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Temperatures in a CRV-7 Plume from a Thermal Imaging Technique (U)

K.M. Ide

Aeronautical and Maritime Research Laboratory

ABSTRACT (R)

Technical Report

(R) Temperatures profiles in the plume of the rocket motor of the CRV-7 missile are reported. Thermal imaging was chosen as the preferred measurement technique because of its non-intrusive nature. The apparent temperatures recorded by the thermal imager were calibrated from the true plume temperatures measured by thermocouples. The 500°C maximum apparent temperature range of the thermal imager proved a limitation when greater spatial resolution of the plume interior was required. The nodal regions in the plume were saturated on the thermal record. The maximum temperature recorded with the thermocouples was 2080°C at 1.4 s, 1.5 m from the nozzle exit plane.

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Temperatures in a CRV-7 Plume from a Thermal Imaging Technique (U)

Executive Summary (U)

(U) The variation in absolute temperature present in the exhaust plume of a statically fired CRV-7 rocket motor is reported. The temperatures were recorded using an infrared radiometer, a device which uses an infrared camera to capture images of the plume. A camera technique avoids the need to place a measuring device, such as a thermocouple, into the plume which in turn alters the state of the plume. The apparent temperatures present in the plume are measured from the plume's infrared radiation signature. These apparent temperatures are converted to true temperatures by comparison with those recorded using a thermocouple in a number of calibration firings. The results reported provide representative information on the temperature profiles present in the CRV-7 rocket motor plume.

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Kym Ide graduated from the University of Adelaide with a BE (Hons) in 1987 and a M. Eng. Sc. in 1990. He joined Explosives Ordnance Division, AMRL Salisbury in 1989. He has worked in the areas of internal ballistic performance and finite element structural analysis of rocket motors for service life assessment. He is currently conducting research into the hysteresis and crack propagation characteristics of non-linear viscoelastic materials employed in rocket motor manufacture.

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1. Introduction

(U) The consequences of rocket motor plume ingestion by an aircraft engine during missile launch is of considerable importance. Currently ARL are conducting such an investigation. The study of this phenomenon requires knowledge of the temperature of the rocket motor exhaust, consequently EOD was tasked to collect local data on the plume temperature.

(U) Thermal imaging is a non-intrusive visual technique, whereby images from a video camera of the rocket motor exhaust plume are recorded onto videotape, which are in turn analysed to obtain temperatures in the plume. Thermal imaging was chosen because of the advantage that no disturbance is caused to the plume, unlike intrusive techniques such as thermocouples. These rely on measuring temperatures at a point, thereby altering downstream conditions such that no information can be recorded in this region. By using thermal imaging, all temperature information, from ignition to burnout, can be obtained for the entire extent of the plume from one static firing.

(U) The thermal imaging system measures apparent temperature by detecting the intensity of infrared (IR) radiation. Measurements therefore require calibration by use of thermocouples placed directly at various points in the rocket motor plume. Thermal images of calibration firings were calibrated with the temperatures recorded by the thermocouples, giving a means of converting apparent temperatures into true plume temperatures in future firings.

(U) The analysis undertaken was aimed at providing temperature profiles of the exhaust plume both radially and axially at fixed points in time during the firing and the temperature variation with time, at various distances behind the nozzle exit plane. This report presents temperatures measured in the exhaust plume of the CRV-7 missile's rocket motor, using a thermal imaging technique. CRV-7 is a 2.75" (70 mm) diameter, unguided air-to-surface/air-to-air missile. Two rocket motor designs are employed in the CRV-7; the RLU-5001/B and RLU-5002/B. The subject of this study is the RLU-5002/B which contains the non-aluminised propellant.

(U) Interior ballistic measurements of the rocket motors statically fired were recorded, as are all ballistic measurements when any rocket motor is statically fired by EOD. The results are compared against the manufacturers interior ballistic specification as a test of motor serviceability.

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2. Experimental

2.1 Thermal Imaging System

(U) The thermal imaging system used was the Inframetrics 610 IR imaging radiometer. A single infrared scanner incorporates servo controlled mirrors which perform horizontal and vertical scanning. A three times (3X) broadband telescope was added to the scanner lens in order to allow the scanner to be remotely located away from the rocket motor for safety. Addition of the telescopic lens increases the spatial resolution and decreases field of view to 5° by 6.6°. The scanned beam is split into 3-5 μm and 8-12 μm spectral bands which are focused onto the mercury/cadmium/telluride detector elements. The radiometer detector elements measure spectral radiation emitted relative to a blackbody. In the absence of any emissivity data the spectral radiation is converted into blackbody or "apparent" temperatures. Each band can be set to measure apparent object temperatures in one of several ranges up to a maximum range of 500°C, with a maximum absolute apparent temperature of +1500°C. For the purposes of this study it was assumed that the plume had an emissivity of 1.0. The apparent temperature range and the offset apparent temperature were adjusted over the series of calibration firings to give a suitable range of temperatures, which would later be calibrated to give true temperatures. The detector output or thermal image is recorded onto a standard VCR tape, for later analysis.

(U) The recorded images are analysed using the Inframetrics ThermoGRAM PC adaptor card and Thermoteknix analysis software. The selected motor firing is replayed from videotape and images at any desired point in time are captured (digitised) by converting the apparent temperatures into intensity levels, which are then stored onto computer disk. These images can be imported into image analysis programs, such as NIH Image, where the digitised intensity levels are extracted as separate pixel intensity values and saved in standard ASCII format for ease of manipulation and charting in spreadsheet programs.

2.2 Thermocouple Setup for Calibration

(U) In order to calibrate the thermal images recorded with the Inframetrics scanner a set of thermocouples capable of measuring temperatures up to 2800°C were employed. The thermocouples were of two types: platinum/13% platinum-rhodium and tungsten/tungsten-26% rhenium. The thermocouple wires were supported in a twin bore ceramic tube which was in turn fitted inside two stainless steel tubes, and a final coating of ceramic paste ensured good protection against the abrasive and highly corrosive rocket plume; see figure 1.

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Seven thermocouples were fitted to a stand at various heights so as to distribute them radially from the axis of the plume towards its outer edge; see figure 2. The stand was placed at various distances from the nozzle exit plane, in the field of view of the thermal imager.

(U) The output from the thermocouples was recorded onto a Racal FM recorder after 50X amplification. The recorded signal was digitised using a MELADIOS II 12 bit DAC at 400 Hz. By use of Superscope software the offset level of the signal was removed and by application of a smoothing function the noise level reduced. EMF values at every 100 ms were converted to °C and plotted as a function of time.

(U) Five test firings were performed to determine the stand position at which the thermocouples provided maximum output while sustaining minimum damage; this was found to be 1.5 m. Calibration was achieved by identifying the pixel intensity assigned by the digitising process to the point where the thermocouple bead was, in the thermal image. Temperatures were assigned to these intensity values from the temperatures recorded by the thermocouple at the same instant. Two tests were then performed without thermocouples present in the field of view, one with the total plume extent visible (a horizontal field of view of 2.12 m), another with a smaller field of view which increased resolution of the plume interior (a horizontal field of view of 0.9 m).

(U) A photograph of the experimental setup during the static firings is presented in figure 3. Damage caused by the exhaust plume to the thermocouples can be seen in figure 4.

3. Results

3.1 Correlation between Pixel Intensity and Temperature

(U) Figure 5 illustrates a temperature record from the thermocouple system as measured during a firing for the purpose of calibration.

(U) A correlation for converting pixel intensity into temperature in °C was arrived at by the following method. The true axial distance from the nozzle exit plane to the thermocouple stand position was 1.5 m and the vertical spacing of thermocouples in millimetres is given in figure 2. A measurement of the axial distance of the thermocouples from the nozzle exit plane, in picture elements (pixels), can be made by image analysis of a digitised thermal image of the firing. This allows calculation of the horizontal length in millimetres represented by one

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pixel. By using the aspect ratio of a pixel the horizontal length per pixel can be converted into a vertical length per pixel. Thus the exact position of each thermocouple tip can be identified in any thermal image of the firing. Starting from the axial centreline of the plume, the intensity assigned to a pixel coinciding with the position of a thermocouple bead can be obtained. The true temperature as measured by the thermocouple, at the same instant in time, can now be correlated to the pixel intensity value on the thermal image. A plot of the temperatures measured by thermocouples 1 to 7 at various times during the calibration firing against pixel intensity at the corresponding position and instant is presented in figure 6. By employing a curve fitting routine a power law relationship for converting pixel intensity into temperature in °C was derived:

$$T = 2.73P(I)^{0.5}$$

where T is temperature in °C and P(I) is pixel intensity (dimensionless).

3.2 Plume Temperature Results

(U) The temperature data presented in this report was generated from thermal images selected from the full video record of each rocket motor firing. An emphasis was placed on images from the first second of burn, ie. when the motor would be in close proximity to the aircraft engine. Each thermal image was divided into a grid, whereby the intensity levels assigned to each pixel on the gridlines in the axial and radial directions were converted into temperatures. Figures 7 to 18 show the variation in temperature axially, at various distances from the centreline of the plume. Similarly, the radial variation in temperature at positions along the plume axis is plotted; see figures 19 to 30. Next, for various distances from the nozzle exit plane, the variation in radial temperature is plotted against time, see figures 31 to 48. Contour plots of all thermal images selected for analysis are reproduced in figures 49 to 60. The contours are labelled with the corresponding temperatures in °C.

3.3 Ballistic Results

(U) All CRV-7 rocket motors used this study were fired in accordance with the Bristol Aerospace test specification (Ref 1). This document specifies that motors will be temperature conditioned prior to firing for a period of 24 hours. The temperature chosen for this study was -54°C, as low temperature limits tend to cause the most variation from the specified ballistic limits.

(U) The ballistic results are presented in table 1. A comparison can be made with the values specified.

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Table 1 (R): Ballistic Results

	CRV-7/90	CRV-7/91	Specification ¹
Motor Type	RLU-5002/B	RLU-5002/B	RLU-5002/B
Motor Serial Number	72	75	-
Firing Temp (°C)	-54	-54	-54
Ignition Delay (s)	0.0142	0.0162	0.040 (max)
Ignition Interval (s)	0.0094	0.0062	-
Ignition Thrust (lbf)	-(1)	-	1000 (min)
Action Time (s)	2.1751	2.2031	1.91 (min)
Total Impulse (lbf-s)	2178	2129.7	2100 (min)
Igniter Squib Resistance (ohm)	1.7	1.65	1-2
Mass before firing (kg)	6.43	6.38	6.38±0.07
Mass after firing (kg)	2.25	2.2	-

(1) Results omitted due to security classification.

4. Discussion

(U) The distinct advantage of the thermal imaging technique is its ability to record the profile of a rocket motor exhaust plume in totality. The plume is undisturbed during the motor burn time and as such a maximum amount of data can be extracted from each individual firing. Data can be generated from each frame of the video record, representing a duration of 1/25th of a second, and from the entire extent of the plume, radially and axially. In comparison an intrusive technique such as temperature gauges will cause disturbance to the downstream conditions, thus any data gathered in this region may be unrepresentative. Also a probe can only record conditions at one point in the plume unless multiple probes are employed, which are in turn limited to deployment radially and cause greater disturbance. Subsequently, if an intrusive technique is selected many test firings will be required in order to gather enough information to characterise the entire plume.

(U) However, the use of intrusive probes is required in order to calibrate the thermal image data. A difficulty encountered with the intrusive thermocouple probes employed in this study was the damage sustained due to the severe environment within the plume. The thermocouples employed were capable of measuring temperatures up to 2800°C however, due to the ablative nature of the plume, the stainless steel tube in which they were housed was often eroded away, at which time the thermocouple failed. A series of test firings was completed in order to deduce the position at which the thermocouples sustained the least damage, whilst maximising the data recorded. Once determined, a

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firing with the thermocouple stand visible in the field of view of the thermal imager would yield a calibration for the infrared thermal images.

(U) Careful alignment of the rocket motor centreline relative to the layout of the thermocouples is required in order to allow accurate identification of the position of each thermocouple tip in the recorded thermal image.

