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Analysis of Flow Stratification in the Surge Line of the Comanche Peak Reactor

Prepared by
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Argonne National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission

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Abstract

A number of nuclear power plants have reported failure of reactor components due to flow stratification. Therefore, a fundamental understanding of, and a capability to predict, flow stratification in a reactor system is critically important to reactor performance and safety. The work presented here is the first step in this direction and will contribute to the resolution of the issue of flow stratification.

An analysis is performed using the COMMIX-1C computer program for the surge line of the Comanche Peak reactor. A comparison is made between the calculated results from the COMMIX code and the plant-measured data, and the agreement is good.

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Executive Summary

Flow stratification is known to occur in various reactor components during normal and off-normal operating conditions of both pressurized water reactors and boiling water reactors. A large temperature difference is normally associated with flow stratification. Thus, when flow stratification occurs in a reactor component, it will be subject to an additional thermal stress resulting from the local temperature difference. A number of nuclear power plants have reported failure of reactor components due to flow stratification. Flow stratification can not only cause reactor shutdown due to an unisolable leak resulting from failure of a reactor component, but also has significant implications to reactor safety and can alter both the sequence and consequence of a reactor accident. Therefore, it is imperative to understand the causes of flow stratification and, more important, we should be able to predict when and where flow stratification will occur and the magnitude of the temperature difference associated with the flow stratification. The work reported here represents the first step in this direction and will contribute to the resolution of the issue of flow stratification.

An analysis is performed using the COMMIX-1C computer program for the surge line of the Comanche Peak reactor. The COMMIX-1C computer code, which is being developed and sponsored by the Office of Nuclear Regulatory Research in the U.S. Nuclear Regulatory Commission, is a three-dimensional transient single-phase computer program for thermal-hydraulic analysis of single- and multicomponent engineering systems. It solves equations of conservation of mass, momentum, and energy as a boundary value problem in space and as an initial value problem in a time domain and has been applied to flow stratification and natural circulation during postulated reactor accidents. The major objective of this work is to demonstrate that the COMMIX code is capable of predicting flow stratification. The numerical results obtained from the COMMIX code for the surge line of the Comanche Peak reactor presented here have been compared with the measurements provided by the Westinghouse Electric Corporation and the agreement is good.

1 Introduction

Flow stratification is due to the density difference of two streams of a fluid or different fluids flowing at relatively low velocities with very little mixing. The density difference is attributed either to the temperature difference of two streams of a given fluid or to different fluids with different intrinsic densities. The scope of this study is limited to flow stratification caused by the temperature difference of two streams of a given fluid. These two streams flow at low velocity with very little turbulent mixing between them. The lighter hot fluid stays above and the heavier cold fluid stays below in the flow domain.

A number of nuclear power plants have reported failure of reactor components due to flow stratification.[1] The most common cases of flow stratification in reactor components during normal operating conditions (including transients) and off-normal conditions occur in the surge line, hot leg, residual heat removal system, feed water line, steam generator feed water ring, etc. Flow stratification can not only cause reactor shutdown due to unisolable leaks caused by failure of reactor components, but also has serious implications

for reactor safety. It has been shown that flow stratification can occur in a hot leg and most likely in a surge line* during a postulated TLMB' accident (station blackout).[2] One possibility is failure of the pressure boundary due to flow stratification prior to breach of the reactor vessel by the molten core; should this failure occur early enough, the reactor system may depressurize sufficiently to avoid direct containment heating when the core debris is ejected after vessel failure. Thus, flow stratification can alter both the sequence and consequence of a severe accident. For these reasons, a fundamental understanding of flow stratification is essential to avoid a possible reactor shutdown or accident. The present work represents the first step in that direction and will provide a reliable predictive capability of flow stratification in terms of when and where, as well as the magnitude of the temperature difference. It is to be noted that flow stratification was not accounted for in the original design of all light water reactors (LWR) and it certainly has significant impact on life extension of all existing LWRs.

2 Objectives

The two principal objectives of this study are:

1. To demonstrate the capability of the COMMIX computer code in predicting flow stratification in various reactor components.

2. To present results obtained from the COMMIX code for the surge line of Comanche Peak reactor and to compare these results with plant-measured data.

3 Brief Description of the COMMIX Code

COMMIX is a generalized computer code for heat transfer and fluid flow analysis.[3-5] Its capabilities include steady-state/transient, three-dimensional, and single-phase analysis of nuclear reactor systems under normal and off-normal operating conditions. Recently, the COMMIX code has been and continues to be extended and modified to multiphase applications of various engineering systems.

COMMIX is a well-refined and -tested code. Already, a large number of computations have been performed for complex situations, and many organizations, both in the U.S. and abroad, are using the code to simulate industrial problems. The structure of the code is modular. Its many unique features are described below.

3.1 Background

Development of the COMMIX code began in the summer of 1976. The initial version, COMMIX-1,[3] was documented and made available to the public (through the U.S. Nuclear

*In this analysis, the surge line was not explicitly included.

Regulatory Commission] in January 1978. The advanced version, COMMIX-1A,[4] with more capability and flexibility, was released in 1983. Developmental work continued to add improved models and to expand applications to nonnuclear systems. The extended version, COMMIX-1B, was released in December 1985. The latest version is COMMIX-1C,[5] which was released very recently (September 1990). Many additional improvements over COMMIX-1B have been incorporated into COMMIX-1C.

3.2 Equations Solved

Three-dimensional, time-dependent conservation equations of mass, momentum, and energy and transport equations of turbulence parameters, along with the equation of state, are solved as a boundary value problem in space and an initial value problem in time.

The solution provides detailed three-dimensional descriptions of

- velocity,
- temperature, and
- pressure,

along with ancillary information such as heat transfer and resistance correlations. For easy interpretation, the numerical results can be transformed into graphic forms (e.g., vector plots, isotherm plots, and video or film showing fluid motion).

3.3 Unique Features

3.3.1 COMMIX Porous-Medium Formulation

COMMIX employs a new porous-medium formulation[6] based on local volume-averaging. This formulation uses four parameters—volume porosity, directional surface porosity, distributed resistance, and distributed heat source (sink)—to model the effects of internal solid structures. In the conventional porous-medium formulation, only three parameters (volume porosity, distributed resistance, and distributed heat source) are used. The addition of a fourth parameter, directional surface porosity, is a new concept that greatly facilitates modeling of velocity and temperature fields in anisotropic media and, in general, improves resolution and accuracy.

3.3.2 Two Solution Algorithms

COMMIX has two solution algorithms for single-phase systems; both algorithms are provided as user options:

- A semi-implicit algorithm derived from the Los Alamos ICE Technique.[7-9] This algorithm is ideally suited for analyzing fast transients, where one is

interested in details at small time intervals (on the order of Courant time-step).

- A fully implicit algorithm named SIMPLEST-ANL.[4] This algorithm is a modification of the Patankar-Spalding numerical procedure[10] known as SIMPLE/SIMPLER. It is particularly suitable for analyzing slow and normal transients.

These two solution procedures are combined into one formulation, but are implemented so that a user can switch from one solution scheme to another at any time during the transient simulation of a problem.

3.3.3 The Geometry Package

The geometry package developed and implemented in COMMIX can approximate any irregular geometry. It uses basic computational cells as building blocks to model the geometry under consideration. Then, both volume porosity and directional surface porosity are used to account for the differences between the approximated and actual configurations.

To reduce computer storage, a computational cell is defined by a number rather than by its conventional (i, j, k) location, where i, j, and k are the computational cell indices in the three principal axes (e.g., x, y, and z in the Cartesian coordinate system). With this approach, the storage requirement depends only on the total number of computational cells and not on the dimensional values of (IMAX * JMAX * KMAX), where IMAX, JMAX, and KMAX denote the maximum values of computational cell indices in the three corresponding principal axes.

A normal three-dimensional computational cell has six surfaces. But to facilitate true and proper modeling of a complex irregular geometry (and most geometries in engineering systems are complex and irregular), we have provided flexibility so that a user can specify an additional seventh surface, called an irregular surface, to a computational cell.

3.4 Other Features

- For single-phase applications, two turbulence model options are provided:
  -Constant turbulent diffusivity model.
  -Two-equation (k-ε) model, where k is the turbulent kinetic energy and ε is the dissipation rate of k.

- A flow-modulated skew-upwind difference scheme[5] has been developed and implemented to reduce numerical diffusion, specifically for the case of flow inclined to grid lines.

- The final form of all of the sets of discretization equations is

$$a_0^* \phi_0 - \sum_{l=1}^{6} a_l^* \phi_l - b_0^* = 0,$$

where ϕ is a dependent variable and the subscript l stands for neighboring points. This general form of the discretization equation lends itself to various solution schemes, e.g., SOR, Preconditioned Conjugate Gradient Method, and direct matrix inversion.

- The solution has a decoupled-transient-simulation option that permits solution of
  -mass-momentum equations only, or
  -energy equation only, or
  -coupled mass-momentum and energy equations,
  at any given time-step.

- The code has an option that allows use of either Cartesian or cylindrical coordinates.

- COMMIX has built-in properties for liquid sodium and water, with an option permitting use of simplified property correlations for any fluid.

- The code also contains:

  -A generalized resistance model to permit specification of resistance due to internal structures (fuel rods, wire wrap, baffles, grid spacers, etc.).

  -A generalized thermal structure formulation to model thermal interaction between structures (fuel rods, wire wrap, duct wall, baffles, etc.) and surrounding fluid.

- The heat source/sink and boundary conditions can be functions of time.

- The COMMIX code is structured to permit solution of one-, two-, or three-dimensional calculations.

4 Flow Stratification in a Surge Line

A detailed three-dimensional and time-dependent analysis is performed using the COMMIX-1C code for the surge line of the Comanche Peak reactor. Temperature distributions of both fluid and surge line wall are calculated. The surge line layout of the reactor is described, the experimental measurements provided by Westinghouse[11] are presented, the numerical model used in the COMMIX calculation is outlined, and both initial and boundary conditions based on the limited measurements used in the COMMIX code are followed. Finally, the detailed velocity profiles and temperature distributions of the surge line obtained from the COMMIX code are presented and compared with the experimental measurements.

4.1 Surge Line Layout of Comanche Peak Reactor

Figure 1 presents the layout of the surge line of the Comanche Peak reactor. All pipe dimensions are shown. The temperature monitoring locations, namely T1, T2, T3, and T4, are also shown in the figure; the temperature monitors record the outside pipe-wall temperature at various circumferential locations.

4.2 Experimental Measurements

Figures 2-5 are temperature measurements as a function of time at T1, T2, T3, and T4, respectively, at the various circumferential locations. Temperatures, as a function of time, of the four hot legs are shown in Fig. 6; the hot leg marked 4 in Fig. 6 is the hot leg with the pressurizer. The water level of the pressurizer as a function of time is marked 7 in Fig. 7. Figure 7a is an enlarged view of a portion of Fig. 7 from 17 to 18 h. The relationship between water level height of the pressurizer and volume is presented in Table 1.

4.3 Numerical Simulation Model Used in COMMIX Code

The numerical models that simulate the surge line of the Comanche Peak reactor are shown in Figs. 8-10. The computational mesh setup along the pipe line is shown in Fig. 8. Figure 9 presents a typical cross section of the surge line, and a typical elbow is modeled as shown in Fig. 10. To avoid modeling complications, the pipe marked L1 in Fig. 1 is modeled as a vertical run, as shown in Fig. 8. This simplification will not affect the results and is discussed in Sec. 5.

The heat-capacity effect of the surge line is explicitly accounted for in the numerical calculation. Wall thickness is equally divided into two computational grids in the numerical model, and the thermal physical properties of the pipe wall us in the COMMIX calculations are

ρ (density) = 7977 - 0.4167 T (kg/m^3),
k (thermal conductivity) = 14.16 + 0.0131 T (W/m-°C),
C_p (specific heat) = 508.67 (J/kg-°C),
T (temperature) in °C.

4.4 Initial and Boundary Conditions

A close examination of the experimental measurements shown in Figs. 2-5 reveals that flow stratification with a large temperature difference occurred at approximately 17-1/2 to 21-1/2 h in the transient. One objective of this work is to demonstrate the capability of the COMMIX code to analyze flow stratification. Consideration is also given to the saving of computer running time. We thus decided to start our calculation at 17 h, 31 min, 10 s into the transient. Because we do not start our calculation at the very beginning of the transient, the initial condition corresponding to the beginning of our calculation must be constructed. Also, the boundary conditions as a function of time at the inlet of the surge line (from the

hot leg to the surge line) must be provided. Both initial and boundary conditions used in the COMMIX calculation are described below.

4.4.1 Initial Conditions

- Velocity distribution based on isothermal steady-state solution with inlet velocity of 0.002 m/s at the inlet of the surge line (from hot leg to surge line).

- The outside pipe-wall temperature distribution of all horizontal pipes (L2 and L3) based on T2 and T3 readings and linearly interpreted and extrapolated both axially (along the pipe length) and circumferentially. The outside pipe-wall temperatures in L1 and L4 are assumed to be uniformly distributed according to T1 and T4 readings, respectively. All fluid temperatures next to the pipe wall of L2 and L3 are assumed to be the same and to be stratified. Temperatures in L1 and L4 are assumed to be uniform at 152.6°F (see Fig. 6) and 440°F (same as surge line wall temperature, Fig. 5), respectively. The assumption of uniform fluid temperature in L1 and L4 is reasonable because both T1 and T4 readings after we started the calculation appear to support the assumption.

4.4.2 Boundary Conditions

- At inlet of surge line (from hot leg to surge line):

  -Inlet velocity based on water level of pressurizer (Fig.7), as shown in Fig. 11. Figure 11 is obtained in the following manner:

  Because water is an incompressible fluid, its level change in the pressurizer is directly related to the water flow rate from the surge line to the pressurizer, which in turn, is related to the flow rate from the hot leg to the surge line. Therefore, the instantaneous mean inlet water velocity v_{in} is evaluated from

$$v_{in} = \frac{Q\,dH}{A\,dt}\ ,$$

  where H is the water level in the pressurizer (in percent) as shown in Fig. 7, Q is the volume of the water (in gallons) in each percent change of the pressurizer level, as shown in Table 1, A is the cross-sectional area of the surge line pipe, and t is the time. It is seen from the above equation that the inlet velocity is proportional to the slope of the water level change in the pressurizer as a function of time. When the experimental data of Fig. 7 for the water level (in percent) is enlarged by many times (see Fig. 7a), it can be seen that the slope becomes positive from about 17 h 31 min and increases to a maximum after about 17 h 36 min. Then the slope decreases, attains

another maximum, and gradually declines, eventually reaching very small value. The inlet velocity follows the same pattern, as shown in Fig. 11.

-Inlet temperature based on the outside pipe-wall temperature reading of the hot leg (near the surge line) with pressurizer (Fig. 6), as shown in Fig. 12.

- At the outlet of surge line (from surge line to pressurizer):

$$\frac{\partial v}{\partial x} = \frac{\partial T}{\partial x} = 0.$$

4.5 COMMIX Results

A number of assumptions were used in the calculation:

- No heat loss through the pipe wall of the surge line.
- No pitch (slope) for horizontal pipe.
- Calculation started at 17 h, 31 min, 10 s in the transient.
- Using "best estimate" initial and boundary conditions based on very limited experimental measurements. These measurements are in graphic plot (see Figs. 2-7), but not in digital form.
- Approximating L1 pipe as a vertical run.
- Pipe-wall conduction limited to one dimension (radial direction only).

The typical velocity profiles and temperature distributions at 10 min after starting the calculation will be presented. Velocity profiles and temperature distributions at the centerline of the surge line in the vertical planes of L2 and L3 are shown in Figs. 13-20 and Figs. 21-28, respectively. The temperature profiles of the surge line cross sections at the locations of T1, T2, T3, and T4 are presented in Figs. 29-32, respectively, and both inside and outside temperatures of the surge line wall corresponding to the measured locations are also shown in these figures.

4.6 Comparison of COMMIX Results with Measurements

A comparison of the outside surge line wall temperatures calculated by the COMMIX code with the measured data provided by the Westinghouse Electric Corp.[11] namely T1, T2, T3, and T4, are shown in Figs. 29-32, respectively. The calculated results and the experimental measurements are in reasonable agreement.

5 Discussion and Conclusions

Despite large uncertainties in constructing the "best estimate" initial and boundary conditions on the basis of limited available measurements, it is gratifying that the agreement between the calculated results obtained from the COMMIX code and the experimental data is reasonably good. In our opinion, the agreement can be further improved if both initial and boundary conditions can be more accurately quantified.

The wall temperatures of the surge line were calculated by one-dimensional (radial direction only) approximation. The calculated results can be improved if the additional conductions from both circumferential and axial directions are incorporated into the COMMIX code. We recommend that this additional capability be implemented into the COMMIX code.

Based on T1 and T4 readings, there appears to be no flow stratification in either inclined pipe L1 or vertical run L4 very soon after the calculation is begun, as shown in Figs. 2 and 5, respectively. Thus, it seems justifiable to model the inclined pipe L1 as a vertical run.

