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AN INELASTIC ANALYSIS OF DISSIMILAR METALLIC PIPE JOINTS FOR CRBRP APPLICATION

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ABSTRACT

A preliminary inelastic analysis of a dissimilar metallic transition joint was made based on the piping design specification for CRBRP applications. The transition joint was analyzed to satisfy the elevated temperature ASME Code requirements. The transition joint analyzed is a tri-metallic joint composed of 316 stainless steel, alloy 800H, and 2-1/4 Cr-1Mo steel sections.

In this paper criteria to satisfy the rules given in the Code Case N-47 are briefly delineated and analytical procedure used in this analysis is outlined. Thermal screening analysis was first made of all transients given and limited number of umbrella transients were selected for detailed analyses. The finite element computer code, MARC was used for the detailed thermal and inelastic stress analysis. The complicated inelastic behavior of materials considered was taken into account in line with the "state-of-the-art". The inelastic analysis included cooling of the transition joint to the room temperature from the post weld heat treatment temperature, at which the transition joint was considered in a stress-free state. A tremendous amount of data from results of the analyses was saved in magnetic tapes for code evaluation. Code evaluation, strain and deformation limit analysis, was performed using a GE proprietary computer code MELTSE2. MELTSE2 calculated incremental inelastic strains for each power cycle as well as the accumulated inelastic (plastic and creep) strains which were conservatively extrapolated to the end-of-life of the transition joint. MELTSE2 also calculated creep-fatigue damage factors for each power cycle and for the end-of-life of the transition joint.

The preliminary results from this analysis showed that the plastic deformation occurs predominantly in the alloy 800H section, while the accumulated inelastic strain due to creep is much more significant in the 2-1/4 Cr-1Mo section. The region of this transition joint which experiences the greatest amount of accumulated damage is at the interface of the 2-1/4 Cr-1Mo steel and the Inconel 82 weldment.

INTRODUCTION

Piping transition joints have been extensively used in power plants, nuclear or non-nuclear. Two transition joints, which are to operate in an elevated temperature environment, in the intermediate heat transport system (IHTS) of the Clinch River Breeder Reactor Plant, a liquid metal fast breeder reactor (LMFBR) were identified as the most severely stressed components. To mitigate the severity of stress levels, a tri-metallic joint design was introduced. A preliminary elastic analysis, however, showed that the strain limits required by Code N-47 (1592) of the ASME Boiler and Pressure Vessel Code [1] were not met. A detailed inelastic analysis of the transition joints was then pursued. Of the two transition joints of concern, the worst case was selected for analysis. This detailed analysis was intended to show adequacy of the design for a specified time span, satisfying the design criteria given in the piping design specification.

The tri-metallic transition joint is composed of 316 stainless steel, Ni-Fe-Cr alloy 800H, and 2-1/4 Cr-1Mo steel sections. They are welded together, with 16-8-2 stainless steel and Inconel 82 weldments, to mitigate the differential thermal expansion stresses at the junctions of these dissimilar metals. Only the section made of 2-1/4 Cr-1Mo and 800H joined by Inconel 82 weldment has been analyzed; since, of the junctions, the 2-1/4 Cr-1Mo/800H section was found to be the worse stressed one.

A thermal transient screening analysis was first performed. Each transient specified was evaluated for its severity and classified into four (4) groups. Histogram was established based on the piping specifications. MARC[2] finite element computer code was then used for thermal and stress analyses of the transition joint. Results from MARC analysis were subsequently post-processed using a GE proprietary code, MELTSE2, to determine the end-of-life inelastic strains and evaluate the creep-fatigue damage. Details are presented in sections that follow.

DESIGN CRITERIA AND ANALYTICAL PROCEDURES

Design and construction of components, systems and structures essential to or associated with the nuclear reactor shall follow the applicable code, standard or practice. As part of the IHTS piping, the transition joint is classified as a seismic category I and ASME Class 2 optionally upgraded to class 1 component. Consequently, this transition joint shall be designed and analyzed in accordance with rules and guidelines of the appropriate documents. Specifically, inelastic analysis of the transition joint is made to satisfy rules given in ASME Code Case N-47 (1592), particularly Appendix T. Two main criteria used in the inelastic analysis are as follows.

(i) Strain Limits and Ratchetting Criteria:

For inelastic analysis, the limits are applied on strains. There are three limits for the maximum positive principal inelastic strain to be satisfied.

(a) The strain averaged through the wall thickness must be less than or equal to 1% for base metal and 0.5% for welds;

(b) The surface strains (based on an equivalent linear distribution of strain through the thickness) must be less than or equal to 2% for base metal and 1% for welds; and

(c) The local strains must be less than or equal to 5% for base metal and 2.5% for welds.

