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THERMOPHYSICAL PROPERTIES OF A
TYPE 308 STAINLESS
STEEL WELD

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OAK RIDGE, TENNESSEE

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ABSTRACT

Thermophysical characterization of a stainless steel weldment for Liquid Metal Fast Breeder Reactor application was conducted over the expected operating temperature interval (25 - 1000° C). Observed behavior was characteristic, and expected thermal anisotropy was not evidenced.

CONTENTS

SUMMARY	4
INTRODUCTION	5
THERMOPHYSICAL STUDY OF TYPE 304 AND 308 STAINLESS STEELS	6
Materials	6
Type and Application	6
Fabrication of Test Specimens	6
Measurement Techniques	7
Linear Thermal Expansion	7
Specific Heat	9
Thermal Diffusivity	9
Results	17
Test Objectives	17
Findings	17
Interpretation	31
Conclusions and Recommendations	32
REFERENCES	33
ACKNOWLEDGEMENTS	34
APPENDIX A	35
Laser Thermal Analysis Program Guide	35
Data Acquisition	35
Data Reduction	37
Equations of Interest	38
Computer Operator Guide	40
Plot Program	40
APPENDIX B	41
Typical Report Form Summary for Laser Thermal Analysis	41
Data Acquisition	41
Data Reduction	48

SUMMARY

Thermal expansion, thermal diffusivity, specific heat, and thermal conductivity measurements were obtained in vacuo for a Type 304-308 stainless steel weldment for use in the Liquid Metal Fast Breeder Reactor. Property measurements were somewhat variant, depending upon the direction of measurement, but the observed differences were small.

INTRODUCTION

Structural design criteria for Liquid Metal Fast Breeder Reactors (LMFBR) present some problems not encountered in light water reactors or in many other high-temperature nuclear systems. Components that are fabricated of Type 304 or 316 stainless steel in current LMFBR designs operate at high temperatures where design rules require consideration of inelastic and time-dependent deformation. Because of the good heat-transfer characteristics of the sodium coolant and its relatively poor thermal conductivity, high thermal expansion coefficient, and load-sustaining characteristics of austenitic stainless steels, changes on the order of those anticipated in the LMFBR can cause rapid temperature transients and severe thermal stresses in structures that are in contact with the coolant. Under these conditions, structural materials tend to creep and deform plastically under load; large strains may concentrate in critical regions such as structural discontinuities; and the repeated cycling of temperature at high temperatures, as will occur during the normal 30-year lifetime of an LMFBR, can lead to progressive deformation through inelastic behavior mechanisms such as ratchetting and creep fatigue.

A program is in progress at the Oak Ridge Y-12 Plant^(a) to evaluate the mechanical properties of test welds that are prototypic longitudinal seam and girth welds for the Fast Flux Test Facility (FFTF) in Hanford, Washington. Understanding the responses of these weldments to thermal stresses is desirable to ascertain the degree of conservativeness of ASME code design rules for elevated temperature structures. For this purpose, thermal properties of the base and weld metal should be known as reliably as the mechanical properties.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the US Energy Research and Development Administration.

THERMOPHYSICAL STUDY OF TYPE 304 AND 308 STAINLESS STEELS

MATERIALS

Type and Application

Test welds have been made in 60.33-mm-thick Type 304 stainless steel plates using a joint design, welding procedures, and materials that have been described previously.⁽¹⁾ The weld was made by the shielded metal-arc process using electrodes that contained controlled amounts of the residual elements—boron, phosphorus, and titanium. These test welds are prototypic of certain welds in the FFTF vessel, and they are not atypical of modern multipass shielded metal-arc Type 308 welds.

Fabrication of Test Specimens

The macrostructure of a polished and etched section taken normal to the welding direction is illustrated in Figure 1. The weld metal consists of elongated austenitic grains whose local orientation nearly parallels the solidification direction, with approximately 5 to 7% ferrite distributed in a cellular dendritic pattern. The details of this microstructure are reported by King, et al.⁽¹⁾

156157

Figure 1. TYPICAL TYPE 304 STAINLESS STEEL WELDMENT. (Test Weld Section FF9-S3)

Because of the directional nature of the structure that might lead to anisotropic thermophysical behavior, the orthogonal directions for property measurements were defined, as shown in Figure 1. The X orientation represents the weld pass direction; Y, the weld width; and Z, the weld depth, which is perpendicular to the plate surface and extends through the plate thickness. The X orientation is the direction perpendicular to the plane of the figure and is only indicated approximately in Figure 1.

Solid cylindrical specimens were fabricated to measure for: (1) the coefficients of thermal expansion of the base metal in one direction and of the weld metal in the X, Y, and Z direction; (2) the specific heats of the weld metal and base metal, and (3) the thermal diffusivity of the base metal in one direction and of the weld metal in the X, Y, and Z directions. Test Weld Section FF9-S3 was used for the thermal expansion and specific heat measurements; Test Weld FF-76 was used for the thermal diffusivity measurements. These welds were nearly identical. In all cases, the specimens were cut from the central most section of the weld.

Dimensions of the specimens, all of a solid cylindrical geometry, in length and diameter (in mm) were as follows: thermal expansion (22×5.1), specific heat (2.5×6.4), and thermal diffusivity (2.5×12.7). The specimens were prepared by light-finish-pass grinding to minimize cold working during fabrication.

MEASUREMENT TECHNIQUES

Linear Thermal Expansion

Linear thermal expansion, $\Delta l/l_0$, was measured using a high-temperature, quartz-push-rod automatic dilatometer (Dynatech-Netzsch Model 402E). The instrument consists of three separate units: (1) the measuring module including the furnace, sample support, and displacement transducer; (2) the temperature programmer and controller, and (3) the display module which includes a carrier-frequency amplifier and a strip-chart recorder. The sample is supported in a half-open horizontal tube made of quartz. The rod which transmits the change in length to the transducer is made of the same quartz material as the holder. The transducer is shielded from the furnace and the sample holder by a water-cooled block which also acts as a convenient base for electrical and vacuum connections. Tests can be performed in air, inert gas, or in high vacuum. These tests were performed in vacuo (1×10^{-4} Pa). The experimental procedure consists of mounting the specimen, moving the furnace into position, and balancing the preamplifier for the recorder chart. Data may be acquired in two ways: (1) a two-channel chart recorder that is supplied with the instrument, and (2) an added digital data acquisition system, as outlined in Figure 2. The furnace temperature is increased at a programmed rate of 2°C/min . The two-channel recorder gives five successive printings of the dimensional change followed by one printing of the temperature at two-second intervals. Magnification of the sample expansion can be increased in seven steps from 125:1 to 12,500:1. In calculating the linear thermal expansion of a specimen, a correction for the expansion of the quartz sample holder and the push-rod system must be applied. This correction factor was obtained by previous calibration of the system using NBS-SRM copper and is the difference between the experimental and literature values. The correction factor is also adjusted slightly for the furnace heating rate.

Figure 2. AUTOMATIC DATA ACQUISITION SYSTEM AND VACUUM DILATOMETER.

Quantitatively, the instantaneous coefficient of linear expansion of a material is the rate of expansion obtained from the slope of the length as a function of temperature, ie:

$$\epsilon = \lim_{T_1 \rightarrow T_2} \frac{\ell_2 - \ell_1}{\ell_0(T_2 - T_1)} \quad (1)$$

where:

- ℓ_1 Represents the original length,
- ℓ_2 the final length,
- ℓ_0 the length at a particular temperature,
- T_1 the original temperature, and
- T_2 the final temperature.

Figure 2 is a block diagram of the automatic data system used with the vacuum dilatometer. The instrument system provides a record of the specimen expansion and temperature signals with a selected time interval between data points. A digital voltmeter (DVM) records these signals and provides a digital output to a parallel-to-serial converter that drives a teleprinter. The teleprinter records the data for immediate evaluation and provides a punched paper tape for subsequent computer analysis. The automatic digital data acquisition system serializes and decodes data, controls the input selector, provides time-interval control, and operates the teleprinter. The parallel-to-serial converter, printout control, and scaler-timer unit are commercially available plug-in modules. The control logic was developed to coordinate the functions of these units with the input selector and the DVM.

The timer determines the time interval between data points and can be preset from 1 - 10,000 seconds. The timing pulse initiates the start of the print cycle. The control logic

waits until the DVM is in the display mode, then outputs a print command to the printer control unit, which outputs a print command to the printout control unit, which then outputs the temperature measurement to the teleprinter. The logic then transfers the input selector so that the DVM is monitoring the linear variable differential transformer (LVDT) signal. The DVM goes through four display cycles to eliminate the possibility of considering an extraneous data point; and, on the fifth cycle, the LVDT measurement is recorded by the teleprinter. The timer is then reset, and the unit is ready to recycle. The linear thermal expansion coefficient, Equation 1, may be more commonly restated as:

$$\bar{\epsilon} = \frac{\Delta l}{l_0 \Delta T} \quad (2)$$

Over a moderate temperature range, the length may be expressed by an empirical equation of the form:

$$l_T = l_0(1 + AT \pm BT^2 + \dots) \quad (3)$$

where A and B are constants for the power series expansion.

Specific Heat

Specific-heat data were obtained using a differential scanning calorimeter (Perkin-Elmer Model DSC-2). This method involves determining the energy, expressed as a peak height amplitude, required to heat a material at a given rate over a small temperature interval, usually 15° C. By correlating this value with one obtained from a calorimetric standard, such as α -Al₂O₃ under identical test conditions, the specific heat, Cp (cal-g⁻¹ · °C⁻¹), of an unknown material (x) is as follows:

$$Cp(x) = \frac{A_x \cdot W_{std}}{A_{std} \cdot W_x} \times Cp_{std} \quad (4)$$

where:

A represents a dimensionless relative amplitude representative of a voltage differential, and

W the weight (g) of the sample.

Thermal Diffusivity

Thermal-diffusivity measurements of the stainless steel weldments were made by the "laser flash" or "positive pulse" technique, whereby one surface of a thin sample disc is heated with a short-duration laser pulse.(2 - 5) For a perfectly insulated specimen of uniform thickness, uniformly irradiated across its front surface by a high-intensity light pulse of short duration compared to the time required for the heat pulse to travel through the specimen, the back surface temperature is given ideally by:

$$\frac{T(d,t)}{T_m} = 1 + 2 \sum_{n=1}^{\infty} (-1)^n e^{-\frac{n^2 \pi^2 \alpha t}{d^2}} \quad (5)$$

where:

$T(d,t)$ represents the instantaneous back surface temperature rise at time, t ,

d the thickness of the specimen, in cm,

T_m the maximum back surface temperature rise, in $^{\circ}\text{C}$, and

α the thermal diffusivity, in $\text{cm}^2\text{-sec}^{-1}$.

The half-rise time, $t_{1/2}$, is the time required for the back surface to reach half of the maximum temperature, $T(d,t)/T_m = 1/2$. Substituting in Equation 5 and solving for thermal diffusivity:

$$\alpha = \frac{1.37d^2}{\pi^2 t_{1/2}}, \text{ or} \quad (6)$$

$$\alpha = \frac{0.139d^2}{t_{1/2}} \quad (7)$$

The validity of Equation 7 is dependent upon the degree of conformity to the following conditions:

1. The energy pulse is uniformly absorbed over the front surface of the sample and only at the surface.
2. The pulse time of the heat source is small compared to the time for the heat pulse to pass through the sample
3. Heat flow is normal to the heated surface of the sample.
4. No heat is lost from the sample during the measuring period.

Ideally, heat losses from the sample should be negligible; however, radiation losses from the sample surfaces increase with temperature. Radial conduction losses from the edge of the sample into the sample holder are usually small and, in most measurements, need not be considered. Radiative heat losses from both the front and back surfaces of the sample are more significant and, if indicated, must be evaluated since the boundary conditions for Equation 5 are not valid.

