables gives the thermal conductivity of diatomite (kieselguhr) in air at 700 torr (0.92 atm) to be 35.6 hectoerg / cm sec C or 0.021 btu/ft hr F. The density and specific heat of kieselguhr are 28 lb/ft³ and 0.21 btu/lb F giving a thermal diffusivity of kieselguhr in air of 0.0036 ft²/hr, a factor of 6.1 less than the measured thermal diffusivity for kieselguhr in helium at 1 atm for Coil #1. However, this difference is reasonable because helium has thermal conductivity 5.6 times as large as air.

The second effect was that of changing helium pressure. The data collected with the present experiment were compared with a simple analysis. The International Critical Tables [7] list the thermal conductivity of diatomite (kieselguhr) over a range of air pressures. Air has a lower thermal conductivity than helium but the trend should be the same. The thermal conductivities for pressures of 5 torr and 700 torr are 0.008 and 0.021 btu/ft hr F. The ratio of those two thermal conductivities is 0.38. The product of density and specific heat for the mixture of kieselguhr and helium is the volume weighted sum of the product of density and specific heat for the two components. However, the density of helium is so low that the contribution from helium is negligible. This means that the product of density and specific heat is independent of helium pressure. Since thermal diffusivity is equal to thermal conductivity divided by the product of density and specific heat, a constant, the ratio of thermal diffusivities for pressures of 5 torr and 700 torr is also equal to 0.38 or 38%. For Coils #1, #2 and #3 the time constants at 1 atm were 22%, 21% and 21% of the time constants at 5 torr. Therefore, the simple technique of using published data for thermal conductivities of kieselguhr at different air pressures under predicts the effect of changing helium pressure.

The third effect was replacing some of the kieselguhr with copper foam in Coil #2. A simple analysis was tried, but was found to be unsuccessful. Rohsenow, et al. [9] suggested that the thermal conductivity of a composite could be approximated as the volume weighted average of the thermal conductivities of the components. Since thermal diffusivity rather than thermal conductivity was measured, a composite thermal diffusivity was calculated. Copper occupies 6.8% of the volume and has a thermal diffusivity of 4.4 ft²/hr. The thermal diffusivity of kieselguhr is negligible in comparison and can be ignored. The calculated composite thermal diffusivity is 0.068 times 4.4 or 0.30 ft²/hr. This is much larger than the measured thermal diffusivity of 0.048 ft²/hr for Coil #2 at 1 atm. Therefore, this suggested method does not work well. A reason may be resistance to heat flow across the interface between copper and kieselguhr.

3.4 Analysis of Transient Sphere Test Data

The purpose of this test was to allow a comparison of thermal response for Pd/k and kieselguhr. Figure 17 is a plot of normalized temperature at the center of the sphere versus time for the four transients. Normalized temperature is defined as the following

$$T_{\text{norm}} = (T - T_0) / (T_{\text{bath}} - T_0)$$

where T_0 is the initial temperature of the sphere. Note that the temperature response is slower with kieselguhr than with Pd/k. Figure 18 shows the result of dividing the times for the kieselguhr transient by a factor of 1.4. This causes the temperature curves to approximately coincide. The primary factor influencing transient heat conduction is thermal diffusivity. Therefore, as an approximation, the thermal diffusivity for Pd/k is a factor of 1.4 larger than the thermal diffusivity listed for kieselguhr in Table 4. For example, the thermal diffusivity of Pd/k in Coil #1 with helium at one atmosphere is estimated to be 0.031 ft²/hr. By extension, if the transient coil tests had been run with Pd/k instead of kieselguhr, the transients would be expected to be 40% faster.

The thermal conductivity of Pd/k in helium at one atmosphere can be estimated using the estimated thermal diffusivity, the density and specific heat listed in Table 1 and the definition of thermal diffusivity. The estimated thermal conductivity is 0.17 btu/ft hr F.

4. CONCLUSIONS

1. The three coils used in the transient tests were filled with kieselguhr instead of Pd/k. Coils #2 and #3 responded almost equally fast and more than twice as fast as Coil #1. Therefore, the use of copper foam is an effective method to compensate for effect of increasing the diameter of the tubing used in coils.
2. Thermal diffusivity was nearly the same for Coils #1 and #3, the two coils that contained only kieselguhr and helium.
3. Coils containing helium at 5 atm responded somewhat faster than coils at 1 atm. Coils containing helium at 5 torr responded much slower than coils at 1 atm. This was expected in light of Reference 1.
4. Coil #3 responded only 10% more slowly when the bath was not agitated. This effect was expected to be small because the coils were intentionally operated in a condition that internal heat conduction was nearly insensitive to the external Biot number and therefore to external heat transfer coefficient.
5. Based on the transient tests that compared the response of kieselguhr and Pd/k it is estimated that the coils would have responded approximately 40% faster if they had been filled with Pd/k rather than kieselguhr.

5. ACKNOWLEDGMENTS

Mike Armstrong constructed the test facility. Vern Bush connected the instruments and connected the data acquisition system.

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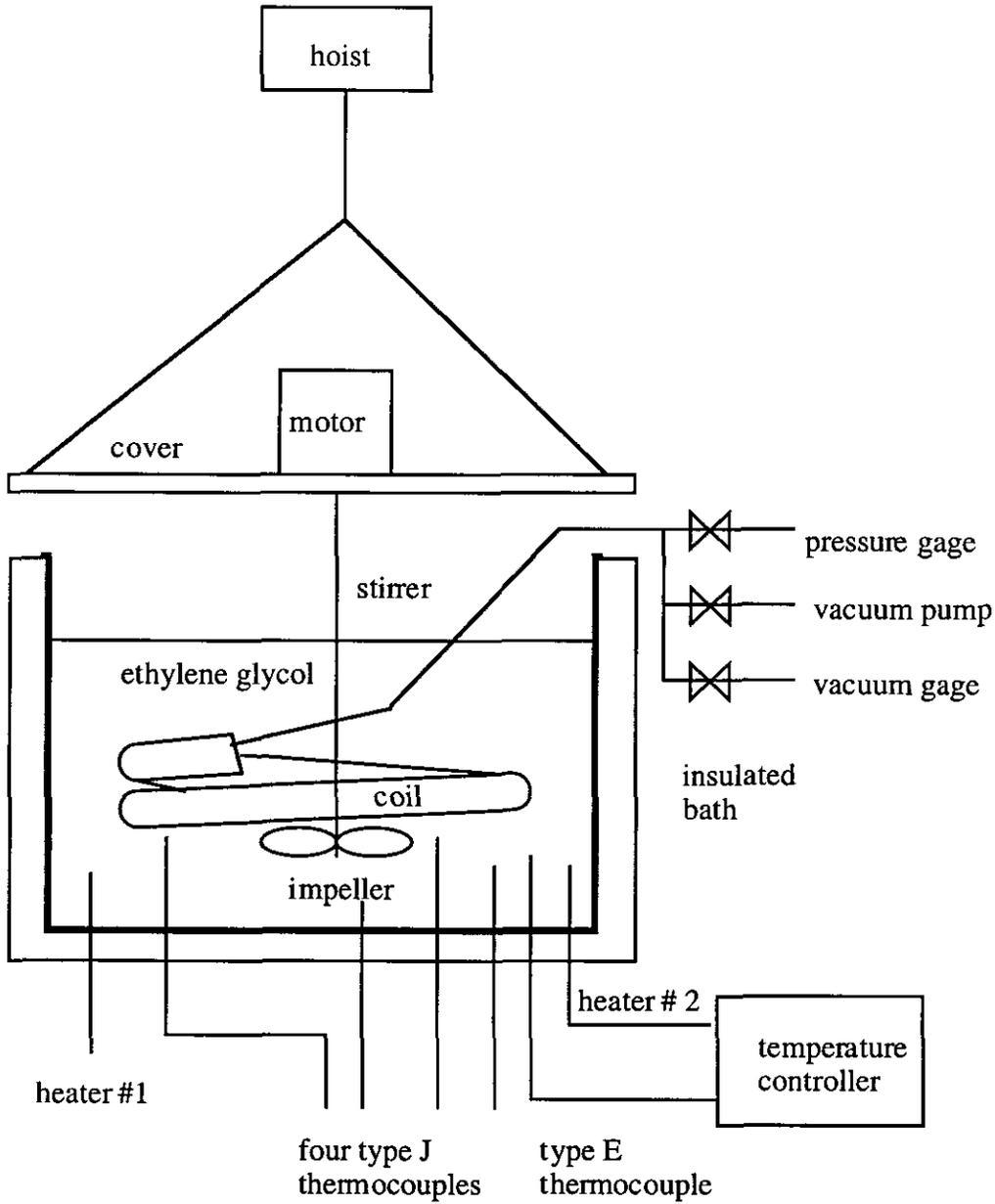
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Table 2 Listing of Log Names for Runs