(R) The calibrated images reveal a limitation of the thermal imager. The maximum apparent temperature range of 500°C proved inadequate for capturing all of the detailed plume temperature information present when the field of view was reduced in order to obtain more spatial resolution in the interior of the plume. The image became saturated in the regions of highest temperature, obscuring the maximum temperature reading; this is illustrated by the plateaus exhibited in figures 7-12, 19-24 and 31-39 related to CRV-7 / 90-72. These plateaus correspond to the nodal regions in the plume. However, figure 5 shows that the maximum temperature recorded by the thermocouple system was 2080°C at 1.4 s. No such limitation is present in the results of firing CRV-7 / 91-75; figures 13-18, 25-30 and 40-48. With an improvement in the maximum apparent temperature range to 1000°C this limitation could be overcome.

(R) Figures 13-18 show that over the burntime, the maximum temperature of the nodes and the number of nodes remains almost constant, as indicated by the T(0 mm) profile. However, the nodal regions themselves and the axial distances between them increases slightly and as the firing continues the temperature of the T(0) profile increases, at axial distances greater than 1250 mm. The temperatures in the other profiles increase and additional profiles can be obtained from the radially expanding plume. From examination of figures 25-30, a gradual increase in the radial dimension of the plume, during the burntime, is confirmed. At t=0.04 s after ignition the plume extends from 110 mm below to 115 mm above, the centreline of the plume. Later, at t=0.24 s the plume has expanded to 140 mm below and 140 mm above the centreline. At t=1.24 s the plume extends from -150 mm to +240 mm about the centreline. The results indicate an increase in the overall temperature and extent of the plume during the burntime, which is in agreement with the expected behaviour.

(R) By inspection of figure 40 it is noted that at the nozzle exit plane the temperature of the radial profile increases considerably over the period of the burntime. In contrast the profiles presented in figures 41-45 show only a gradual increase. In figures 46-48 the profiles show a marked increase in the temperature at t=1.24 s from that at t=0.64 s, which is consistent with the plume having attained its fully developed state. However, the maximum temperatures obtained are progressively lower than those at positions closer to the nozzle exit plane.

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(R) The maximum temperature observed in the plume from firing CRV-7 / 91-75 was 1530°C at 1.24 secs, at the plume centreline. The maximum temperature observed in firing CRV-7 / 91-75 within the first half second of ignition was 1402°C, again at the plume centreline.

(R) Although an individual motor plume will exhibit random variations in temperature and axial and radial extent based on many factors, including ambient temperature, wind speed and gusts, the plume temperatures reported here are representative of those present in the CRV-7 rocket motor.

(U) Table 1 details the ballistic performance of each motor against the specified values. It can be seen that all parameters conformed to the specification. In the case of these CRV-7 rocket motors the temperature during storage was not controlled and as such any exposure to high ambient temperatures will accelerate the propellant aging process. For the purposes of this study the motor performance is adequate and the motors fired are considered serviceable.

5. Conclusions

(R) The temperatures in the plume of the CRV-7 rocket motor have been measured using a thermal imaging technique. Thermal imaging was chosen as it can record without intrusion the entire plume profile during the burn time of the motor, whereas intrusive techniques, which necessarily disturb the plume, require that many more firings be conducted in order to fully characterise the plume. The apparent temperatures recorded by the thermal imager were calibrated from the true plume temperatures measured by thermocouples present in the plume and the field of view of the thermal imager during a series of calibration firings. Firing CRV-7 / 90-72, where a reduced field of view was employed in order to gain greater spatial resolution of the plume interior, revealed a limitation of the 500°C maximum apparent temperature range of the thermal imager. The nodal regions in the plume, where temperatures are highest, were saturated on the thermal record, obscuring the maximum temperature values present in the plume; the maximum temperature recorded with the thermocouples was 2080°C at 1.4 s. The maximum temperature recorded during firing CRV-7 / 91-75, which employed a larger field of view with less spatial resolution that encompassed the entire plume, was 1530°C at 1.24 s at the plume axial centreline. The results reported are a good representation of plume temperatures present in the CRV-7 rocket motor.

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6. Recommendations

(U) Test firings where a thermal imager field of view is reduced revealing greater detail of the plume interior, should be repeated with an extended maximum apparent temperature range of 1000°C, in order to obtain maximum plume temperatures present in the nodal regions.

7. References

1. "Specification for Rocket Motor, 70 mm, RLU-5002/B", Bristol Aerospace, D-74-340-ABO/SF-001, 1986-07-03.
2. "Manual on the use of Thermocouples in Temperature Measurement", ASTM Special Publication 470B, ASTM (Pa).
3. "Sensors - A Comprehensive Survey", Volume 1, Fundamentals and General Aspect, Ko, W. H. and Grandke, T. (Ed.), VCH (New York), 1989.
4. "Temperature - Its Measurement and Control in Science and Industry", Volume 3, Part 2, Applied Methods and Instruments, Dahl, A. I. (Ed.), Reinhold (New York).

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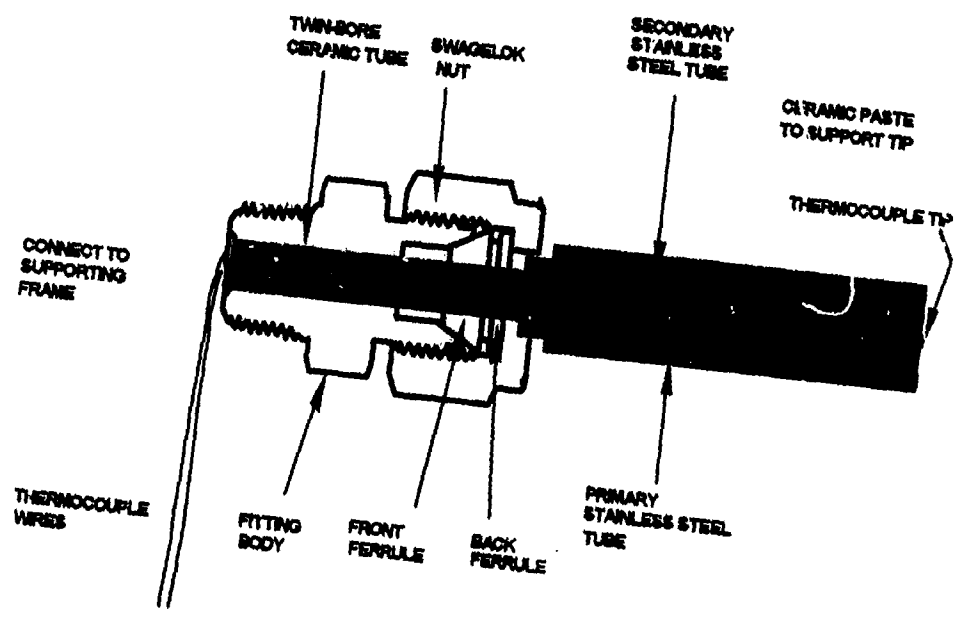


Figure 1 (U): Thermocouple housing.

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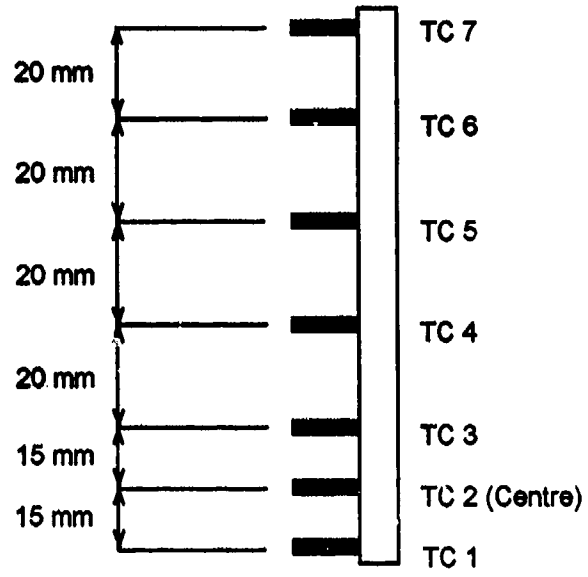


Figure 2 (U): Schematic of thermocouple spacing.

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Figure 3 (U): Experimental setup during static firing of rocket motor.

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Figure 4 (U): Damage caused to thermocouples by rocket motor plume.

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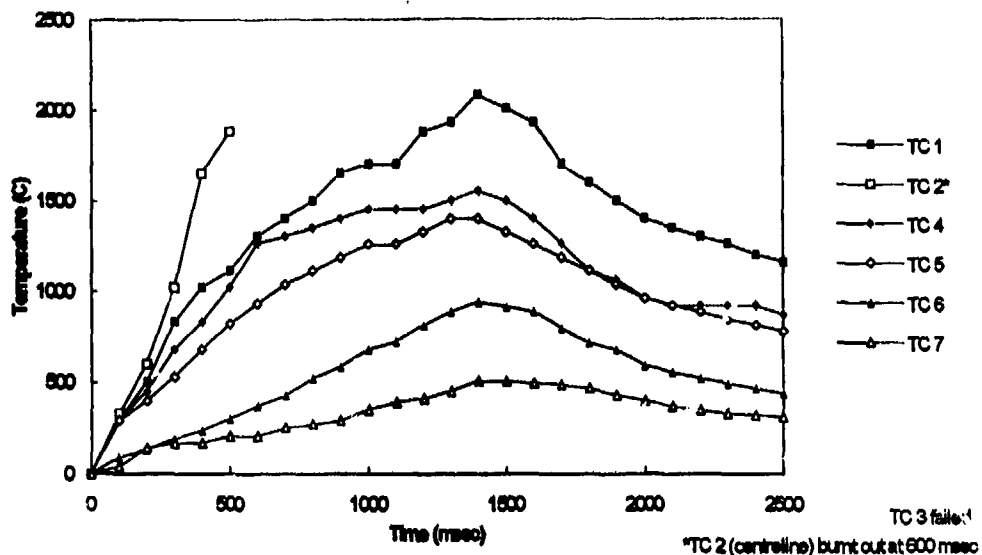


Figure 5 (R) : Temperatures recorded by the thermocouple.

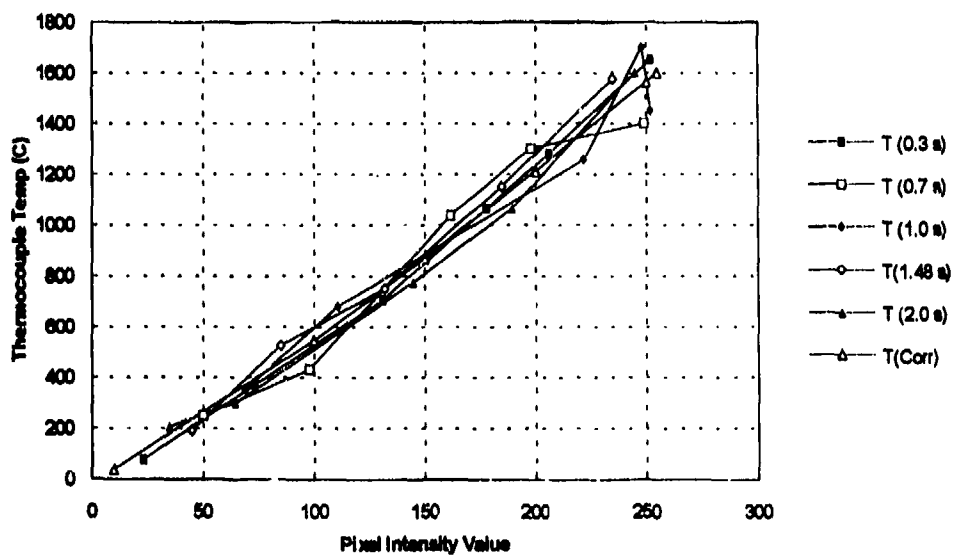


Figure 6 (R) : Calibration chart for thermal images.