The effect of radiation heat losses from the sample surfaces has been considered by Parker,⁽⁴⁾ Cowan,⁽⁵⁾ and Cape.⁽⁶⁾ The subject has been applied in a very straightforward

fashion by Bates⁽⁷⁾ after whom this analysis was developed. The generally accepted approach considers losses at elevated temperatures from both front and back surfaces. If heat losses occur, the shape of the temperature-response curve changes as the sample surfaces are cooled (Figure 3). The correction can be made by comparing the back-surface temperature at some multiple of the half time with the maximum temperature rise. This ratio is:

$$R = \frac{\Delta T(n \times t_{1/2})}{\Delta T(t_{1/2})} \quad (8)$$

The term ΔT represents the incremental temperature rise above the ambient temperature measured at an n^{th} multiple time interval of $t_{1/2}$ (Figure 3). When there are no heat losses, the ratio of Equation 8 is 2.0, and the constant, 0.139, of Equation 7 is valid according to Cowan's analysis.⁽⁵⁾ As heat losses increase, R in Equation 8 decreases, as does the constant (Equation 7). Thus, employment of Equation 7 under nonideal experimental conditions wherein heat losses occur will result in apparent thermal-diffusivity values which are biased. If other boundary conditions are obeyed, the bias will be nonsystematic and positive.

Figure 3. THERMAL TRANSIENT WAVEFORM THAT DEFINES THE IMPORTANT HEAT-LOSS PARAMETERS.

When the heating pulse, τ , of the laser is comparable to the time for the heat pulse to pass through the sample, the rate of the temperature rise is delayed.^(6,7) This condition results in an apparent decrease in thermal diffusivity. While radiation losses are reduced by decreasing the sample thickness, finite pulse-time effects are increased. Thus, there is an

optimum sample thickness which will minimize the error in calculating the thermal diffusivity.

The characteristic time, t_c , or the approximate time for a heat pulse to pass through the sample, is defined by the relationship:

$$t_c = \frac{d^2}{\alpha\pi^2} \quad (9)$$

For a square-waveform-type heating pulse,⁽⁸⁾ such as that from the pulsed ruby laser used in these experiments, t_c may be expressed in terms of $t_{1/2}$ and τ as:

$$t_c = \frac{t_{1/2} \cdot 0.55\tau}{1.37} \quad (10)$$

When $t_c > 50 \tau$, Equation 7 can be used to calculate thermal diffusivity within $\pm 1\%$. Corrections for finite pulse-time effects were inconsequential for stainless steels with the employed specimen geometry. The sample thickness, d , may be corrected for thermal expansion according to the relation:

$$d = d_0 \left(1 + \frac{\Delta\ell}{\ell_0} \right) \quad (11)$$

where:

$\Delta\ell/\ell_0$ represents the fractional thermal expansion at temperature $T(^{\circ}\text{C})$,

ℓ_0 the sample length at 25°C , and

d_0 the sample thickness at 25°C .

Thermal-expansion corrections would increase the thermal-diffusivity values by, at most, less than 1.5%, which is small compared to the other errors and were therefore disregarded.

The thermal conductivity, $K(\text{w-m}^{-1} - ^{\circ}\text{C}^{-1})$, was calculated from the relationship:

$$K = 4.19 \times 10^2 \times \rho(\bar{T}) \times C_p(T)\alpha(T) \quad (12)$$

where:

$C_p(\text{cal-g}^{-1} - ^{\circ}\text{C}^{-1})$ represents the heat capacity, and

$\rho(\text{g-cm}^{-3})$ the sample density.

Although ρ is somewhat dependent on temperature, its slight variation was again negligible compared to the overall method imprecision.

An overview of the experimental setup for thermal-diffusivity testing is given in Figure 4. The pulsed-laser system (Hadron Model 8512) provides a $3\text{--}10\text{ J}\cdot\text{cm}^{-2}$ pulse from a 15.9-mm-diameter by 279-mm-long ruby rod ($\lambda = 694.3\text{ nm}$). The pulse time was 1.0 ms and approximated a square wave. The 19.1-mm-diameter radiant flux is focussed to 11.1 mm at the sample front surface by a high-power silica converging lens that has been "hard coated" for antireflection at the ruby wavelength. The tubular furnace (Marshall Model 1011), capable of temperatures approaching 1000°C , is equipped with a radial chromel-alumel Type K thermocouple for steady-state temperature determination and an axial platinum/platinum-10% rhodium Type S thermocouple for furnace temperature control. A 51.0-mm vacuum system with air-cooled diffusion and mechanical pumping is capable of maintaining pressures of $1 \times 10^{-4}\text{ Pa}$ at operating temperatures in the quartz envelope which houses the sample and holder assembly.

Figure 4. OVERVIEW OF THE THERMAL-DIFFUSIVITY APPARATUS.

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Two methods are under development for measuring specimen steady-state temperatures and transient-temperature excursions. An intrinsic thermocouple (IT) assembly, seen in Figure 5, consists of a 30-mm-OD quartz envelope having an intrinsic chromel-alumel thermocouple employing size 28 B+S (0.32-mm-diameter) matched pairs of bare wire housed in Inconel tubing. Ceramic insulation and a custom spring-loading mechanism are contained inside the

tubing with a two-conductor thermocouple gland and assorted pipe fittings necessary for maintaining a vacuum integrity. The threaded Lavite holder (American Lava Grade A) contains the sample and attaches to the 9.5-mm FPT connector to complete the chromel-sample/sample-alumel thermojunction. This couple measures both steady-state and transient sample temperature, with a response time of approximately 1 ms. An end view of the IT transducer is presented in Figure 6. The couple is placed in intimate contact with the central-most 32-mm² area of the 127-mm² specimen.

The noncontact-detection system is capable of measuring only the transient temperature excursion. When this technique is employed, a chromel-alumel Type K thermocouple, inserted radially into the furnace muffle, is used to determine the steady-state specimen temperature, based on a prior calibration. The sample holder assembly for the noncontact-detection technique can be seen in Figure 7. The standard 30-mm-OD quartz envelope houses the Lavite sample holder and sight tube which is employed to shield the infrared detector from extraneous furnace radiation. The male quartz joint contains a silicon window which is approximately 40% transmissive in the 1 to 5.5- μ m wavelength region of detector responsivity.

The noncontact-detection operational setup is shown in Figure 8. A 25-mm-diameter planoconvex silicon lens (FL: 150 mm) focuses a back-surface specimen image (3-mm-diameter spot) on the 3-mm-diameter detector aperture with a 1:1 magnification.

The detector is an indium antimonide (InSb), cryogen-cooled, III-V semiconductor (Judson Research Model J-10A) which was custom designed for this application. A low-noise preamplifier automatically provides the bias current that is necessary to optimize the detector performance and sensitivity, ie, the signal-to-noise ratio, which is critical for successful operation at ambient specimen

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Figure 5. INTRINSIC CHROMEL-ALUMEL THERMOCOUPLE ASSEMBLY.

Figure 6. END VIEW OF THE INTRINSIC THERMOCOUPLE APPENDAGE.

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temperatures. A differential amplifier is employed to further enhance the detector sensitivity under these conditions. The detector gives a steady-state DC output that ranges from 100 to 300 mV, with a zero-bias current between RT and 1000° C. The response time of the detector is approximately 1 μ s. Its output increases exponentially with increasing temperatures; thus, at 400° C, a neutral density filter (A: 1.0) is placed between the lens and detector to maintain the voltage null and prevent saturation. A DVM is employed to monitor the bias preamplifier output and to verify the condition of thermal equilibrium between laser pulses. A schematic of the thermal analysis instrumentation is given in Figure 9. Disregarding the laser and furnace controls, which are standard, the instrumentation may be separated into two integrated systems: One system monitors the back-surface specimen temperature; the other relevantly correlates this temperature with respect to elapsed time. When the laser pulsing switch is actuated, a finite, predetermined time elapses, depending on the capacitor bank charging voltage which is employed. Therefore, a variable delay circuit is required to allow triggering sweeps of the transient recorder (Biomation Model 802) and the display oscilloscope (Tektronix Model 602) in the interval between the pulse command and the actual laser burst. In order to analyze back surface transient heat-pulse waveforms by computer, there must be synchronization between the waveform and the actual laser burst. This synchronization is accomplished by employing a photosensitive solar cell to detect the xenon flash lamp discharge. This signal is converted into a single pulse and added to the

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Figure 7. COMPONENTS OF THE NONCONTACT DETECTOR SAMPLE HOLDER ASSEMBLY.

Figure 8. TEST CONFIGURATION FOR THE NONCONTACT TECHNIQUE.

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Figure 9. COMPONENTS OF THE LASER THERMAL ANALYSIS DATA ACQUISITION SYSTEM.

signal received from the back surface of the specimen. The transient recorder is triggered prior to the laser burst and, thus, records, digitizes, and displays the integrated sum. The computer (PDP 15/35), remote from the test station but in the same area, uses the superimposed pulse as a reference point to initiate the data analysis and reduction. The computer provides real-time analysis of the thermal-diffusivity data. Hardware and software development has been described elsewhere;⁽⁹⁾ only a brief functional description of its operation will be given here.

A typical heat-pulse transient is illustrated in Figure 10. Upon command of the operator, this transient oscillographic display, residing in digital format in the transient recorder, and other pertinent operational parameters are scanned. The data are then analyzed with FORTRAN routines and the results are printed out at the test station on a teletypewriter. The analysis includes finding an average value and computing statistical measurement parameters and other test conditions. A report-form summary is printed out at the end of a determination.

Figure 10. TYPICAL HEAT-PULSE WAVEFORM AS DISPLAYED ON THE TRANSIENT RECORDER.

The schematic diagram, illustrated in Figure 11, shows the basic computer analysis system and its interactions. An auxiliary program for regression analysis and graphic display of $\alpha(T)$ and $K(T)$ functions is also employed. Typical data acquisition and reduction routines are given in the Appendixes.

RESULTS

Test Objectives

Because of their excellent compatibility; ie, corrosion resistance, strength, and fabricability, various types of stainless steel are used in nuclear reactors as fuel cladding, structures, welds, and as general piping. Types 304 and 308 have been the subject of a number of separate mechanical and thermophysical studies. However, their character in service together as a weldment has not been well defined. Concern about the possible mechanical and thermal anisotropy of 304/308 SS weldments at elevated temperatures led to this evaluation of the isotropic base material and the three orthogonal directions of the weld material.