Coil #1	kieselguhr only, 2" diameter tubing	
1 atm	5 atm	5 torr
TCAP 0901 1321,1325	TCAP 0901 1655	TCAP 0910 1410
TCAP 0903 1555	TCAP 0902 1036, not used	TCAP 0910 1658
TCAP 0908 1424	TCAP 0902 1624	TCAP 0911 1352
	TCAP 0903 1333	
Coil #2	kieselguhr and copper foam, 2" diameter tubing	
1 atm	5 atm	5 torr
TCAP 0911 1543	TCAP 0910 1241	TCAP 0915 1459
TCAP 0914 1237	TCAP 0910 1540	TCAP 0921 1341, 1352
TCAP 0914 1642, 1649	TCAP 0911 1241	TCAP 0922 1351, 1358
TCAP 0915 1128,1135,1159		TCAP 0923 1325, 1335
Coil #3	kieselguhr only, 1.25" diameter tubing	
1 atm	5 atm	5 torr
TCAP 0922 1612, 1617	TCAP 0915 1330, 1336	TCAP 0923 1552, 1602
TCAP 0923 1045, 1102	TCAP 0921 1618, 1623	TCAP 0921 1508, 1516
TCAP 0923 1220, 1226	TCAP 0922 1217, 1224	TCAP 0925 1428, 1447
Coil #3	kieselguhr only, 1.25" diameter, no agitation	
1 atm		
TCAP 1005 1608, 1614		
Aluminum Bar Test		
TCAP 1013 1310		

Note: A listing such as TCAP 0901 1321,1325 in the table is shorthand for two logs; log TCAP 0901 1321 was made at a high sampling rate for the initial part of the transient, followed by log TCAP 0901 1325 made at a lower sampling rate for the remainder of the transient.

Figure 1 TCAP Equipment Schematic



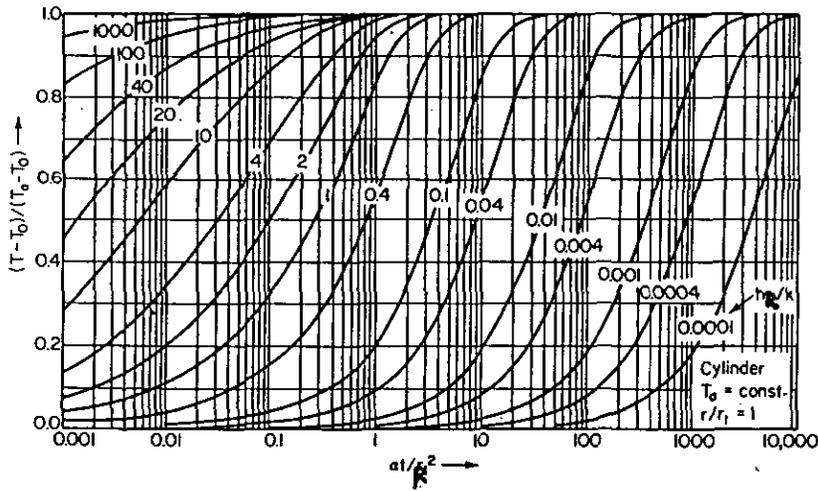


Figure 2 Surface Temperature Response of Long Cylinder After Sudden Exposure to Uniform Convective Environment

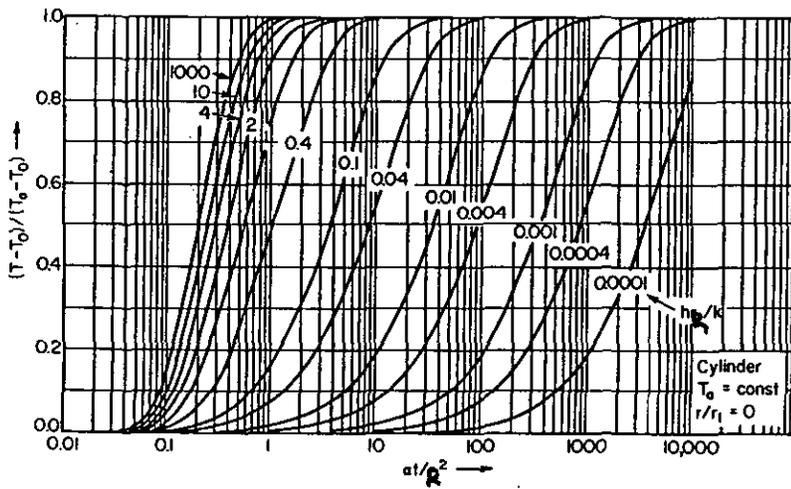


Figure 3 Centerline Temperature Response of Long Cylinder After Sudden Exposure to Uniform Convective Environment