As stated earlier, the major thrust of this work is to demonstrate the capability of the COMMIX code, which can be used to predict the time, location, and magnitude of a local temperature difference in a flow-stratified pipe. Based on the comparison between the calculated results from COMMIX code and the experimental measurements (Figs. 33-36), it seems reasonable to conclude that the COMMIX code has demonstrated its capability for predicting the flow stratification in the surge line. Nevertheless, it is desirable to conduct more assessments and validations. In particular, validation must be carried out to compare the COMMIX results with the well-instrumented experiments, which are not limited to temperature measurements but also include velocity data.

Based on the calculated velocity profiles and temperature distributions (Figs. 13-20 and Figs. 21-28, respectively) 10 min after starting the calculation, the following important observations may be summarized below.

- The maximum flow stratification or maximum local temperature difference between the top and bottom of the surge line is located at L2 immediately after the flow passes through the elbow from L1. This location is different from the T1, T2, T3, and T4 locations. From an instrumentation standpoint, it is very desirable to take measurements at or near the point of maximum flow stratification.

- The calculated velocity profiles after 10 min of the transient calculation are similar to those shown in Figs. 13-20. The calculated velocity profile in the surge line is very complicated. In a large portion of horizontal pipes L2 and L3, the fluid in both the top and bottom of these pipes flows in the same direction, while in the middle portion, the fluid flows in the opposite direction. It is our belief that the flow pattern is highly sensitive to the geometrical arrangement of a surge line as well as to operating conditions.

Thus, it is very difficult to pregeneralize both the flow pattern and the temperature distribution in a stratified pipe.

- The calculated temperature at the top of the surge line (0° curve) is slightly higher than the temperature at 60°, as shown in Fig. 35 approximately 10 min into the transient. This is because the local velocity at 0° is higher than that at the 60° location; thus, the corresponding heat transfer coefficient is higher. As mentioned earlier, the pipe-wall conduction model used in the COMMIX code is limited to one dimension (radial direction only, in this case); therefore, the spread of the calculated temperatures between the 0° and 90° locations of T3 could be larger if the circumferential conduction of the pipe wall is included. Furthermore, the validity of the assumption of no heat loss through the surge line wall must be examined for future calculations.

Finally, it is to be noted that the COMMIX code is a general-purpose, multidimensional computer program that is not limited to flow stratification in a surge line. In fact, the COMMIX code can be applied to flow stratification problems in any reactor component, including the high-pressure injection system, steam generator feedwater ring, etc., under various reactor operating conditions. The code has also been used extensively for analyzing natural circulation under severe accident conditions. Recently, the Office of Nuclear Reactor Regulatory in the U.S. Nuclear Regulatory Commission expressed some concern about the thermal stripping problem. It is our belief that with some modification of the COMMIX code, we will be in a position to tackle this problem.

Table 1. Pressurizer water level vs. volume (reproduced from best available source)

INSIDE DIAMETER. 84.000 INCHES — TOTAL INSIDE LENGTH OF TANK. 598.500 INCHES

HEIGHT OF TANK CYLINDER. 530.900 INCHES — DEPTH OF ELLIPTICAL HEADS: 33.800 INCHES

LEVEL INDICATION BEGINS AT 39.800 INCHES — LEVEL INDICATION ENDS AT 561.500 INCHES

LIQUID HEIGHT (INCHES)	VOLUME (GALLONS)	LEVEL IND. (%)	LIQUID HEIGHT (INCHES)	VOLUME (GALLONS)	LEVEL IND. (%)	LIQUID HEIGHT (INCHES)	VOLUME (GALLONS)	LEVEL IND. (%)
39.80	694.5	0.00	45.02	809.7	1.00	50.23	934.8	2.00
55.45	1060.0	3.00	60.67	1185.2	4.00	65.89	1310.3	5.00
71.10	1435.5	6.00	76.32	1560.6	7.00	81.54	1685.8	8.00
86.75	1810.9	9.00	91.97	1936.1	10.00	97.19	2061.3	11.00
102.40	2186.4	12.00	107.62	2311.6	13.00	112.84	2436.7	14.00
118.06	2561.9	15.00	123.27	2687.0	16.00	128.49	2812.2	17.00
133.71	2937.4	18.00	138.92	3062.5	19.00	144.14	3187.7	20.00
149.36	3312.8	21.00	154.57	3438.0	22.00	159.79	3563.1	23.00
165.01	3688.3	24.00	170.23	3813.5	25.00	175.44	3938.6	26.00
180.66	4063.8	27.00	185.88	4188.9	28.00	191.09	4314.1	29.00
196.31	4439.3	30.00	201.53	4564.4	31.00	206.74	4689.6	32.00
211.96	4814.7	33.00	217.18	4939.9	34.00	222.40	5065.1	35.00
227.61	5190.2	36.00	232.83	5315.4	37.00	238.05	5440.5	38.00
243.26	5565.7	39.00	248.48	5690.8	40.00	253.70	5816.0	41.00
258.91	5941.1	42.00	264.13	6066.3	43.00	269.35	6191.5	44.00
274.57	6316.6	45.00	279.78	6441.8	46.00	285.00	6566.9	47.00
290.22	6692.1	48.00	295.43	6817.2	49.00	300.65	6942.4	50.00
305.87	7067.6	51.00	311.08	7192.7	52.00	316.30	7317.9	53.00
321.52	7443.0	54.00	326.74	7568.2	55.00	331.95	7693.4	56.00
337.17	7818.5	57.00	342.39	7943.7	58.00	347.60	8068.8	59.00
352.82	8194.0	60.00	358.04	8319.1	61.00	363.25	8444.3	62.00
368.47	8569.5	63.00	373.69	8694.6	64.00	378.91	8819.8	65.00
384.12	8944.9	66.00	389.34	9070.1	67.00	394.56	9195.2	68.00
399.77	9320.4	69.00	404.99	9445.6	70.00	410.21	9570.7	71.00
415.42	9695.9	72.00	420.64	9821.0	73.00	425.86	9946.2	74.00
431.07	10071.3	75.00	436.29	10196.5	76.00	441.51	10321.7	77.00
446.73	10446.8	78.00	451.94	10572.0	79.00	457.16	10697.1	80.00
462.38	10822.3	81.00	467.59	10947.4	82.00	472.81	11072.6	83.00
478.03	11197.8	84.00	483.25	11322.9	85.00	488.46	11448.1	86.00
493.68	11573.2	87.00	498.90	11698.4	88.00	504.11	11823.6	89.00
509.33	11948.7	90.00	514.55	12073.9	91.00	519.76	12199.0	92.00
524.98	12324.2	93.00	530.20	12449.3	94.00	535.42	12574.5	95.00
540.63	12699.7	96.00	545.85	12824.8	97.00	551.07	12950.0	98.00
556.28	13075.1	99.00	561.50	13200.3	100.00			

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SOURCE: TECHNICAL SUPPORT — REVIEWED BY: [signature] 2/2/90

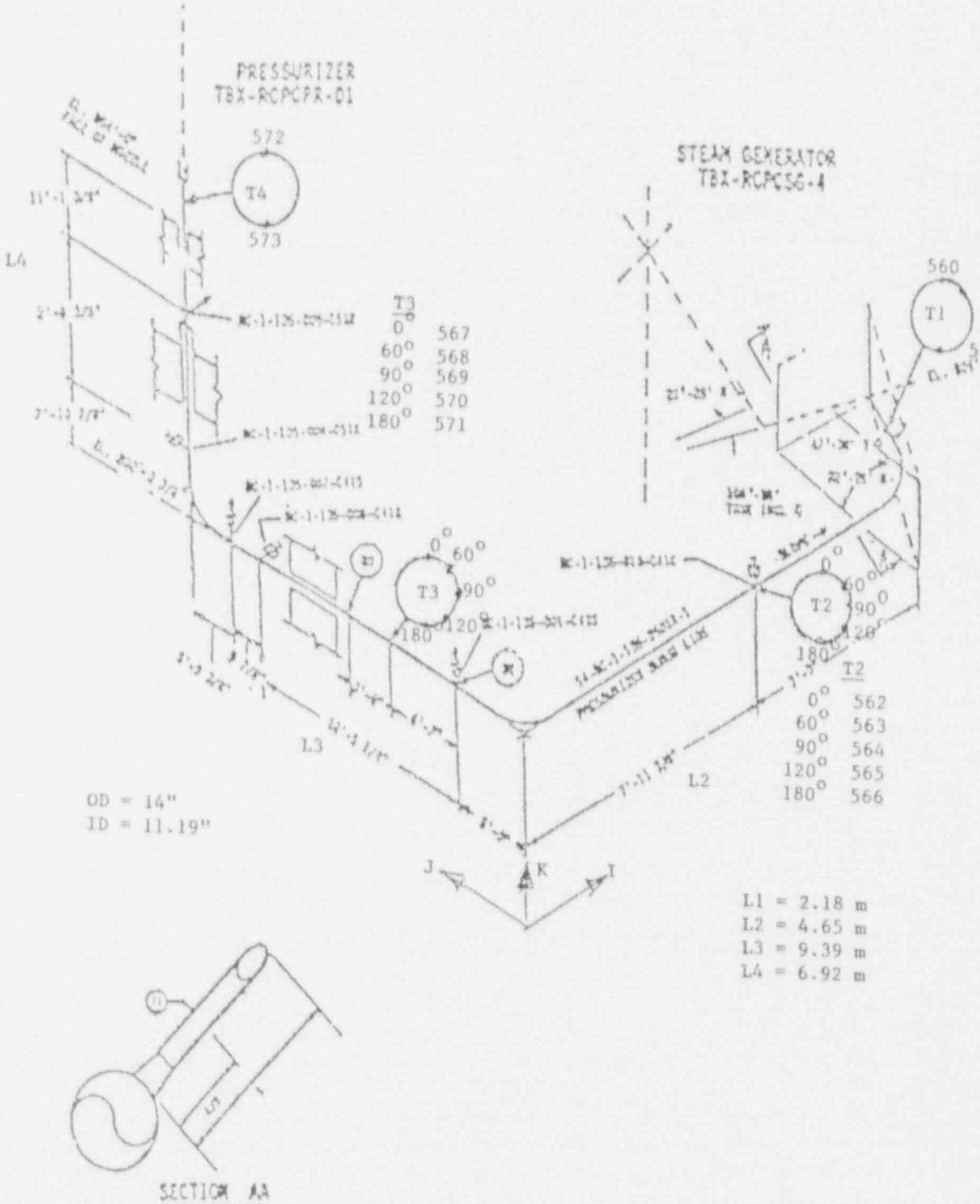


Fig. 1. Pressurizer surge line layout and monitoring locations for the Comanche Peak Reactor

COMANCHE PEAK STEAM ELECTRIC STATION - UNIT 1
STRATIFICATION AND THERMAL CYCLING

STRATIFY
Revision 0
9 Mar 1990

CH-SG0		CH-SG1	
PZR SGL PT 00T-1-000 TEMP		PZR SGL PT 00T-1-180 TEMP	
Minimum =	151.833 DEGF	Minimum =	151.198 DEGF
Maximum =	350.549 DEGF	Maximum =	208.737 DEGF
Average =	193.062 DEGF	Average =	185.979 DEGF
SD =	18.595 DEGF	SD =	12.812 DEGF
Top Curve		Bottom Curve	

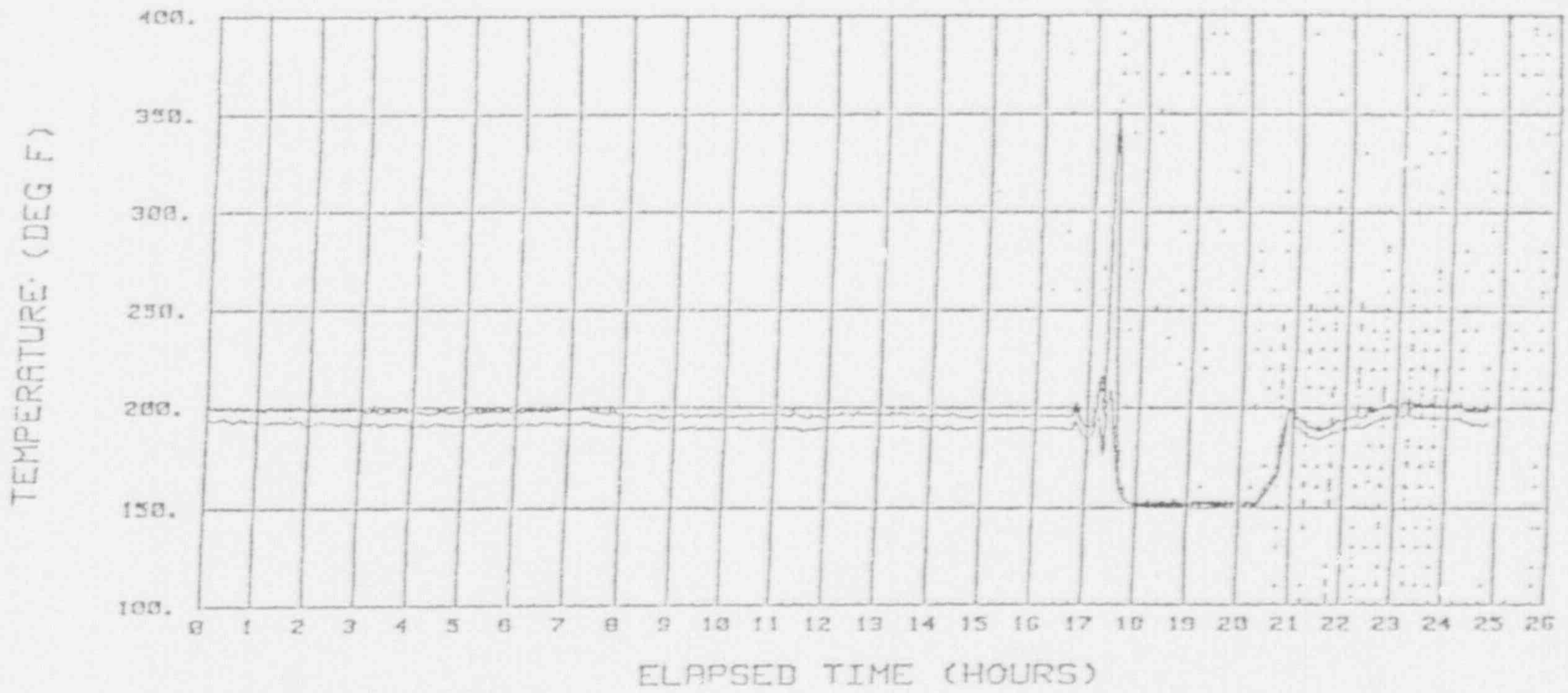


Fig. 2. T1 temperature readings

COMANCHE PEAK STEAM ELECTRIC STATION - UNIT 1
STRATIFICATION AND THERMAL CYCLING

STRATIFY
Revision 0
9 Mar 1990

CH-S62		CH-S63		CH-S64	
PZR SGL PT 00T-2-000 TEMP		PZR SGL PT 00T-2-060 TEMP		PZR SGL PT 00T-2-090 TEMP	
Minimum -	253.304 DEGF	Minimum -	239.289 DEGF	Minimum -	216.155 DEGF
Maximum -	408.107 DEGF	Maximum -	409.330 DEGF	Maximum -	410.873 DEGF
Average -	393.373 DEGF	Average -	390.939 DEGF	Average -	386.995 DEGF
SD -	36.150 DEGF	SD -	44.689 DEGF	SD -	57.365 DEGF

CH-S65		CH-S66	
PZR SGL PT 00T-2-120 TEMP		PZR SGL PT 00T-2-180 TEMP	
Minimum -	175.474 DEGF	Minimum -	159.031 DEGF
Maximum -	407.420 DEGF	Maximum -	392.923 DEGF
Average -	379.020 DEGF	Average -	351.704 DEGF
SD -	68.469 DEGF	SD -	72.373 DEGF