(ii) Creep-Fatigue Damage:

Before creep-fatigue limits for inelastic analyses can be applied, a detailed inelastic analysis of the structure must be performed for normal, upset and emergency loading conditions. The criterion for creep-fatigue damage using inelastically calculated strains is to assure that the total of the use factors for time and cycles are less than or equal to a damage factor limit (D). Limits for base metal and welds are taken as the same.

A detailed inelastic analysis is generally complicated. Therefore, a systematic procedure is needed to complete the complex inelastic analysis. Prior to an inelastic stress analysis, various loading conditions shall be examined, defined, and classified. Loadings on the transition joint include thermal, pressure, and other mechanical loads. They have specific numbers of loading cycles and are sequential. A specific loading sequence establishes a histogram. Histograms shown in the piping design specification are analyzed and put into a form most efficient for the inelastic analysis of transition joint. Concurrently, a simplification is made by performing a screening analysis of all transient events specified. Transients are classified according to their severity and are grouped. Limited number of transients are chosen to umbrella the rest of transients to simplify the problem and to give a conservative result. A detailed inelastic stress analysis is then performed to obtain stresses, creep time, and accumulated inelastic strains for code evaluation. Details on the design criteria and analytical procedures are discussed in a separate paper.[3]

Analytical Model

A finite element model based on the axisymmetric 2-dimensional formulation was set up to represent the transition joint as shown in Figure 1. Only the 2 1/4 Cr-1Mo/800H section was analyzed. The model consists of 126 elements and 399 nodal points.

For heat transfer analysis, two element types were selected - element type 42 (elements 1 through 50 and 64 through 113), an 8-node bi-quadratic quadrilateral element and element type 70 (element 51 through 63 and 113 through 126), an 8-node biquadrilateral element with reduced integration points. Corresponding to these two element types, element type 28 and element type 55 were chosen for stress analysis. Elements 22 through 63 represent the 2 1/4 Cr-1Mo steel section and elements 85 through 126 represent the 800H steel section of the transition joint, while the remaining elements represent the weldment between the two sections. Element type 28 (and 42) is a second order isoparametric element with 9 interior integration points. It is used in and around the weld. While element type 55 (and so is 70) is also a second order isoparametric element, it has only 4 integration points and it is less detailed. Because of the importance of interfaces at the weld, finer mesh was used in the vicinity of the interfaces.

Loading Conditions

i) Service Life

The service life used for this CRBRP plant study is 30 years. For the purpose of design analysis, the service time was allocated for each reactor operation as shown in Table 1, using an availability factor of 0.85.

TABLE 1 SERVICE LIFE

Condition	Hours	Years
100% Power Operation	163,000	18.70
80% Power Operation	25,600	2.9
40% Power Operation	33,900	3.9
Refueling	26,000	2.9
Hot Standby	13,600	1.6

ii) Steady State Conditions

Table 2 shows the steady state conditions given in the design specification (E-spec). The steady state condition of the piping at 40% power or full power is not unique. One of the two alternate conditions shown may exist. Conservative estimate of these conditions should be made for evaluations involving steady state conditions.

TABLE 2 INTERMEDIATE PIPING, SECTION A - STEADY STATE CONDITIONS

CONDITION (STATE) DESIGNATION	CONDITION	T (°F)	P_{MAX} PSIG	W^* (10^6 lbm/hr)	TIME OF OPER. (Hrs.)
1	Room temperature	70	0	0	Negligible
2	Refueling Temperature, drained	400	0	0	Negligible
3	Refueling condition	400	124.4	1.2	26,000
4	Hot standby condition	593	124.4	1.2	13,600
5a	40% Power	908	134.9	4.3	------
5b	40% Power	867	139.6	5.1	33,900
6	80% Power	935	182.9	9.8	25,600
7a	Full Power	965	217.0	12.3	------
7b	Full Power	958	224.5	12.78	163,000

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*Based on 24" piping.

iii) Operating Cycles

The plant operation is visualized as a series of power operation cycles where each cycle, in addition to the power fluctuation, consists of a normal startup from either hot standby or refueling temperature to full power operation and back to either hot standby or refueling conditions. Each cycle shall be assumed to have the following characteristics:

a)	Number of cycles	863
b)	Duration of each cycle	∿ 12 days
c)	Number of loading and unloading to 40% power	1 day
d)	Number of power fluctuation (80%-100%)	5 per day
e)	Number of cycles per year	∿ 29

The operating cycles shall also include transients under normal, upset, emergency, and faulted conditions specifically given in the E-spec. The sequency of application of transients shall be selected to provide the most conservative loading history of the applicable events.

iv) Creep Hold Time

Creep is generally expected at a higher temperature. Table 1 shows the service life for this LMFBR components. Considering the fact that creep takes place at a higher temperature only, the hold time during the reactor operation can be estimated as follows:

Power Level	Total Hour	No. of Cycles	Hold Time/Cycle (hours)
40%	33,900	9,756	3.47
80%	25,600	46,500	0.55
100%	163,000	863	188.88

Creep hold time of less than one hour is not meaningful. Therefore, the creep hold time for 80% power was included into that for 100% power. In this analysis the following hold time were used:

40% power ------------------------3.47 hours/cycle,
100% power ----------------------218.5 hours/cycle.