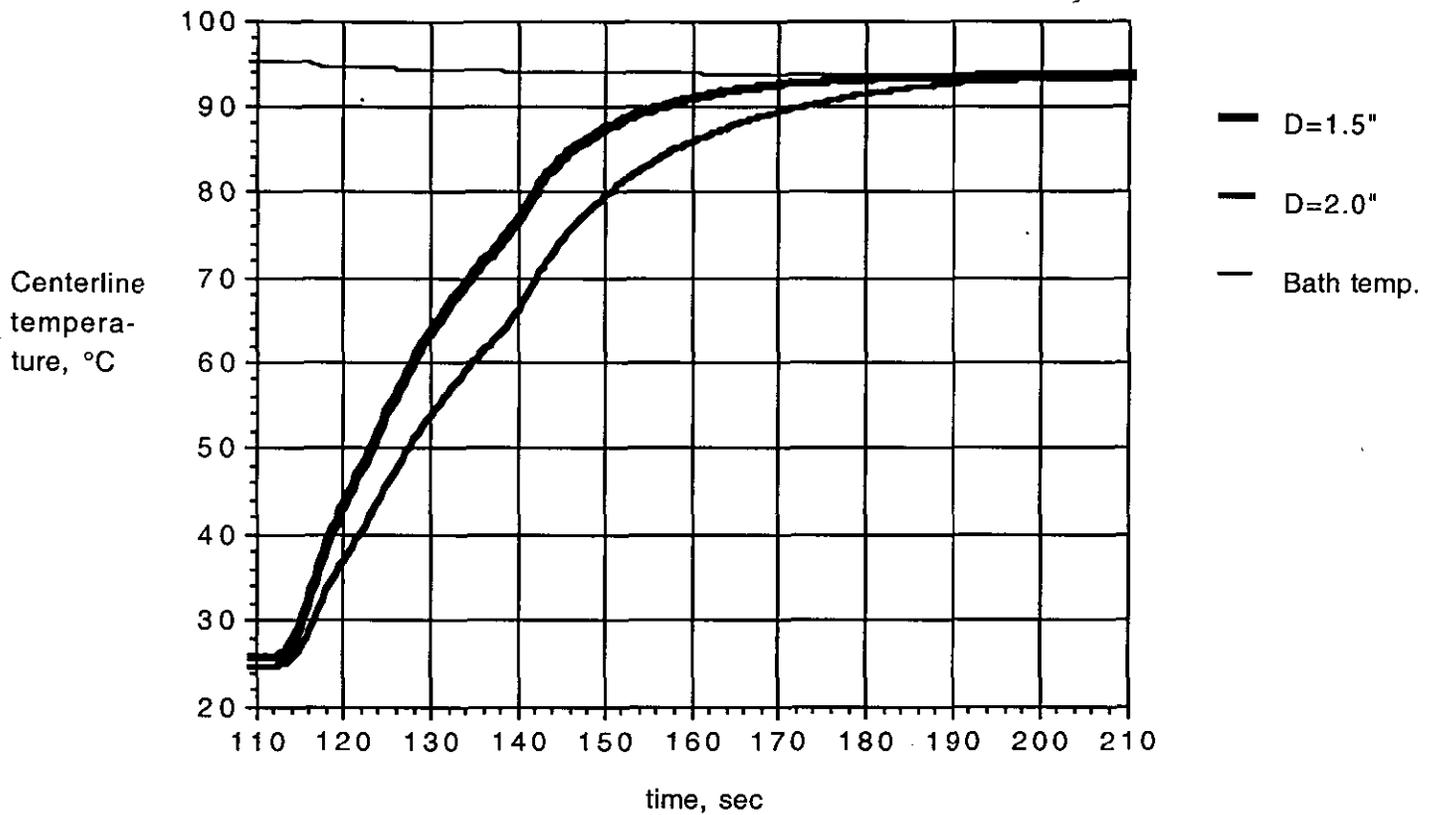


Figure 4 Measured Temperature Transients for Centerlines of Aluminum Bar

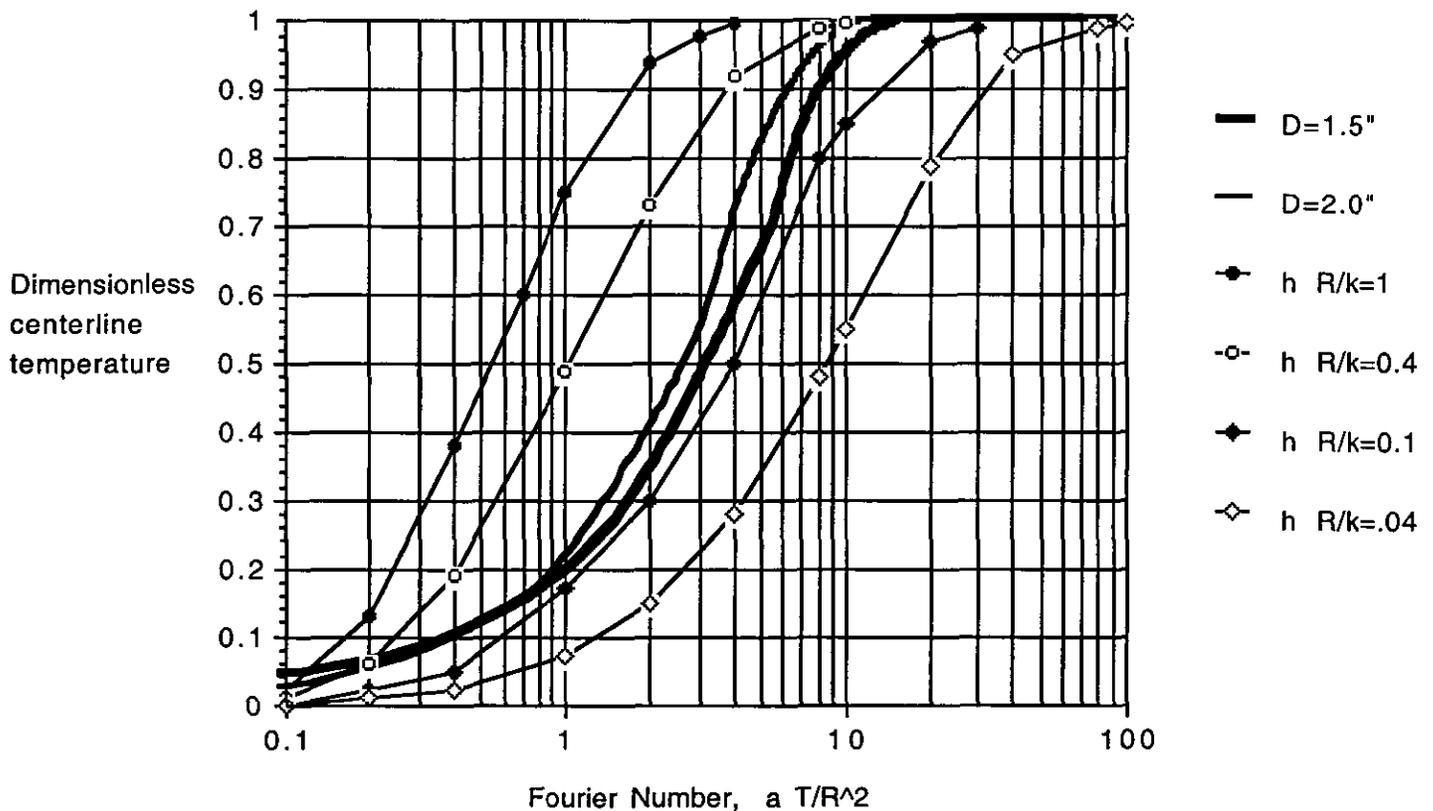


Figure 5 Measured and Theoretical Temperature Transients for Centerlines of Cylir