Findings

Chemical compositions of the Type 304 base metal and Type 308 weld metal are given in Table 1. Thermal-expansion results are compiled in Tables 2 through 6 and are illustrated in Figures 12 through 16 wherein the diamonds (◆) represent the data points obtained during the heating cycles and the circles (●) denote the measurements upon cooling. Also, as a reproducibility check, the Y-direction sample was rerun (Table 5 and Figure 15), but

Figure 11. COMPUTER ANALYSIS SYSTEM FOR THERMAL-DIFFUSIVITY DATA.

showed little variation. Both the heating and cooling data were combined and reduced by least-squares analysis to compute the polynomial functions of the temperature for $\Delta\ell/\ell_0$ as follows:

$$\text{Base Material} - \Delta\ell/\ell_0(\times 10^{-6}) = -440.7 + 16.95T + 3.058 \times 10^{-3}T^2, \quad (13)$$

$$\text{X Direction} - \Delta\ell/\ell_0(\times 10^{-6}) = -419.6 + 16.61T + 2.85 \times 10^{-3}T^2, \quad (14)$$

$$\text{Y Direction} - \Delta\ell/\ell_0(\times 10^{-6}) = -462.6 + 17.72T + 3.787 \times 10^{-3}T^2, \text{ and} \quad (15)$$

$$\text{Z Direction} - \Delta\ell/\ell_0(\times 10^{-6}) = -506.2 + 16.47T + 2.968 \times 10^{-3}T^2, \quad (16)$$

Table 2
LINEAR THERMAL EXPANSION OF TYPE 304 STAINLESS STEEL
(VD 84-3; Base Material)

Temperature (° C)	$\Delta l/l_0$ (x 10 ⁻⁶)			$\epsilon_{\text{instant}}$ (x 10 ⁻⁶ /° C)
	Measured	Computed(1)	Difference	
0.2500E+02	0.0000E+00	-0.1495E+02	0.1495E+02	0.1711E+02
0.4100E+02	0.2360E+03	0.2595E+03	-0.2354E+02	0.1720E+02
0.5400E+02	0.4100E+03	0.4837E+03	-0.7372E+02	0.1728E+02
0.7000E+02	0.6440E+03	0.7611E+03	-0.1171E+03	0.1738E+02
0.1080E+03	0.1299E+04	0.1426E+04	-0.1270E+03	0.1761E+02
0.1610E+03	0.2219E+04	0.2368E+04	-0.1492E+03	0.1794E+02
0.2340E+03	0.3611E+04	0.3694E+04	-0.8297E+02	0.1839E+02
0.3080E+03	0.4996E+04	0.5071E+04	-0.7521E+02	0.1884E+02
0.3830E+03	0.6472E+04	0.6501E+04	-0.2923E+02	0.1930E+02
0.4560E+03	0.7889E+04	0.7926E+04	-0.3715E+02	0.1974E+02
0.5280E+03	0.9253E+04	0.9363E+04	-0.1105E+03	0.2018E+02
0.5990E+03	0.1073E+05	0.1081E+05	-0.8388E+02	0.2060E+02
0.6700E+03	0.1222E+05	0.1229E+05	-0.7312E+02	0.2105E+02
0.7400E+03	0.1377E+05	0.1378E+05	-0.1370E+02	0.2148E+02
0.7560E+03	0.1418E+05	0.1412E+05	0.5985E+02	0.2158E+02
0.7450E+03	0.1393E+05	0.1389E+05	0.4283E+02	0.2151E+02
0.7320E+03	0.1362E+05	0.1361E+05	0.1694E+02	0.2143E+02
0.6930E+03	0.1280E+05	0.1278E+05	0.2008E+02	0.2119E+02
0.6250E+03	0.1136E+05	0.1135E+05	0.1400E+02	0.2078E+02
0.5540E+03	0.9909E+04	0.9890E+04	0.1870E+02	0.2034E+02
0.4850E+03	0.8526E+04	0.8501E+04	0.2474E+02	0.1992E+02
0.4150E+03	0.7172E+04	0.7122E+04	0.5016E+02	0.1949E+02
0.3430E+03	0.5809E+04	0.5734E+04	0.7473E+02	0.1905E+02
0.2760E+03	0.4563E+04	0.4472E+04	0.9146E+02	0.1864E+02
0.2090E+03	0.3378E+04	0.3236E+04	0.1417E+03	0.1823E+02
0.1480E+03	0.2311E+04	0.2135E+04	0.1755E+03	0.1786E+02
0.1120E+03	0.1635E+04	0.1497E+04	0.1385E+03	0.1764E+02
0.1030E+03	0.1450E+04	0.1338E+04	0.1120E+03	0.1758E+02

(1) $\Delta l/l_0$ (x 10⁻⁶) = - 440.7 + 16.95T + 3.058 x 10⁻³ T²; σ = 90.

Table 1
TYPICAL CHEMICAL COMPOSITION OF TYPES 304
AND 308 STAINLESS STEELS USED IN THE
FAST FLUX TEST FACILITY

Element	Composition (wt %)	
	Type 304 SS (base material)	Type 308 SS (weld material)
C	0.061	0.065
Cr	18.88	19.73
Fe(1)	69.349	67.169
Mn	1.48	1.95
Ni	9.56	9.88
P	0.016	0.043
S	0.014	0.015
Si	0.64	0.52
Other(2)	-	0.626

(1) By difference.

(2) Includes Mo, Nb, Ti, Cu, B, V, and N.

Table 3
LINEAR THERMAL EXPANSION OF TYPE 308 STAINLESS STEEL
[VD 84-1; Weld Pass (x) Direction]

Temperature (°C)	$\Delta l/l_0$ ($\times 10^{-6}$)		Difference	$\epsilon_{\text{instant}}$ ($\times 10^{-6}/^{\circ}\text{C}$)
	Measured	Computed ⁽¹⁾		
0.2500E+02	0.0000E+00	-0.2477E+01	0.2477E+01	0.1675E+02
0.4300E+02	0.3250E+03	0.3000E+03	0.2497E+02	0.1686E+02
0.5400E+02	0.4870E+03	0.4858E+03	0.1194E+01	0.1692E+02
0.6900E+02	0.7220E+03	0.7402E+03	-0.1825E+02	0.1701E+02
0.1070E+03	0.1357E+04	0.1391E+04	-0.3357E+02	0.1722E+02
0.1610E+03	0.2108E+04	0.2154E+04	-0.4587E+02	0.1747E+02
0.1950E+03	0.2874E+04	0.2928E+04	-0.5420E+02	0.1772E+02
0.2580E+03	0.4041E+04	0.4056E+04	-0.1513E+02	0.1808E+02
0.3200E+03	0.5217E+04	0.5188E+04	0.2876E+02	0.1844E+02
0.3930E+03	0.6575E+04	0.6549E+04	0.2569E+02	0.1885E+02
0.4640E+03	0.7916E+04	0.7902E+04	0.1377E+02	0.1926E+02
0.5340E+03	0.9248E+04	0.9264E+04	-0.1624E+02	0.1966E+02
0.6040E+03	0.1063E+05	0.1065E+05	-0.2018E+02	0.2006E+02
0.6720E+03	0.1193E+05	0.1203E+05	-0.9617E+02	0.2044E+02
0.7400E+03	0.1344E+05	0.1343E+05	0.8484E+01	0.2083E+02
0.7300E+03	0.1334E+05	0.1323E+05	0.1105E+03	0.2077E+02
0.7170E+03	0.1295E+05	0.1296E+05	-0.3904E+01	0.2070E+02
0.6910E+03	0.1239E+05	0.1242E+05	-0.2763E+02	0.2055E+02
0.6240E+03	0.1106E+05	0.1106E+05	0.4558E+01	0.2017E+02
0.5550E+03	0.9671E+04	0.9678E+04	-0.7289E+01	0.1978E+02
0.4870E+03	0.8325E+04	0.8347E+04	-0.2167E+02	0.1939E+02
0.4190E+03	0.7028E+04	0.7041E+04	-0.1341E+02	0.1900E+02
0.3500E+03	0.5773E+04	0.5744E+04	0.2909E+02	0.1861E+02
0.2820E+03	0.4533E+04	0.4492E+04	0.4123E+02	0.1822E+02
0.2170E+03	0.3355E+04	0.3320E+04	0.3549E+02	0.1785E+02
0.1540E+03	0.2255E+04	0.2206E+04	0.4868E+02	0.1749E+02
0.1120E+03	0.1496E+04	0.1477E+04	0.1924E+02	0.1725E+02
0.9700E+02	0.1198E+04	0.1219E+04	-0.2064E+02	0.1717E+02

(1) $\Delta l/l_0$ ($\times 10^{-6}$) = $-419.6 + 16.61T + 2.851 \times 10^{-3} T^2$; $\sigma = 40$.

Table 4
LINEAR THERMAL EXPANSION OF TYPE 308 STAINLESS STEEL
[VD 84-2; Weld Width (y) Direction]

Temperature (°C)	$\Delta l/l_0$ ($\times 10^{-6}$)		Difference	$\epsilon_{\text{instant}}$ ($\times 10^{-6}/^{\circ}\text{C}$)
	Measured	Computed ⁽¹⁾		
0.2500E+02	0.0000E+00	-0.1732E+02	0.1732E+02	0.1791E+02
0.3600E+02	0.1620E+03	0.1801E+03	-0.1812E+02	0.1799E+02
0.4900E+02	0.4000E+03	0.4146E+03	-0.1464E+02	0.1809E+02
0.6500E+02	0.7040E+03	0.7050E+03	-0.1040E+01	0.1821E+02
0.8200E+02	0.1051E+04	0.1016E+04	0.3529E+02	0.1834E+02
0.1040E+03	0.1443E+04	0.1421E+04	0.2199E+02	0.1851E+02
0.1250E+03	0.1832E+04	0.1811E+04	0.2070E+02	0.1866E+02
0.1470E+03	0.2219E+04	0.2224E+04	-0.4755E+01	0.1883E+02
0.2190E+03	0.3584E+04	0.3599E+04	-0.1525E+02	0.1938E+02
0.2930E+03	0.4988E+04	0.5054E+04	-0.6586E+02	0.1994E+02
0.3650E+03	0.6491E+04	0.6509E+04	-0.1797E+02	0.2048E+02
0.4380E+03	0.7971E+04	0.8024E+04	-0.5337E+02	0.2104E+02
0.5080E+03	0.9408E+04	0.9515E+04	-0.1074E+03	0.2157E+02
0.6770E+03	0.1030E+05	0.1102E+05	-0.1185E+03	0.2209E+02
0.6450E+03	0.1240E+05	0.1254E+05	-0.1430E+03	0.2200E+02
0.7130E+03	0.1401E+05	0.1410E+05	-0.8648E+02	0.2312E+02
0.7430E+03	0.1472E+05	0.1479E+05	-0.6743E+02	0.2335E+02
0.7260E+03	0.1449E+05	0.1440E+05	0.9135E+02	0.2322E+02
0.6740E+03	0.1336E+05	0.1320E+05	0.1624E+03	0.2282E+02
0.6080E+03	0.1186E+05	0.1171E+05	0.1532E+03	0.2232E+02
0.5400E+03	0.1029E+05	0.1021E+05	0.8262E+02	0.2181E+02
0.4720E+03	0.8781E+04	0.8744E+04	0.3705E+02	0.2129E+02
0.4030E+03	0.7341E+04	0.7293E+04	0.4823E+02	0.2077E+02
0.3320E+03	0.5872E+04	0.5837E+04	0.3483E+02	0.2023E+02
0.2650E+03	0.4540E+04	0.4499E+04	0.4141E+02	0.1973E+02
0.2020E+03	0.3300E+04	0.3271E+04	0.2906E+02	0.1925E+02
0.1320E+03	0.1967E+04	0.1942E+04	0.2486E+02	0.1872E+02
0.1010E+03	0.1279E+04	0.1366E+04	-0.8652E+02	0.1848E+02

(1) $\Delta l/l_0$ ($\times 10^{-6}$) = $-462.6 + 17.72T + 3.787 \times 10^{-3} T^2$; $\sigma = 77$.