Transient Screening Analysis

i) Pressure

Pressure changes when the operating conditions change, as shown in Table 2. During thermal transient calculations, pressure and flow rate time histories are also calculated (in the thermal hydraulic analysis) and are also given in the E-spec. The pressure time history is needed as a source of mechanical loadings, while the flow rate time history is used in the heat transfer analysis.

ii) Other Mechanical Loads

Interface loads of the transition joint are obtained from system mechanical analyses which include effects of component dead weight, thermal expansion and support reaction, earthquake (OBE and SSE), and sodium water reaction (SWR). The extent of such effects depends on temperature in the system (and components) among others.

iii) Selection of Thermal Transients

A one-dimensional heat transfer analysis was made to evaluate severity of each transient specified for the transition joint.[4] They are then compared against each other and are properly grouped together. The worst case in each group was selected to represent that group and to umbrella the rest of transients in that group. Four (4) transients, 1U, 2U, 5U and 3E were selected for detailed analyses. 1U was selected to encompass 1U, 3U, 4U, 6U, 9U, and 10U transients; while 2U envelopes 11U transient. 5U is also used for 2E transient.

iv) Simplified Histogram

The transient loading conditions based on the E-spec are shown in Figure 2. Numerals shown along the flow pass indicate number of occurrences, while the same shown in the circles are the condition designation of Table 2. The transient events are shown in the parentheses. The worst combination of transient events was chosen from the histogram given in E-spec based on a 3-year period analysis in which the number of events for each transient is shown. Based on the previous thermal screening analysis, only 4 transients were retained for the detailed analysis. These four transients conservatively envelope the rest of the transients. To facilitate the inelastic analysis, the histogram was further simplified to a one-year period. In summary, the conservatively estimated transient events for a one-year period are as follows:

22 - upset & emergency transients
11 - Normal transients,
33 - 100% power cycles,
1550 - 80% power cycles,
337 - 40% power cycles.

These are compared against actual numbers of events specified in the E-spec as following:

Transients	990	vs.	893	(actual),
100% power	990	vs.	863,	
80% power	46,500	vs.	46,500	
40% power	10,110	vs.	9,756	

Figure 3 shows the loading scenario adopted for this analysis.

ANALYTICAL RESULTS

Thermal Transient Responses

As delineated above, a 126-element model was set up for the heat transfer analysis. The 8-node bi-quadrilateral isoparametric element of MARC computer code was used. The boundary conditions were as follows. Both ends of the transition joint were assumed adiabatic, so was the outer surface of the transition joint. Heat transmitted to the transition joint from the sodium flowing within the piping through convection at the inner surface of the transition joint. The film coefficient was calculated according to Seban and Shinazaki.[5] Before a transient started, a uniform temperature of the transition joint at 965°F was assumed. Given initial boundary conditions and input time histories of sodium temperature as described above, temperature time histories everywhere in the transition joint were calculated for the umbrellaing transients, 1U, 2U, 5U/2E, and 3E. Results were saved on magnetic tapes for stress calculations. Figure 4 shows the temperature field in the transition joint at one instant of time during the 1U transient.

Stresses and Inelastic Strains

Using MARC, stresses and strains were calculated for each loading increment in the entire cyclic process under various transients specified. Analytical results for the following quantities were written on magnetic tapes and saved for post processing.

Components of total strain,
Equivalent plastic strain,
Equivalent creep strain,
Temperature,
Components of stress,
Equivalent Mises tensile stress,
Physical components of the total plastic strain,
Total equivalent plastic strain,
Physical components of the total creep strain,
Total equivalent creep strain.

Partial results were listed for selected increments and selected number of integration points.

An example from the initial result is shown in a form of contour plots as follows. Figures 5 through 7 show contour plots of Mises stress, plastic strain, and creep strain for a specified time increment (step 552). High gradient of stress and strain fields is observed in the vicinity of materials discontinuity. The interpolation scheme adopted in the contour plotting can result in an error at these materials discontinuities. Accurate results can be obtained by removing the boundary elements of the adjacent material before plotting, as shown in these figures for the base metals.