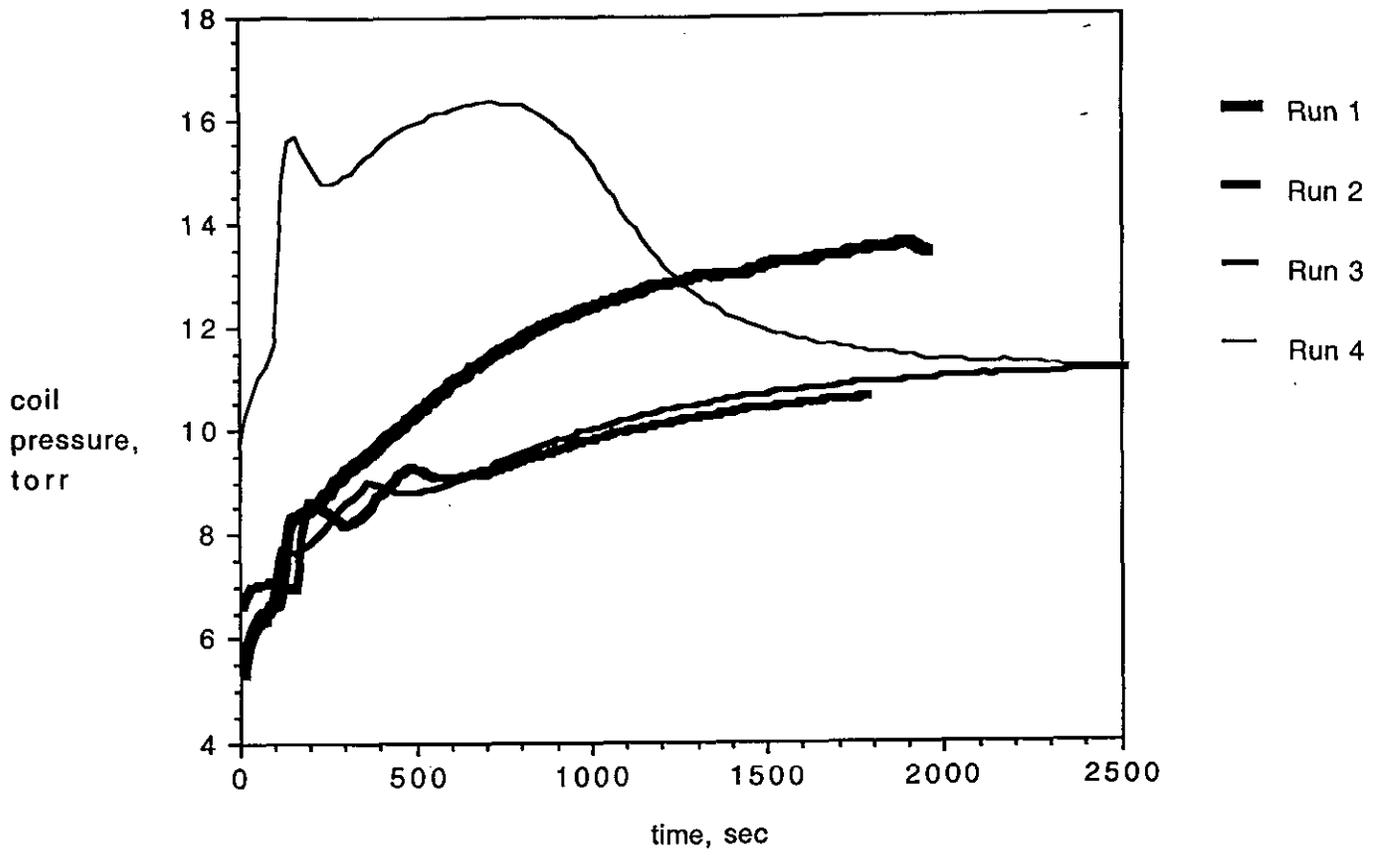


Figure 6 Transient for Coil 1 and 5 torr

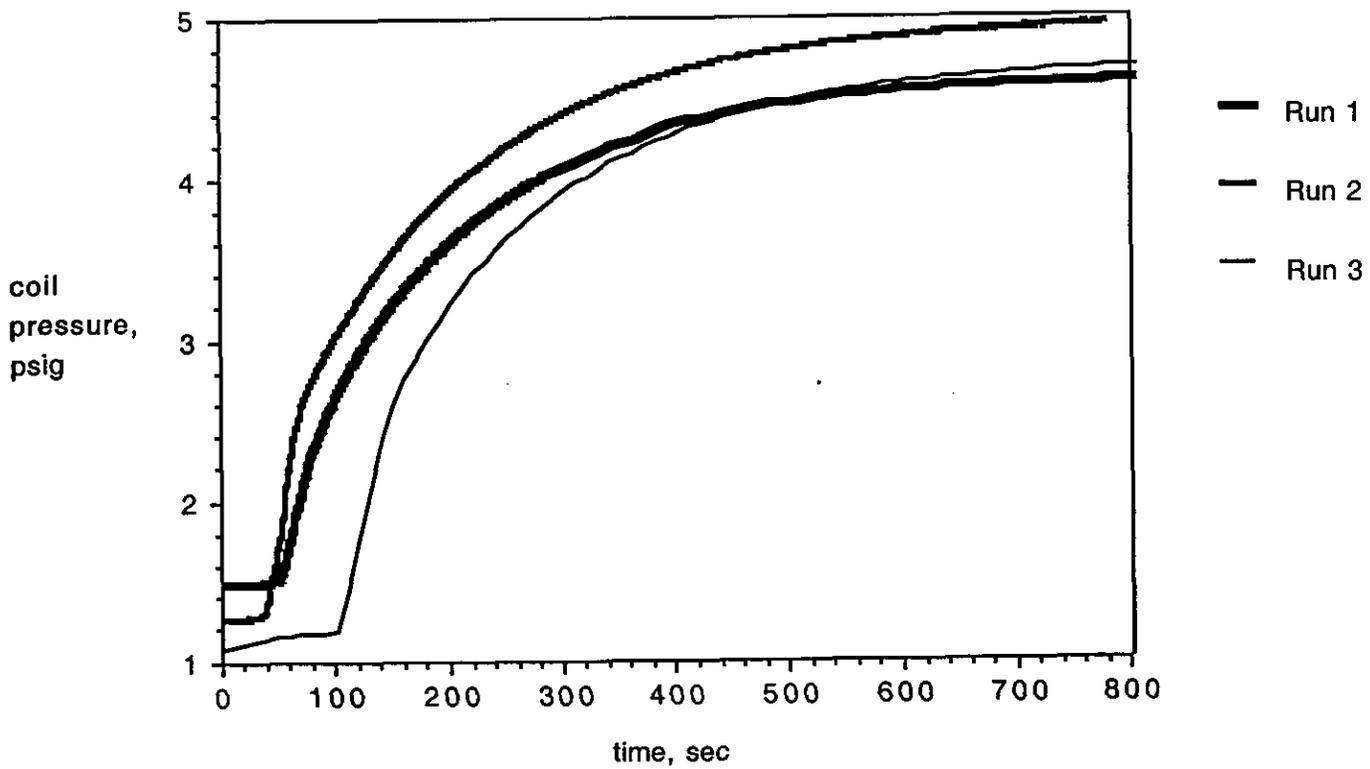


Figure 7 Transient for Coil 1 and 1 atm

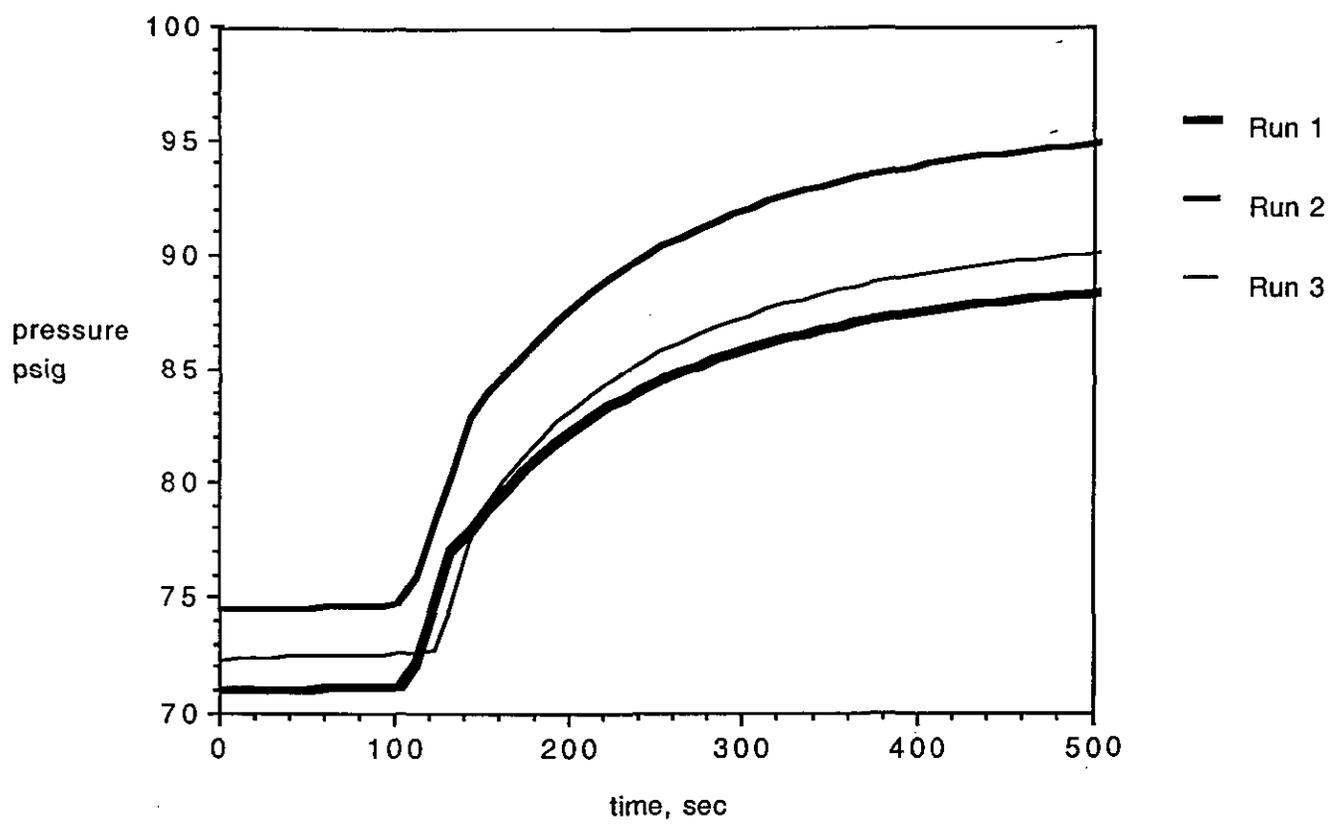


Figure 8 Transient for Coil 1 and 5 atm