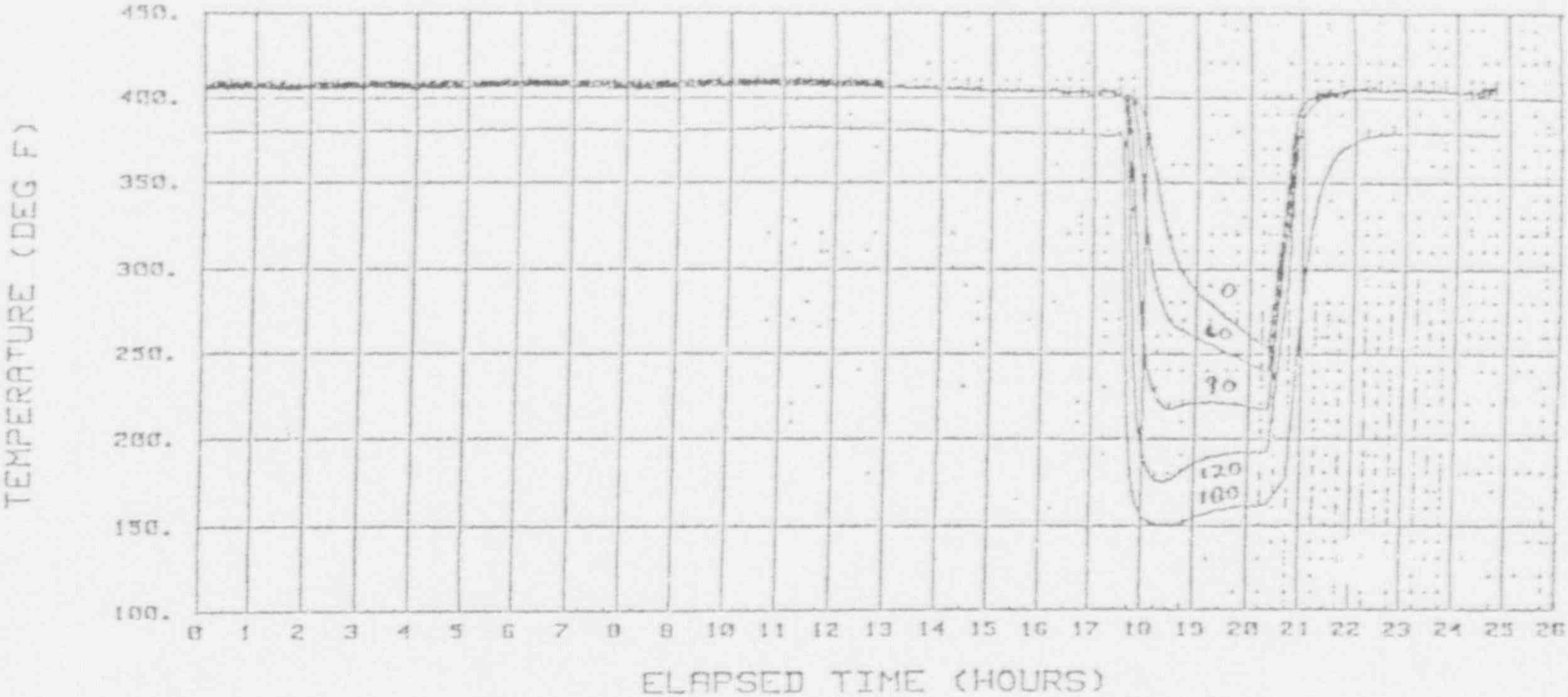


Fig. 3. T2 temperature readings

COMANCHE PEAK STEAM ELECTRIC STATION - UNIT 1
STRATIFICATION AND THERMAL CYCLING

STRATIFY
Revision 0
8 Mar 1990

CH-567

PZR SGL PT 00T-3-000 TEMP		
Minimum	-	272.462 DEGF
Maximum	-	430.097 DEGF
Average	-	416.032 DEGF
SD	-	34.997 DEGF

CH-568

PZR SGL PT 00T-3-060 TEMP		
Minimum	-	240.904 DEGF
Maximum	-	427.707 DEGF
Average	-	409.740 DEGF
SD	-	45.310 DEGF

CH-569

PZR SGL PT 00T-3-090 TEMP		
Minimum	-	221.353 DEGF
Maximum	-	423.189 DEGF
Average	-	399.561 DEGF
SD	-	57.818 DEGF

CH-570

PZR SGL PT 00T-3-120 TEMP		
Minimum	-	189.126 DEGF
Maximum	-	409.338 DEGF
Average	-	382.633 DEGF
SD	-	65.346 DEGF

CH-571

PZR SGL PT 00T-3-180 TEMP		
Minimum	-	150.464 DEGF
Maximum	-	366.523 DEGF
Average	-	330.841 DEGF
SD	-	65.304 DEGF

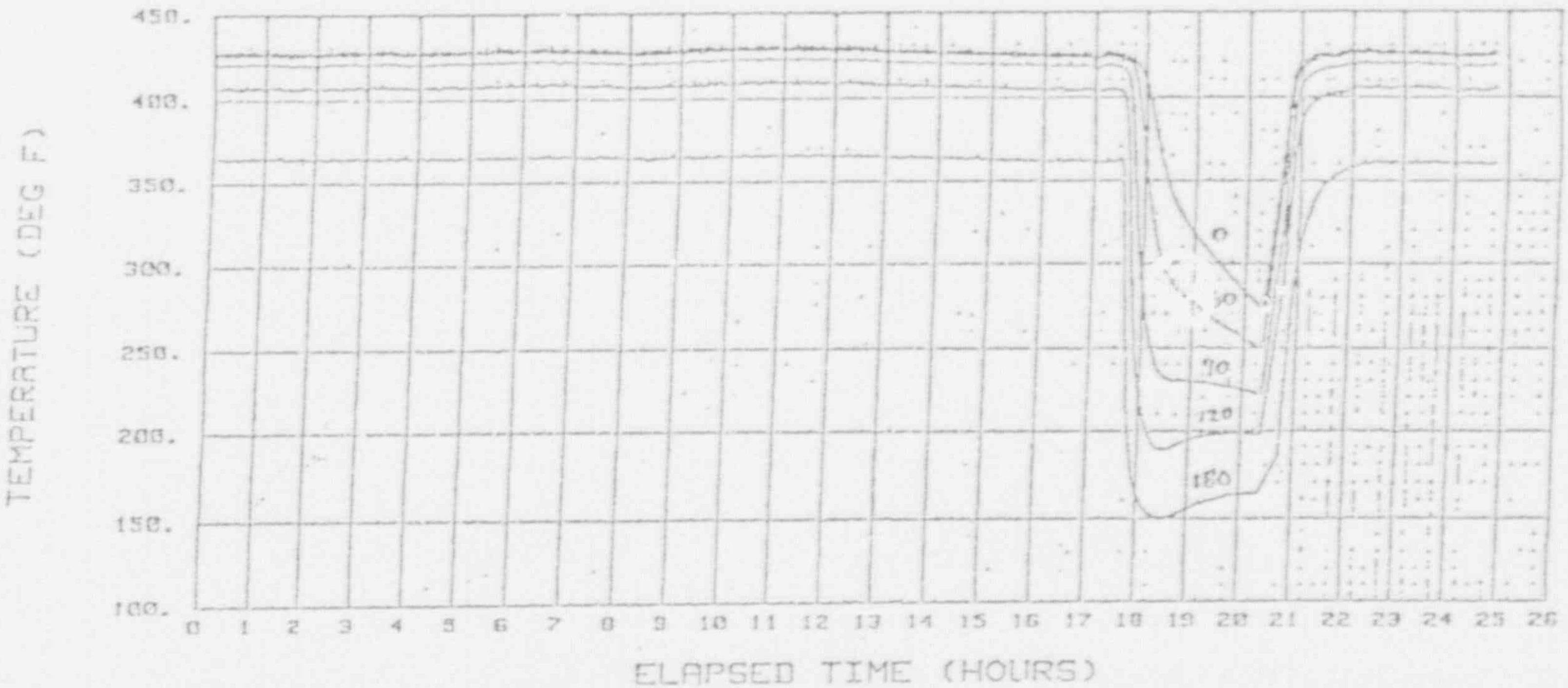


Fig. 4. T3 temperature readings

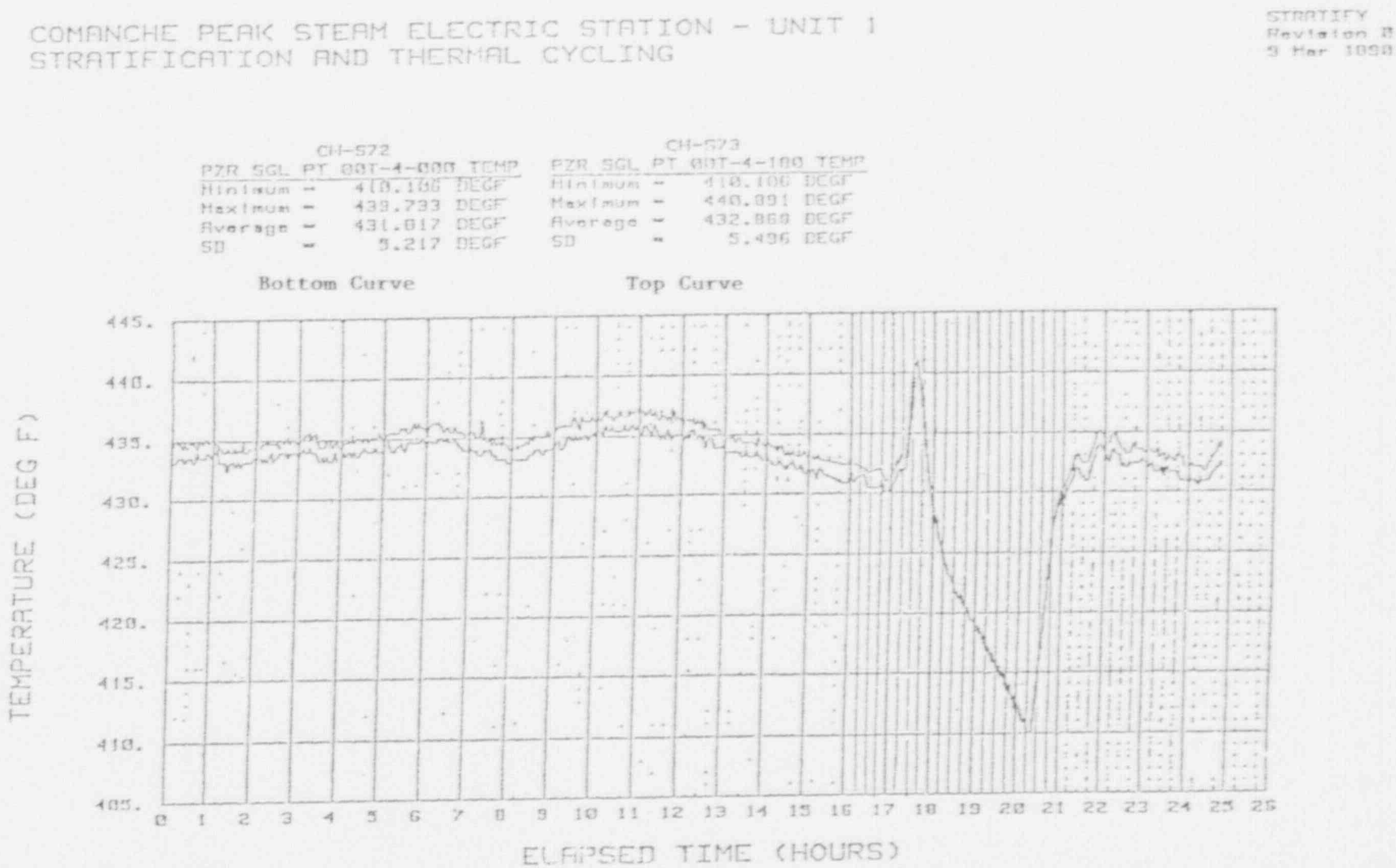


Fig. 5. T4 temperature readings

COMANCHE PEAK STEAM ELECTRIC STATION - UNIT 1
STRATIFICATION AND THERMAL CYCLING

STRATIFY
Revision 0
9 Mar 1990

CH-054	CH-055	CH-056	CH-057
RCS LP1 HL TEMP (WR)	RCS LP2 HL TEMP (WR)	RCS LP3 HL TEMP (WR)	RCS LP4 HL TEMP (WR)
Minimum - 154.000 DEGF	Minimum - 154.175 DEGF	Minimum - 154.000 DEGF	Minimum - 152.600 DEGF
Maximum - 162.925 DEGF	Maximum - 163.100 DEGF	Maximum - 160.825 DEGF	Maximum - 163.625 DEGF
Average - 157.502 DEGF	Average - 157.989 DEGF	Average - 157.196 DEGF	Average - 158.214 DEGF
SD - 2.400 DEGF	SD - 2.332 DEGF	SD - 1.600 DEGF	SD - 2.768 DEGF