Accumulated Inelastic Strains

Results from the MARC stress analysis were post-processed using a GE proprietary code MELTSE2. For the evaluation of accumulated inelastic strains, selective "cross-sections" were drawn across the transition joint wall. The cross-sections were selected to ensure that the worst situation (accumulated inelastic strain and creep-fatigue damage) was examined. Contour plots presented in the previous section facilitated the selection. In either base metals under consideration, as well as the weldment, the selected cross-sections were located near the interfaces of the base metals and the weldment. Nine (9) equally spaced points were defined along the cross-section for inelastic strain evaluation. The average, equivalent linear, and peak inelastic (creep and plastic) strains were calculated for each operating cycle. Given number of occurences for each operating cycle, the end-of-life accumulated inelastic strains were calculated. The last cycle of each transient analyzed (1U transient for example) was considered to approach a stable condition and was used to extrapolate to the end-of-life. Table 3 shows the conservatively estimated cumulative inelastic strains at the end of 30 year life for alloy 800H, Inconel 82, and 2 1/4 Cr-1Mo steel respectively. Except for 2 1/4 Cr-1Mo, requirements of the strain and deformation limits are met for the full 30 year service life of the plant.

Creep-Fatigue Damage

Creep damage and fatigue damage were calculated only at the cross-section points which correspond to the inner surface, mid-thickness, and outer surface of the cross-section. For each creep-fatigue cycle defined, the incremental creep and fatigue damages were calculated. Creep damage for each cycle was evaluated using the integral form of the damage equation. Fatigue damage calculations utilized the total strain components for cases where the principal strains changed direction. The calculation of the maximum equivalent strain range considered every possible combination of strain states within the cycle. Upon completing the incremental creep and fatigue damage calculation for each cycle, the end-of-life creep and fatigue damage factors were calculated by a linear summation/extrapolation of the various cyclic occurrences. Results are also shown in Table 3. Code requirements of the creep-fatigue damage are met except for the 2 1/4 Cr-1Mo section. Further calculations show that the 2 1/4 Cr-1Mo section can comfortably meet 15 year life requirements.

It is noticed that conservative assumptions were made during the simplification process in the analysis. By removing some of the conservative assumptions made, it is likely that this particular section of the transition joint can also meet 30 year life requirements, as the 800H section and the In 82 weld do.

The failure of this transition joint is expected to occur at the interface of the 2 1/4 Cr-1Mo steel and the Inconel 82 weldment as demonstrated by the contour plots of inelastic strains and damage calculations by MELTSE2.

CONCLUDING REMARKS

- Extensive search on materials properties for 800H, In 82, and 2 1/4 Cr-1Mo were carried out. 800H has a lower yield strength. However, it has a better creep resistant property. 2 1/4 Cr-1Mo, on the other hand, has a complicated property, especially creep behavior. Furthermore, interdependence of plastic deformation and creep behavior of 2 1/4 Cr-1Mo is prominent. Although the effect of reversed plasticity on the subsequent creep was taken into account in the analysis, the so-called α-reset characteristics of the 2 1/4 Cr-1Mo was neglected due to limitation of the current version of the MARC computer code. 2 1/4 Cr-1Mo has a higher yield strength, however. In82 has a higher yield strength and a moderate creep property.

- No distinction in strength was made between the base metal and the heat-affected zone (HAZ) of the base metal in this detailed inelastic analysis due to the uncertainty of information on HAZ properties. It is noticed that failure of the transition joint shall initiate at the interface of the 2-1/4 Cr-1Mo section and the Inconel 82 weldment. Accuracy of analytical results can naturally be improved by availabiltiy of reliable material data of the HAZ.

- The transition joint was assumed to be stress free at the post weld heat treatment (PWHT) temperature, 1350°F (732°C). It was cooled down to the room temperature (70°F/20°C) gradually by step-wise isothermal changes. Due to difference in the coefficients of thermal expansion, stresses were induced. In fact, the stress levels were so high that local plastic deformation was observed. Stress free state at 1350°F (732°C), however, has to be confirmed.

- Based on the previous code analysis, it is concluded that the transition joint of interest has a minimum safe life of 15 years. Although the alloy 800H section as well as the Inconel 82 weldment of the transition joint satisfy the code requirements for a plant life of 30 years, the 2 1/4 Cr-1Mo steel section was shown to be design limiting based on the conservative approach adopted in this preliminary analysis. Additional analyses options are available that can be used to demonstrate full 30 year life. They are as follows:
  (1) Before extrapolating to the end-of-life, the present inelastic analysis is extended to include more load cycles which lead to a more stable

(shakedown) condition.

(2) The umbrella 1U-transient is broken down into 2 groups to include less severe transients under a separate umbrella transient.