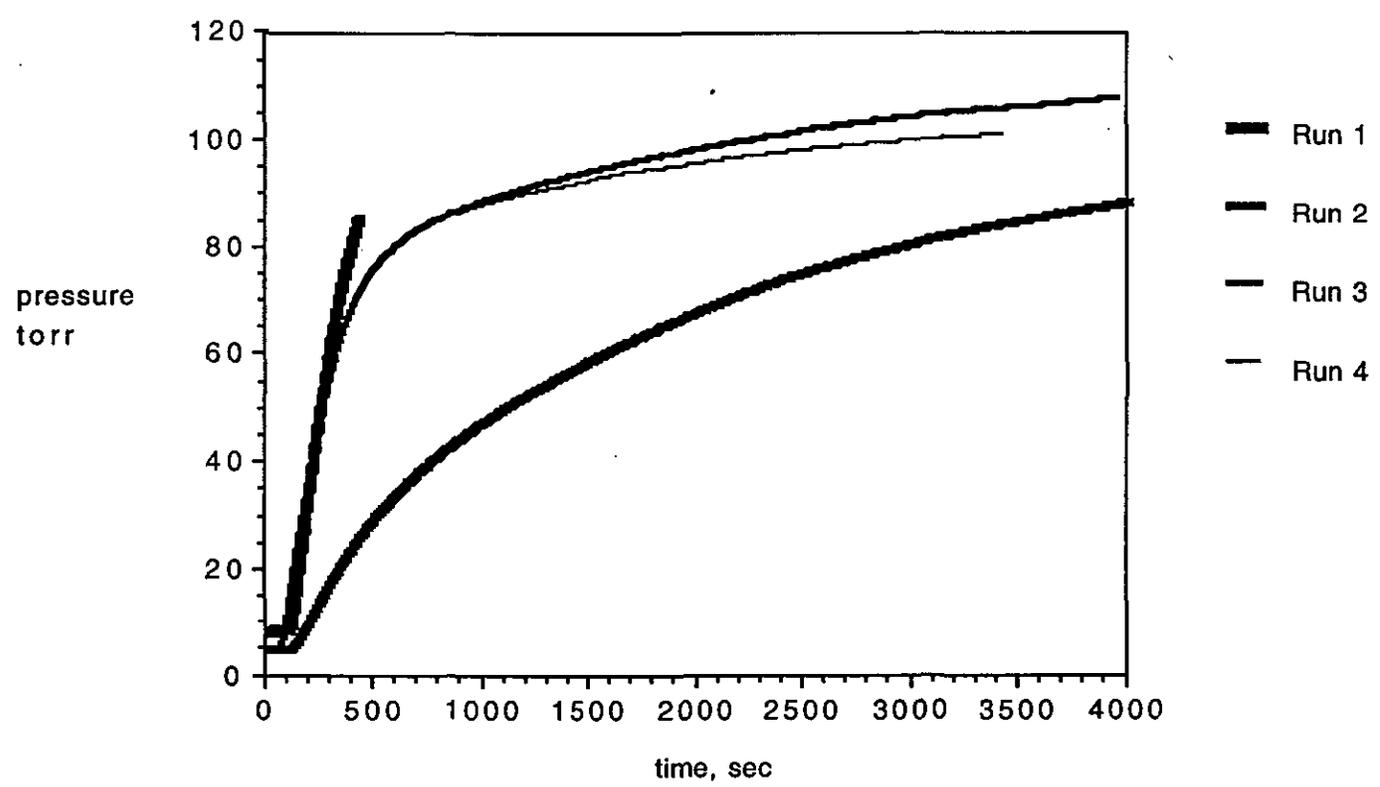


Figure 9 Transient for Coil 2 and 5 torr

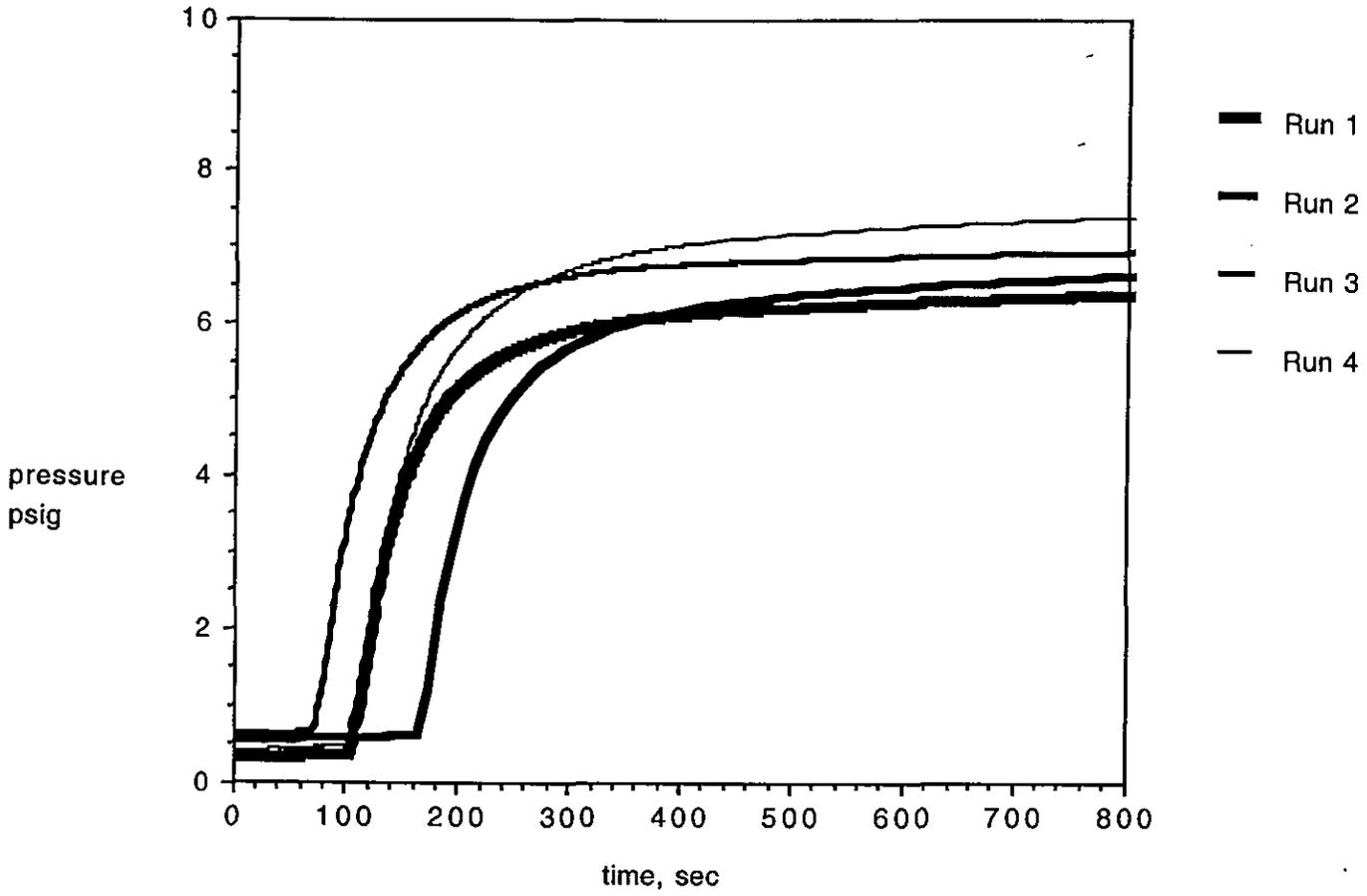


Figure 10 Transient for Coil 2 and 1 atm

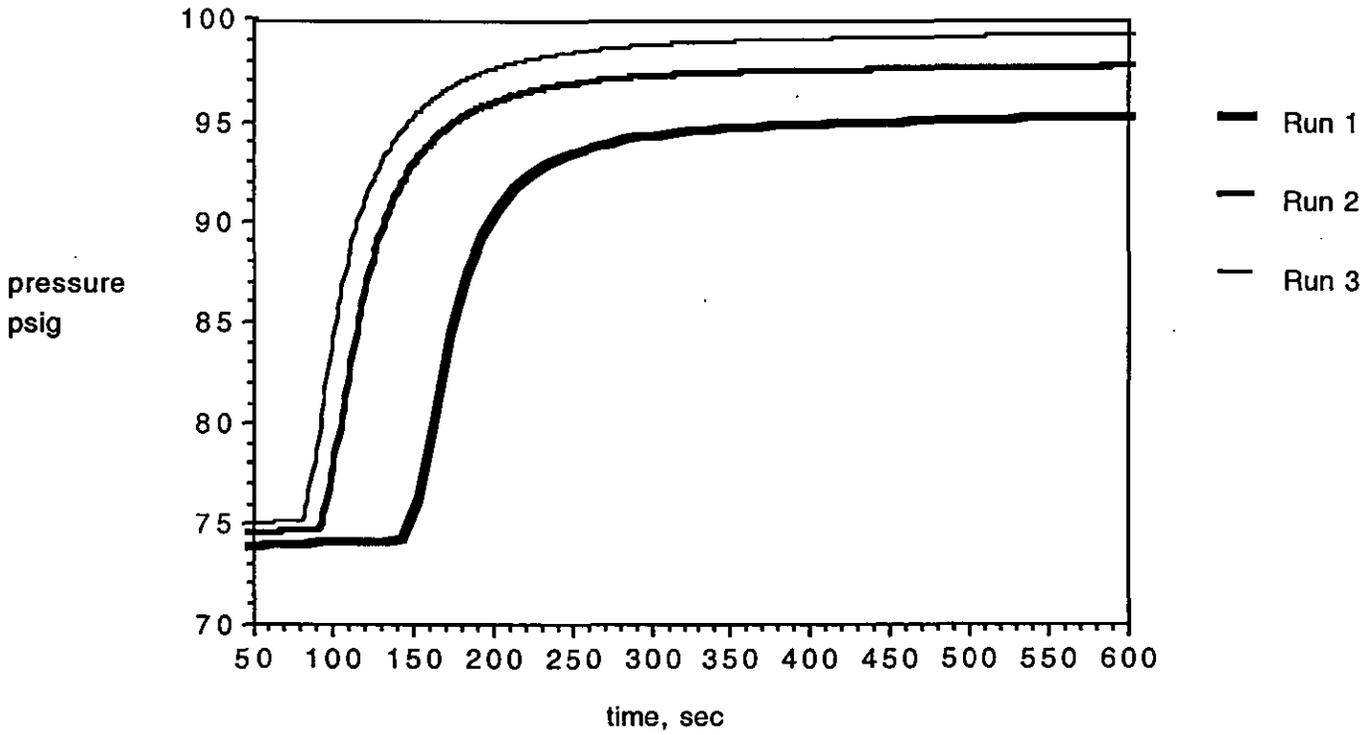


Figure 11 Transient for Coil 2 and 5 atm