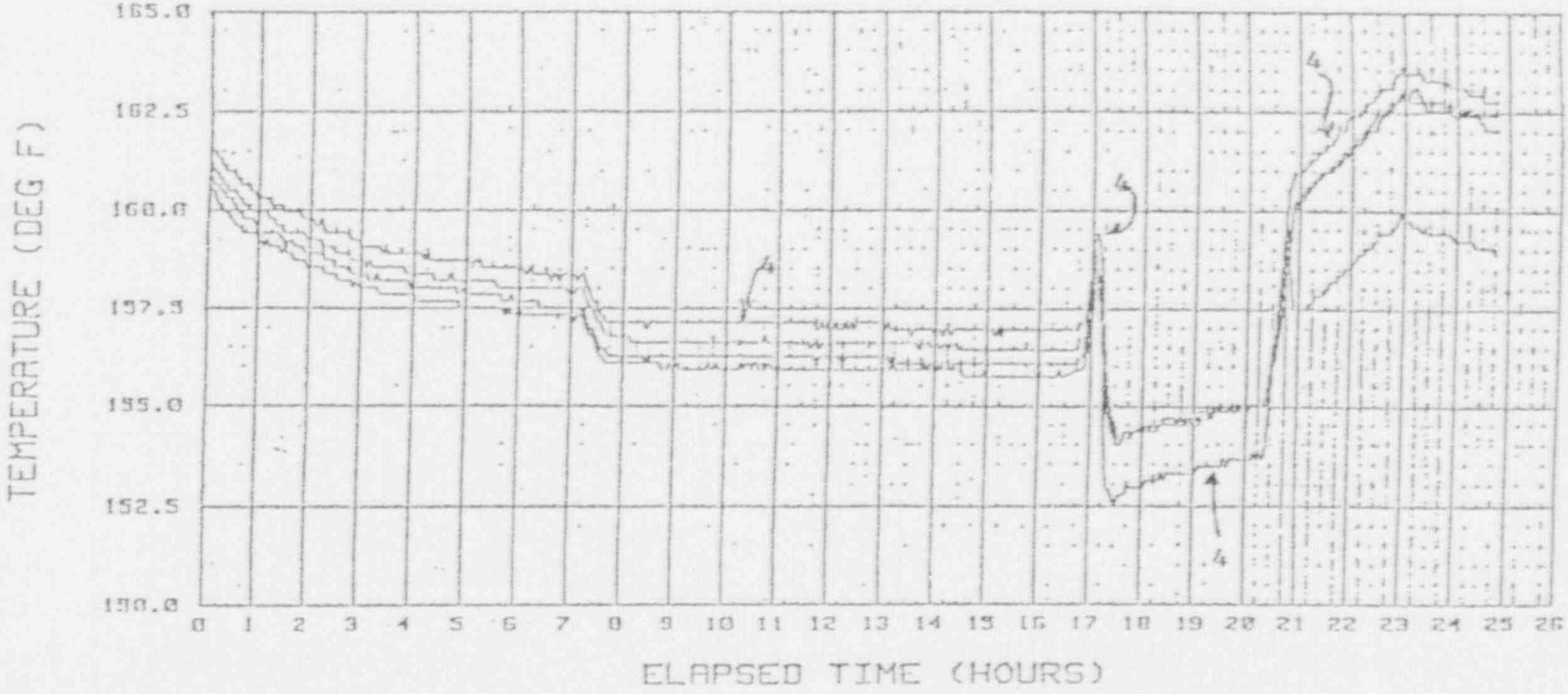


Fig. 6. Hot-leg temperature readings

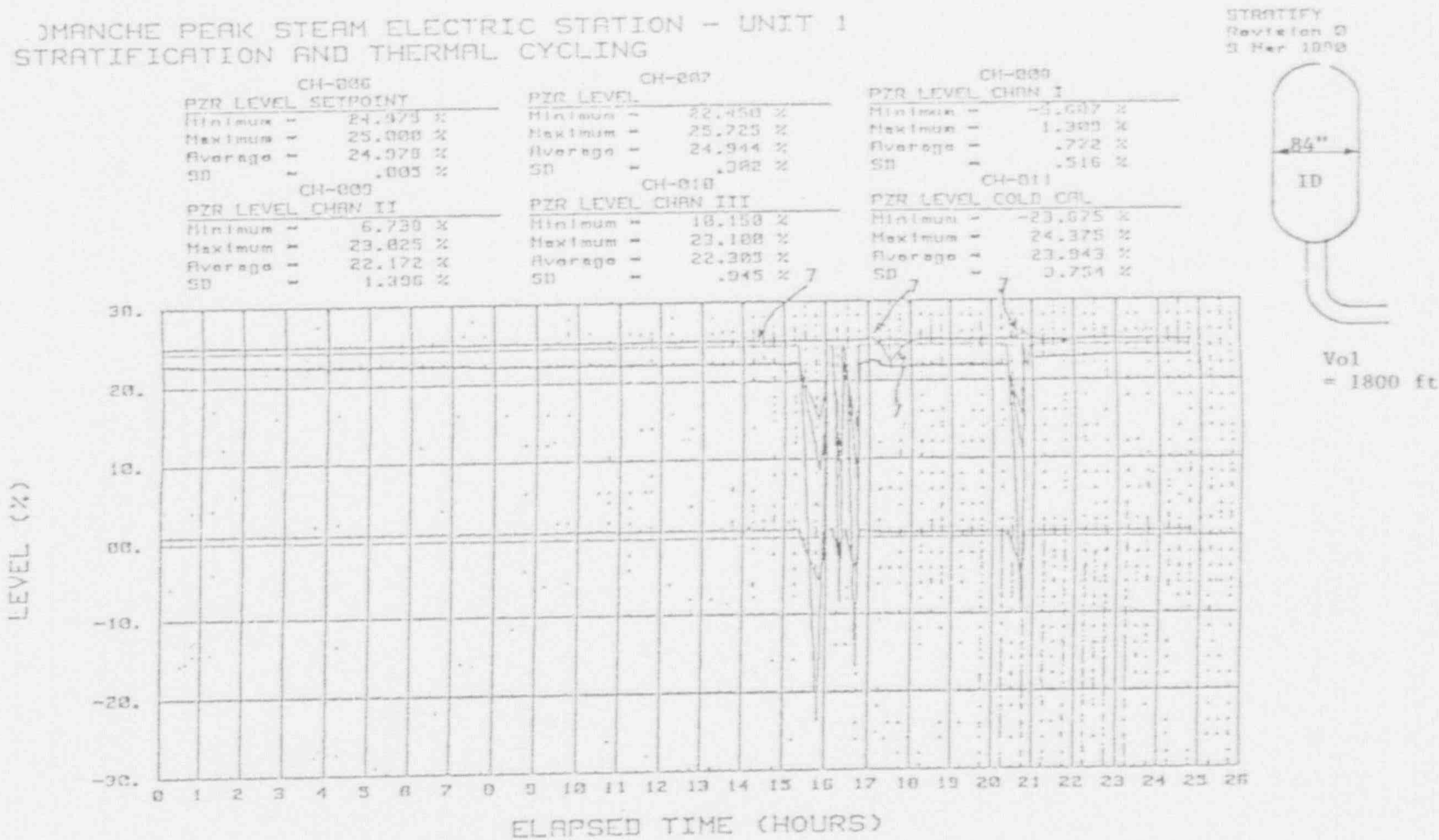


Fig. 7. Pressurizer water level readings

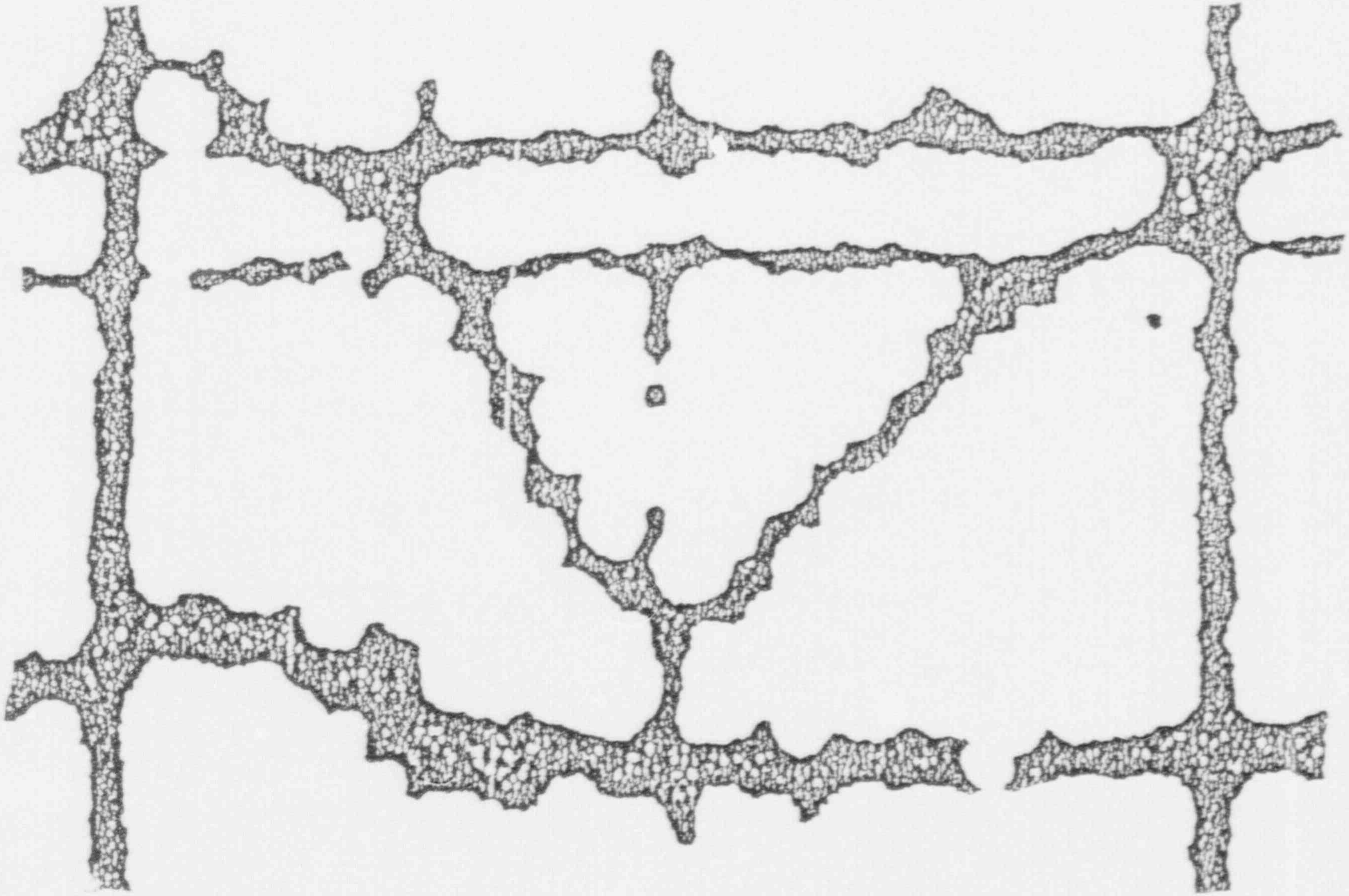


Fig. 7a. Enlarged view of a portion of Fig. 7 for 17 to 18 h

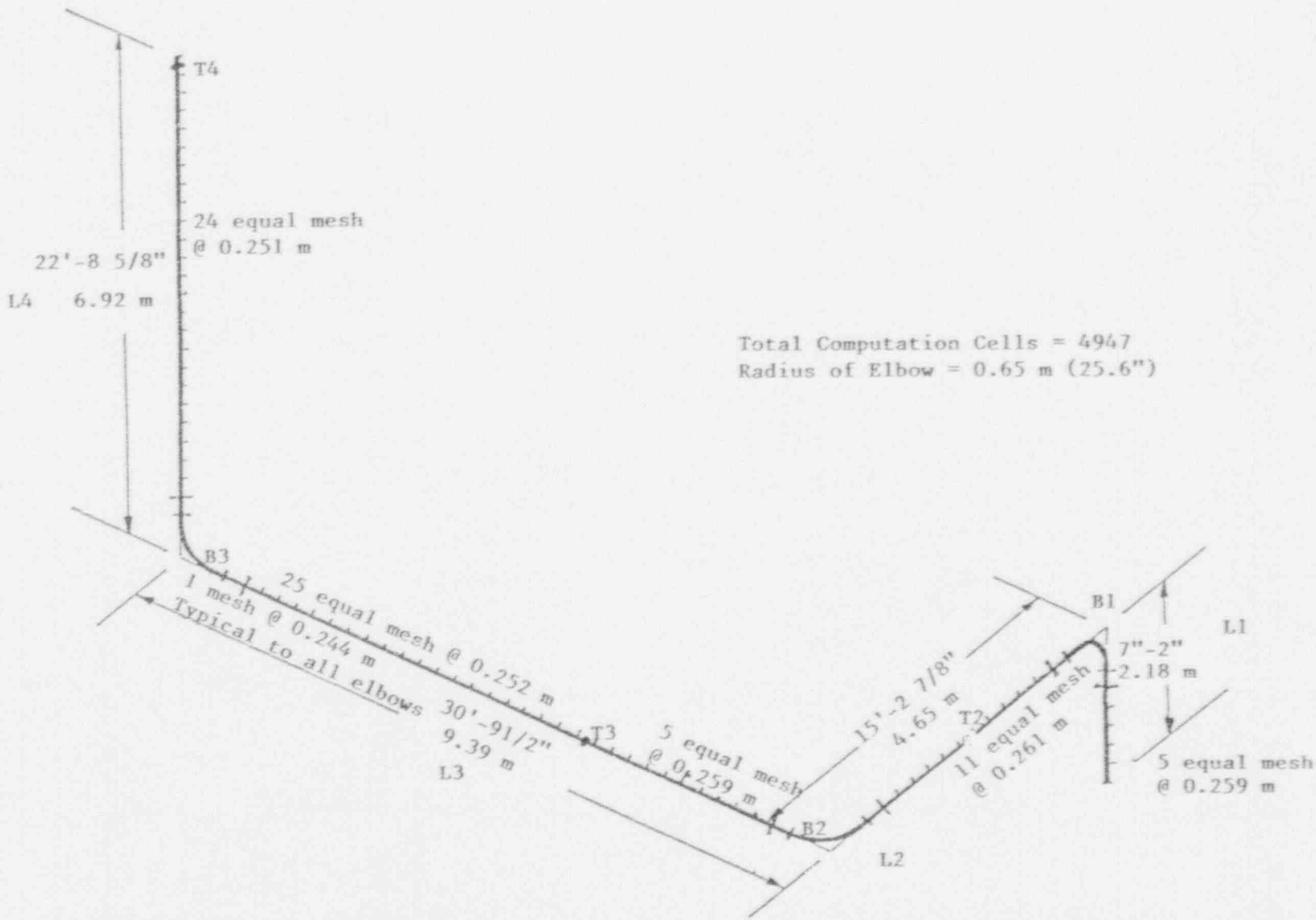


Fig. 8. Surge line layout used in COMMIX code

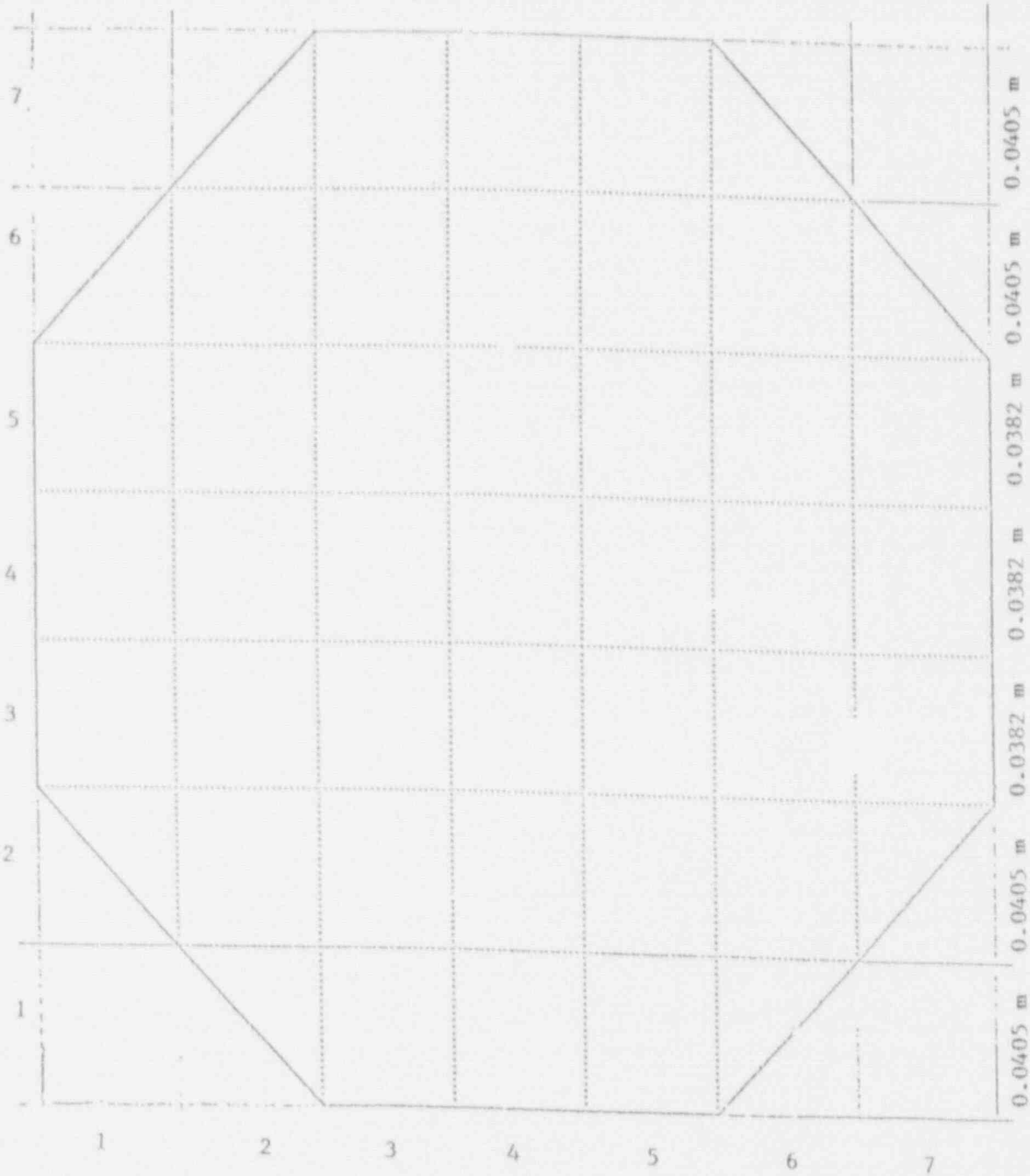


Fig. 9. Typical cross section of surge line

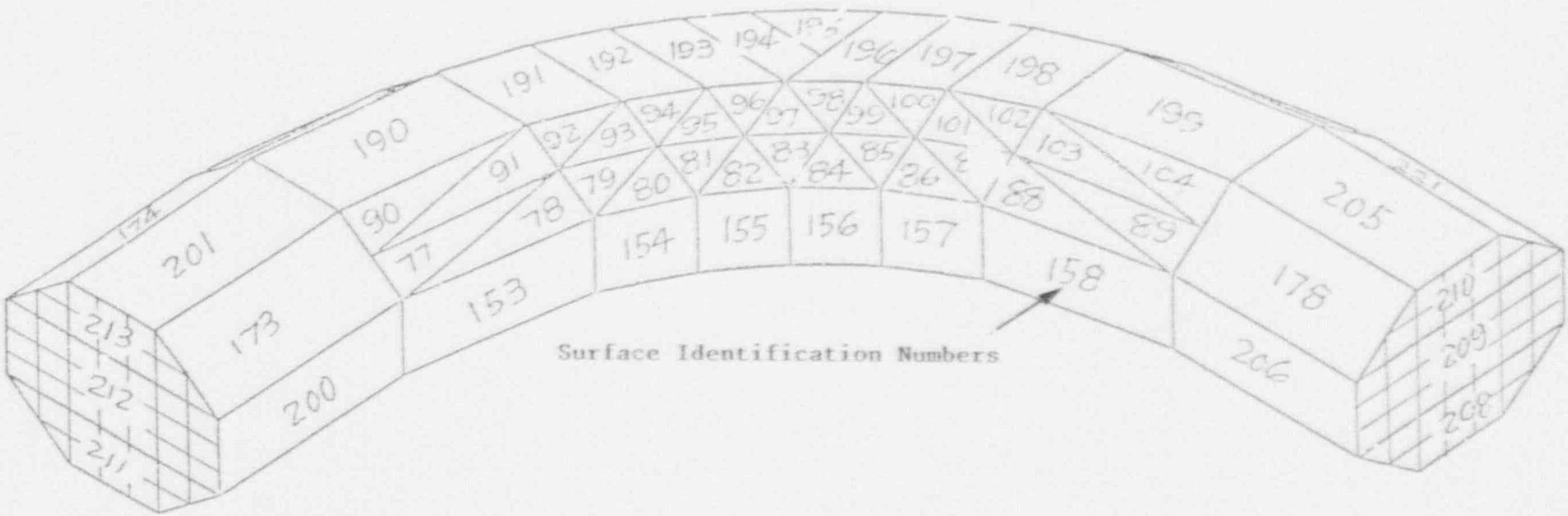


Fig. 10. Typical elbow

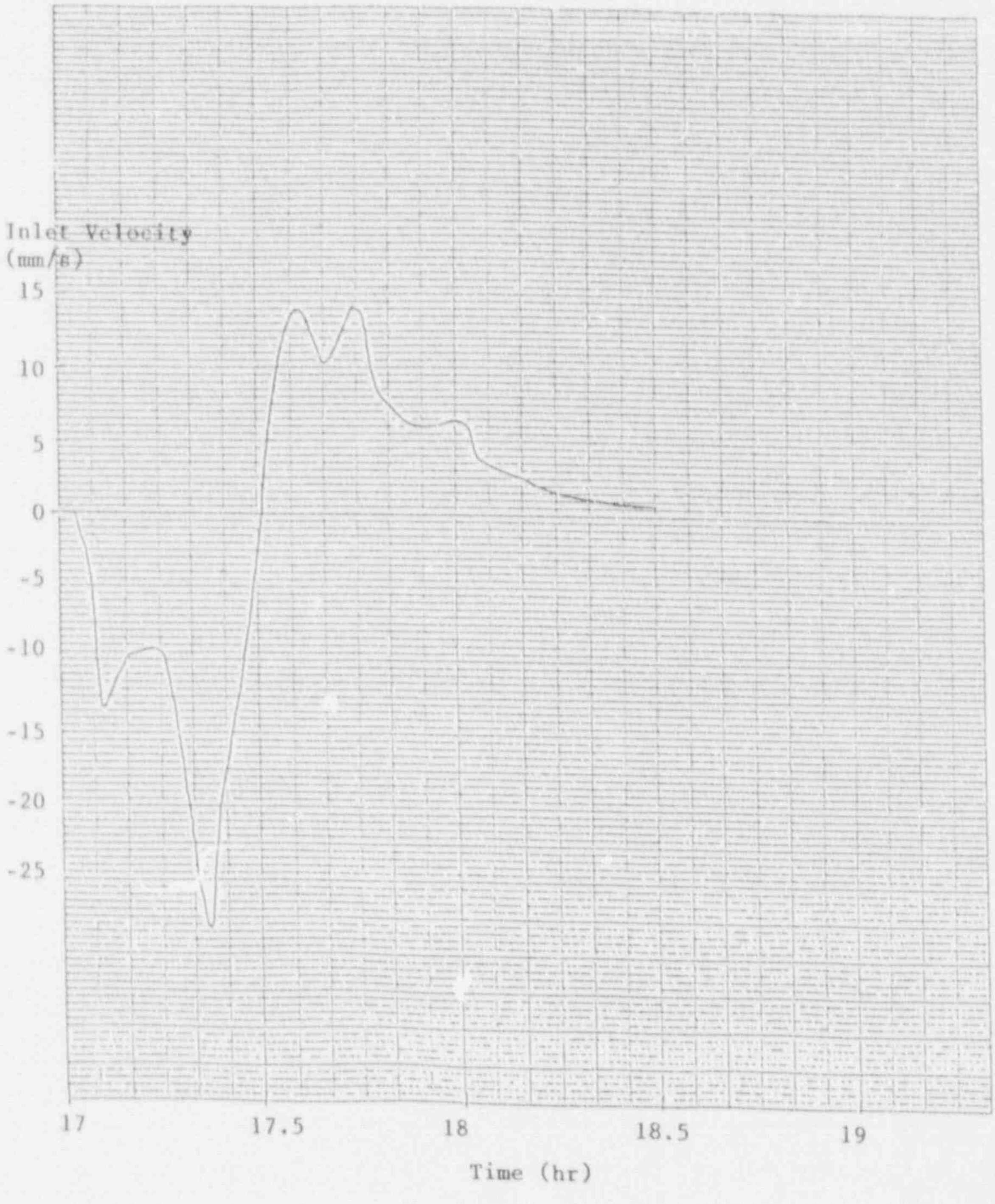


Fig. 11. Inlet velocity of surge line

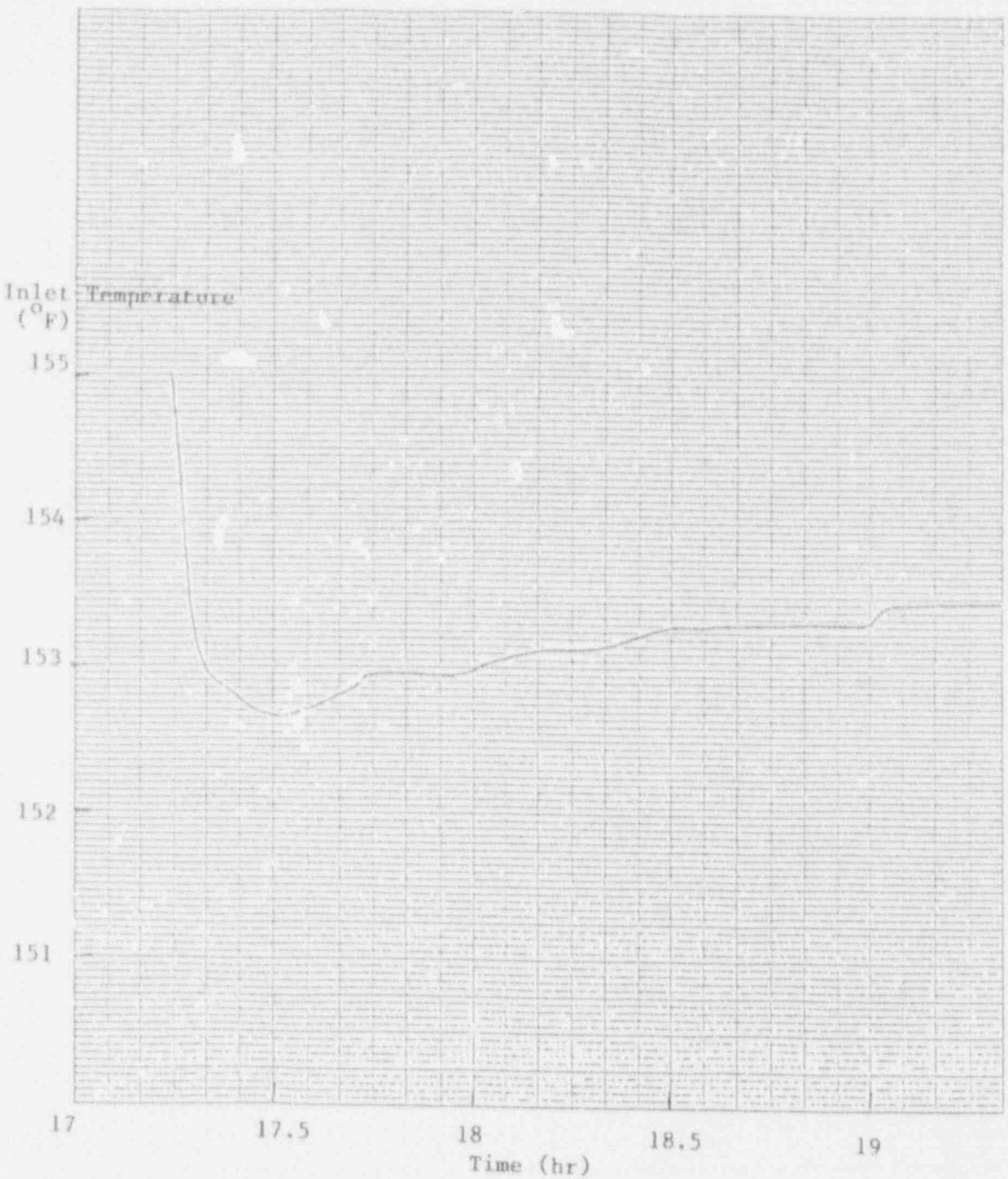


Fig. 12. Inlet temperature of surge line

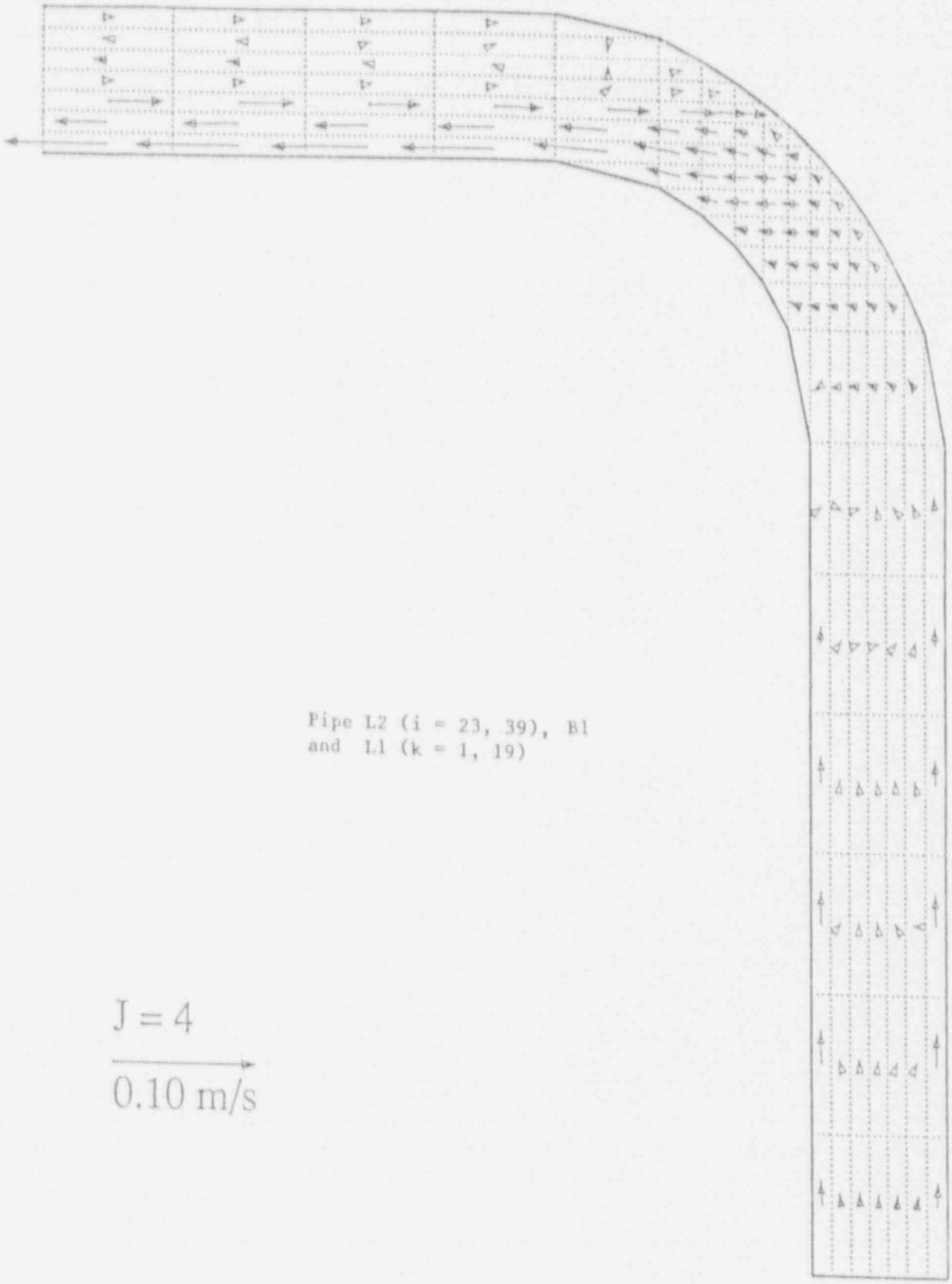


Fig. 13. Velocity profile at 10 min into transient, Pipes L1 and L2

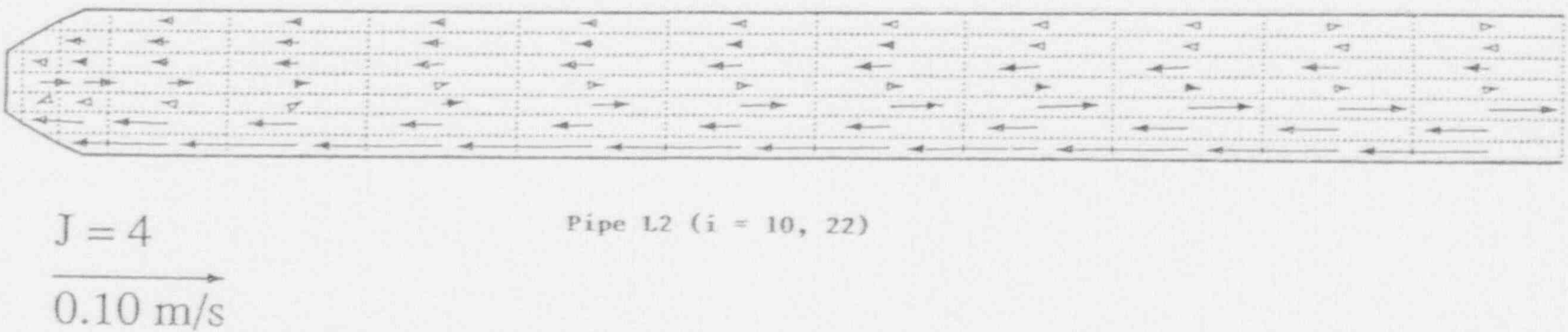