REFERENCE

1. Case N-47-7 (1592-7), Cases of ASME Boiler and Pressure Vessel Code, July 10, 1974, ASME.
2. MARC-User Information Manual, MARC-CDC, Rev. J. 1, MARC Analysis Research Corp., Palo Alto, CA., 1980.
3. A. W. Dalcher and C. C. Yang, "Structural Integrity Evaluation of an Engineered Component by Using ASME Code Case N-47 Procedure," to be published at the 1982 PV & P Div. Conf. and Exh., June 27-July 2, Orlando, Florida.
4. C. C. Yang and A. W. Dalcher, "A Simple Technique for Structural Screening Analysis," to be published at the 1982 Joint ASME/ANS Nuclear Engineering Conf., July 25-28, Portland, Oregon.
5. R. A. Seban and T. Shinajaki, "Heat Transfer to a Fluid Flowing Turbulently in a Smooth Pipe with Walls at Constant Temperature," ASME Paper No. 50-A-128, 1950.

Caption of Table:

3. Damage Factors and Accumulated Inelastic Strain for 30 Year Life.

Captions of Figures:

1. Analytical Model
2. Flow Diagram for 30 Year Operating Cycles
3. Histogram - Loading Scenario
4. A Temperature Field
5. Mises Stress in Base Metals
6. Plastic Strain in Base Metals
7. Creep Strain in Base Metals

TABLE 3   C. C. Yang and A. W. Dalcher

	800H	In82	2 1/4 Cr-1Mo
Creep Damage	5.873-03	5.558-06	1.37-00
Fatigue Damage	2.769-03	2.604-08	4.08-09
Total Damage	8.642-03	5.584-06	1.37-00
Average Strain	0.114%	0.070%	1.392%
Linear Surface	0.369%	0.184%	3.352%
Peak Strain	0.889%	0.252%	3.677%