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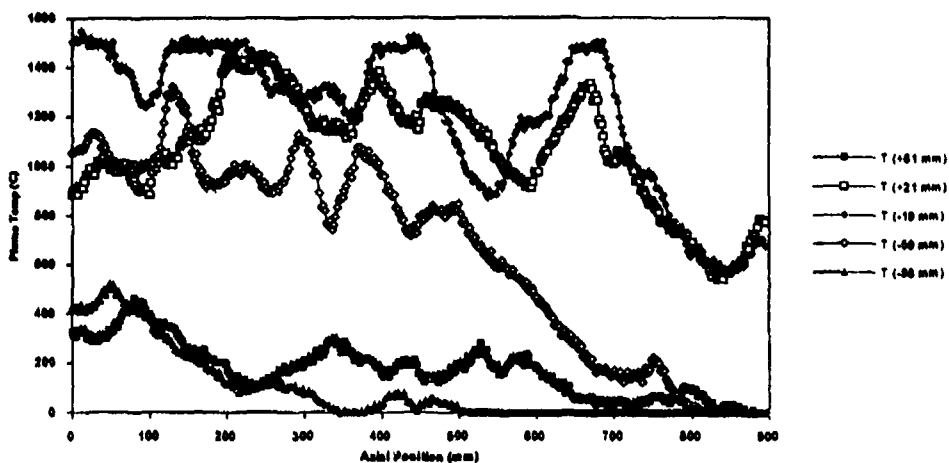


Figure 7 (R): CRV-7 / 90-72 $t=0.12$ sec

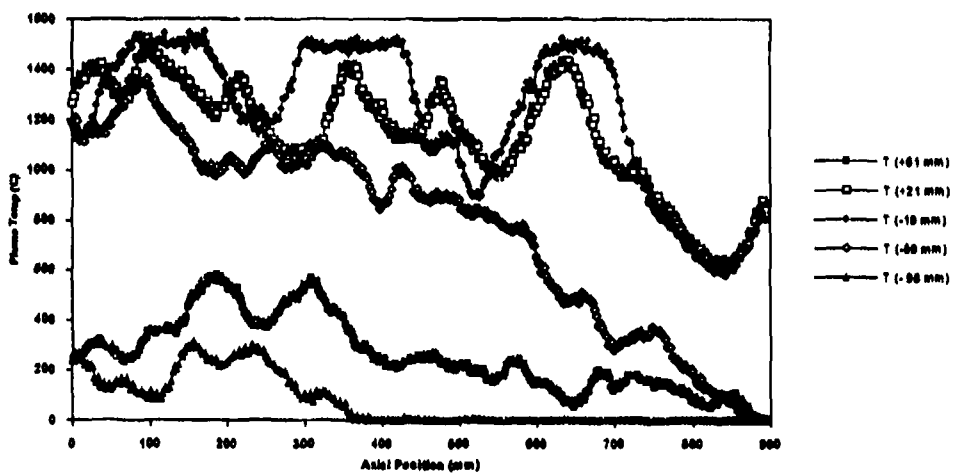


Figure 8 (R): CRV-7 / 90-72 $t=0.32$ sec

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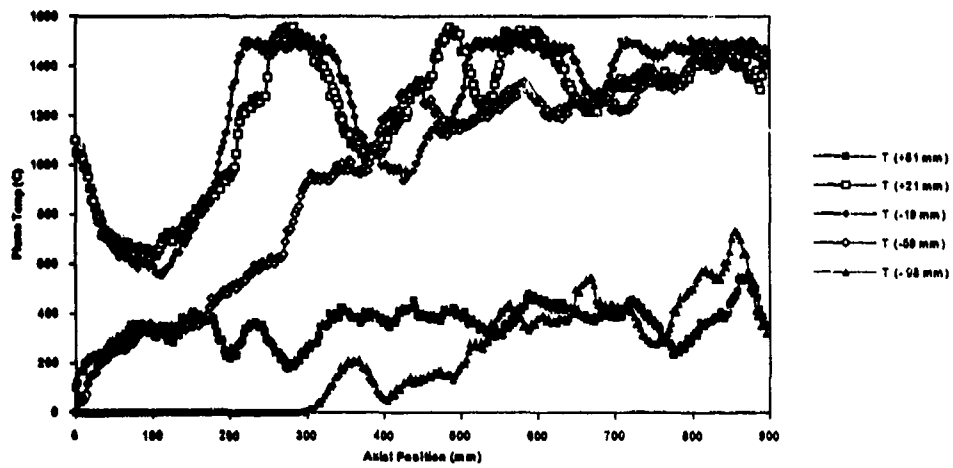


Figure 9 (R): CRV-7 / 90-72 $t=0.52$ sec

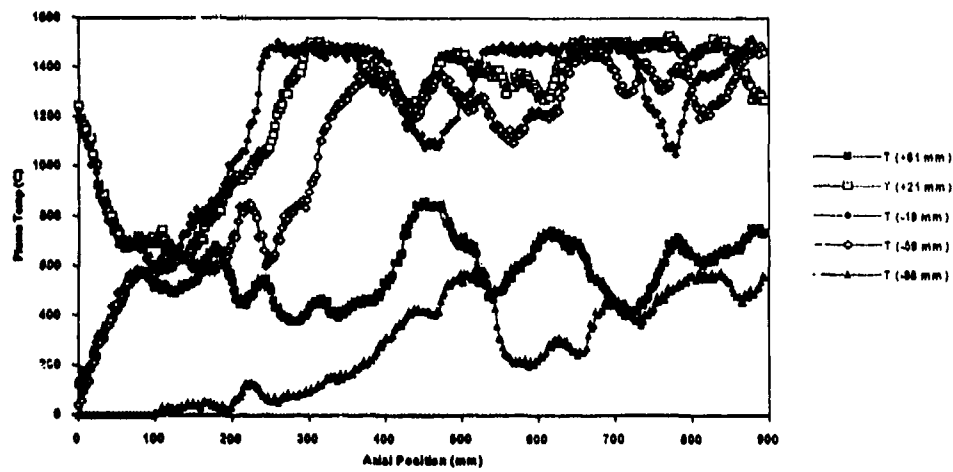


Figure 10 (R): CRV-7 / 90-72 $t=0.92$ sec

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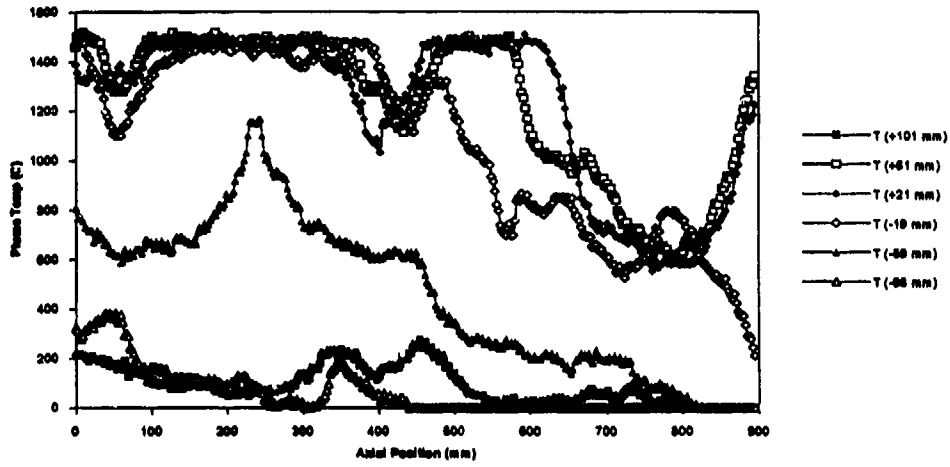


Figure 11 (R): CRV-7/90-72 $t=1.32$ sec

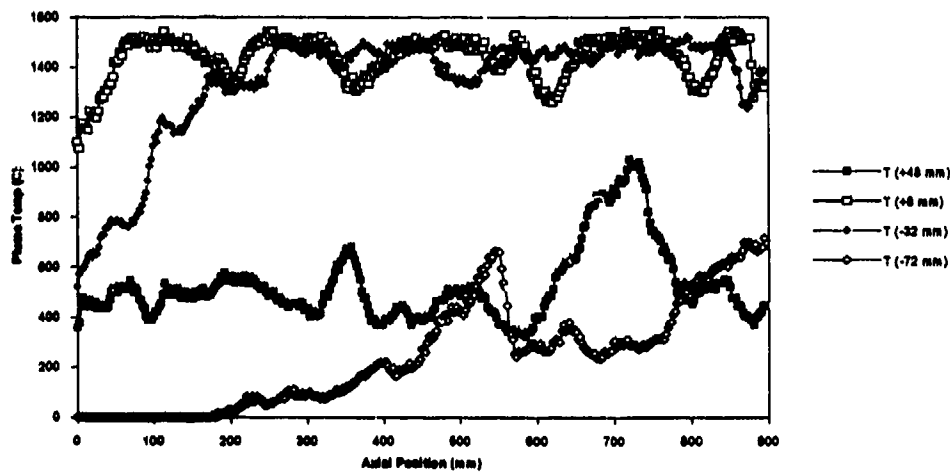


Figure 12 (R): CRV-7/90-72 $t=2.12$ sec

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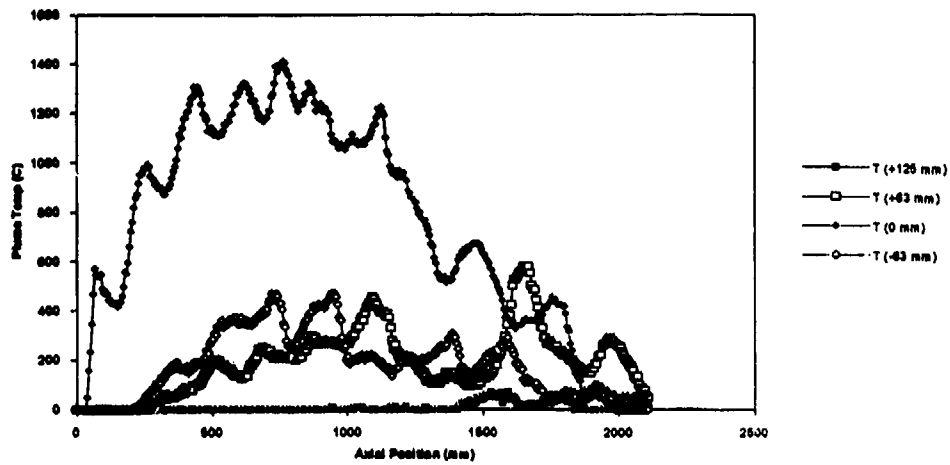


Figure 13 (R): CRV-7 /91-75 $t=0.04$ sec

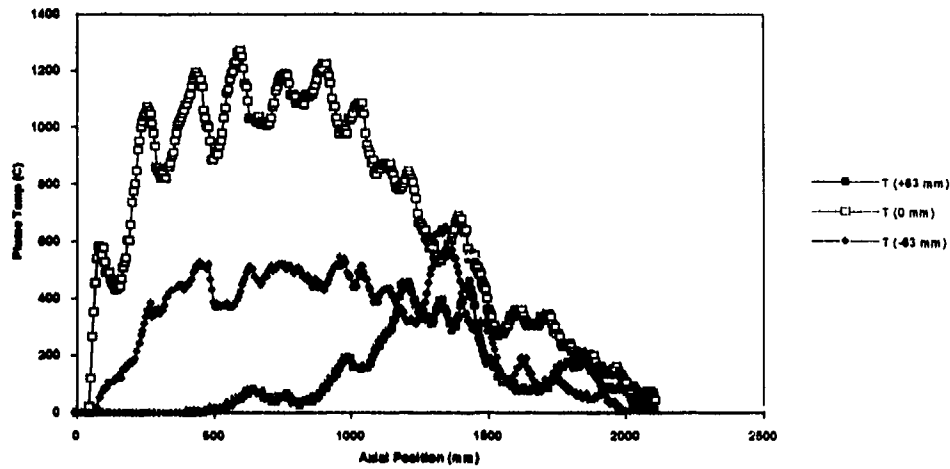


Figure 14 (R): CRV-7 /91-75 $t=0.12$ sec

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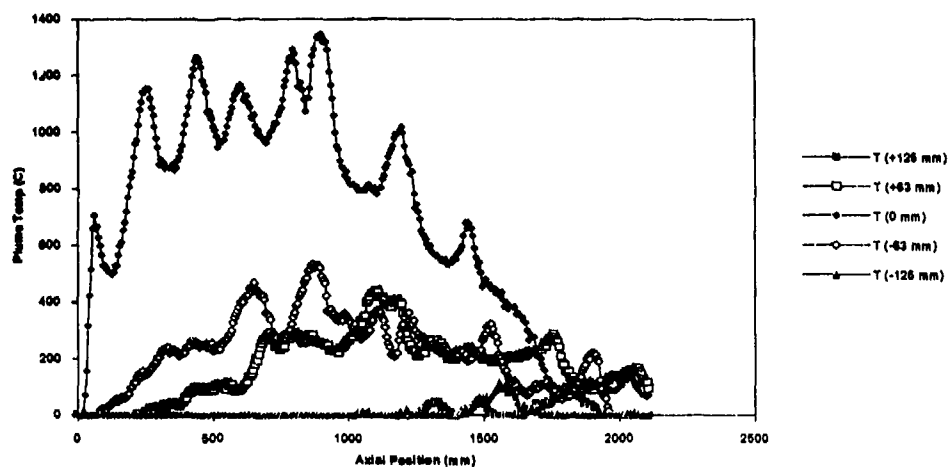