Fig. 14. Velocity profile at 10 min into transient, Pipe L2

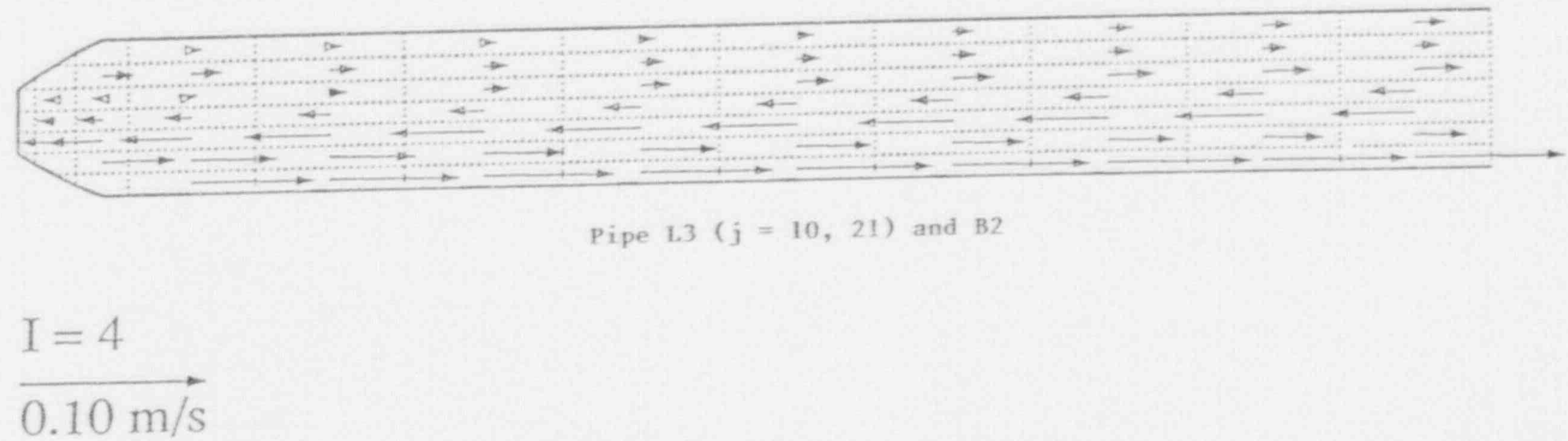


Fig. 15. Velocity profile at 10 min into transient, Pipe L3

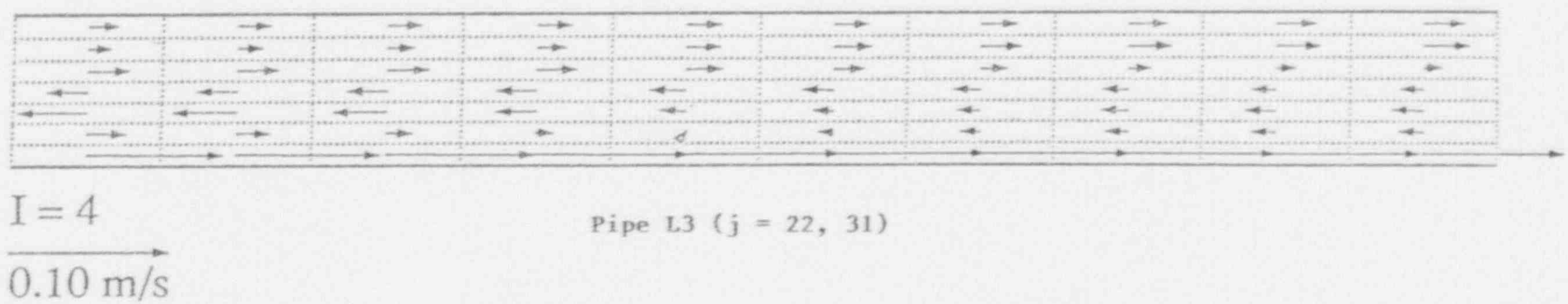


Fig. 16. Velocity profile at 10 min into transient, Pipe L3

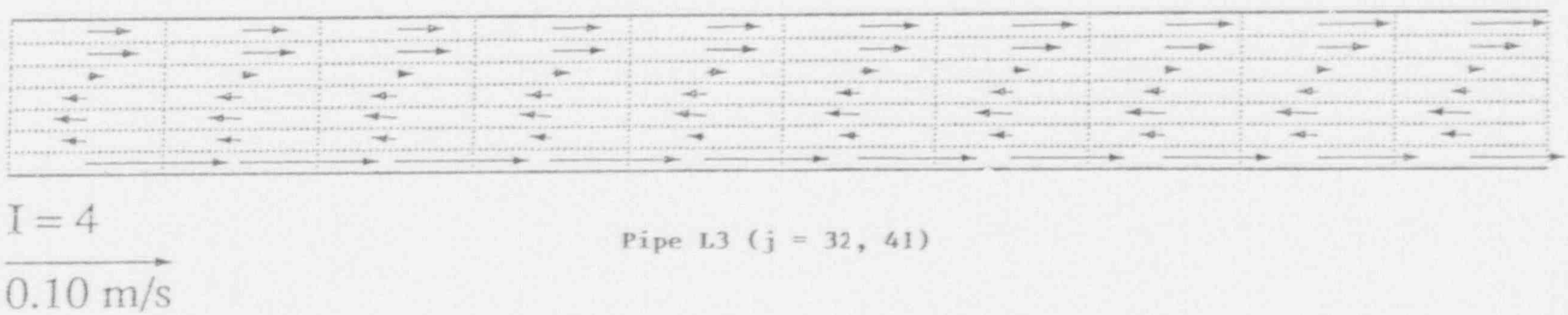


Fig. 17. Velocity profile at 10 min into transient, Pipe L3

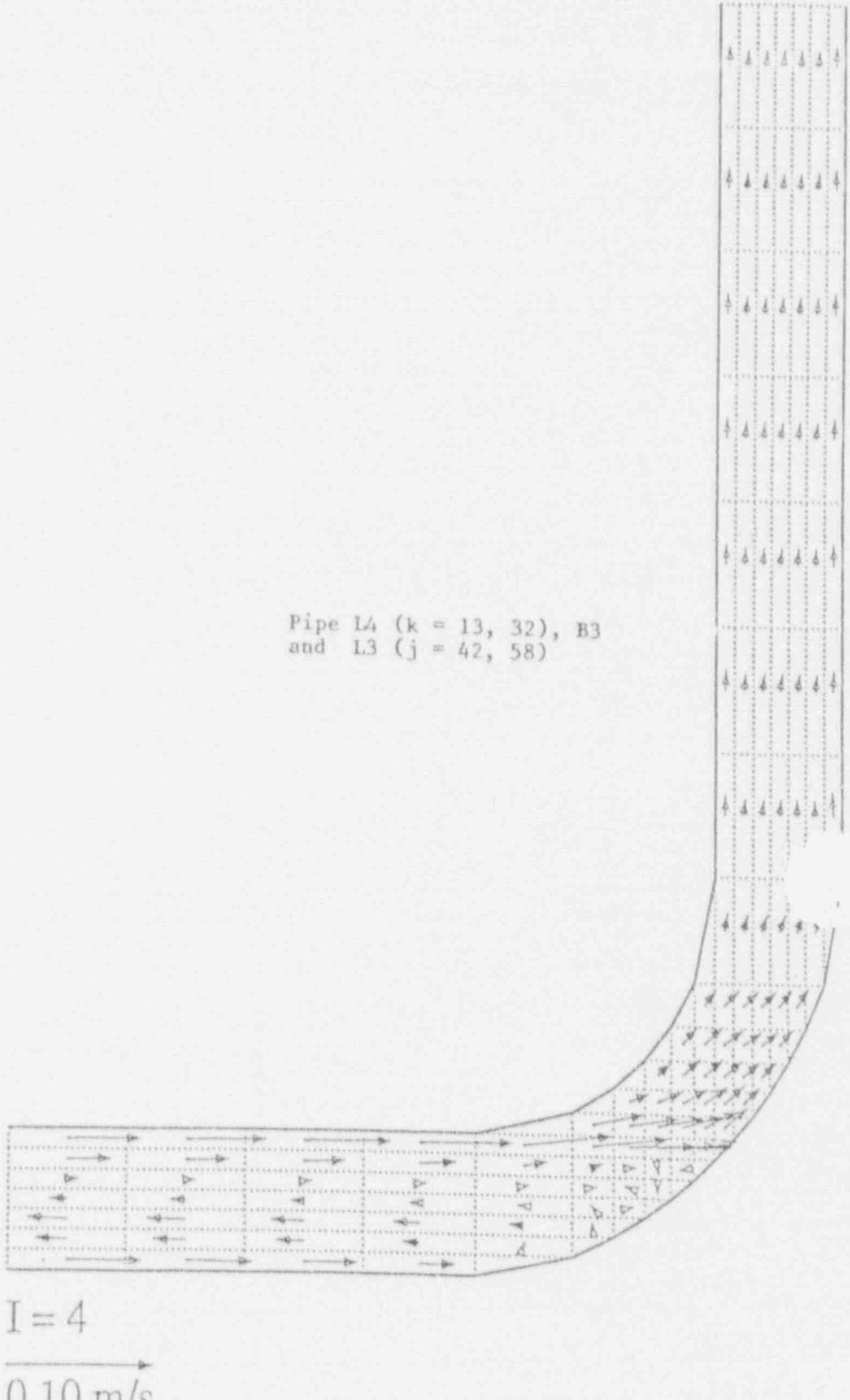


Fig. 18. Velocity profile at 10 min into transient, pipes L3 and L4

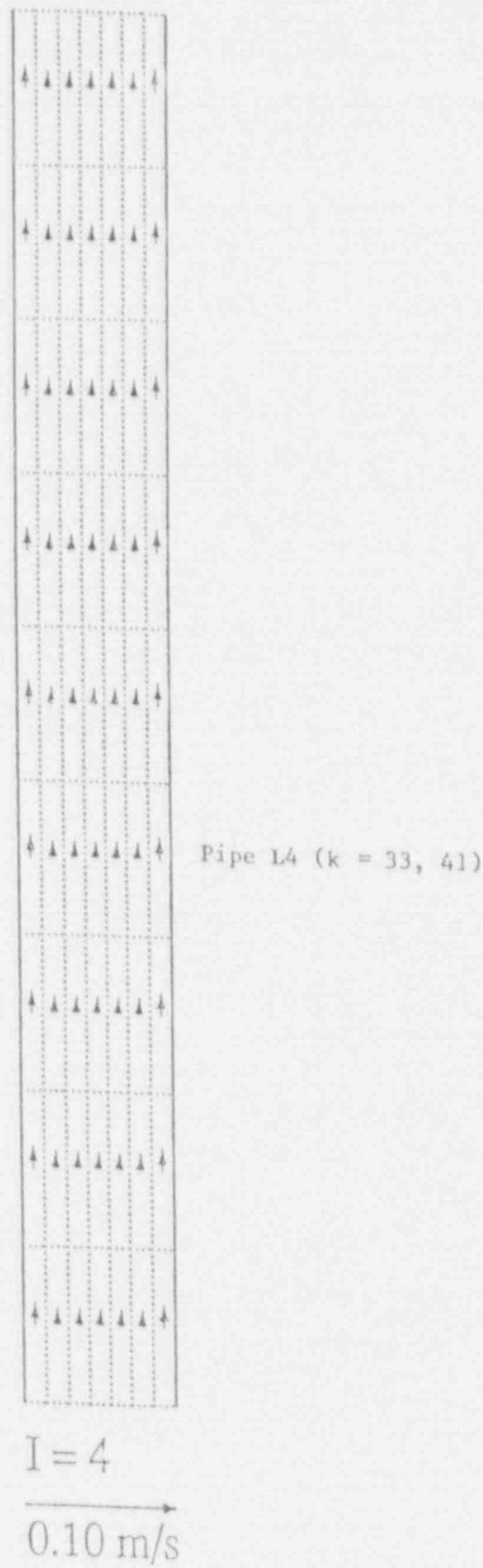


Fig. 19. Velocity profile at 10 min into transient, pipe L4

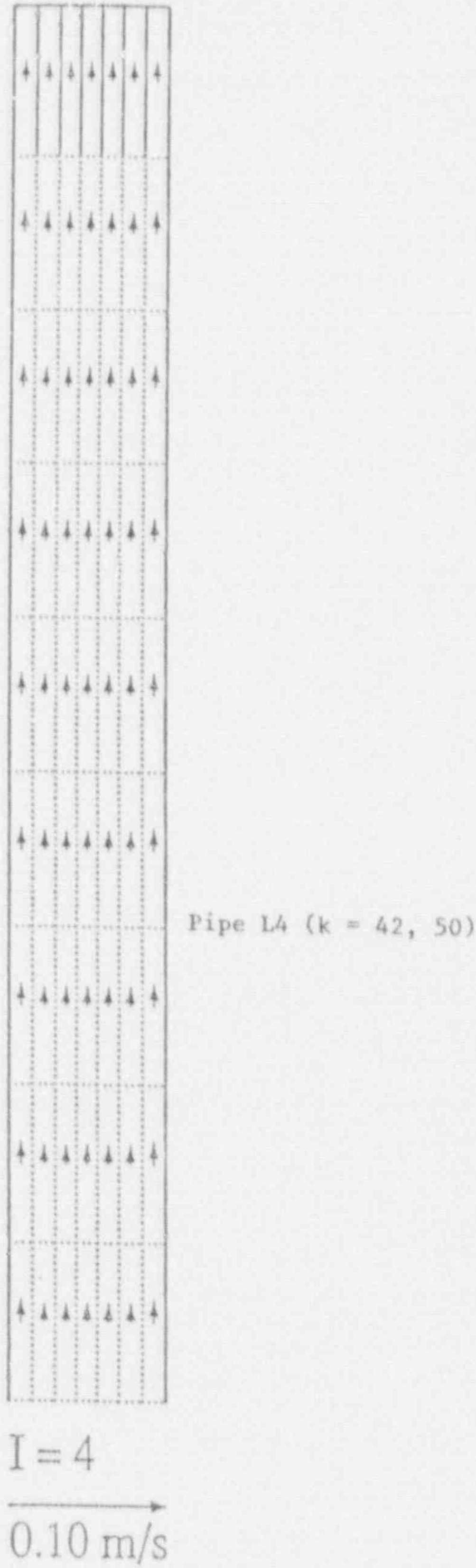


Fig. 20. Velocity profile at 10 min into transient, pipe L4

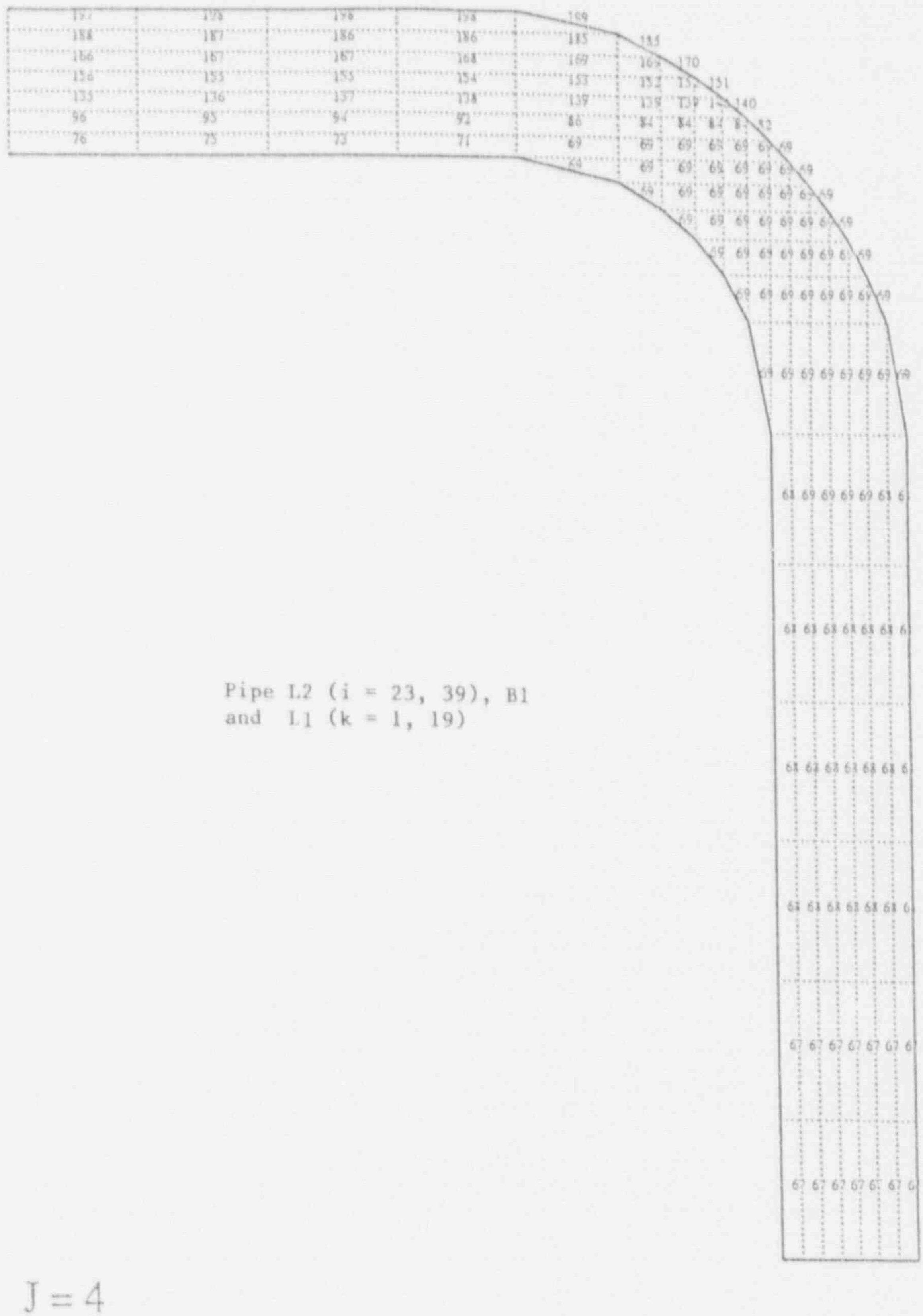
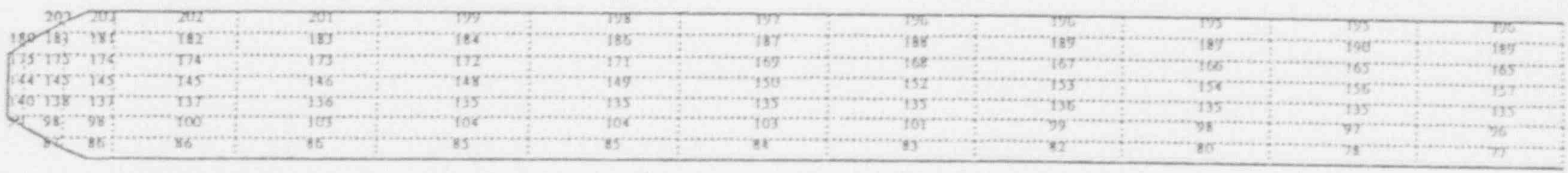


Fig. 21. Temperature distributions at 10 min into transient, pipes L1 and L2



J = 4

Pipe L2 (i = 10, 22)