FIGURE 1, C. C. Yang and A. W. Dalcher

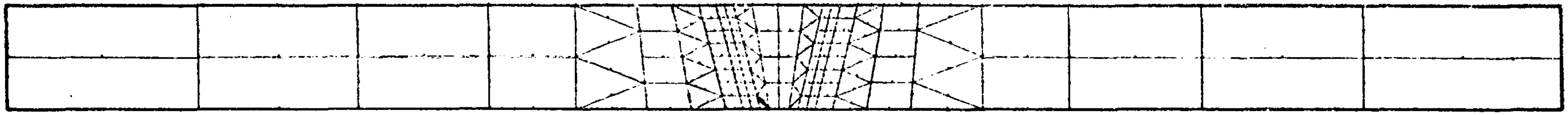


FIGURE 2. C. C. Yang and A. W. Dalcher

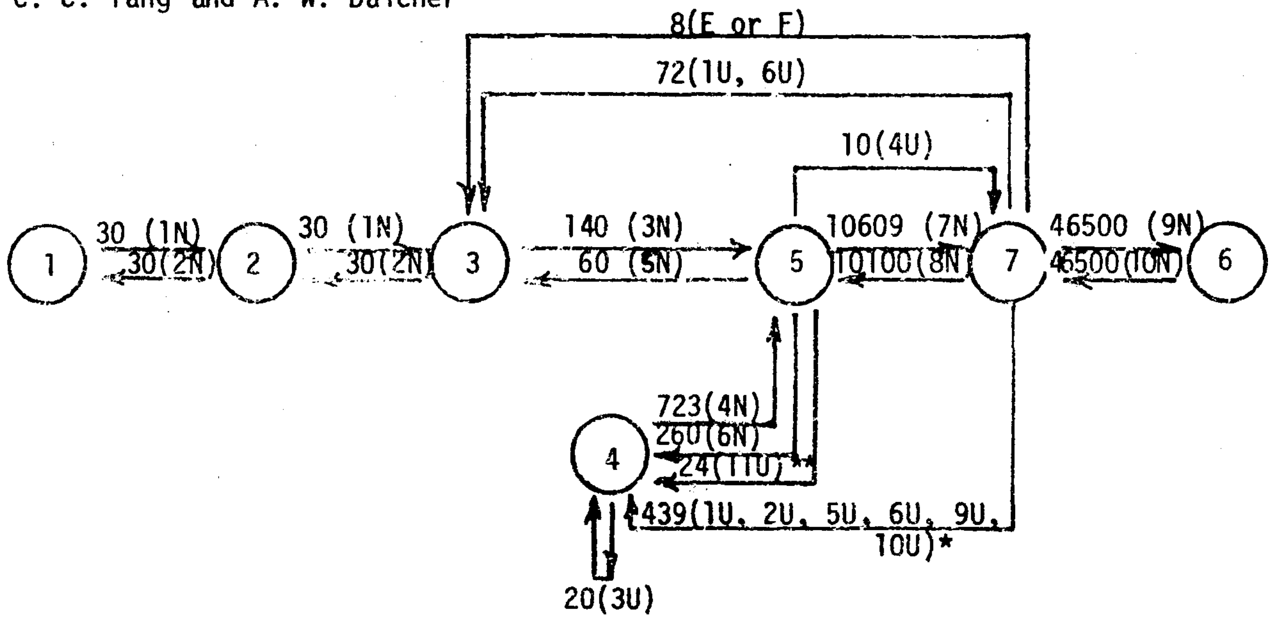


FIGURE 3 C. C. Yang and A. W. Dalcher

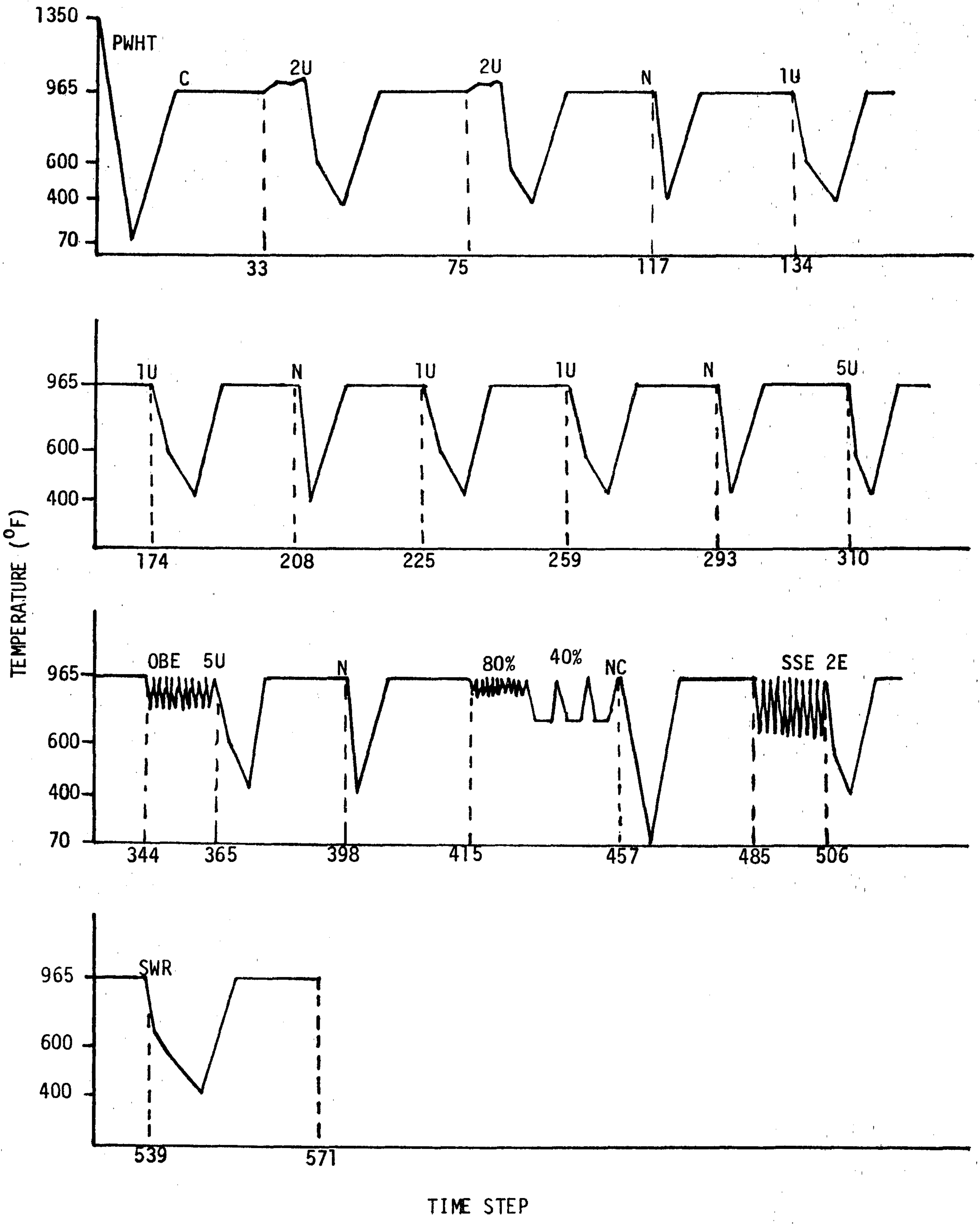
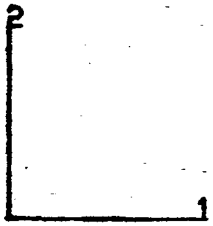