Figure 15 (R): CRV-7 / 91-75 $t=0.24$ sec

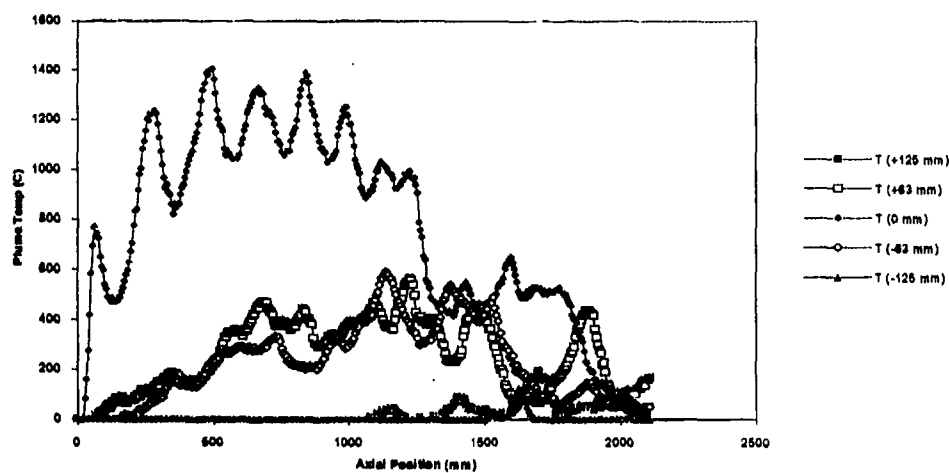


Figure 16 (R): CRV-7 / 91-75 $t=0.44$ sec

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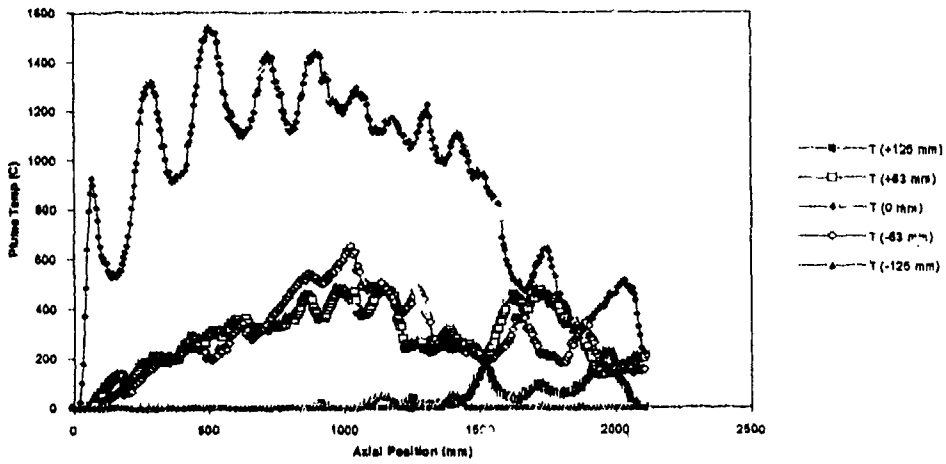


Figure 17 (R): CRV-7/91-75 $t=0.64$ sec

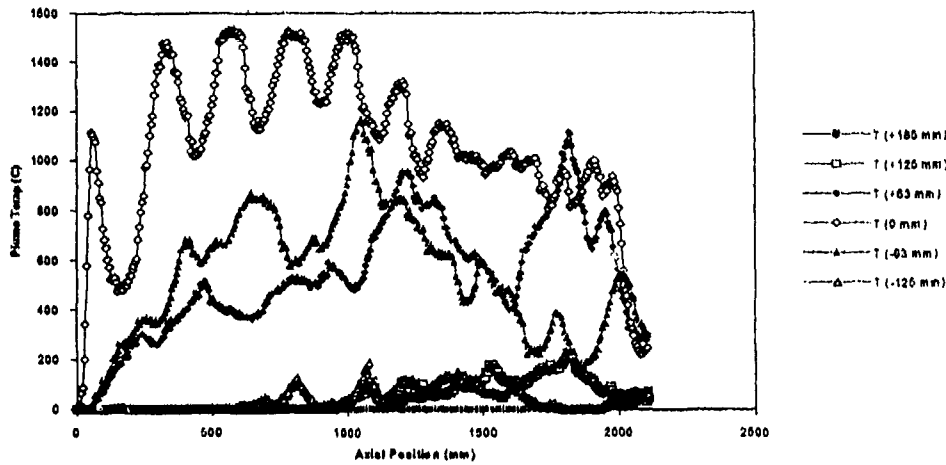


Figure 18 (R): CRV-7/91-75 $t=1.24$ sec

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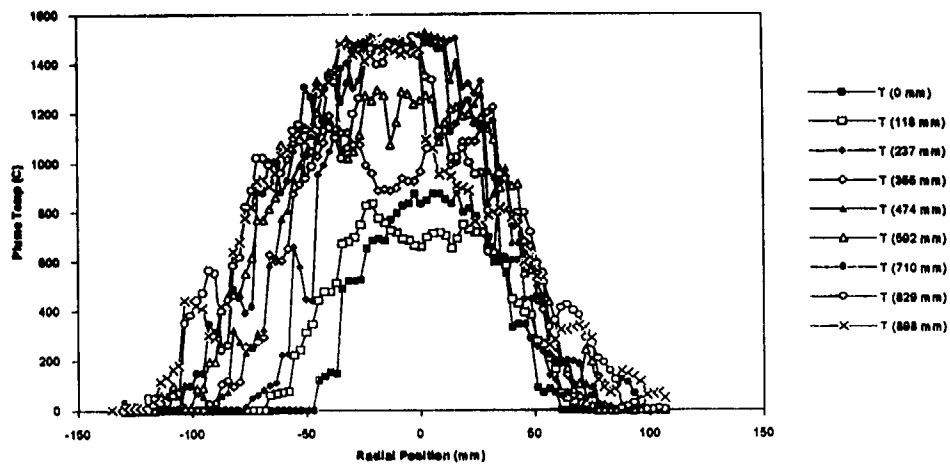


Figure 19 (R): CRV-7 / 90-72 $t=0.12$ sec

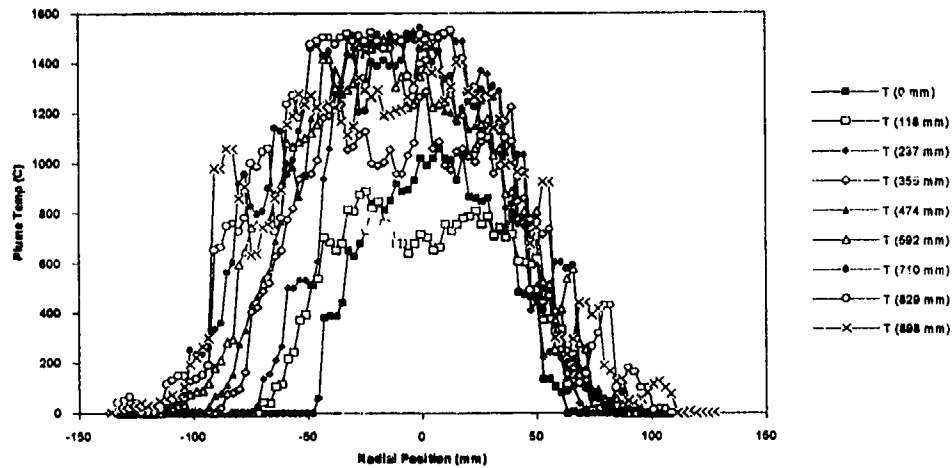


Figure 20 (R): CRV-7 / 90-72 $t=0.32$ sec

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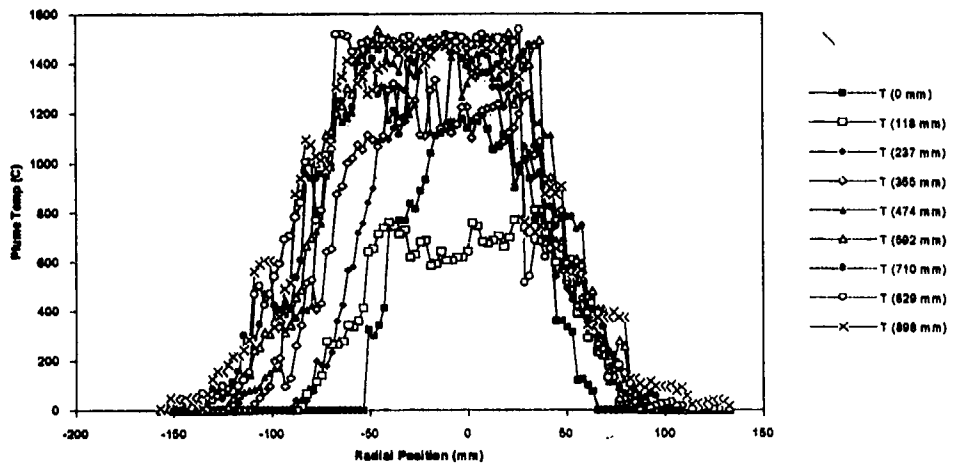


Figure 21 (R): CRV-7/91-75 $t=0.52$ sec

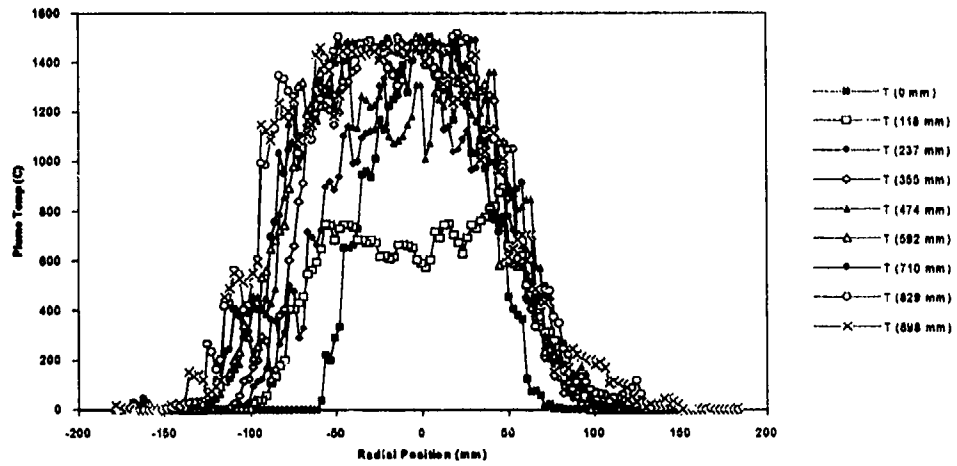


Figure 22 (R): CRV-7/90-72 $t=0.92$ sec

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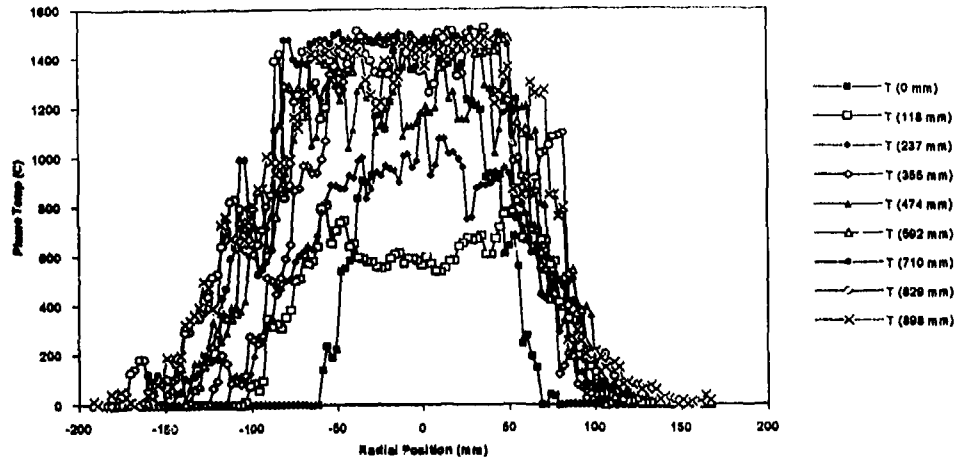