Table 5
LINEAR THERMAL EXPANSION OF TYPE 308 STAINLESS STEEL
[VD 84-2 Rerun; Weld Width (y) Direction]

Temperature (° C)	$\Delta l/l_0$ (x 10 ⁻⁶)		Difference	$\epsilon_{\text{instant}}$ (x 10 ⁻⁶ /° C)
	Measured	Computed ⁽¹⁾		
0.2500E+02	0.0000E+00	0.9429E+01	-0.9429E+01	0.1752E+02
0.3600E+02	0.2080E+03	0.2027E+03	0.5310E+01	0.1762E+02
0.5000E+02	0.4550E+03	0.4503E+03	0.4699E+01	0.1775E+02
0.7300E+02	0.8430E+03	0.8611E+03	-0.1808E+02	0.1797E+02
0.9400E+02	0.1198E+04	0.1240E+04	-0.4248E+02	0.1817E+02
0.1470E+03	0.2105E+04	0.2216E+04	-0.1114E+03	0.1866E+02
0.2190E+03	0.3343E+04	0.3584E+04	-0.2414E+03	0.1934E+02
0.2920E+03	0.4886E+04	0.5021E+04	-0.1351E+03	0.2002E+02
0.3660E+03	0.6393E+04	0.6529E+04	-0.1356E+03	0.2072E+02
0.4370E+03	0.7847E+04	0.8023E+04	-0.1762E+03	0.2138E+02
0.5080E+03	0.9341E+04	0.9565E+04	-0.2241E+03	0.2205E+02
0.5770E+03	0.1087E+05	0.1111E+05	-0.2429E+03	0.2270E+02
0.6460E+03	0.1248E+05	0.1270E+05	-0.2164E+03	0.2335E+02
0.7140E+03	0.1417E+05	0.1431E+05	-0.1336E+03	0.2398E+02
0.7420E+03	0.1502E+05	0.1498E+05	0.3713E+02	0.2425E+02
0.7300E+03	0.1478E+05	0.1469E+05	0.8541E+02	0.2413E+02
0.6790E+03	0.1365E+05	0.1347E+05	0.1770E+03	0.2366E+02
0.6790E+03	0.1209E+05	0.1191E+05	0.1819E+03	0.2303E+02
0.5440E+03	0.1052E+05	0.1037E+05	0.1560E+03	0.2239E+02
0.4750E+03	0.8998E+04	0.8843E+04	0.1554E+03	0.2174E+02
0.4060E+03	0.7557E+04	0.7365E+04	0.1922E+03	0.2109E+02
0.3380E+03	0.6147E+04	0.5952E+04	0.1949E+03	0.2046E+02
0.2710E+03	0.4807E+04	0.4603E+04	0.2043E+03	0.1983E+02
0.2060E+03	0.3492E+04	0.3334E+04	0.1582E+03	0.1922E+02
0.1360E+03	0.2129E+04	0.2012E+04	0.1173E+03	0.1856E+02
0.1050E+03	0.1458E+04	0.1441E+04	0.1714E+02	0.1827E+02

(1) $\Delta l/l_0$ (x 10⁻⁶) = - 425.6 + 17.28T + 4.692 x 10⁻³ T²; σ = 160.

Table 6
LINEAR THERMAL EXPANSION OF TYPE 308 STAINLESS STEEL
[VD 84-4; Weld Depth (z) Direction]

Temperature (° C)	$\Delta l/l_0$ (x 10 ⁻⁶)		Difference	$\epsilon_{\text{instant}}$ (x 10 ⁻⁶ /° C)
	Measured	Computed ⁽¹⁾		
0.2500E+02	0.0000E+00	-0.9258E+02	0.9258E+02	0.1662E+02
0.4400E+02	0.2910E+03	0.2243E+03	0.6673E+02	0.1673E+02
0.7600E+02	0.7550E+03	0.7627E+03	-0.7748E+01	0.1692E+02
0.1160E+03	0.1434E+04	0.1444E+04	-0.1039E+02	0.1716E+02
0.1580E+03	0.2168E+04	0.2170E+04	-0.2343E+01	0.1741E+02
0.2000E+03	0.2940E+04	0.2907E+04	0.3324E+02	0.1766E+02
0.2540E+03	0.3906E+04	0.3869E+04	0.3702E+02	0.1798E+02
0.3260E+03	0.5277E+04	0.5179E+04	0.9815E+02	0.1841E+02
0.3990E+03	0.6653E+04	0.6538E+04	0.1147E+03	0.1884E+02
0.4700E+03	0.8002E+04	0.7891E+04	0.1111E+03	0.1926E+02
0.5410E+03	0.9317E+04	0.9273E+04	0.4356E+02	0.1968E+02
0.6090E+03	0.1067E+05	0.1063E+05	0.4642E+02	0.2009E+02
0.6780E+03	0.1197E+05	0.1203E+05	-0.5467E+02	0.2050E+02
0.7450E+03	0.1342E+05	0.1341E+05	0.7773E+01	0.2089E+02
0.7280E+03	0.1309E+05	0.1306E+05	0.3611E+02	0.2079E+02
0.6370E+03	0.1114E+05	0.1119E+05	-0.4633E+02	0.2026E+02
0.5680E+03	0.9738E+04	0.9807E+04	-0.6903E+02	0.1984E+02
0.5000E+03	0.8390E+04	0.8471E+04	-0.8144E+02	0.1944E+02
0.4310E+03	0.7092E+04	0.7144E+04	-0.5225E+02	0.1903E+02
0.3620E+03	0.5810E+04	0.5845E+04	-0.3533E+02	0.1862E+02
0.2940E+03	0.4553E+04	0.4593E+04	-0.3989E+02	0.1822E+02
0.2280E+03	0.3361E+04	0.3404E+04	-0.4263E+02	0.1782E+02
0.1650E+03	0.2244E+04	0.2292E+04	-0.4835E+02	0.1745E+02
0.1200E+03	0.1433E+04	0.1513E+04	-0.8008E+02	0.1718E+02
0.1040E+03	0.1122E+04	0.1239E+04	-0.1169E+03	0.1709E+02

(1) $\Delta l/l_0$ (x 10⁻⁶) = - 506.2 + 16.47T + 2.968 x 10⁻³ T²; σ = 68.

Figure 12. THERMAL EXPANSION OF TYPE 304 STAINLESS STEEL BASE MATERIAL. (VD 84-3)

Figure 13. THERMAL EXPANSION OF TYPE 308 STAINLESS STEEL IN THE WELD PASS (X) DIRECTION. (VD 84-1)

Figure 14. THERMAL EXPANSION OF TYPE 308 STAINLESS STEEL IN THE WELD WIDTH (Y) DIRECTION. (VD 84-2)

Figure 15. THERMAL EXPANSION RERUN OF TYPE 308 STAINLESS STEEL IN THE WELD WIDTH (Y) DIRECTION. (VD 84-2r)

Figure 16. THERMAL EXPANSION OF TYPE 308 STAINLESS STEEL IN THE WELD DEPTH (Z) DIRECTION. (VD 84-4)

where:

Δl Represents the change in length,

l_0 the length at 25° C, and

T the temperature in ° C.

The linear coefficients of expansion ($\bar{\epsilon}$), as defined by Equation 2, are given in Table 7.

Table 7

LINEAR COEFFICIENTS OF THERMAL EXPANSION OF TYPE 308 STAINLESS
STEEL BASE MATERIAL AND THE x, y, z WELD DIRECTIONS
AT 100-DEGREE TEMPERATURE INTERVALS

Temperature Range (° C)	Linear Coefficient of Expansion [$\bar{\epsilon}$ ($\times 10^{-6}/^{\circ}\text{C}$)]				
	x VD84-1	y		BM(1) VD84-3	z VD84-4
		VD84-2	VD84-2R		
25-100	16.93	17.96	17.99	17.13	15.61
25-200	17.24	18.47	18.39	17.55	16.61
25-300	17.53	18.89	18.84	17.89	17.10
25-400	17.81	19.28	19.30	18.21	17.48
25-500	18.10	19.67	19.76	18.52	17.83
25-600	18.39	20.06	20.23	18.84	18.16
25-700	18.67	20.44	20.70	19.14	18.48

(1) Base material.

Specific-heat results for the base-metal and weld-metal sections, as given in Table 8, were indistinguishable and were therefore aggregated for regression analysis, as compiled in Tables 9 through 12 and illustrated as a linear dependence of temperature in Figure 17. Base and weld-metal results agreed to within $\pm 1\%$, which is the stated accuracy of the differential scanning calorimeter.(10)

Thermal-diffusivity measurements on the base material were obtained using both the intrinsic thermocouple (IT) and the noncontact (NC) techniques in order to assess their relative merits for this application. Comparative results with reference data are compiled in Table 13 and are displayed in Figure 18. Base-metal values based on IT measurements do agree with the Thermophysical Properties Research Center's (TPRC) provisional mean reference data for AISI Type 304 austenitic stainless steel to within 9% over the temperature interval from 25 to 1000°C.(11) The base metal was totally austenitic in structure; the weld metal was 5 to 7% ferritic. Diffusivities based on NC measurements, however, diverge from the TPRC data with increasing temperatures, exhibiting a progressively increasing positive bias. Radiative-heat-loss effects would give rise to the same tendency, and radial-conduction losses may also contribute to this trend of divergence. Figure 19 illustrates the characteristic heat-pulse transients as recorded by the IT and NC techniques. The IT temperature maxima were flat over ten half-time intervals, whereas the NC maxima were progressively skewed with increasing temperatures. Thus, numerical and qualitative indications of excessive heat losses and nonideal behavior were evidenced for the NC technique. Such losses would install a positive bias for diffusivity, as computed by Equation 7. The utility and desirability of implementing heat-loss corrections for such data by computer analysis of the nonideal transients is a recognized need that has not yet been realized. Thus, the IT technique was adopted for this test application.

Measured IT values of α using Equation 7, typically variant to $\pm 0.7\%$ relative to the mean of four observations at a given temperature and average Cp values ($\pm 1.0\%$) variant, are compiled in Tables 9 through 12 and are illustrated in Figures 20 through 24. Thermal-diffusivity and specific-heat values were separately grouped and statistically reduced to mathematical expressions (Tables 9 - 12) to facilitate the condition of isothermicity for Equation 12, to expedite interpolative and extrapolative operations necessary for determining the computed K values, and for construction of the temperature functions noted in Figure 25 through 29. Tolerance intervals ($\pm$ tolerance limit) are defined

Table 8
SPECIFIC HEAT OF TYPES 304 AND 308 STAIN-
LESS STEEL FROM WELDED AND
BASE MATERIAL AREAS
(DSC 32 - 2 & 3)

Temperature (° C)	Specific Heat, Cp [cal/g ° C)]		
	Measured	Computed(1)	Difference
0.3500E+02	0.1140E+00	0.1154E+00	-0.1389E-02
0.6500E+02	0.1166E+00	0.1170E+00	-0.3616E-03
0.1000E+03	0.1195E+00	0.1188E+00	0.7041E-03
0.1500E+03	0.1210E+00	0.1214E+00	-0.4164E-03
0.2000E+03	0.1248E+00	0.1240E+00	0.7631E-03
0.3000E+03	0.1307E+00	0.1293E+00	0.1422E-02
0.4000E+03	0.1344E+00	0.1345E+00	-0.1190E-03
0.5000E+03	0.1390E+00	0.1398E+00	-0.7600E-03
0.6000E+03	0.1447E+00	0.1450E+00	-0.3010E-03
0.7000E+03	0.1504E+00	0.1502E+00	0.1580E-03
0.3500E+02	0.1140E+00	0.1154E+00	-0.1389E-02
0.6500E+02	0.1166E+00	0.1170E+00	-0.3616E-03
0.1000E+03	0.1195E+00	0.1188E+00	0.7041E-03
0.1500E+03	0.1213E+00	0.1214E+00	-0.1164E-03
0.2000E+03	0.1256E+00	0.1240E+00	0.1563E-02
0.3000E+03	0.1299E+00	0.1293E+00	0.6220E-03
0.4000E+03	0.1347E+00	0.1345E+00	0.1810E-03
0.5000E+03	0.1396E+00	0.1398E+00	-0.1600E-03
0.6000E+03	0.1447E+00	0.1450E+00	-0.3010E-03
0.7000E+03	0.1498E+00	0.1502E+00	-0.4420E-03

(1) $C_p = 0.1136 + 5.241 \times 10^{-5} T$; $\sigma = 8.1 \times 10^{-4}$.