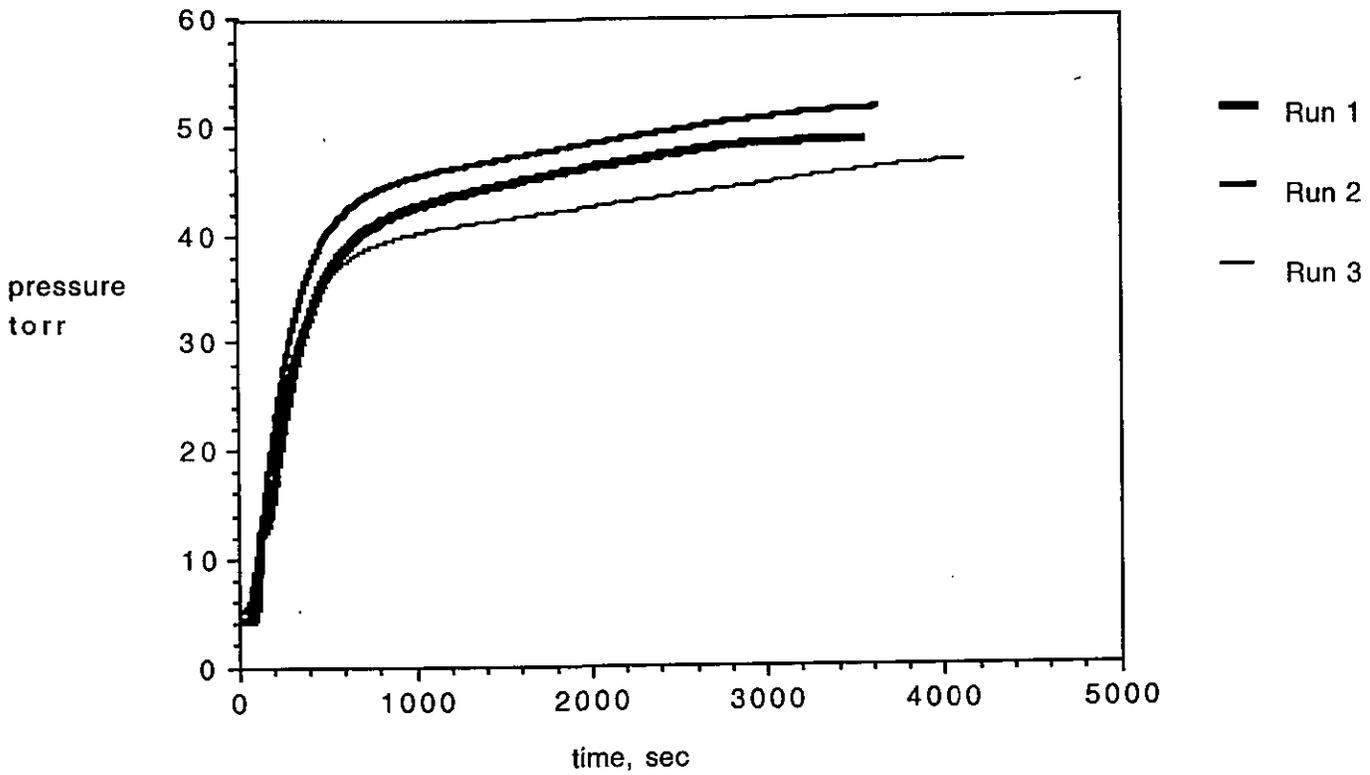


Figure 12 Transient for Coil 3 and 5 torr

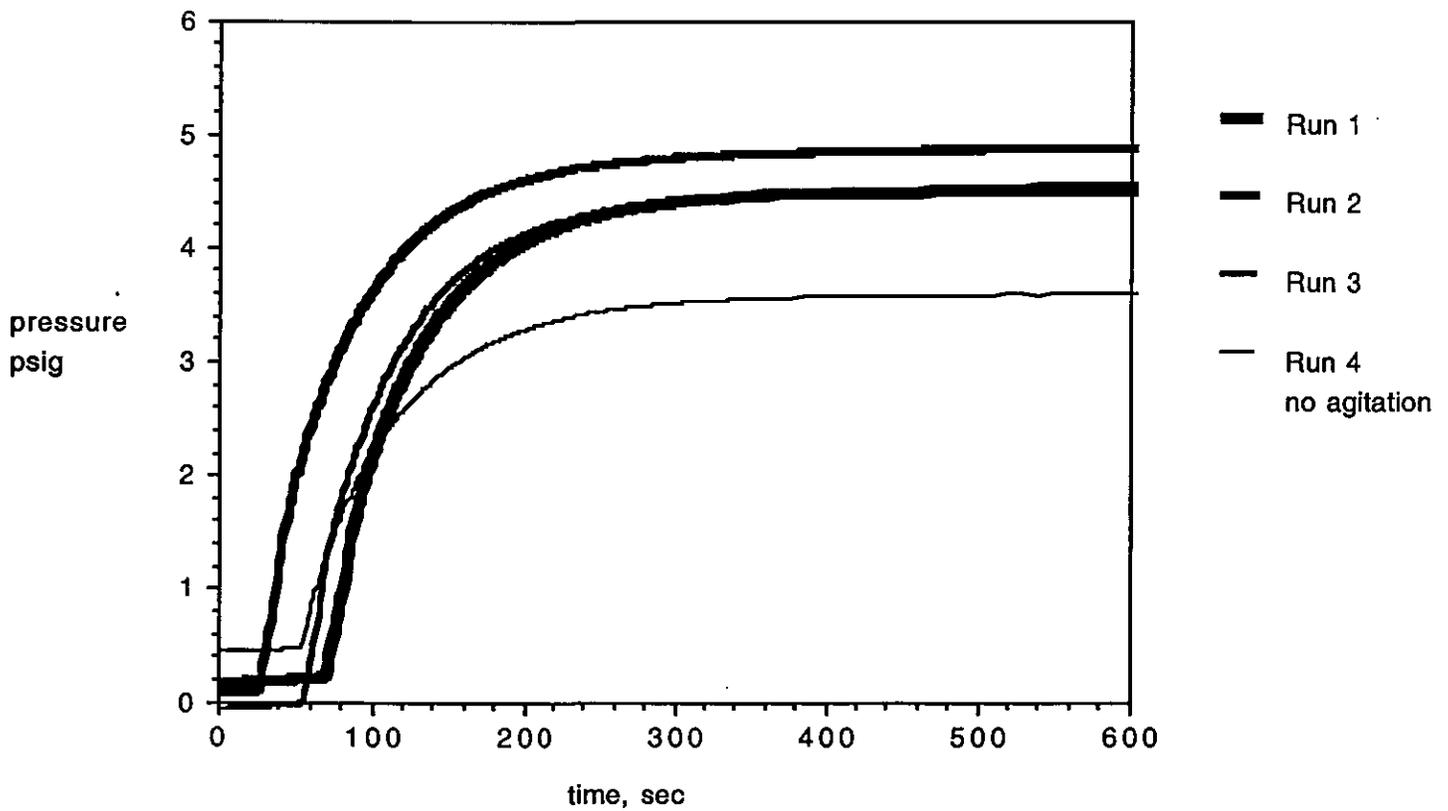


Figure 13 Transient for Coil 3 and 1 atm

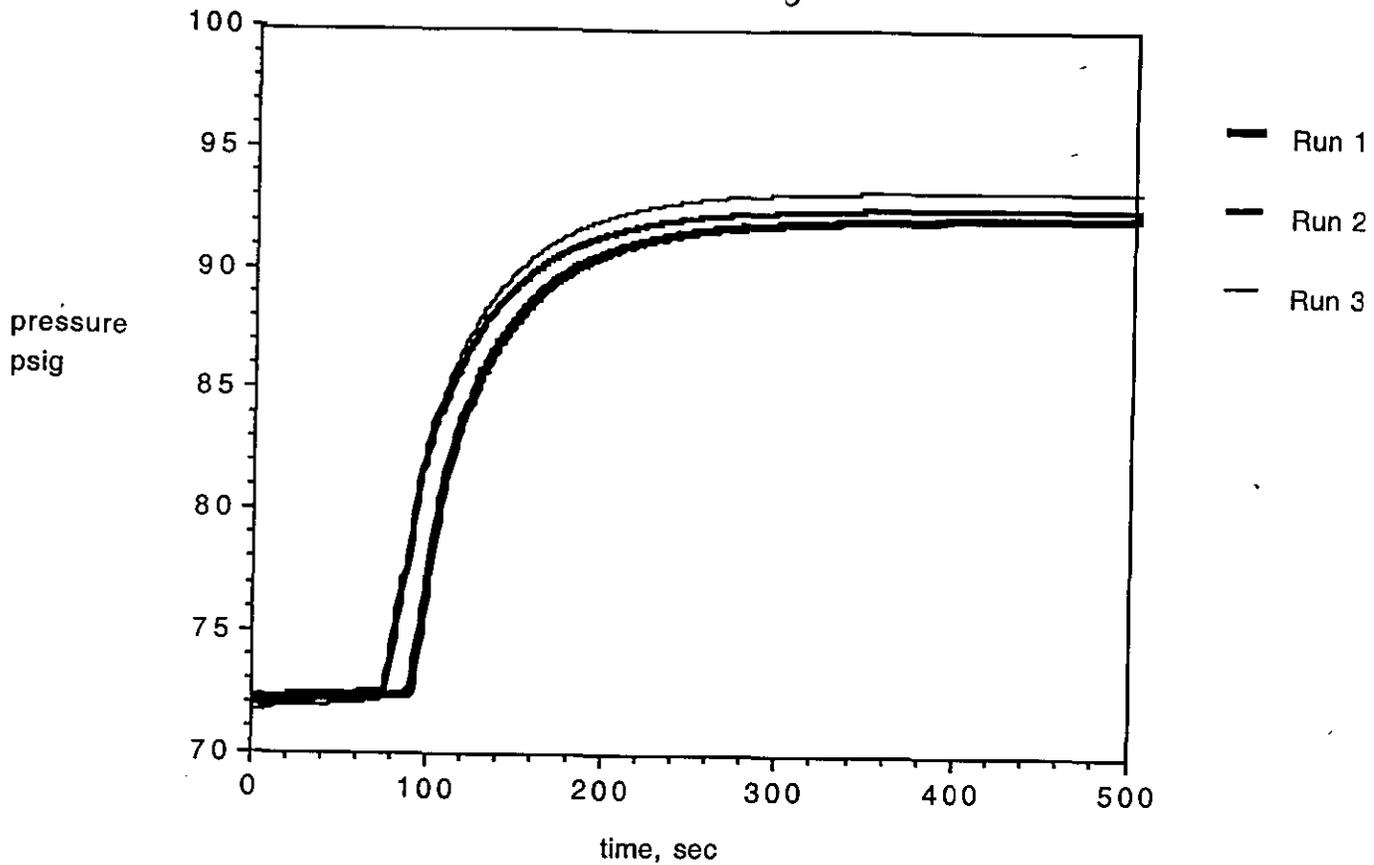


Figure 14 Transient for Coil 3 and 5 atm