Figure 23 (R): CRV-7 / 90-72 $t=1.32$ sec

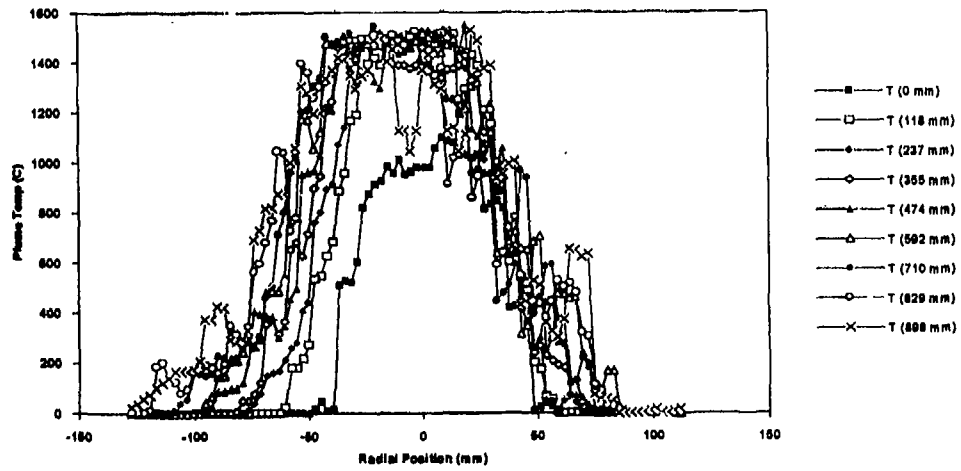


Figure 24 (R): CRV-7 / 90-72 $t=2.12$ sec

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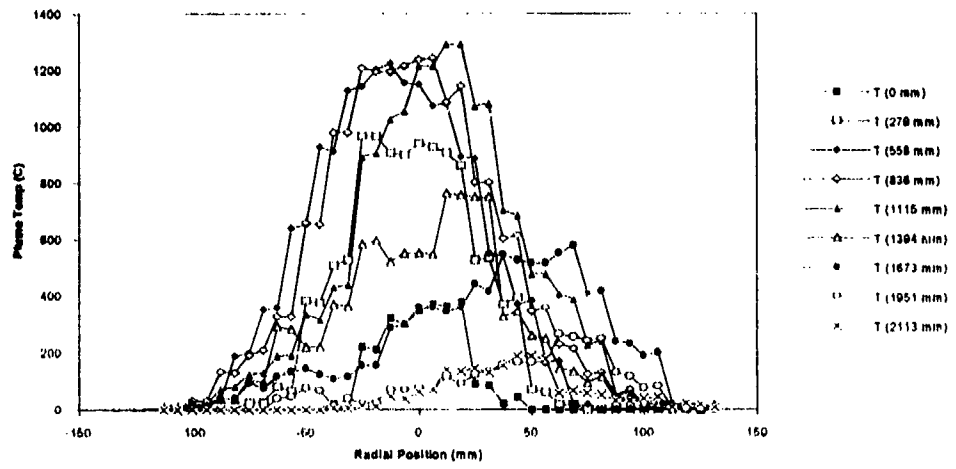


Figure 25 (R): CRV-7/91-75 $t=0.04$ sec

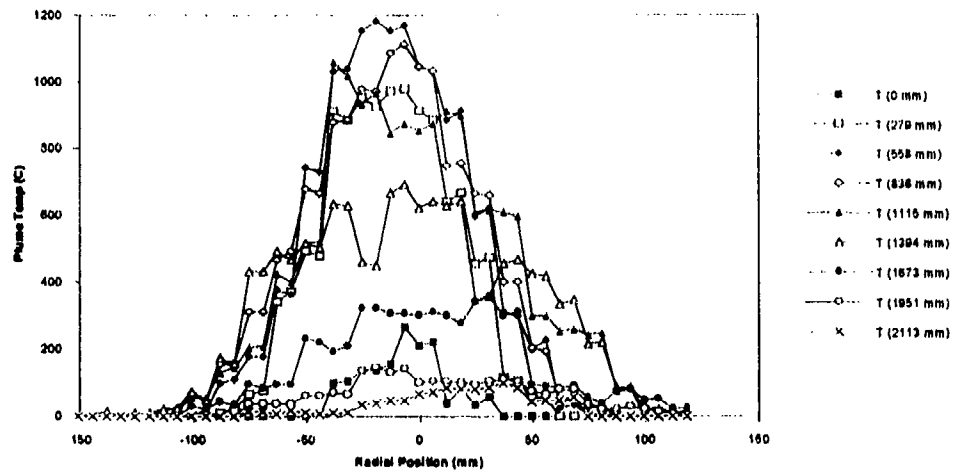


Figure 26 (R): CRV-7/91-75 $t=0.12$ sec

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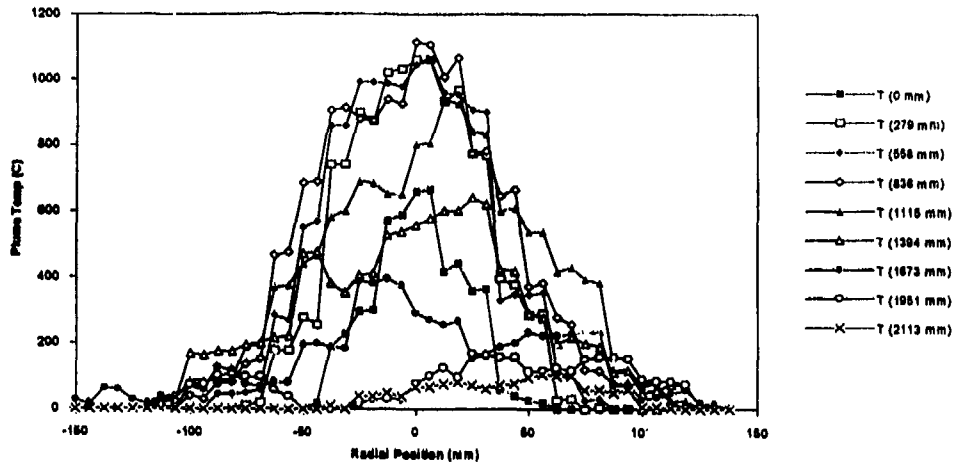


Figure 27 (R): CRV-7 /91-75 $t=0.24$ sec

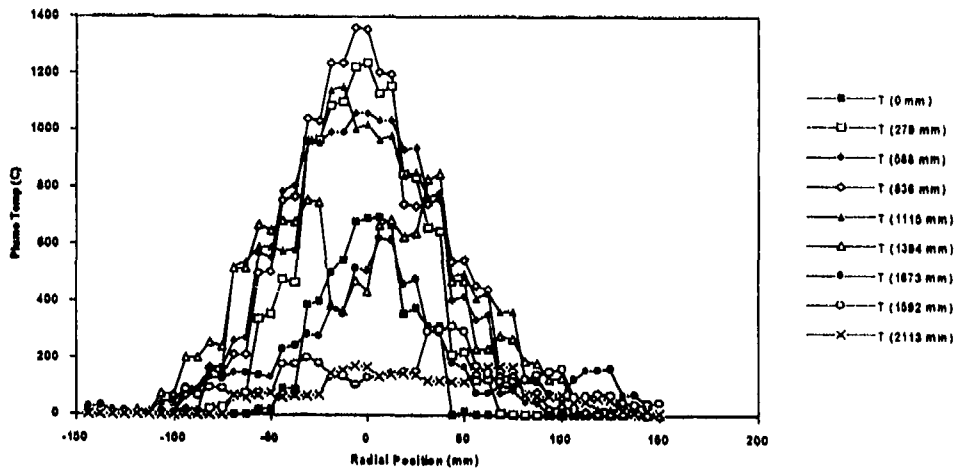


Figure 28 (R): CRV-7 /91-75 $t=0.44$ sec

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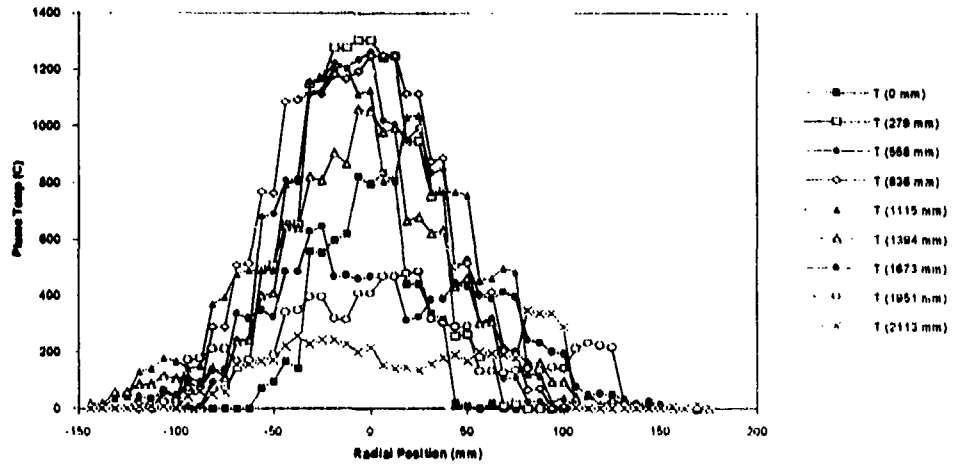


Figure 29 (R): CRV-7 / 91-75 $t=0.64$ sec

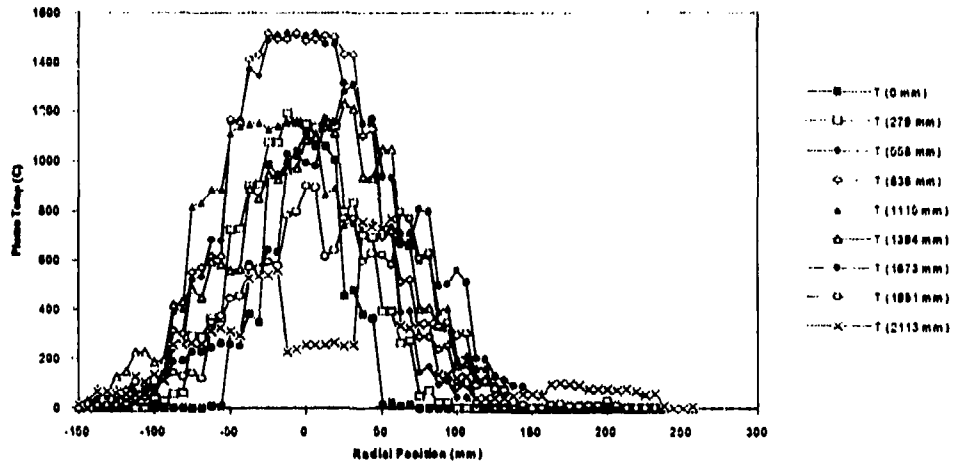


Figure 30 (R): CRV-7 / 91-75 $t=1.24$ sec

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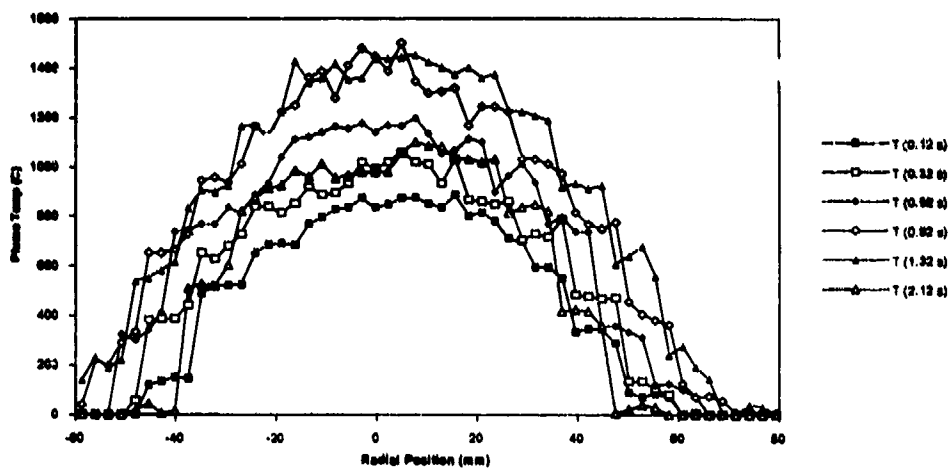