Table 9
SPECIFIC-HEAT, THERMAL-DIFFUSIVITY, AND THERMAL-CONDUCTIVITY
RESULTS FOR TYPE 304 STAINLESS STEEL⁽¹⁾
(Base Material of Weldment CE-76)

Average Temperature (° C)	Thermal Diffusivity, α ($\times 10^{-2} \text{ cm}^2\text{-sec}^{-1}$)		Standard Deviation of Fit, σ (4)	Correlation Coefficient, r (5)	Specific Heat, C_p ($\text{cal-q}^{-1}\text{ }^\circ\text{C}^{-1}$)		Computed Thermal Conductivity, k (7) ($\text{watt-m}^{-1}\text{ }^\circ\text{C}^{-1}$)
	Measured(2)	Computed(3)			Measured	Computed(6)	
25		3.38	0.0019	0.944		0.115(8)	12.8
26	3.40	3.38					
100		3.53			0.120	0.119	13.8
114	3.64	3.56					
154	3.58	3.63					
191	3.92	3.71					
200		3.72			0.125	0.124	15.2
229	3.76	3.78					
282	4.01	3.85					
300		3.92			0.131	0.129	16.7
322	3.88	3.97					
350	4.18	4.02					
395	4.00	4.11					
400		4.12			0.134	0.135	18.3
430	4.24	4.18					
479	4.18	4.28					
500		4.32			0.139	0.140	19.9
505	4.40	4.33					
549	4.29	4.42					
583	4.40	4.48					
600		4.52			0.145	0.145	21.6
631	4.33	4.58					
663	4.54	4.64					
697	4.36	4.71					
700		4.72			0.150	0.150	23.4
734	4.75	4.78					
769	4.47	4.05					
800		4.92				0.156(8)	25.2
801	5.20	4.92					
843	4.88	5.00					
877	5.37	5.07					
900		5.11				0.101(8)	27.1
925	5.35	5.16					
958	5.44	5.23					
1000		5.31				0.166(8)	29.1

(1) Average apparent density, $\rho = 7.90 \text{ g-cm}^{-3}$.
(2) Number of observations, $n_0 = 4$.
(3) Values computed by regression analyses, $\alpha_{\text{comp}} = 3.33 \times 10^{-2} + 1.98 \times 10^{-5} T$.
(4) $\sigma = \left[\frac{\sum (a_{\text{meas}} - a_{\text{comp}})^2 / (n_i - p - 1)}{1/2} \right]^{1/2}$, where n_i = the number of data points and the order of the polynomial function, $p = 1$.
(5) $r = \left[1 - \frac{\sum (a_{\text{meas}} - a_{\text{comp}})^2 / \sum (a_{\text{meas}} - \bar{a})^2}{1/2} \right]^{1/2}$.
(6) Values computed by regression analyses, $C_{p\text{comp}} = 0.114 + 5.24 \times 10^{-5} T$.
(7) Values computed by regression analyses, $k = 12.5 + 1.32 \times 10^{-2} T + 3.43 \times 10^{-6} T^2$.
(8) Extrapolated value.

Table 10
SPECIFIC-HEAT, THERMAL-DIFFUSIVITY, AND THERMAL-CONDUCTIVITY
RESULTS FOR TYPE 308 STAINLESS STEEL⁽¹⁾
[Measured in the Weld Pass (x) Direction of Weldment CE-76]

Average Temperature (° C)	Thermal Diffusivity, α ($\times 10^{-2} \text{ cm}^2\text{-sec}^{-1}$)		Standard Deviation of Fit, σ (4)	Correlation Coefficient, r (5)	Specific Heat, C_p ($\text{cal-q}^{-1}\text{ }^\circ\text{C}^{-1}$)		Computed Thermal Conductivity, k (7) ($\text{watt-m}^{-1}\text{ }^\circ\text{C}^{-1}$)
	Measured(2)	Computed(3)			Measured	Computed(6)	
25	3.01	3.01	0.0008	0.986		0.115(8)	11.4
25		3.01					
25	3.20	3.01					
100	3.00	3.12					
100		3.12			0.120	0.119	12.2
114	3.07	3.14					
171	3.14	3.23					
191	3.20	3.26					
200		3.28			0.126	0.124	13.4
242	3.34	3.34					
274	3.38	3.40					
300		3.43			0.130	0.129	14.6
318	3.47	3.46					
350	3.51	3.51					
392	3.58	3.58					
400		3.59			0.135	0.135	15.9
434	3.67	3.64					
480	3.78	3.72					
500		3.75			0.140	0.140	17.3
510	3.73	3.78					
551	3.88	3.83					
589	3.87	3.89					
600		3.90			0.145	0.145	18.7
614	3.93	3.92					
663	4.09	4.00					
696	4.13	4.05					
700		4.06			0.150	0.150	20.1
737	4.13	4.12					
767	4.18	4.16					
800		4.21				0.156(8)	21.6
807	4.25	4.22					
854	4.28	4.30					
885	4.44	4.35					
900		4.37				0.161(8)	23.2
932	4.34	4.42					
964	4.29	4.47					
1000		4.53				0.166(8)	24.8

(1) Average apparent density, $\rho = 7.88 \text{ g-cm}^{-3}$.
(2) Number of observations, $n_0 = 4$.
(3) Values computed by regression analyses, $\alpha_{\text{comp}} = 2.97 \times 10^{-2} + 1.56 \times 10^{-5} T$.
(4) $\sigma = \left[\frac{\sum (a_{\text{meas}} - a_{\text{comp}})^2 / (n_i - p - 1)}{1/2} \right]^{1/2}$, where n_i = the number of data points and the order of the polynomial function, $p = 1$.
(5) $r = \left[1 - \frac{\sum (a_{\text{meas}} - a_{\text{comp}})^2 / \sum (a_{\text{meas}} - \bar{a})^2}{1/2} \right]^{1/2}$.
(6) Values computed by regression analyses, $C_{p\text{comp}} = 0.114 + 5.24 \times 10^{-5} T$.
(7) Values computed by regression analyses, $k = 11.1 + 1.10 \times 10^{-2} T + 2.70 \times 10^{-6} T^2$.
(8) Extrapolated value.

Table 11
SPECIFIC-HEAT, THERMAL-DIFFUSIVITY, AND THERMAL-CONDUCTIVITY
RESULTS FOR TYPE 308 STAINLESS STEEL⁽¹⁾
[Measured in the Weld Width (y) Direction of Weldment CE-76]

Average Temperature (° C)	Thermal Diffusivity, α ($\times 10^{-2} \text{ cm}^2\text{-sec}^{-1}$)		Standard Deviation of Fit, σ (4)	Correlation Coefficient, r (5)	Specific Heat, C_p ($\text{cal-g}^{-1}\text{ }^\circ\text{C}^{-1}$)		Computed Thermal Conductivity, k (7) ($\text{watt-m}^{-1}\text{ }^\circ\text{C}^{-1}$)
	Measured(2)	Computed(3)			Measured	Computed(6)	
24	3.38	3.32	0.0015	0.951		0.115(8)	12.6
25		3.32					
92	3.51	3.43					
100		3.44			0.120	0.119	
125	3.42	3.48					
167	3.88	3.55					
193	3.60	3.59					
200		3.60			0.126	0.124	14.8
245	3.68	3.68					
272	3.71	3.72					
300		3.77			0.130	0.129	16.1
320	3.76	3.80					
358	3.84	3.86					
400		3.93			0.135	0.135	17.4
401	3.90	3.93					
434	3.80	3.99					
478	4.06	4.06					
500		4.09			0.140	0.140	18.9
517	3.85	4.12					
557	4.12	4.19					
591	4.08	4.24					
600		4.26			0.145	0.145	20.4
626	4.42	4.30					
662	4.32	4.36					
694	4.42	4.41					
700		4.42			0.150	0.150	21.9
730	4.38	4.47					
767	4.54	4.53					
800		4.58				0.156(8)	23.5
804	4.47	4.59					
841	4.85	4.65					
874	4.62	4.70					
900		4.75				0.161(8)	25.2
920	5.20	4.78					
954	4.78	4.83					
1000		4.91				0.166(8)	26.9

(1) Average apparent density, $\rho = 7.88 \text{ g-cm}^{-3}$.
(2) Number of observations, $n_o = 4$.
(3) Values computed by regression analyses, $a_{\text{comp}} = 3.28 \times 10^{-2} + 1.63 \times 10^{-5} T$.
(4) $\sigma = \left[\sum (a_{\text{meas}} - a_{\text{comp}})^2 / n_i - p - 1 \right]^{1/2}$, where n_i = the number of data points and the order of the polynomial function, $p = 1$.
(5) $r = \left[1 - \sum (a_{\text{meas}} - a_{\text{comp}})^2 / \sum (a_{\text{meas}} - \bar{a})^2 \right]^{1/2}$.
(6) Values computed by regression analyses, $C_{p\text{comp}} = 0.114 + 5.24 \times 10^{-5} T$.
(7) Values computed by regression analyses, $k = 12.3 + 1.18 \times 10^{-2} T + 2.82 \times 10^{-6} T^2$.
(8) Extrapolated value.

Table 12
SPECIFIC-HEAT, THERMAL-DIFFUSIVITY, AND THERMAL-CONDUCTIVITY
RESULTS FOR TYPE 308 STAINLESS STEEL⁽¹⁾
[Measured in the Weld Depth (z) Direction of Weldment CE-76]

Average Temperature (° C)	Thermal Diffusivity, α ($\times 10^{-2} \text{ cm}^2\text{-sec}^{-1}$)		Standard Deviation of Fit, σ (4)	Correlation Coefficient, r (5)	Specific Heat, C_p ($\text{cal-g}^{-1}\text{ }^\circ\text{C}^{-1}$)		Computed Thermal Conductivity, k (7) ($\text{watt-m}^{-1}\text{ }^\circ\text{C}^{-1}$)
	Measured(2)	Computed(3)			Measured	Computed(6)	
24	3.41	3.26	0.0008	0.977		0.115(8)	12.4
25		3.26					
81	3.44	3.34					
100		3.36			0.120	0.119	
122	3.27	3.39					
153	3.41	3.43					
200		3.49			0.126	0.124	14.3
202	3.50	3.49					
247	3.57	3.55					
281	3.47	3.59					
300		3.61			0.130	0.129	15.4
319	3.54	3.64					
366	3.74	3.70					
395	3.65	3.73					
400		3.74			0.135	0.135	16.6
440	3.82	3.79					
482	3.81	3.84					
500		3.86			0.140	0.140	17.8
520	3.92	3.89					
561	3.90	3.94					
595	4.09	3.98					
600		3.99			0.145	0.145	19.1
635	4.00	4.03					
664	4.21	4.07					
700		4.12			0.150	0.150	20.4
706	4.08	4.12					
735	4.02	4.16					
772	4.16	4.21					
800		4.24				0.156(8)	21.8
812	4.28	4.26					
845	4.30	4.30					
880	4.38	4.34					
900		4.37				0.161(8)	23.2
915	4.40	4.39					
974	4.52	4.46					
1000		4.49				0.166(8)	24.6

(1) Average apparent density, $\rho = 7.88 \text{ g-cm}^{-3}$.
(2) Number of observations, $n_o = 4$.
(3) Values computed by regression analyses, $a_{\text{comp}} = 3.23 \times 10^{-2} + 1.26 \times 10^{-5} T$.
(4) $\sigma = \left[\sum (a_{\text{meas}} - a_{\text{comp}})^2 / n_i - p - 1 \right]^{1/2}$, where n_i = the number of data points and the order of the polynomial function, $p = 1$.
(5) $r = \left[1 - \sum (a_{\text{meas}} - a_{\text{comp}})^2 / \sum (a_{\text{meas}} - \bar{a})^2 \right]^{1/2}$.
(6) Values computed by regression analyses, $C_{p\text{comp}} = 0.114 + 5.24 \times 10^{-5} T$.
(7) Values computed by regression analyses, $k = 12.1 + 1.03 \times 10^{-2} T + 2.18 \times 10^{-6} T^2$.
(8) Extrapolated value.

Figure 17. SPECIFIC HEAT OF TYPE 304 AND 308 STAINLESS STEELS FROM WELDED AND BASE MATERIAL AREAS. (DSC 322.3)

Figure 18. COMPARISON OF THERMAL-DIFFUSIVITY TRENDS FOR TYPE 304 STAINLESS STEEL. [Data Based on the: (1) Noncontact and (2) Intrinsic Thermocouple Techniques Versus the (3) TPRC Provisional Data]

Figure 19. TYPICAL HEAT-PULSE TRANSIENT WAVEFORMS FOR TYPE 304 STAINLESS STEEL. [Curves Illustrate: (1) the Intrinsic Thermocouple and Noncontact Techniques at (2) Low-< 500° C and (3) High-500 - 1000° C Temperatures.]