FIGURE 4   C. C. Yang and A. W. Dalcher

1 = 7.25E2
2 = 7.33E2
3 = 7.41E2
4 = 7.49E2
5 = 7.57E2
6 = 7.65E2
7 = 7.73E2
8 = 7.81E2
9 = 7.89E2



1U-1, STEP 149 - TEMPERATURE

1 = 5 .79E3

2 = 9 .03E3

3 = 1 .23E4

4 = 1 .55E4

5 = 1 .88E4

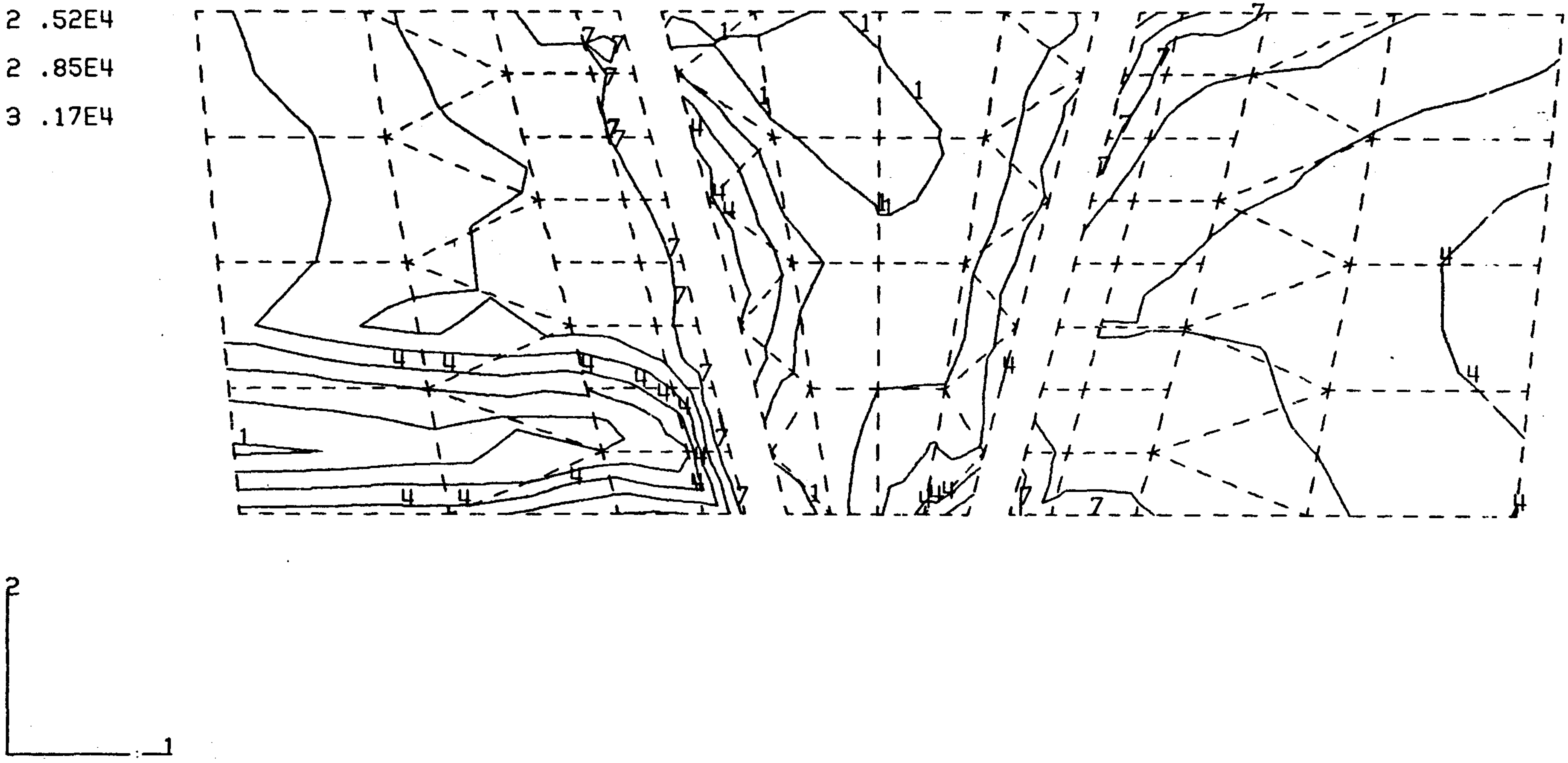
6 = 2 .20E4

7 = 2 .52E4

8 = 2 .85E4

9 = 3 .17E4

FIGURE 5, C. C. Yang and A. W. Dalcher



1 = 1 .14E-4