Figure 31 (R): CRV-7 / 90-72 axial position 0 mm

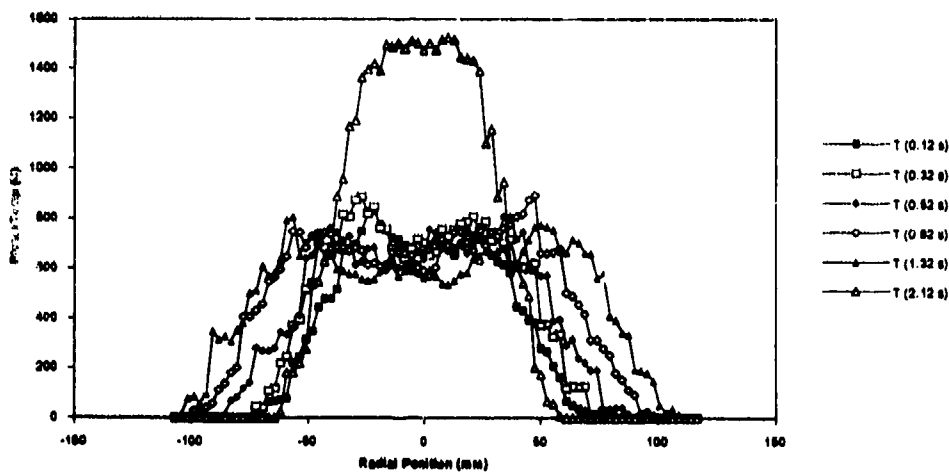


Figure 32 (R): CRV-7 / 90-72 axial position 118 mm

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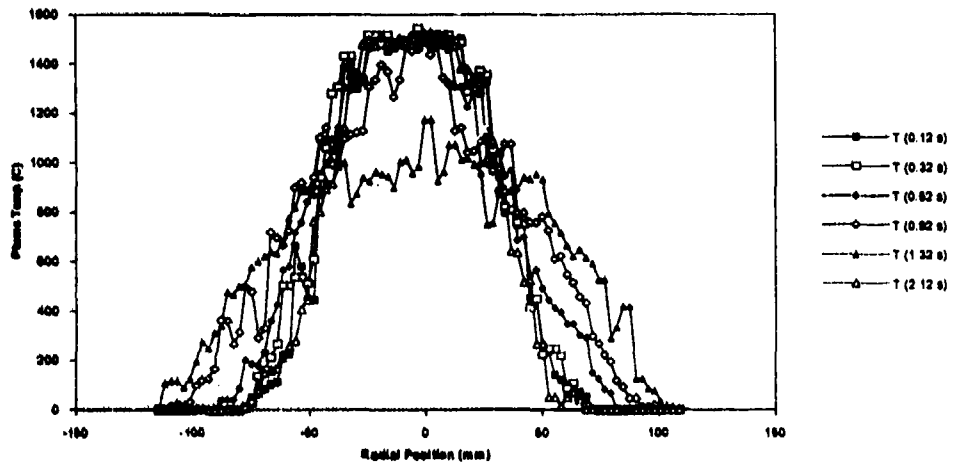


Figure 33 (R): CRV-7 / 90-77 axial position 237 mm

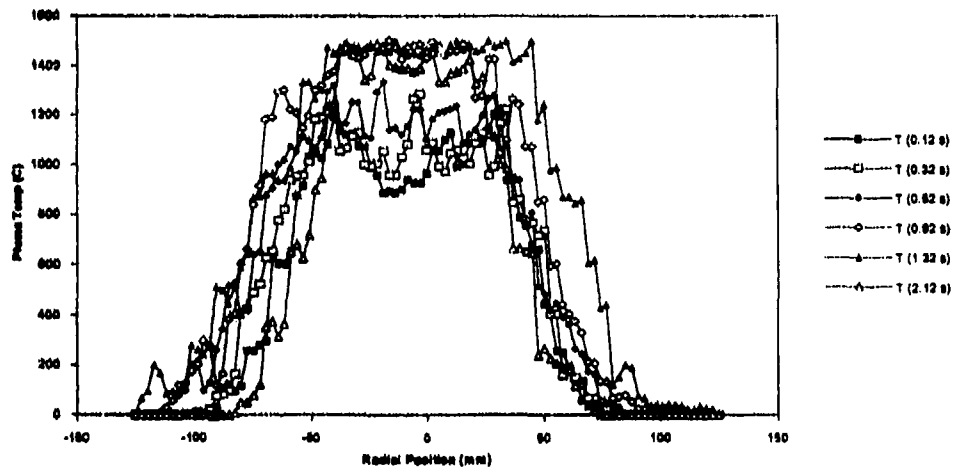


Figure 34 (R): CRV-7 / 90-72 axial position 355 mm

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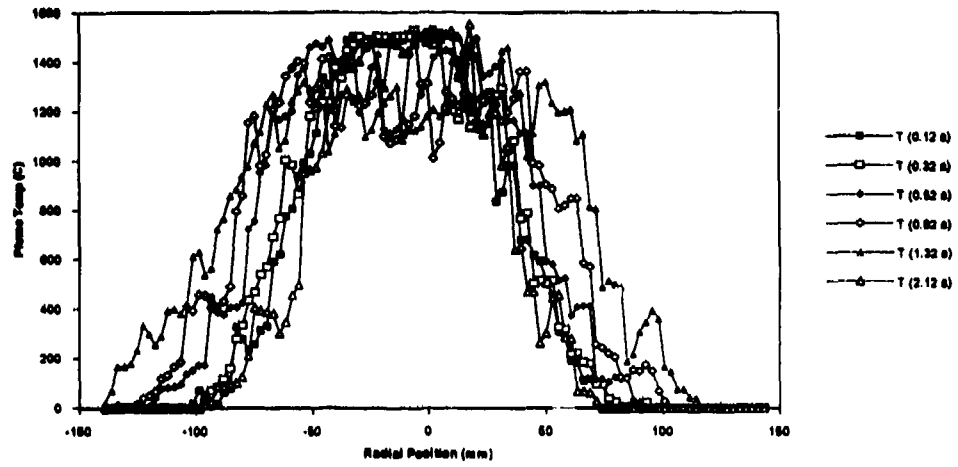


Figure 35 (R): CRV-7 / 90-72 axial position 474 mm

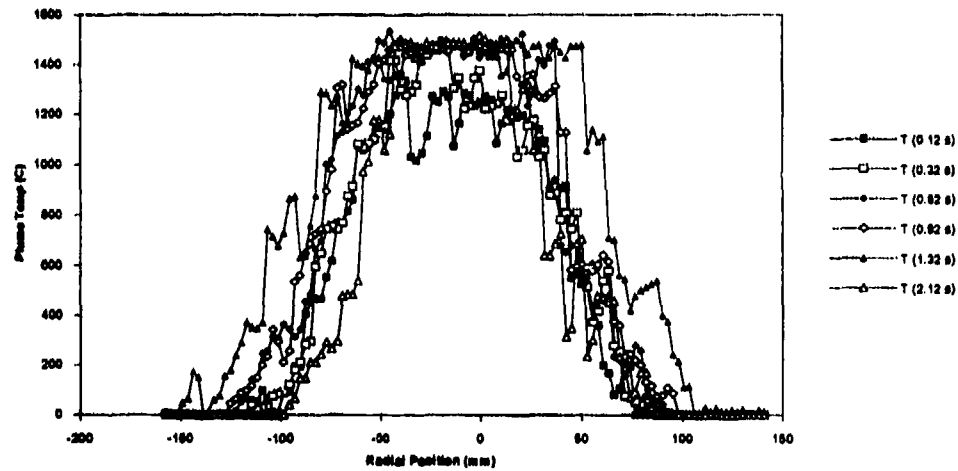


Figure 36 (R): CRV-7 / 90-72 axial position 592 mm

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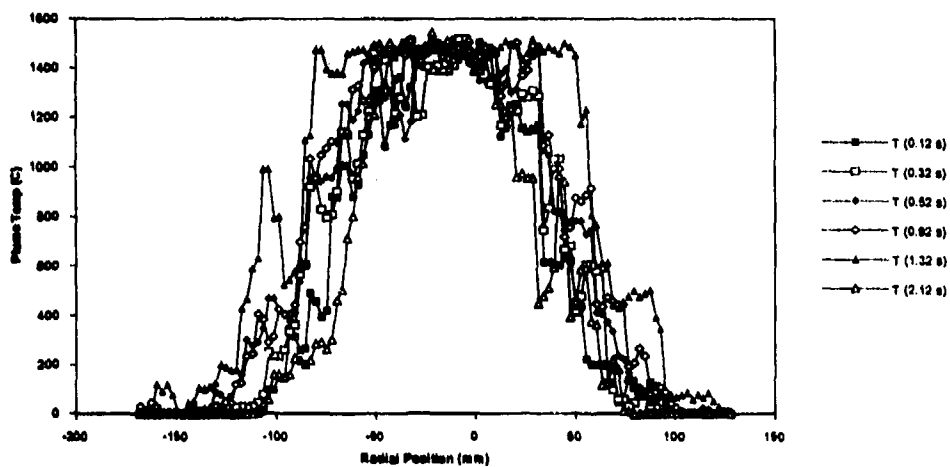


Figure 37 (R): CRV-7 / 90-72 axial position 710 mm

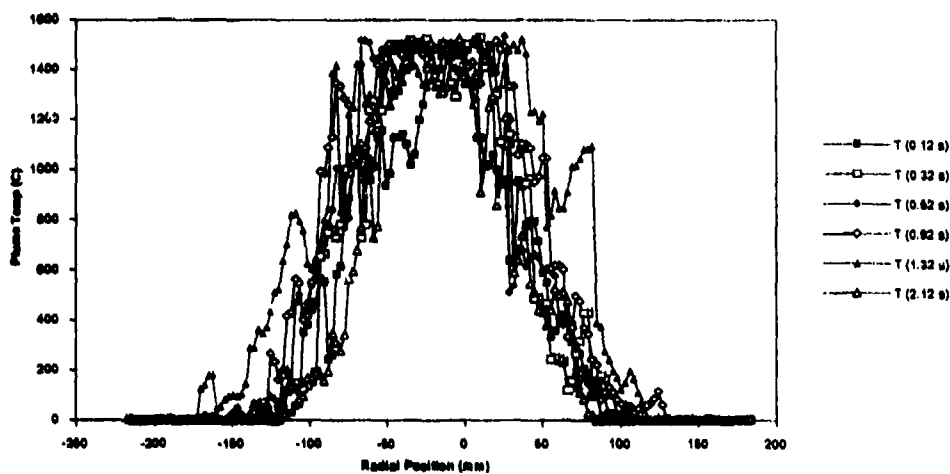


Figure 38 (R): CRV-7 / 90-72 axial position 829 mm

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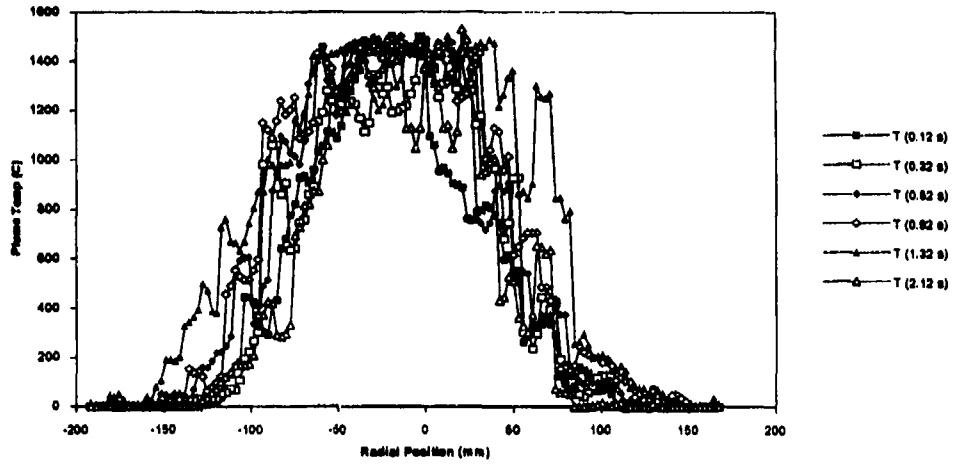