Figure 20. THERMAL DIFFUSIVITY OF BASE MATERIAL FROM TYPE 304 STAINLESS STEEL WELDMENT.

Figure 21. THERMAL DIFFUSIVITY OF TYPE 308 STAINLESS STEEL WELDMENT. [Measured in the Weld Pass (X) Direction]

Figure 22. THERMAL DIFFUSIVITY OF TYPE 308 STAINLESS STEEL WELDMENT. [Measured in the Weld Width (Y) Direction]

Figure 23. THERMAL DIFFUSIVITY OF TYPE 308 STAINLESS STEEL WELDMENT. [Measured in the Weld Depth (Z) Direction]

Figure 24. COMPARISON OF THERMAL DIFFUSIVITY TRENDS. [For Base Material (1) and in the X (2), Y (3), and Z (4) Weld Directions]

Figure 25. THERMAL CONDUCTIVITY OF THE BASE MATERIAL FROM A TYPE 304 STAINLESS STEEL WELDMENT.

Figure 26. THERMAL CONDUCTIVITY OF TYPE 308 STAINLESS STEEL WELDMENT. [Measured in the Weld Pass (X) Direction]

Figure 27. THERMAL CONDUCTIVITY OF TYPE 308 STAINLESS STEEL WELDMENT. [Measured in the Weld Width (Y) Direction]

Figure 28. THERMAL CONDUCTIVITY OF TYPE 308 STAINLESS STEEL WELDMENT. [Measured in the Weld Depth (Z) Direction]

Figure 29. COMPARISON OF THE THERMAL-CONDUCTIVITY TRENDS. [For Base Material (1) and in the X (2), Y (3), and Z (4) Weld Direction]

Table 13
COMPARISON OF THERMAL-DIFFUSIVITY DATA OBTAINED FOR
TYPE 304 STAINLESS STEEL

Average Temperature, T (°C)	Thermal Diffusivity α ($\times 10^{-2} \text{cm}^2\text{-sec}^{-1}$)			Percent Difference, % D	
	TPRC(1)	IT(2)	NC(3)	NC vs TPRC(4)	IT vs TPRC(5)
25	3.71	3.38	3.98	+ 7.3	- 8.9
100	3.81	3.53	4.16	+ 9.2	- 7.3
200	3.94	3.72	4.40	+ 11.7	- 5.6
300	4.07	3.92	4.63	+ 13.8	- 3.7
400	4.20	4.12	4.86	+ 15.7	- 1.9
500	4.33	4.32	5.10	+ 17.8	- 0.2
600	4.46	4.52	5.34	+ 19.7	+ 1.3
700	4.58	4.72	5.57	+ 21.6	+ 3.1
800	4.71	4.92	5.81	+ 23.4	+ 4.4
900	4.85	5.11	6.04	+ 24.5	+ 5.4
1000	4.98	5.31	6.27	+ 25.9	+ 6.6

- (1) Thermophysical Properties Research Center mean provisional values: 18 - 20 wt % Cr, 8 - 12 wt % Ni, 0.08 wt % C, 2 wt % Mn, 0.045 wt % P, 0.03 wt % S, 1 wt % Si, and 64.845 - 70.845 wt % Fe (by difference). Nominal composition from Crucible Data Book, Crucible Steel Company of America. The austenitic specimen was cut from Number 2 finish cold-rolled steel, subjected to a minimum of working and tested without further surface preparation. No heat treatment occurred prior to testing. Thermal pulses were supplied by a xenon flash tube. Values were computed by regression analysis:

$$\alpha = 3.68 \times 10^{-2} + 1.30 \times 10^{-5}T \text{ (see Toularkion, et al⁽¹¹⁾)}.$$

- (2) Intrinsic thermocouple technique using chromel-alumel thermojunction:

$$\alpha = 3.33 \times 10^{-2} + 1.98 \times 10^{-5}T.$$

- (3) Noncontact technique using the InSb detector:

$$\alpha = 3.92 \times 10^{-2} + 2.35 \times 10^{-5}T.$$

$$(4) \% D = \frac{\alpha_{NC} - \alpha_{TPRC}}{\alpha_{TPRC}} \times 10^2.$$

$$(5) \% D = \frac{\alpha_{IT} - \alpha_{TPRC}}{\alpha_{TPRC}} \times 10^2.$$

for the directly determined thermal-diffusivity-temperature dependencies of Figures 20 through 24 by dashed lines. This interval represents the limits around the computed mean regression line within which the mean value for an infinite number of normally distributed measurements can be expected to be found with a 90% probability.

Interpretation

Adoption of linear $\alpha(T)$ trend lines (shown in Figures 20 through 24) was somewhat arbitrary in light of the data scatter, which is indicative of both the material nonhomogeneity between duplicate specimens (differentiated symbolically) and/or experimental error.

The linear $\alpha(T)$ model correlates with experimental findings about as well as any polynomial of order three or lower, according to covariance analyses. The $\rho C_p(T)\alpha(T)$ product,

representing the coupling of two linear functions, becomes a polynomial of the second order, which is consistent with the findings of this laboratory for a vacuum-arc-remelted Type 304-L stainless steel, as determined by the steady-state axial rod technique.

Figure 29 illustrates the trends of thermal conductivity with increasing temperatures for the base and weld materials. The base metal trendline conductivities were from 6 to 15% higher than the mean weld metal values for the X, Y, and Z measurement directions. The range of X, Y, and Z values at a given temperature was approximately 9%. At 500° C, k for the base metal was approximately 11% greater than the mean k value for the weld metal. At and above this temperature [after accounting for the average weld 90% tolerance limit (TL) bandwidth of approximately $\pm 6\%$], the larger magnitude of base metal k values ($\pm 10\%$, 90% TL) begins to have some significance.

CONCLUSIONS AND RECOMMENDATIONS

In summary, thermal conductivities of the weld material, while somewhat variant (depending upon the direction of measurement) are essentially equivalent over the temperature interval from 25 to 1000° C. Trends in the base material k values are predominantly higher than for weld material, and these differences become statistically valid above approximately 500° C.

Additional studies are planned with other candidate weld materials. Development of the noncontact InSb detector to provide credible results would allow extension of the thermal diffusivity test to temperatures in the melting range of stainless steel (1400 to 1450° C). These data would provide a more accurate evaluation of the thermal performance of such materials in the event of any incident which might cause the reactor to overheat. When practical, direct steady-state thermal-conductivity measurements by the axial-rod technique should be obtained for the candidate steel materials as a confirmatory check analysis.

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APPENDIX A

LASER THERMAL ANALYSIS PROGRAM GUIDE

The laser thermal analysis program provides for two modes of operation: data acquisition and data reduction. These modes are interlinked so that acquired data may be readily introduced to the analysis program.

Descriptions of the data acquisition and data reduction formats follow; and, in Appendix B, typical report-form summaries are reproduced.

The data acquisition program (Appendixes A and B) requests and assimilates pertinent measurement parameters and then cycles through the TEMPERATURE POINT statement as data are acquired. At the conclusion of the test, either termination or introduction to the data-reduction program is available.

The data reduction program (Appendixes A and B) operates on stored data points obtained in the data acquisition sequence. After requesting and assimilating the sample density and the predetermined least-squares equation for specific heat, the routine of curve-fitting commences. Least-squares equations, representing the thermal diffusivity and thermal conductivity-temperature dependencies, are next obtained with standard statistical parameters, defining the precision of the regression analyses.

After selection of the most appropriate equations for $\alpha(T)$ and $k(T)$, off-line mechanical plotting of these functions with or without data points and tolerance limits is available. Tables and figures displaying $\alpha(T)$ and $k(T)$ dependencies, included in the body of this report, were obtained using these routines.

Data Acquisition

Upon program initiation, the program identifies itself by typing

THERMAL MAIN
 CURVE FIT?

If the operator types "Y", see data analysis section. If "N" is inputted, then

ANALYTICAL REQ #?

Input floating point number (decimal point required).

TRANSDUCER OPTION

Input the employed temperature measurement technique.

SAMPLE THICKNESS (CM)?

Enter sample thickness in cm, floating point format.

PULSE WIDTH (MSEC)?

Enter floating point laser burst time for half-time correction.

CURVE FIT INITIATION POINT?

Input integer (no decimal point) number representing the channel address where the curve fit will start. This channel must be after the fall of the laser burst and not nearer than 300 channels to the scale change channel. This value must be between 100 and 400.

START OVER?

If an error has been made, type "Y"; and the question-answer sequence will restart. Assume "N".

TEMPERATURE POINT #?

Enter integer number between 1 - 50. This number is used to identify the data point.

SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?			

Type "Y" to allow data collection. The operator may now push TEMP SEND and DATA SEND buttons. The computer responds by outputting the results under the appropriate headings and asking for another. This process continues until "N" is typed or 10 shots have been sent.

AVERAGE WHICH SHOTS?

Type the shot numbers (0 - 9) in ascending order and separated by commas. The temperature point averages and standard deviation are printed.

KEEP?

If "Y" is typed, this data overlays the previous data at this temperature point.

ANOTHER POINT?

Type "Y", and the computer will return to the temperature point number question after the TEMP SEND button is pushed. This button is examined immediately and every two minutes thereafter. Assume "N" in the following.

CURVE FIT?

"N" terminates the laser program. "Y" enters the data analysis mode.

Data Reduction

INPUT POINTS:

POINT #	X	Y
**	*****	*****

The point number is between 01 and 50, right justified integer. The data are entered in floating point format anywhere beneath the asterisks. This data will replace any previous data for the same point number. A 00 point number will terminate the data input.

CHANGE THERMAL COND CONSTANTS?

"N" input causes control to transfer to program ALLFIT. Assume "Y" in the following.

DENSITY (GM/CC)?

Input floating point sample density.

CURVE TYPE?

Enter integer curve type (1 - 9).

(X) SP HT COEF?

X is outputted as the number of coefficients. Enter coefficients, one per line, in ascending order in either floating-point or scientific notation format.

PROGRAM ALLFIT
LIST CURVE OPTIONS?

Type "Y" for a list of options.

OPTION?

Input integer option (0 - 9).

POINT LIMITS?
** **

Enter point limits (01 - 50), right justified.

STDEV =
CORR COEF =
INDEX OF DET =
COEF IN ASCENDING ORDER

These values are listed.

COMPARISON TABLE?

Type "N" and control goes to "FIT ANOTHER CURVE". Assume "Y" in the following.

EVERY NTH POINT WILL BE PRINTED, INPUT N.

Input integer value. The values are written under the proper heading. X = 25, 100, 200...1,000 is included in the table even if N = 0. The headings are:

X	Y	YCALC	%DIFF	SLOPE
FIT ANOTHER CURVE?				

If "N" is inputted, control goes to "PLOT". Assume "Y" in the following.

FIT THERMAL COND?

If "N" is inputted, control goes to "INPUT POINTS". If "Y" is inputted, the conductivity is calculated from the last diffusivity fit. Control goes to "PROGRAM ALLFIT".

PLOT?

If "N" is inputted, the laser program terminates. Assume "Y" in the following.

FILE NAME?

Input a 5 character alphanumeric name which will identify the data set.

HEADER?

Enter up to 40 alphanumeric characters to identify the graph.

PLOT COND?

If the answer is "Y", the conductivity data will be plotted. If the answer is "N", diffusivity data will be plotted.

PLOT OPTIONS? (1 = DATA, 2 = FIT, 3 = CLS, 4 = SAME PLOT)

Enter integer values separated by commas. Option 4 refers to the next plot, which can be plotted on the same set of coordinates.

FIT ANOTHER CURVE?

Enter "Y" or "N", the sequence repeats as before.