2 = 4 .01E-4
3 = 6 .89E-4
4 = 9 .76E-4
5 = 1 .26E-3
6 = 1 .55E-3
7 = 1 .84E-3
8 = 2 .13E-3
9 = 2 .41E-3

FIGURE 6 C. C. Yang and A. W. Dalcher

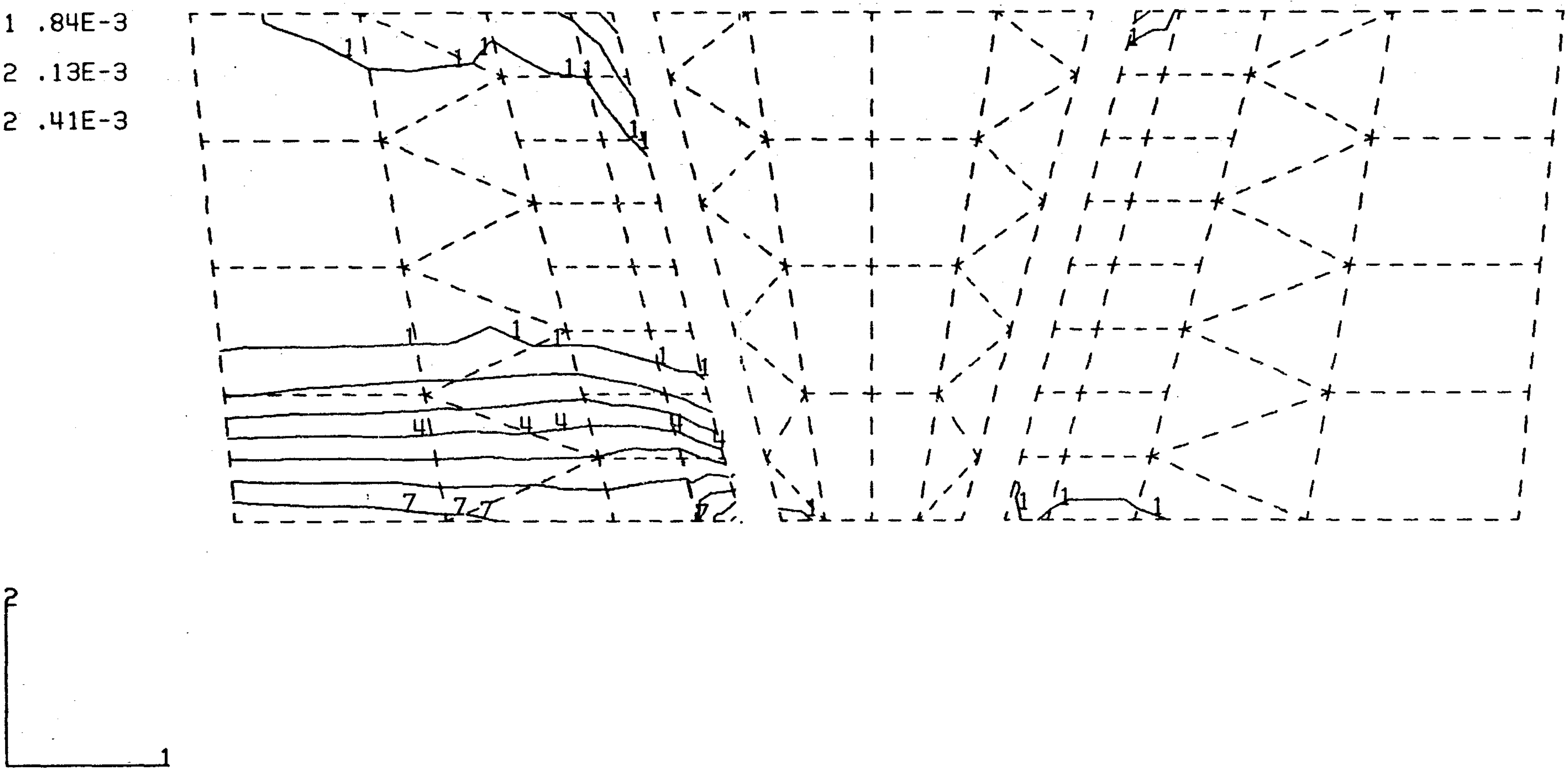


Figure 7, C.C. Yang and A.W. Dalcher

FIGURE 7 C. C. Yang and A. W. Dalcher

1 = 4 .30E-5
2 = 1 .30E-4
3 = 2 .16E-4
4 = 3 .03E-4
5 = 3 .90E-4
6 = 4 .76E-4
7 = 5 .63E-4
8 = 6 .50E-4
9 = 7 .36E-4