Figure 39 (R): CRV-7 / 90-72 axial position 898 mm

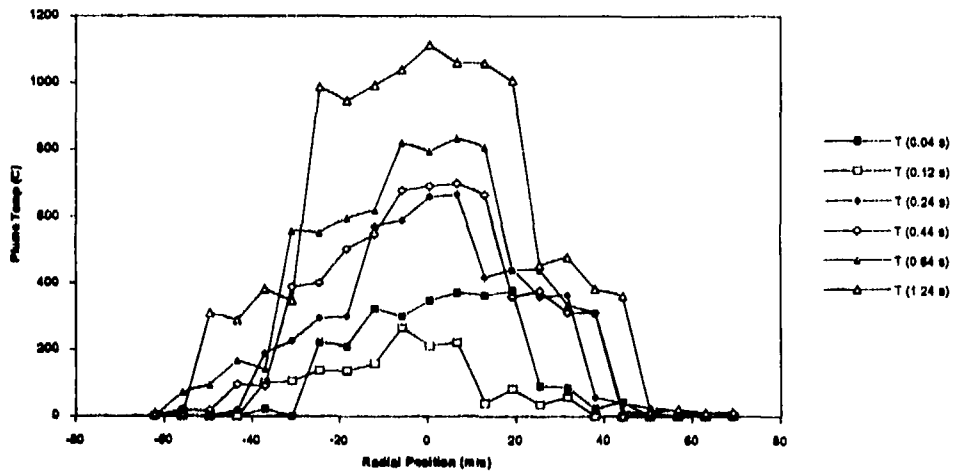


Figure 40 (R): CRV-7 / 91-75 axial position 0 mm

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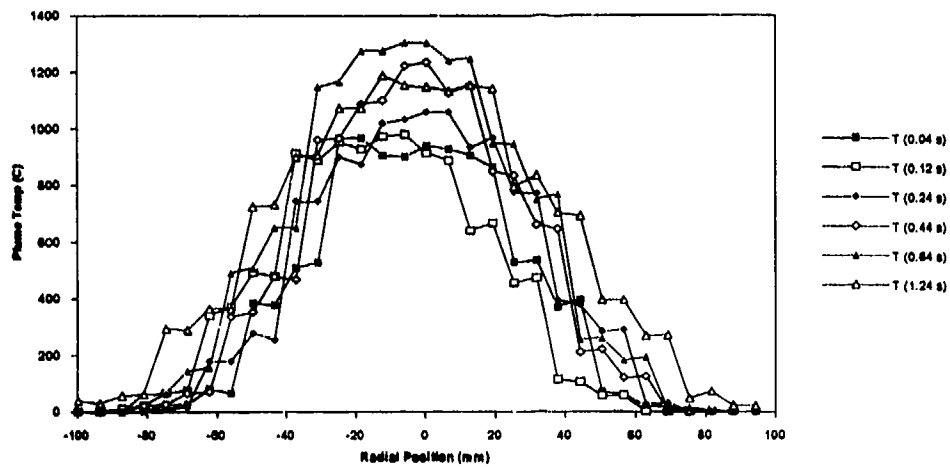


Figure 41 (R): CRV-7 / 91-75 axial position 279 mm

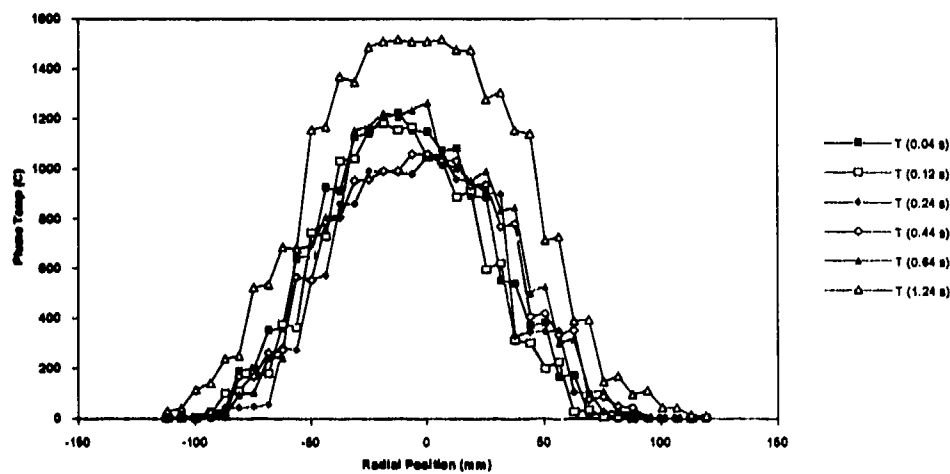


Figure 42 (R): CRV-7 / 91-75 axial position 558 mm

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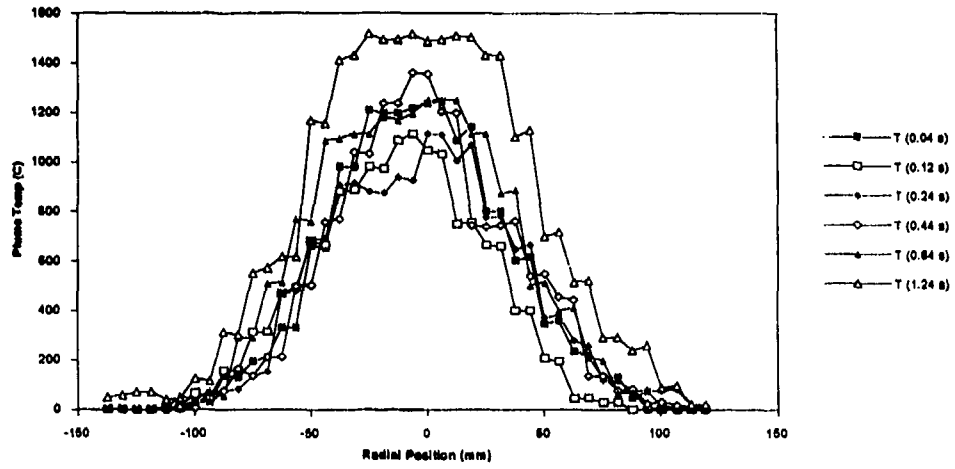


Figure 43 (R): CRV-7/91-75 axial position 836 mm

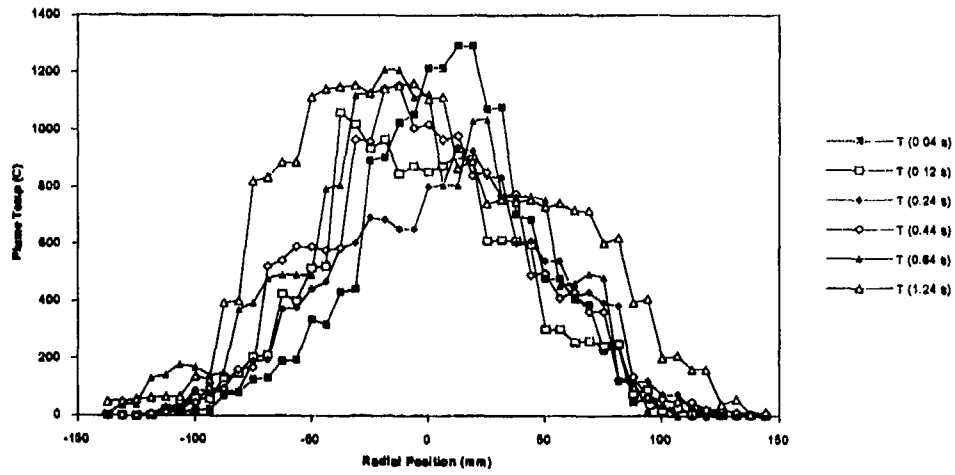


Figure 44 (R): CRV-7/91-75 axial position 1115 mm

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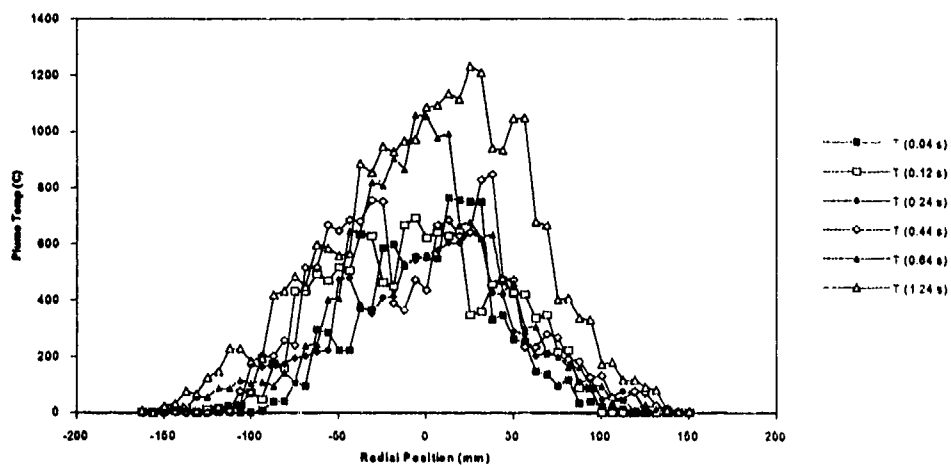


Figure 45 (R): CRV-7 / 91-75 axial position 1394 mm

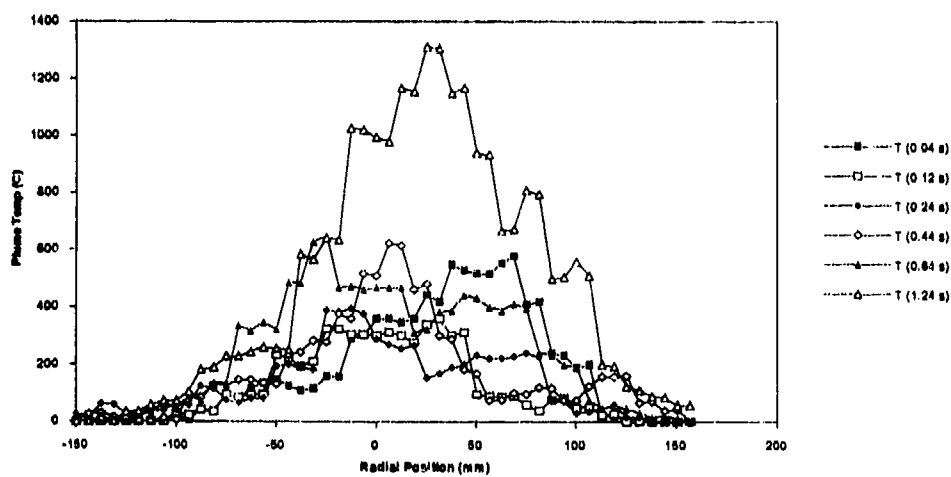


Figure 46 (R): CRV-7 / 91-75 axial position 1673 mm

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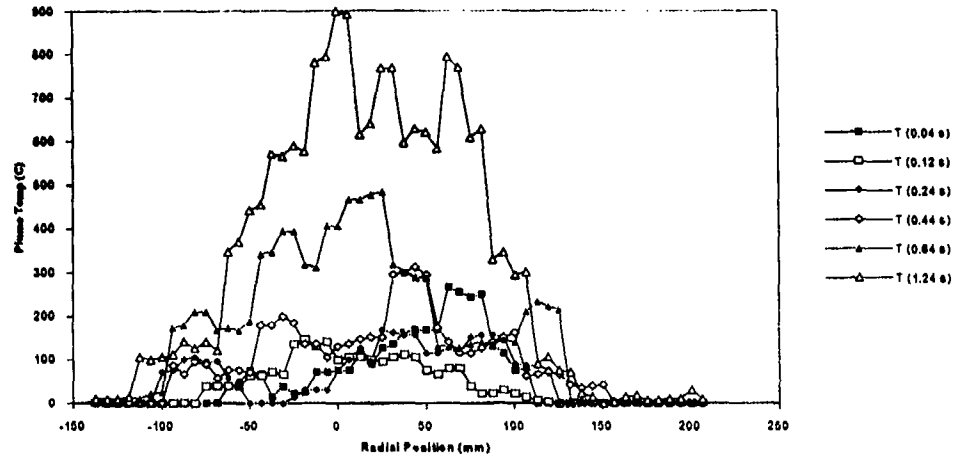