Equations of Interest

Diffusivity (α) (at temperature, T):

$$\alpha = \frac{d^2}{t_c \pi^2}, \text{ and}$$

$$t_c = \frac{t_{1/2} - 0.55 \tau}{1.37} ,$$

where:

d represents the sample thickness,

t_c the characteristic time,

$t_{1/2}$ the half time, and

τ the laser pulse width.

Conductivity (K), (at temperature, T):

$$K = \rho a_c C_p,$$

where:

ρ represents the density,

a_c the calculated diffusivity, and

C_p the calculated specific heat.

Standard deviation (σ):

$$\sigma = \sqrt{\frac{\sum (Y - Y')^2}{(n - o - 1)}} ,$$

where:

Y represents the experimental value,

Y' the calculated value,

n the number of points, and

o the order of equation of fit.

Index of determination (r^2):

$$r^2 = 1 - \frac{\sum (Y - Y')^2}{\sum (Y - \bar{Y})^2} ,$$

where:

$\bar{Y}$ represents the average Y value.

Correlation coefficient (r):

$$r = \pm \sqrt{r^2}$$

90% Tolerance Interval (TI):

$$TI = \pm \sigma \cdot t(0.95, df) \cdot (1 + 1/n)^{1/2}$$

where:

(0.95, df) represents a t factor from student t distribution with df degrees of freedom.

Computer Operator Guide

TAPE	UNIT 2	LUN	8
TTY	UNIT 1	LUN	6

Partition USER2

Entries to Laser Program:

1. LASR - restores core images from tape and requests LASR1
2. LASR1 - assume core image unchanged.
3. LSCHD - Between shots LSCHD monitors "TEMP SEND" button every two minutes, MCR partition. To signal this operation, LASER STANDBY + RFC DATA lights are on. USER2 partition is free during this time. The system may be restarted if LSCHD is requested.

A tape image is always saved at laser sign off.

Plot Program

```
PLOT PROGRAM
PDP-15/20, KM9-V5A
PROGRAM LASR
.DAT SLOTS:
A_DKC1_-4/DTC1_3/CP_2/TT_4
E_LASR
```

Enter file names in order. Plotter pen should be < 4 inches from right stop.

LASR XCT and LASR XCU are on a DECTAPE marked LASER PLOT BIN and should be transferred to disk 1, if not already there. Source copies and batch files are on LASER PLOT SRC.

APPENDIX B

TYPICAL REPORT FORM SUMMARY FOR LASER THERMAL ANALYSIS

Data Acquisition

THERMAL MAIN
 CURVE FIT?
 N
 ANALYTICAL REF #?
 60.85
 TRANSDUCER OPTION?
 1
 SAMPLE THICKNESS (CM)?
 .2647
 PULSE WIDTH? (MSEC)
 1.0
 CURVE FIT INITIATION POINT?
 175
 START OVER?
 N
 TEMPERATURE POINT #?
 1

	SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?				
Y	0	22.6	0.2287E+00	0.4269E-01
ANOTHER?				
Y	1	22.6	0.2204E+00	0.4431E-01
ANOTHER?				
Y	2	22.6	0.3135E+00	0.3112E-01
ANOTHER?				
Y	3	22.6	0.2200E+00	0.4438E-01
ANOTHER?				
Y	4	22.6	0.2258E+00	0.4324E-01
ANOTHER?				
Y	5	22.6	0.2362E+00	0.4133E-01
ANOTHER?				
Y	6	22.6	0.2417E+00	0.4039E-01
ANOTHER?				
Y	7	22.6	0.2340E+00	0.4172E-01
ANOTHER?				
Y	8	22.6	0.2371E+00	0.4117E-01
ANOTHER?				
Y	9	22.6	0.2421E+00	0.4032E-01

AVERAGE WHICH SHOTS?
 6,7,8,9

POINT: 1 AVERAGES: 22.6 0.2387E+00 0.4090E-01
 SD DEV= 0.6670E-03

KEEP?
 Y
 ANOTHER POINT?
 N
 START OVER?

N
 CURVE FIT?
 N
 THERMAL MAIN
 CURVE FIT?
 N
 ANALYTICAL REQ #?
 6085
 TRANSDUCER OPTION?
 6
 SAMPLE THICKNESS (CM)?
 .2647
 PULSE WIDTH? (MSEC)
 1.0
 CURVE FIT INITIATION POINT?
 175
 START OVER?
 N
 TEMPERATURE POINT #?
 2

	SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?				
Y	0	105.3	0.2057E+00	0.4747E-01
ANOTHER?				
Y	1	106.0	0.3109E+00	0.3138E-01
ANOTHER?				
Y	2	106.0	0.2355E+00	0.4145E-01
ANOTHER?				
Y	3	106.0	0.2303E+00	0.4238E-01
ANOTHER?				
Y	4	106.4	0.2529E+00	0.3860E-01
ANOTHER?				
Y	5	107.8	0.2283E+00	0.4275E-01
ANOTHER?				
Y	6	108.6	0.2345E+00	0.4163E-01
ANOTHER?				
N				
AVERAGE WHICH SHOTS?				
2,3,5,6				
POINT: 2 AVERAGES:	107.1	0.2322E+00	0.4205E-01	
SD DEV=	0.6179E-03			

KEEP?
 Y
 ANOTHER POINT?
 Y
 TEMPERATURE POINT #?
 3

	SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?				
Y	0	184.7	0.2195E+00	0.4449E-01
ANOTHER?				
Y	1	185.7	0.2206E+00	0.4426E-01
ANOTHER?				
Y	2	186.4	0.2269E+00	0.4303E-01
ANOTHER?				
Y	3	186.8	0.2295E+00	0.4255E-01
ANOTHER?				
N				
AVERAGE WHICH SHOTS?				
0,1,2,3				

KEEP?
Y
ANOTHER POINT?
Y
TEMPERATURE POINT #?
4

	SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?				
Y	0	270.8	0.2186E+00	0.4467E-01
ANOTHER?				
Y	1	271.8	0.2118E+00	0.4609E-01
ANOTHER?				
Y	2	272.5	0.2127E+00	0.4592E-01
ANOTHER?				
Y	3	273.1	0.2025E+00	0.4823E-01
ANOTHER?				
Y	4	273.5	0.1283E+00	0.7622E-01
ANOTHER?				
Y	5	274.1	0.2101E+00	0.4647E-01

ANOTHER?
N
AVERAGE WHICH SHOTS?
0,1,2,5

POINT: 4 AVERAGES: 272.3 0.2133E+00 0.4579E-01
SD DEV= 0.7770E-03

KEEP?
Y
ANOTHER POINT?
Y
TEMPERATURE POINT #?
5

	SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?				
Y	0	350.6	0.2041E+00	0.4786E-01
ANOTHER?				
Y	1	351.5	0.1775E+00	0.5504E-01
ANOTHER?				
Y	2	351.9	0.2076E+00	0.4703E-01
ANOTHER?				
Y	3	353.8	0.2121E+00	0.4604E-01
ANOTHER?				
Y	4	354.1	0.2066E+00	0.4726E-01

ANOTHER?
N
AVERAGE WHICH SHOTS?
0,2,3,4

POINT: 5 AVERAGES: 352.6 0.2076E+00 0.4705E-01
SD DEV= 0.7569E-03

KEEP?
Y
ANOTHER POINT?
Y
TEMPERATURE POINT #?
6

	SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?				

Y

ANOTHER?	0	440.0	0.1965E+00	0.4970E-01
Y	1	440.9	0.2021E+00	0.4833E-01
ANOTHER?	2	442.5	0.1906E+00	0.5125E-01
Y	3	443.7	0.1488E+00	0.6571E-01
ANOTHER?	4	444.0	0.2035E+00	0.4799E-01
Y	5	444.6	0.1980E+00	0.4934E-01

ANOTHER?
N
AVERAGE WHICH SHOTS?
0,1,4,5

POINT: 6 AVERAGES: 442.4 0.2000E+00 0.4884E-01
STD DEV= 0.8081E-03

KEEP?

Y
ANOTHER POINT?

Y
TEMPERATURE POINT #?
7

	SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?				
Y	0	516.0	0.1941E+00	0.5032E-01
ANOTHER?				
Y	1	516.9	0.1919E+00	0.5091E-01
ANOTHER?				
Y	2	517.2	0.1885E+00	0.5180E-01
ANOTHER?				
Y	3	518.0	0.1996E+00	0.4892E-01

ANOTHER?
N
AVERAGE WHICH SHOTS?
0,1,2,3

POINT: 7 AVERAGES: 517.0 0.1935E+00 0.5049E-01
STD DEV= 0.1211E-02

KEEP?

Y
ANOTHER POINT?

Y
TEMPERATURE POINT #?
8

	SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?				
Y	0	-22.0	0.1817E+00	0.5375E-01
ANOTHER?				
Y	1	607.4	0.1817E+00	0.5375E-01
ANOTHER?				
Y	2	607.9	0.1788E+00	0.5464E-01
ANOTHER?				
Y	3	608.5	0.1811E+00	0.5395E-01
ANOTHER?				
Y	4	608.7	0.1846E+00	0.5291E-01

ANOTHER?
N
AVERAGE WHICH SHOTS?
1,2,3,4

POINT: 8 AVERAGES: 608.1 0.1816E+00 0.5381E-01
STD DEV= 0.7115E-03

KEEP?

Y

ANOTHER POINT?

Y

TEMPERATURE POINT #?

9

	SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?				
Y	0	685.6	0.1800E+00	0.5426E-01
ANOTHER?				
Y	1	685.8	0.1867E+00	0.5232E-01
ANOTHER?				
Y	2	686.1	0.1784E+00	0.5475E-01
ANOTHER?				
Y	3	686.6	0.1688E+00	0.5790E-01
ANOTHER?				
Y	4	686.8	0.1766E+00	0.5531E-01
ANOTHER?				
Y	5	687.1	0.1706E+00	0.5729E-01
ANOTHER?				

N

AVERAGE WHICH SHOTS?

0,2,4,5

POINT: 9 AVERAGES: 686.4 0.1764E+00 0.5540E-01
SD DEV= 0.1326E-02

KEEP?

Y

ANOTHER POINT?

Y

TEMPERATURE POINT #?

10

	SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?				
Y	0	757.4	0.1724E+00	0.5669E-01
ANOTHER?				
Y	1	757.6	0.1694E+00	0.5767E-01
ANOTHER?				
Y	2	757.9	0.1709E+00	0.5718E-01
ANOTHER?				
Y	3	759.0	0.1677E+00	0.5827E-01
ANOTHER?				

N

AVERAGE WHICH SHOTS?

0,1,2,3

POINT: 10 AVERAGES: 758.0 0.1701E+00 0.5745E-01
SD DEV= 0.6783E-03

KEEP?

Y

ANOTHER POINT?

Y

TEMPERATURE POINT #?

11

	SHOT	TEMP	T 1/2	DIFFUS
--	------	------	-------	--------

ANOTHER?
 Y 1 839.5 0.1605E+00 0.6087E-01
 ANOTHER?
 Y 2 839.7 0.1711E+00 0.5711E-01
 ANOTHER?
 Y 3 839.7 0.1753E+00 0.5572E-01
 ANOTHER?
 Y 4 839.7 0.1698E+00 0.5755E-01
 ANOTHER?
 Y 5 839.7 0.1718E+00 0.5686E-01
 ANOTHER?
 Y 6 839.7 0.1695E+00 0.5765E-01
 ANOTHER?
 N
 AVERAGE WHICH SHOTS?
 1,2,4,6

POINT: 11 AVERAGES: 839.7 0.1677E+00 0.5829E-01
 SD DEV= 0.1734E-02

KEEP?
 Y
 ANOTHER POINT?
 Y
 TEMPERATURE POINT #?
 12

	SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?				
Y	0	915.1	0.1600E+00	0.6110E-01
ANOTHER?				
Y	1	915.4	0.1550E+00	0.6304E-01
ANOTHER?				
Y	2	915.8	0.1609E+00	0.6076E-01
ANOTHER?				
Y	3	916.1	0.1611E+00	0.6066E-01
ANOTHER?				
Y	4	916.3	0.1657E+00	0.5897E-01
ANOTHER?				
Y	5	916.5	0.1739E+00	0.5618E-01
ANOTHER?				
Y	6	916.8	0.2100E+00	0.4650E-01
ANOTHER?				
Y	7	917.0	0.1559E+00	0.6268E-01
ANOTHER?				
N				
AVERAGE WHICH SHOTS?				
0,2,3,7				

POINT: 12 AVERAGES: 916.0 0.1595E+00 0.6130E-01
 SD DEV= 0.9408E-03

KEEP?
 Y
 ANOTHER POINT?
 Y
 TEMPERATURE POINT #?
 13

	SHOT	TEMP	T 1/2	DIFFUS
ANOTHER?				
Y	0	967.0	0.1500E+00	0.6517E-01
ANOTHER?				
Y	1	967.4	0.1595E+00	0.6129E-01
ANOTHER?				