Fig. 22. Temperature distributions at 10 min into transient, Pipe L2

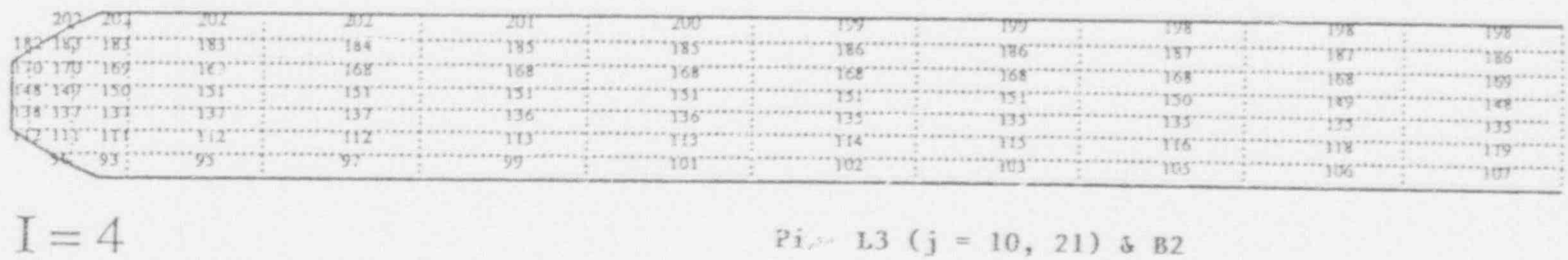


Fig. 23. Temperature distributions at 10 min into transient. Pipe L3

198	199	199	200	200	201	200	200	200	200
186	186	185	185	184	184	184	183	183	185
169	170	171	171	172	171	170	170	169	169
147	147	146	144	143	144	145	145	145	146
134	134	133	133	132	132	132	132	131	130
121	123	126	128	131	131	131	130	130	129
108	109	110	110	111	111	111	112	112	112

I = 4

Pipe L3 (j = 22, 31)

Fig. 24. Temperature distributions at 10 min into transient, Pipe L3

201	201	201	201	200	199	197	197	197	198
185	185	185	186	186	186	186	185	185	185
169	165	168	168	168	165	169	169	169	169
146	146	146	146	145	142	145	143	145	145
130	130	129	129	129	129	129	129	128	128
129	128	128	128	128	128	128	128	127	127
113	113	114	113	116	116	113	112	118	119

I = 4

Pipe L3 (j = 32, 41)