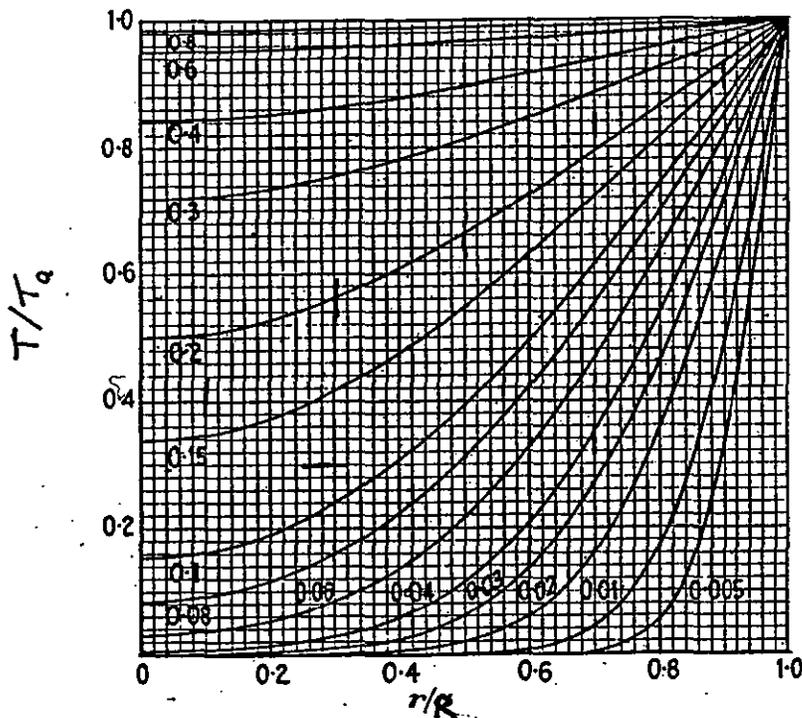


Figure 15 Temperature Distribution at Various Times in a Cylinder of Radius R with Zero Initial Temperature and Surface Temperature T_a . The Numbers on the Curves are Values of $\alpha t/R^2$