Figure 47 (R): CRV-7 / 91-75 axial position 1951 mm

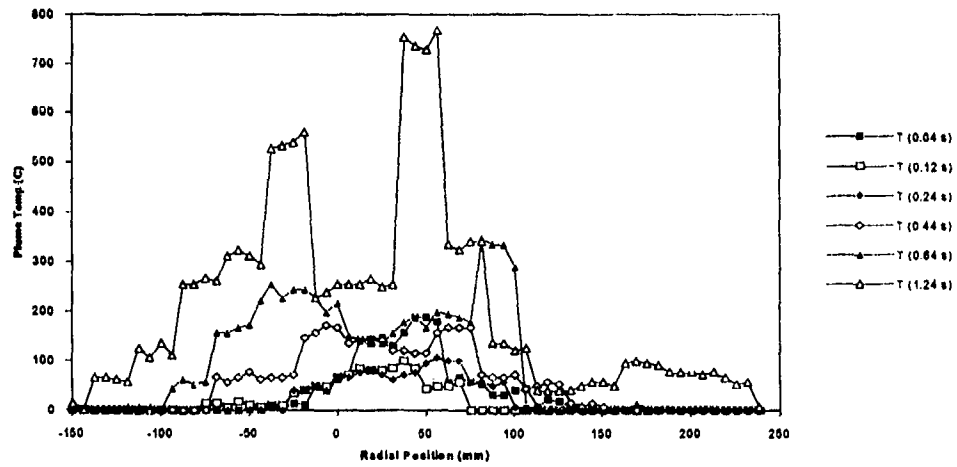


Figure 48 (R): CRV-7 / 91-75 axial position 2113 mm

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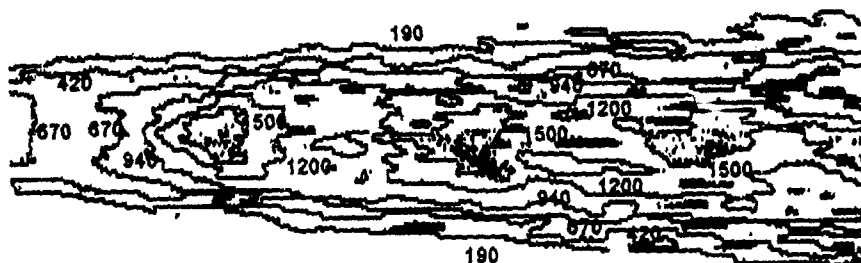


Figure 49 (R): CRV-7 / 90-72 $t=0.12$ s

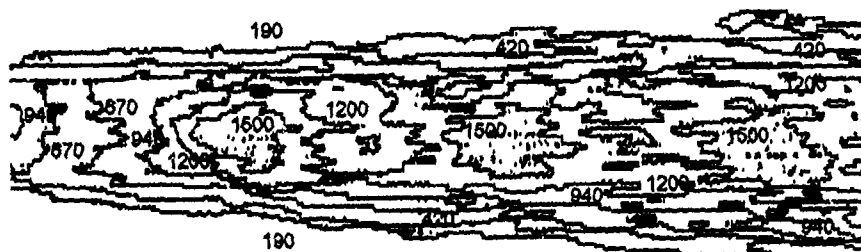


Figure 50 (R): CRV-7 / 90-72 $t=0.32$ s

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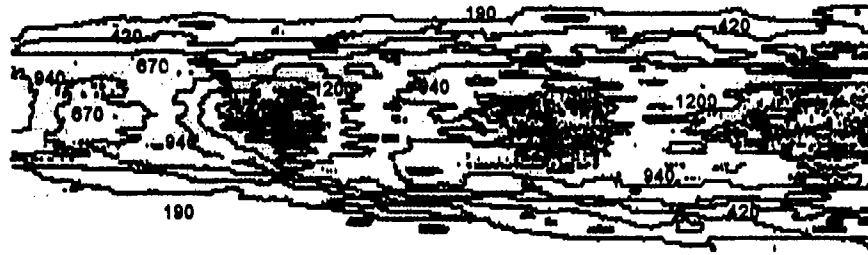


Figure 51 (R): CRV-7 / 90-72 $t=0.52$ s

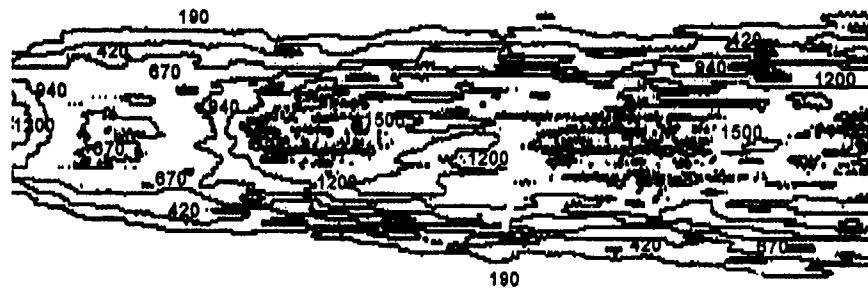


Figure 52 (R): CRV-7 / 90-72 $t=0.92$ s

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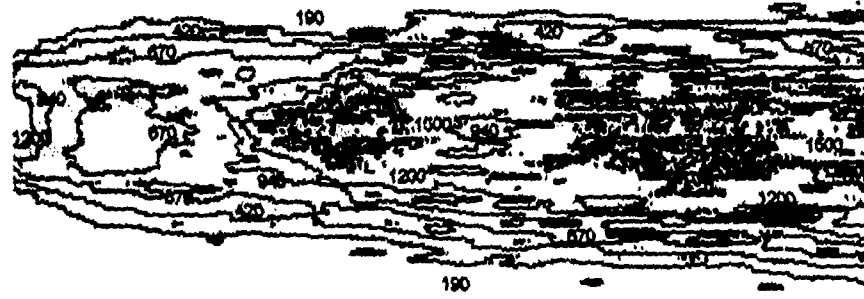


Figure 53 (R): CRV-7 / 90-72 t=1.32 s

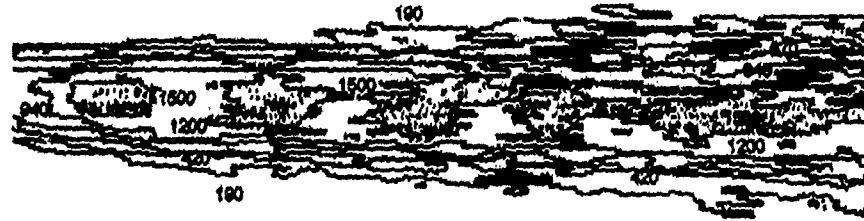


Figure 54 (R): CRV-7 / 90-72 t=2.12 s

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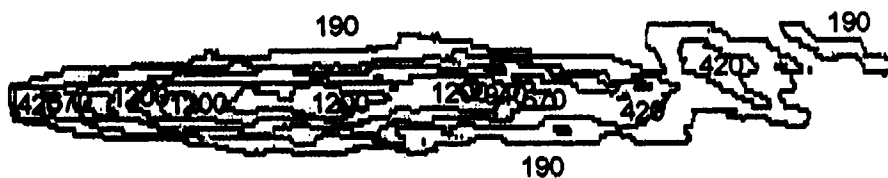


Figure 55 (R): CRV-7 / 91-75 $t=0.04 s$

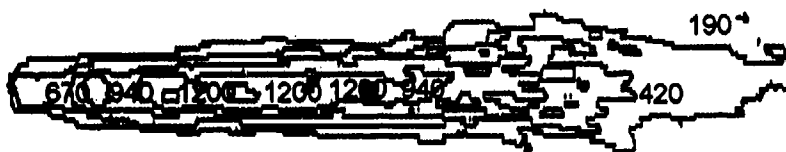


Figure 56 (R): CRV-7 / 91-75 $t=0.12 s$

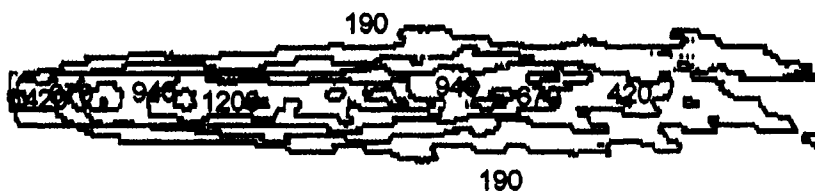


Figure 57 (R): CRV-7 / 91-75 $t=0.24 s$

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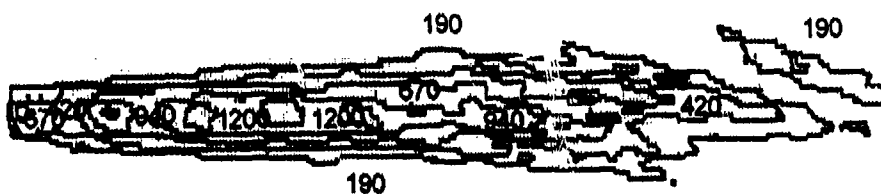


Figure 58 (R): CRV-7 / 91-75 $t=0.44$ s

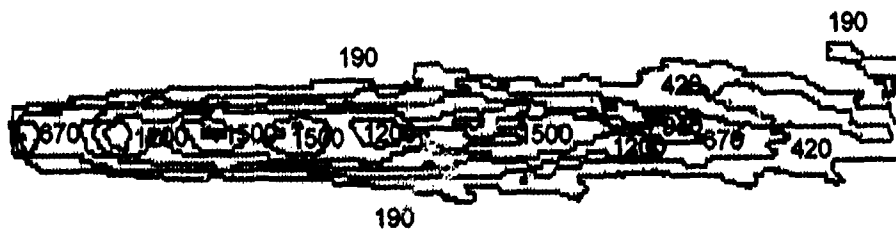


Figure 59 (R): CRV-7 / 91-75 $t=0.64$ s

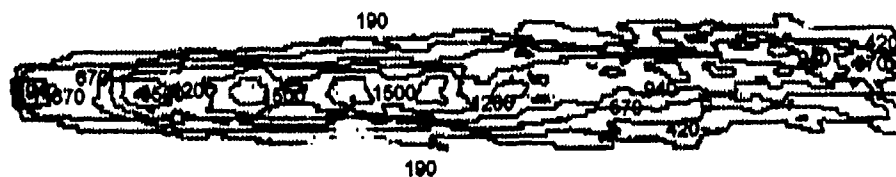


Figure 60 (R): CRV-7 / 91-75 $t=1.24$ s

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Temperatures in a CRV-7 plume from a thermal imaging technique (U)

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KEYWORDS

Temperature profiles

Rocket motor plumes

Thermal imaging

ABSTRACT

(R) Temperatures profiles in the plume of the rocket motor of the CRV-7 missile are reported. Thermal imaging was chosen as the preferred measurement technique because of its non-intrusive nature. The apparent temperatures recorded by the thermal imager were calibrated from the true plume temperatures measured by thermocouples. The 500°C maximum apparent temperature range of the thermal imager proved a limitation when greater spatial resolution of the plume interior was required. The nodal regions in the plume were saturated on the thermal record. The maximum temperature recorded with the thermocouples was 2080°C at 1.4 s, 1.5 m from the nozzle exit plane.

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Temperatures in a CRV-7 Plume from a Thermal Imaging Technique (U)

K.M. Ide

(DSTO-TR-0010)

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