Fig. 25. Temperature distributions at 10 min into transient, Pipe L3

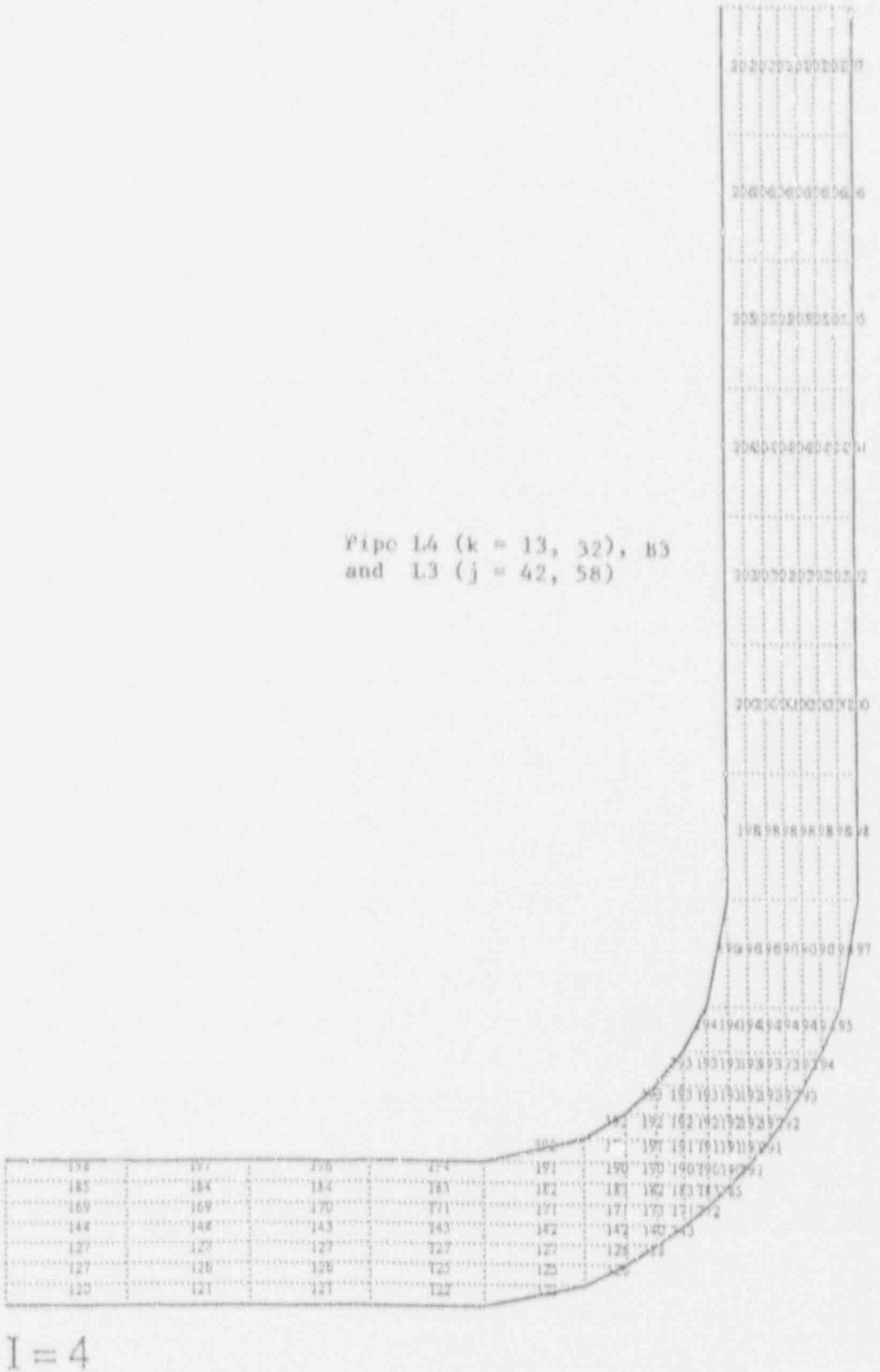


Fig. 26. Temperature distributions at 10 min into transient, pipes L3 and L4

Pipe L4 (k = 33, 41)

I = 4

Fig. 27. Temperature distributions at 10 min into transient, pipe L4

Pipe L4 (k = 42, 50)