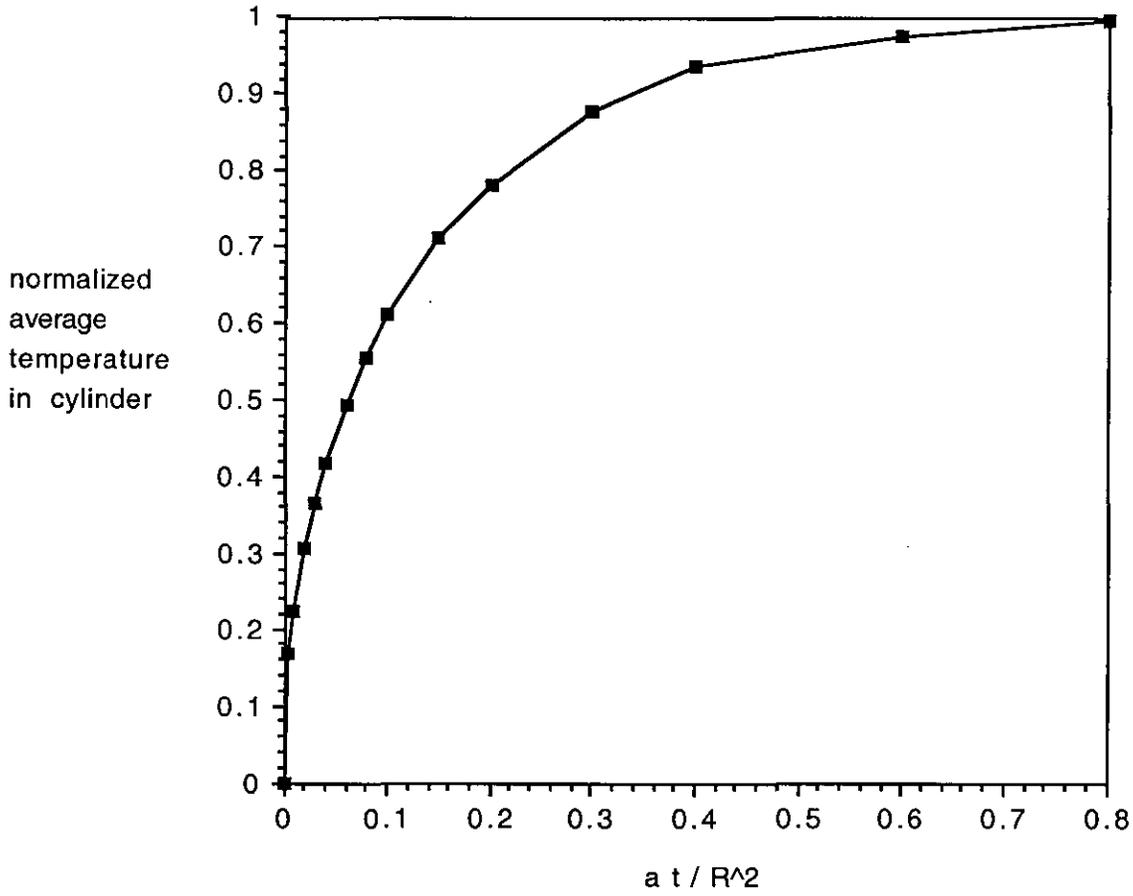
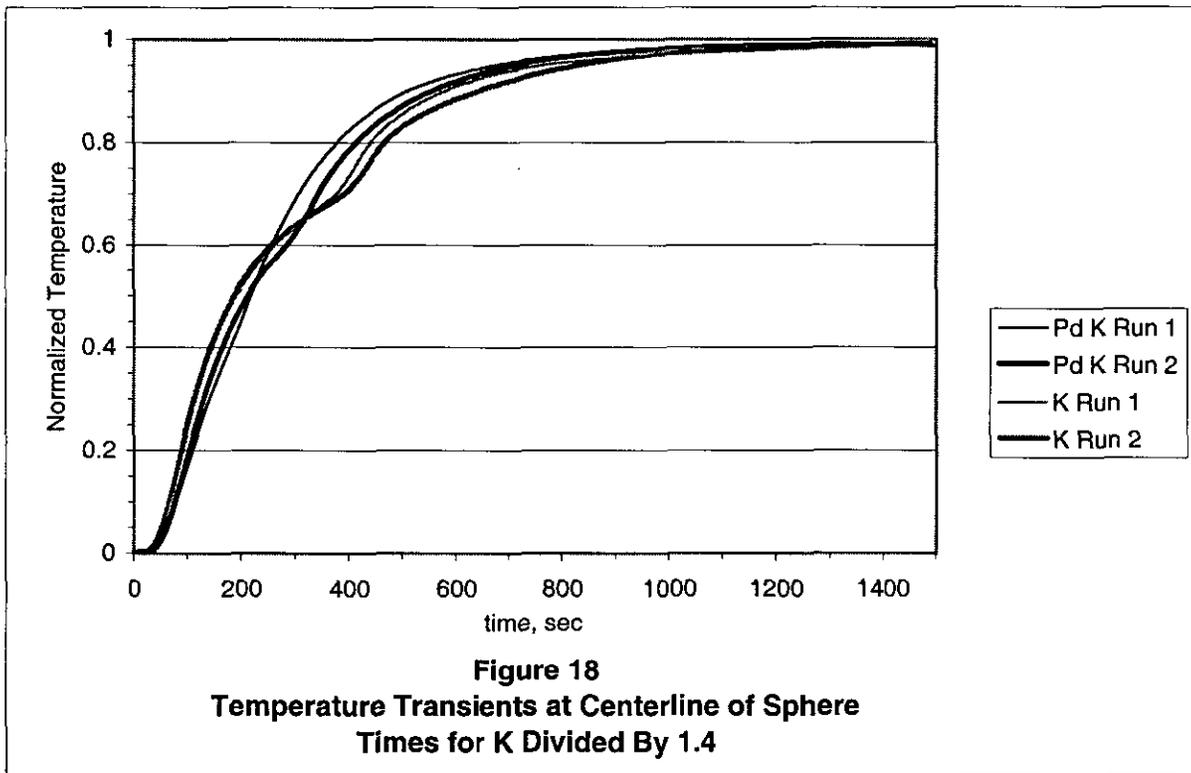
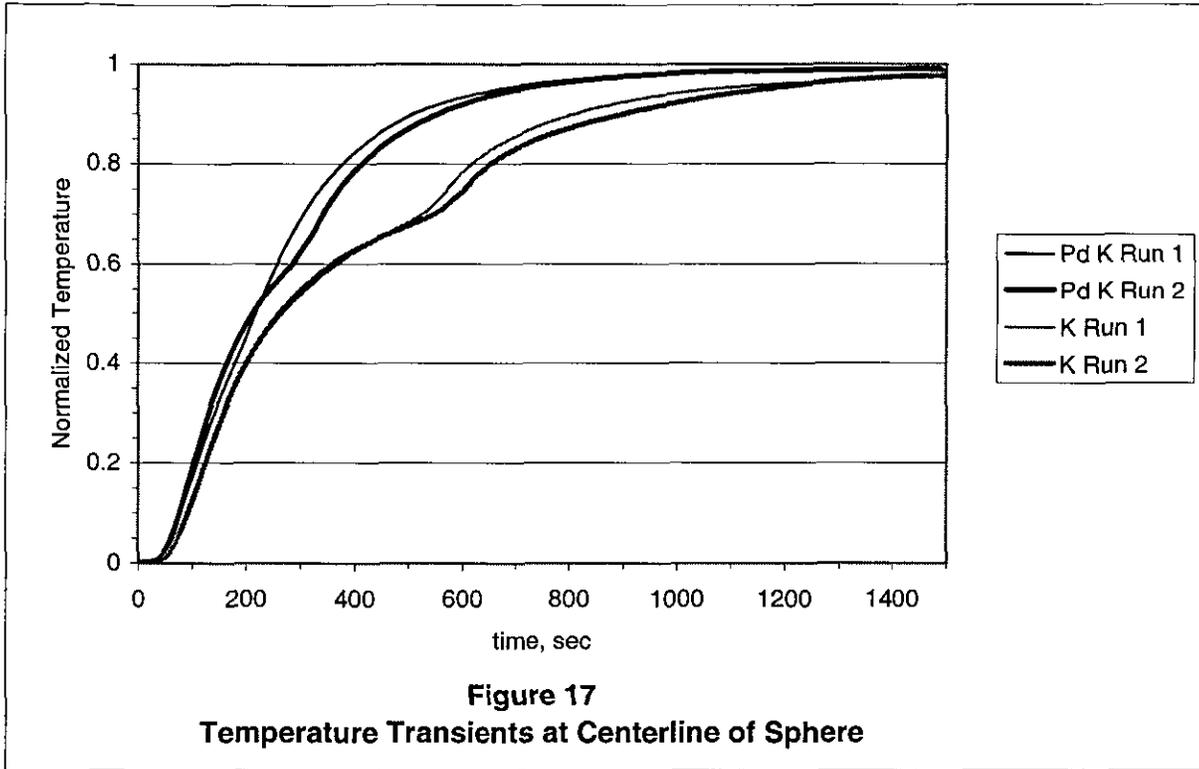


Figure 16
Transient Average Temperature in Cylinder with Conduction



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