Y				
	2	967.9	0.1688E+00	0.5790E-01
ANOTHER?				
Y	3	967.9	0.1672E+00	0.5843E-01
ANOTHER?				
Y	4	968.1	0.1614E+00	0.6055E-01
ANOTHER?				
Y	5	968.1	0.1540E+00	0.6346E-01
ANOTHER?				
Y	6	968.1	0.1569E+00	0.6230E-01
ANOTHER?				
Y	7	967.9	0.1536E+00	0.6363E-01
ANOTHER?				
Y	8	968.1	0.1658E+00	0.5892E-01
ANOTHER?				
Y	9	967.9	0.1679E+00	0.5818E-01

AVERAGE WHICH SHOTS?
1,5,6,7

POINT: 13 AVERAGES:	967.9	0.1560E+00	0.6267E-01
STD DEV= 0.1093E-02			

KEEP?

Y

ANOTHER POINT?

N

START OVER?

N

CURVE FIT?

N

Data Reduction

```

THERMAL MAIN
CURVE FIT?
Y
INPUT POINTS:
POINT #      X      Y
**      *****      *****

CHANGE THERMAL COND CONSTANTS?
Y
DENSITY (GM/CC)?
7.90
SPEC HT CURVE TYPE?
1
2 SP HT COEFF?
.113555
5.24101E-5
PROGRAM ALLP11
LIST CURVE OPTIONS?
Y
1-6 DEGREE 1-6 POLYNOMIALS
7 Y=A/T
8 Y=A+B/T
9 Y=A+B*T+C/T
10 Y=A+B*T+C/(T*T)
OPTION?
1
POINT LIMITS?
**,**
01,25
STD DEV      0.570403E-03
CORR COEFF    0.996774E+00
INDEX OF DET   0.993559E+00
COEF IN ASCENDING ORDER
0.392457E-01
0.235128E-04

COMPARISON TABLE?
Y
EVERY NTH POINT WILL BE PRINTED. INPUT N:
1

```

X	Y	YCALC	PCT DIFF	SLOPE
0.2264E+02	0.4090E-01	0.3978E-01	0.2747E+01	0.2351E-04
0.1071E+03	0.4205E-01	0.4176E-01	0.6880E+00	0.2351E-04
0.1859E+03	0.4358E-01	0.4362E-01	-0.8049E-01	0.2351E-04
0.2723E+03	0.4579E-01	0.4565E-01	0.3028E+00	0.2351E-04
0.3526E+03	0.4705E-01	0.4754E-01	-0.1042E+01	0.2351E-04
0.4424E+03	0.4884E-01	0.4965E-01	-0.1656E+01	0.2351E-04
0.5170E+03	0.5049E-01	0.5140E-01	-0.1811E+01	0.2351E-04
0.6081E+03	0.5381E-01	0.5354E-01	0.4941E+00	0.2351E-04
0.6864E+03	0.5540E-01	0.5538E-01	0.3121E-01	0.2351E-04
0.7580E+03	0.5745E-01	0.5707E-01	0.6718E+00	0.2351E-04

0.8397E+03	0.5829E-01	0.5399E-01	-0.1192E+01	0.2351E-04
0.9160E+03	0.6130E-01	0.6078E-01	0.8401E+00	0.2351E-04
0.9679E+03	0.6267E-01	0.6200E-01	0.1063E+01	0.2351E-04
0.8295E+02	0.4099E-01	0.4120E-01	-0.5017E+00	0.2351E-04
0.1537E+03	0.4371E-01	0.4286E-01	0.1951E+01	0.2351E-04
0.2370E+03	0.4485E-01	0.4482E-01	0.6241E-01	0.2351E-04
0.3110E+03	0.4638E-01	0.4656E-01	-0.3753E+00	0.2351E-04
0.3970E+03	0.4847E-01	0.4858E-01	-0.2311E+00	0.2351E-04
0.4846E+03	0.4949E-01	0.5064E-01	-0.2332E+01	0.2351E-04
0.5775E+03	0.5257E-01	0.5282E-01	-0.4811E+00	0.2351E-04
0.6465E+03	0.5423E-01	0.5445E-01	-0.4021E+00	0.2351E-04
0.7214E+03	0.5630E-01	0.5621E-01	0.1641E+00	0.2351E-04
0.7982E+03	0.5768E-01	0.5801E-01	-0.5877E+00	0.2351E-04
0.8829E+03	0.6033E-01	0.6000E-01	0.5348E+00	0.2351E-04
0.9411E+03	0.6207E-01	0.6137E-01	0.1129E+01	0.2351E-04
0.2500E+02		0.3983E-01		0.2351E-04
0.1000E+03		0.4160E-01		0.2351E-04
0.2000E+03		0.4395E-01		0.2351E-04
0.3000E+03		0.4630E-01		0.2351E-04
0.4000E+03		0.4865E-01		0.2351E-04
0.5000E+03		0.5100E-01		0.2351E-04
0.6000E+03		0.5335E-01		0.2351E-04
0.7000E+03		0.5570E-01		0.2351E-04
0.8000E+03		0.5806E-01		0.2351E-04
0.9000E+03		0.6041E-01		0.2351E-04
0.1000E+04		0.6276E-01		0.2351E-04

FIT ANOTHER CURVE?

Y

FIT THERMAL COND?

Y

LIST CURVE OPTIONS?

N

OPTION?

2

POINT LIMITS?

,

01,25

STD DEV 0.118557E-05

CORR COEF 0.100000E+01

INDEX OF DET 0.100000E+01

COFF IN ASCENDING ORDER

0.147403E+02

0.156345E-01

0.407594E-05

COMPARISON TABLE?

Y

EVERY NTH POINT WILL BE PRINTED. INPUT N:

1

X	Y	YCALC	PCT DIFF	SLOPE
0.2264E+02	0.1510E+02	0.1510E+02	0.1579E-04	0.1582E-01
0.1071E+03	0.1646E+02	0.1646E+02	0.8690E-05	0.1651E-01
0.1859E+03	0.1779E+02	0.1779E+02	0.5361E-05	0.1715E-01
0.2723E+03	0.1930E+02	0.1930E+02	0.0000E+00	0.1785E-01
0.3526E+03	0.2076E+02	0.2076E+02	-0.2297E-05	0.1851E-01
0.4424E+03	0.2245E+02	0.2245E+02	-0.4247E-05	0.1924E-01
0.5170E+03	0.2391E+02	0.2391E+02	-0.5982E-05	0.1985E-01
0.6081E+03	0.2576E+02	0.2576E+02	-0.5554E-05	0.2059E-01
0.6864E+03	0.2739E+02	0.2739E+02	-0.3482E-05	0.2123E-01

0.7580E+03	0.2893E+02	0.2893E+02	0.0000E+00	0.2181E-01
0.8397E+03	0.3074E+02	0.3074E+02	-0.1551E-05	0.2248E-01
0.9160E+03	0.3249E+02	0.3249E+02	0.2936E-05	0.2310E-01
0.9679E+03	0.3369E+02	0.3369E+02	0.5661E-05	0.2352E-01
0.8295E+02	0.1607E+02	0.1607E+02	0.1187E-04	0.1631E-01
0.1537E+03	0.1724E+02	0.1724E+02	0.5532E-05	0.1689E-01
0.2370E+03	0.1867E+02	0.1867E+02	0.0000E+00	0.1757E-01
0.3110E+03	0.2000E+02	0.2000E+02	-0.4769E-05	0.1817E-01
0.3970E+03	0.2159E+02	0.2159E+02	-0.2209E-05	0.1887E-01
0.4846E+03	0.2327E+02	0.2327E+02	-0.4098E-05	0.1958E-01
0.5775E+03	0.2513E+02	0.2513E+02	-0.3795E-05	0.2034E-01
0.6465E+03	0.2655E+02	0.2655E+02	-0.3592E-05	0.2090E-01
0.7214E+03	0.2814E+02	0.2814E+02	-0.3389E-05	0.2152E-01
0.7982E+03	0.2982E+02	0.2982E+02	0.1599E-05	0.2214E-01
0.8829E+03	0.3172E+02	0.3172E+02	0.3006E-05	0.2283E-01
0.9411E+03	0.3306E+02	0.3306E+02	0.2884E-05	0.2331E-01
0.2500E+02		0.1513E+02		0.1584E-01
0.1000E+03		0.1634E+02		0.1645E-01
0.2000E+03		0.1803E+02		0.1726E-01
0.3000E+03		0.1930E+02		0.1808E-01
0.4000E+03		0.2165E+02		0.1890E-01
0.5000E+03		0.2358E+02		0.1971E-01
0.6000E+03		0.2559E+02		0.2053E-01
0.7000E+03		0.2768E+02		0.2134E-01
0.8000E+03		0.2986E+02		0.2216E-01
0.9000E+03		0.3211E+02		0.2297E-01
0.1000E+04		0.3445E+02		0.2379E-01

FIT ANOTHER CURVE?

N

PLOT?

Y

FILE NAME?

0037A

HEADER?

F#0037A. ARN 60.85-.90. DEG. 1

PLOT COND?

N

SYMBOL CHANGE POINT?

14

PLOT OPTIONS? (1=DATA, 2=FIT, 3=CL'S, 4=SAME PLOT)

1,2,3

FIT ANOTHER CURVE?

N

PLOT?

Y

FILE NAME?

0038K

HEADER?

F#0038K. ARN 60.85 .90. DEG. 2

PLOT COND?

Y

SYMBOL CHANGE POINT?

14

PLOT OPTIONS? (1=DATA, 2=FIT, 3=CL'S, 4=SAME PLOT)

2

FIT ANOTHER CURVE?

Distribution

Energy Research and Development Administration - Oak Ridge

Hickman, H. D.
Leed, R. E.
Zachry, D. S., Jr
Technical Information Center (2)

Holifield National Laboratory

Brinkman, C. R.
Corum, J. M.
Cunningham, J. E.
King, R. T. (12)
Martin, W. R.
McCurdy, H. C.
Patriarca, P.
Williams, R. K.

Oak Ridge Gaseous Diffusion Plant

Barton, J. C.
Ward, M. E.
Wilcox, W. J., Jr
Winkel, R. A.

Oak Ridge Y-12 Plant

Briscoe, O. W.
Burditt, R. B.
Burkhart, L. E.
Cadden, J. L.
Carver, D. W.
Darby, D. M. (4)
Davenport, C. M.
Dodson, W. H.
Ebert, T. H.
Fraser, R. J.
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Jones, F. W.
Kahl, K. G.
Keith, A.
Kite, H. T. (12)

Lore, J. D. (20)
Lundin, M. I.
Marrow, G. B.
Mason, D. L.
McLendon, J. D.
Mills, J. M., Jr
Neeley, A. C.
Phillips, L. R.
Pollock, C. B.
Reynolds, C. D.
Richards, H. L. (16)
Rowan, J. H.
Schreyer, J. M.
Smith, D. D.
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