Fig. 28. Temperature distributions at 10 min into transient, pipe L4

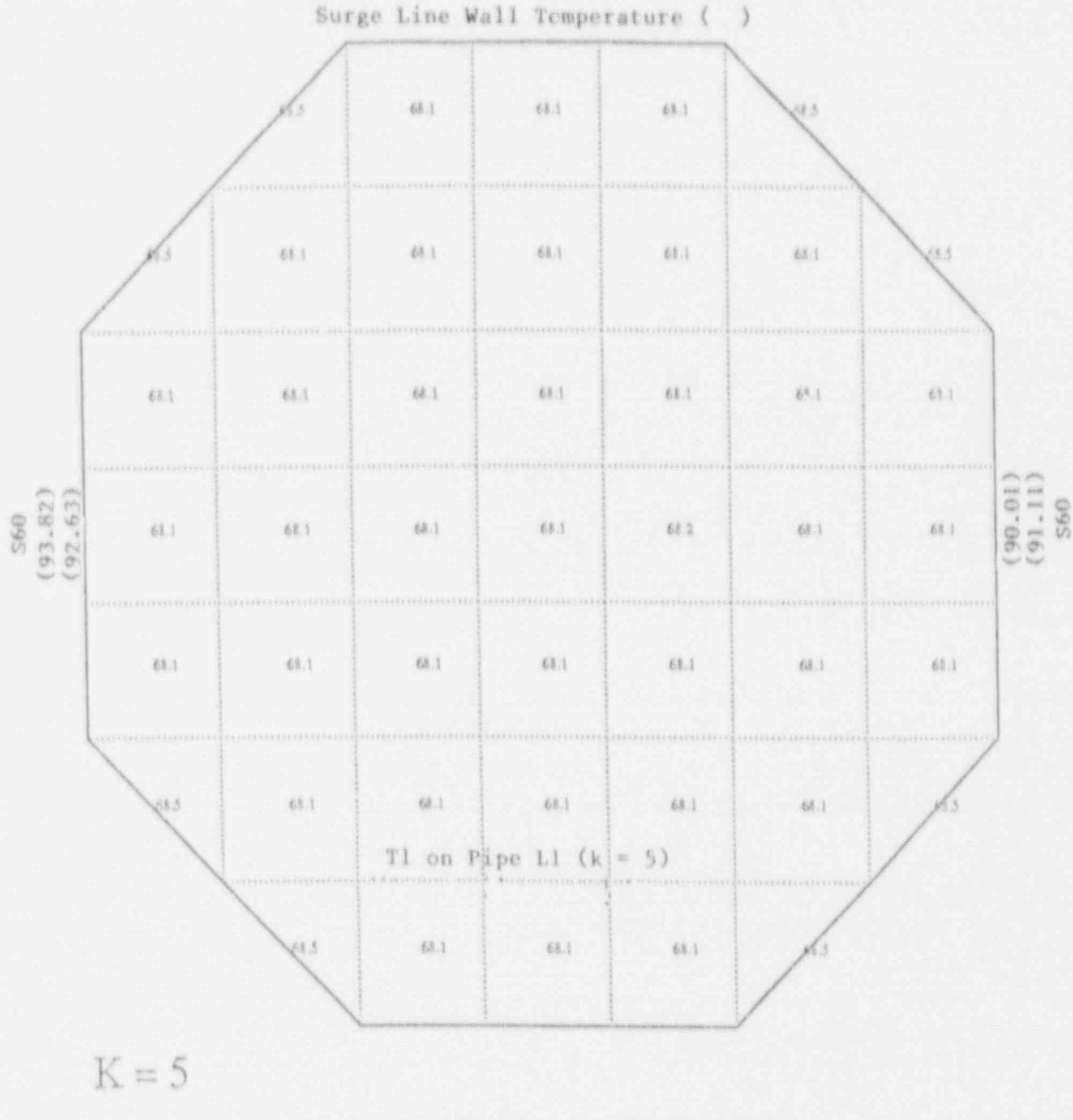


Fig. 29. Temperature profile at T1

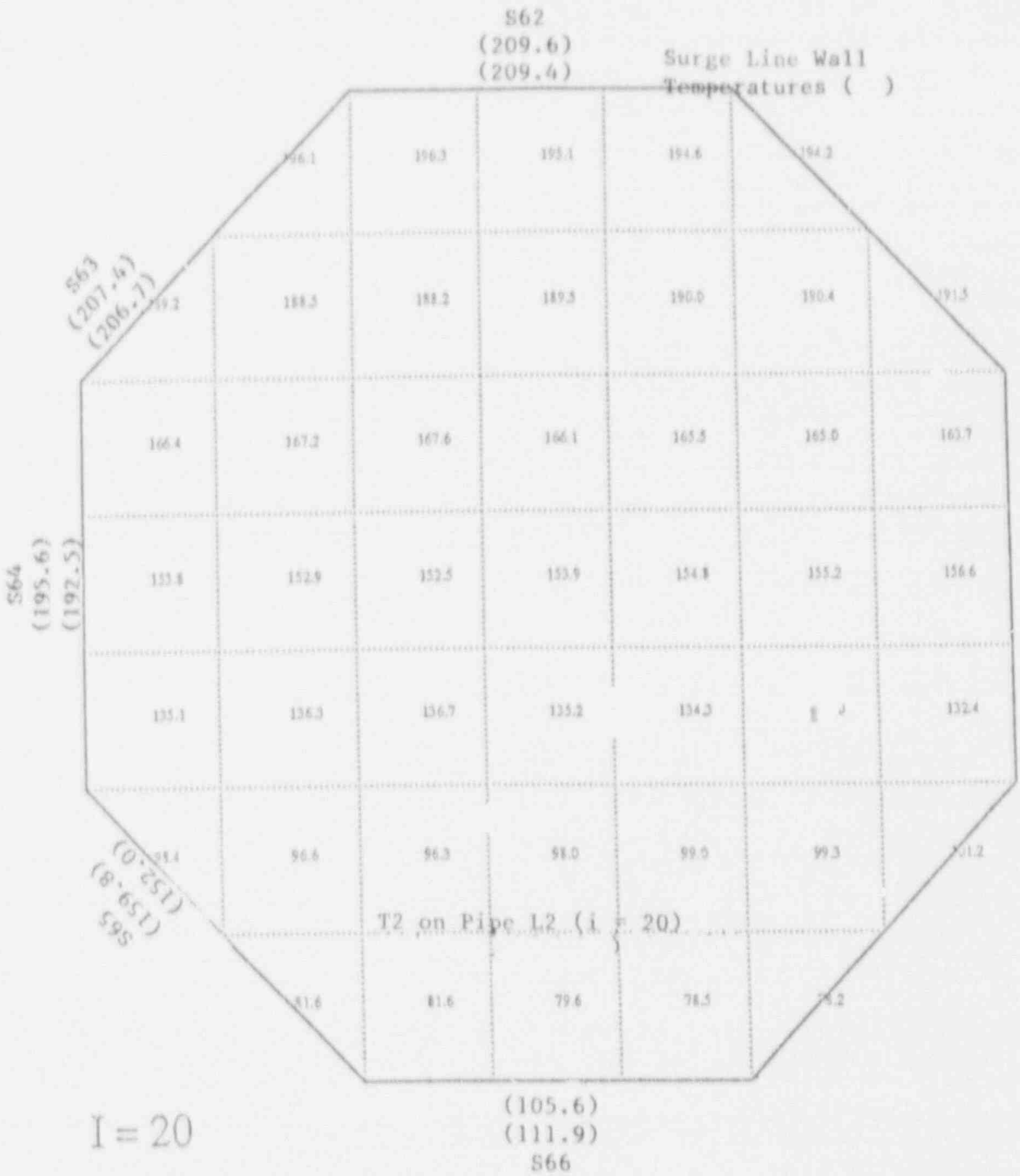


Fig. 30. Temperature profile at T2

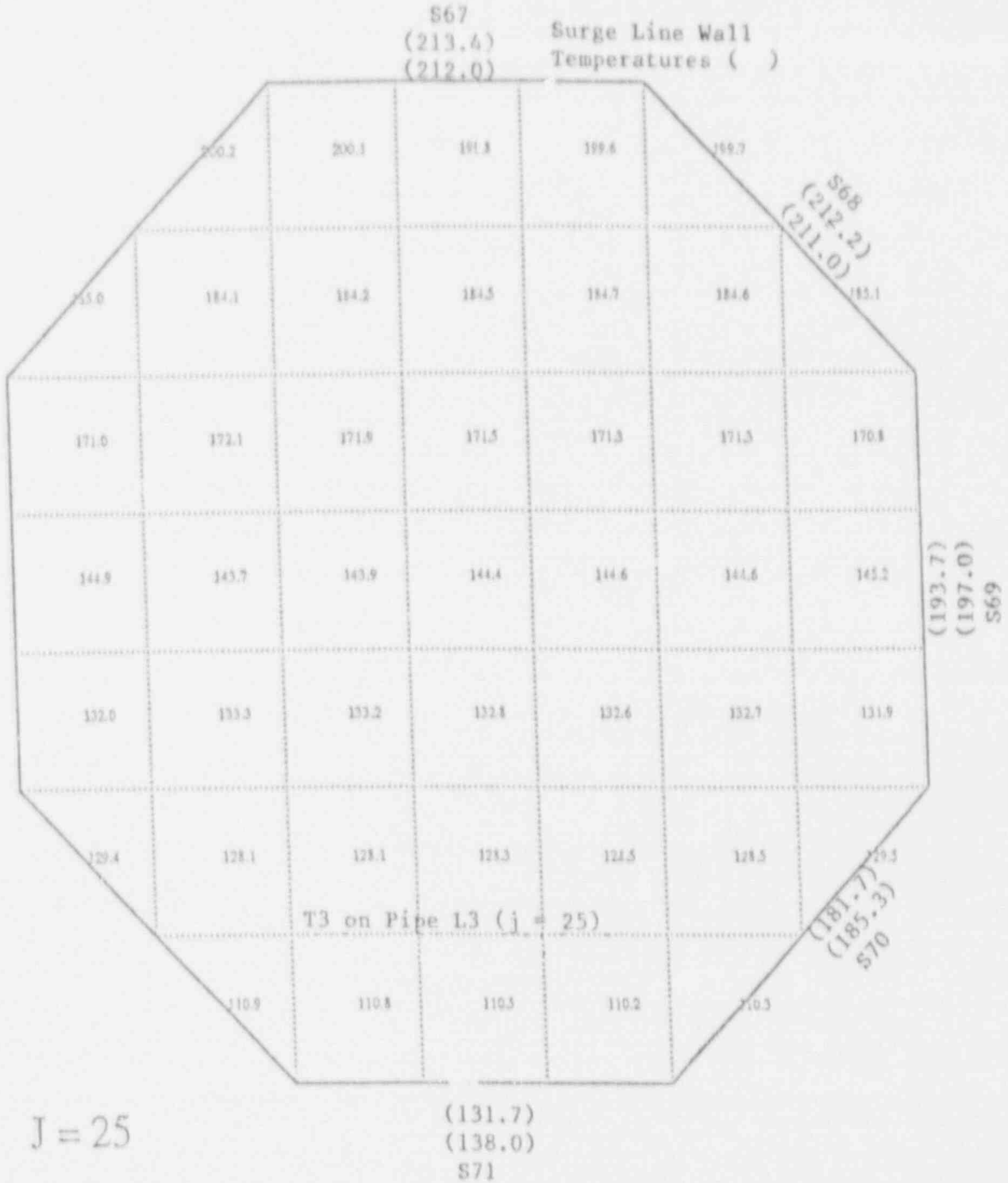


Fig. 31. Temperature profile at T3

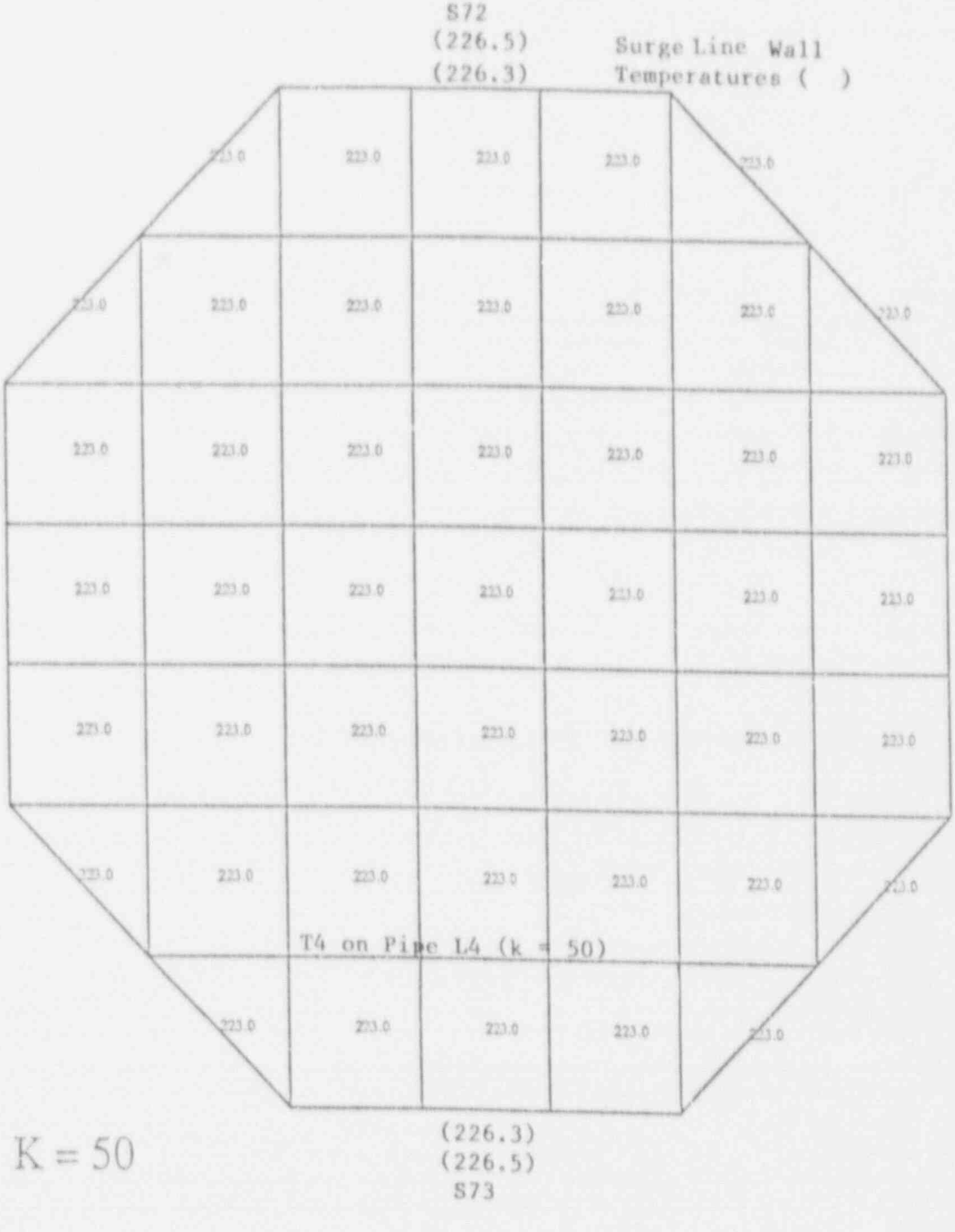


Fig. 32. Temperature profile at T4

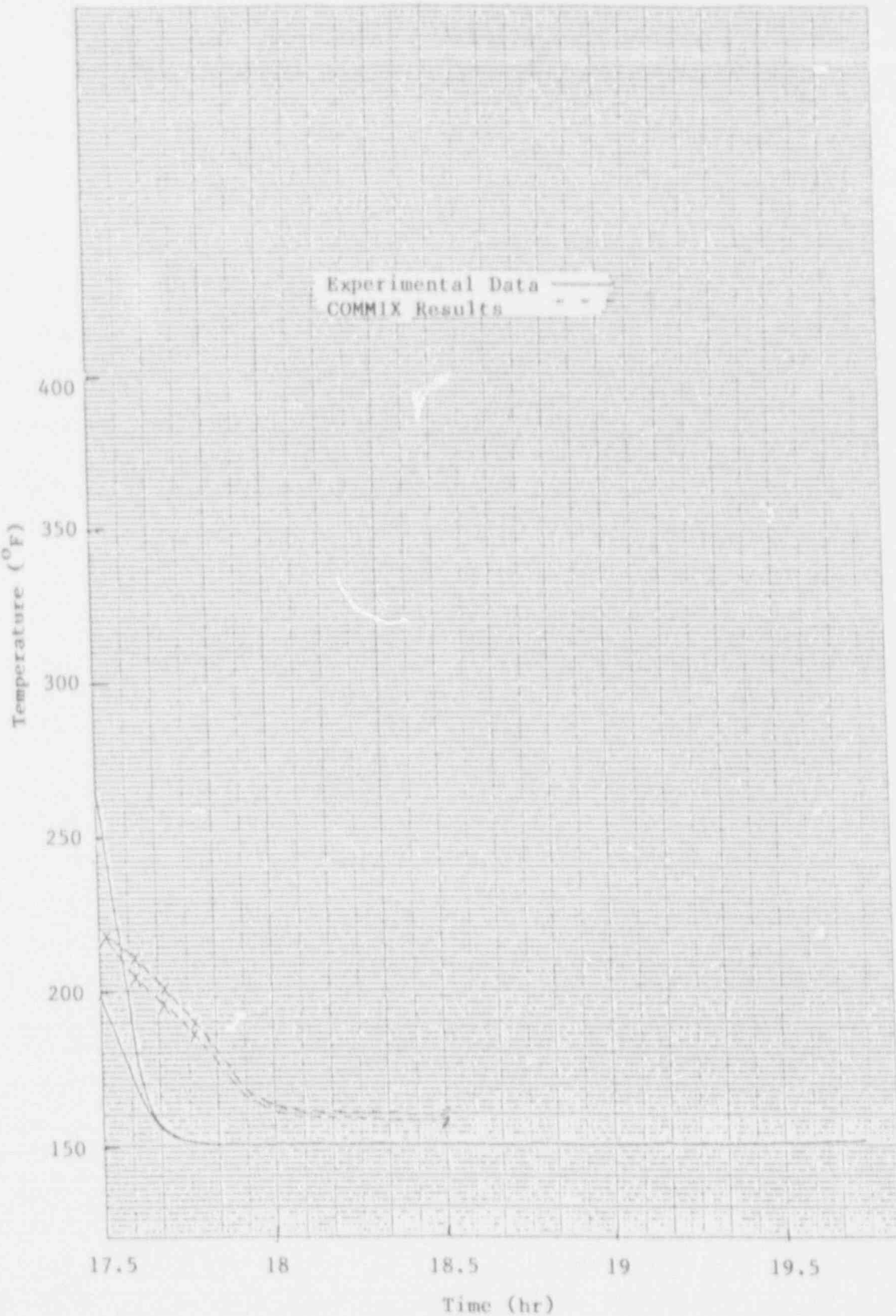


Fig. 33. COMMIX results vs. experimental data, T1

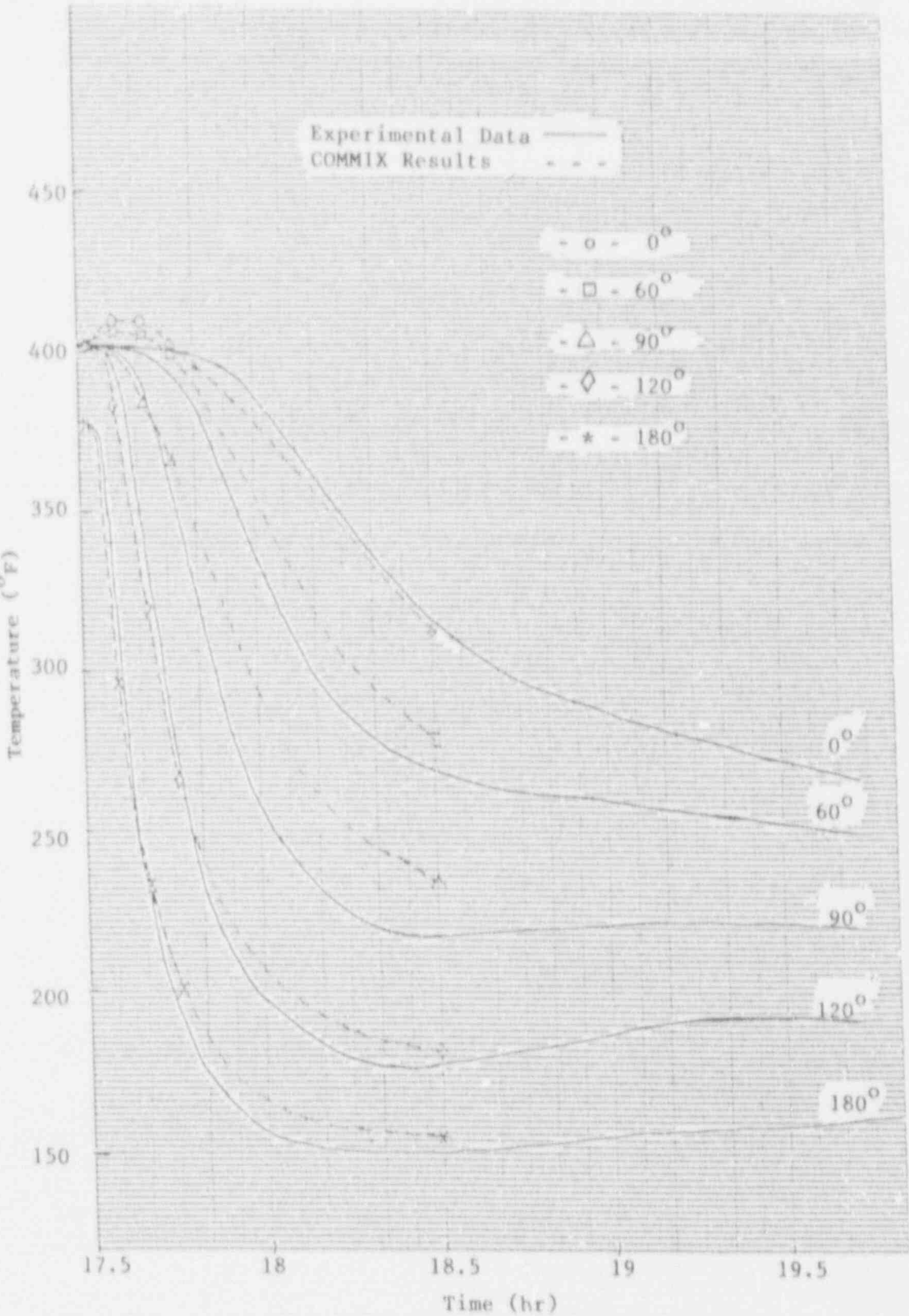


Fig. 34. COMMIX results vs. experimental data, T2

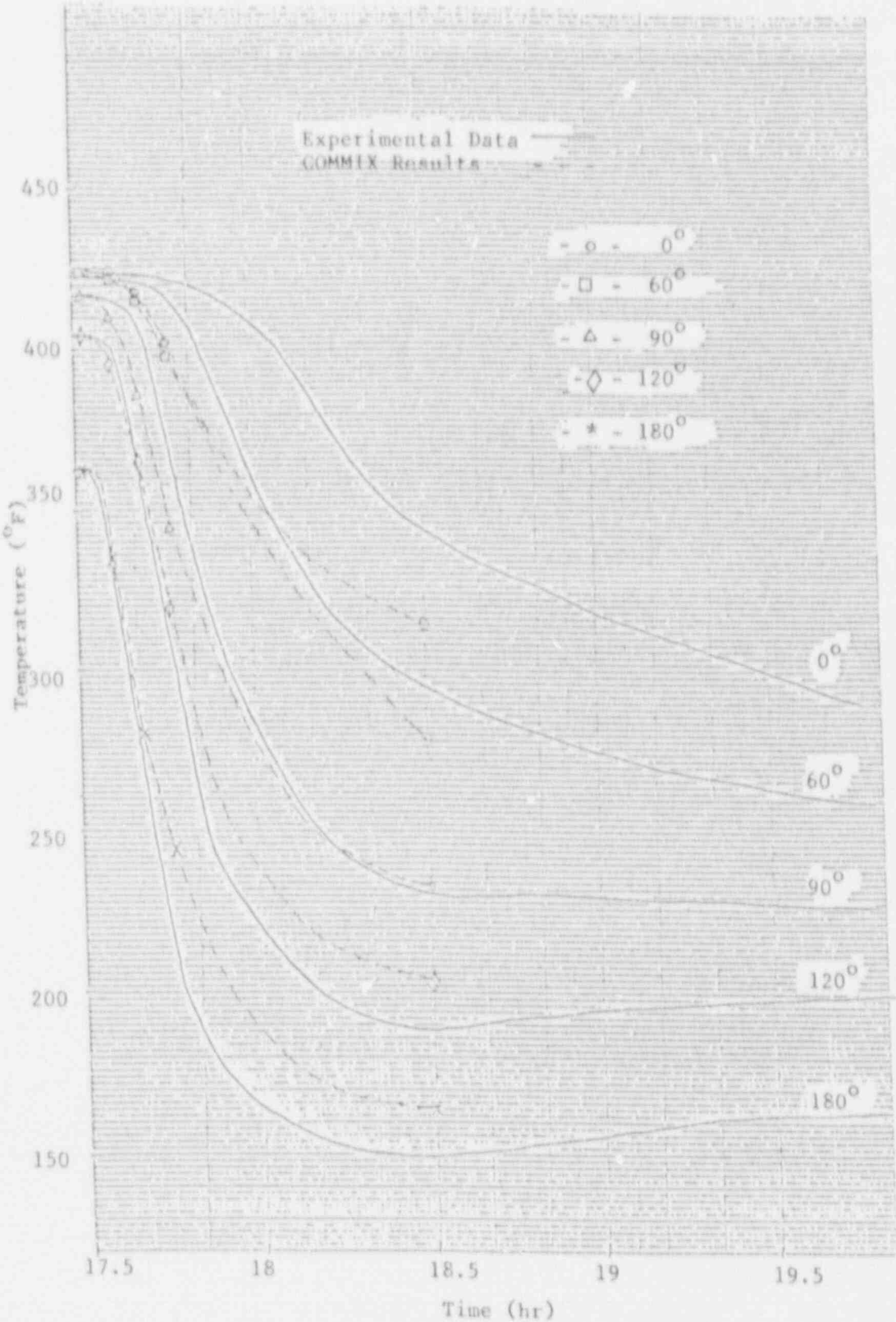


Fig. 35. COMMIX results vs. experimental data, T3

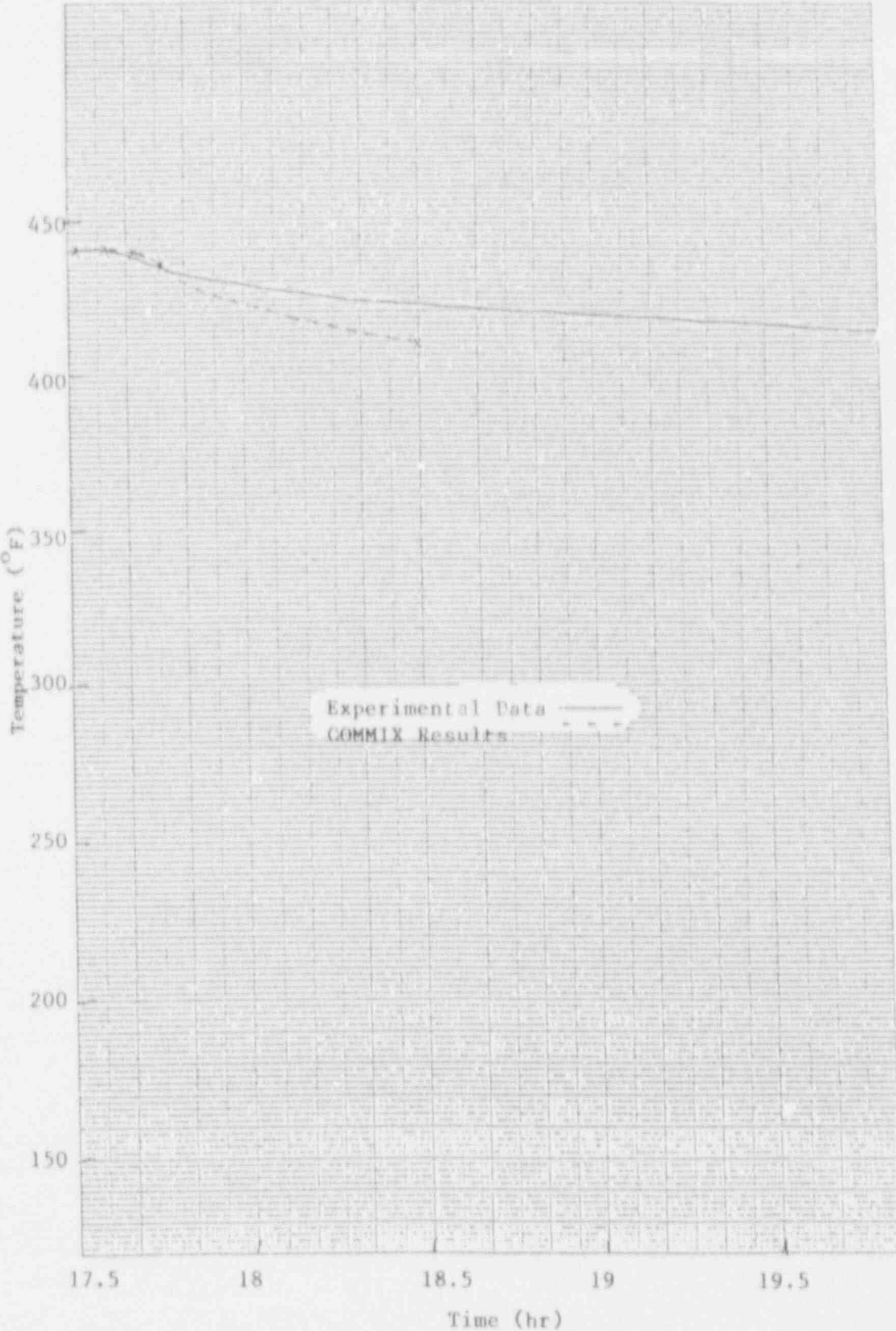


Fig. 36. COMMIX results vs. experimental data, T4

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11. ABSTRACT (200 words or less)

A number of nuclear power plants have reported failure of reactor components due to flow stratification. Therefore, a fundamental understanding of, and a capability to predict, flow stratification in a reactor system is critically important to reactor performance and safety. The work presented here is the first step in this direction and will contribute to the resolution of the issue of flow stratification.

An analysis is performed using the COMMIX-1C computer program for the surge line of the Comanche Peak reactor. A comparison is made between the calculated results from the COMMIX code and the plant-measured data, and the agreement is good.

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Solution of Navier Stokes and energy equations

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