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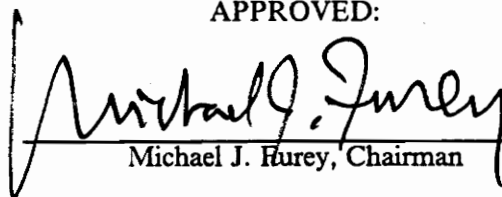
**INFRARED MEASUREMENTS OF SURFACE TEMPERATURES
DURING OSCILLATING/FRETTING CONTACT
WITH CERAMICS**

by

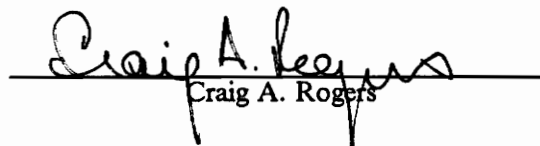
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in
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APPROVED:


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**INFRARED MEASUREMENTS OF SURFACE TEMPERATURES
DURING OSCILLATING/FRETTING CONTACT
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Michael J. Furey, Chairman

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(ABSTRACT)

Surface temperatures generated by friction during oscillating/fretting contact were measured using an infrared microscope coupled to a digital data acquisition system developed at Virginia Polytechnic Institute and State University. The contact geometry consisted of a stationary test specimen loaded against a vibrating sapphire disk driven by an electromagnetic shaker. Ceramic materials including zirconium oxide, sapphire, aluminum oxide, and tungsten carbide were used as test specimens since they are inert in air, and generate high surface temperatures when used in the oscillating contact system.

Instantaneous fluctuations in surface temperature over a single cycle were measured and recorded. This information was compared with instantaneous friction force and velocity data. The friction force data was measured using semiconductor strain gages connected to a new octagonal ring designed specifically for this research.

Zirconium oxide-on-sapphire experiments were performed at various loads, frequencies, and amplitudes. The resulting temperature rises, friction coefficients, heat generation rates, and wear scar sizes were compared.

Surface temperature rises were measured as a function of position within the contact region. From this data, and scanning electron micrographs of the wear scars, inferences were made about the size, location, and distribution of real contact areas.

Experimental measurements were compared with theoretical predictions obtained using a new numerical model developed by B. Vick and S. J. Foo.

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1. INTRODUCTION

1.1 Rationale for this Study

As the complexity of man's society increases, so does the complexity of his machines. These machines are comprised of various sliding and oscillating components that rub together and generate heat. This frictional heat can cause the components to wear, and can decrease the service life of the machine. In fact, hundreds of millions of dollars are lost each year due to the wear and destruction associated with materials rubbing together. Because of this, the study of surface temperatures generated during frictional processes is extremely important. Surface temperatures not only play a role in the wear and degradation of materials, but also affect the performance of lubricants used to reduce this wear. Many theories have been presented to predict surface temperatures; however, few experimental measurements of surface temperatures have been documented. Therefore, the effective measurement of surface temperatures represents a significant contribution to the field of tribology. Furthermore, the experimental measurement of surface temperatures generated during oscillating contact has never been successfully accomplished.

Oscillating contact--in particular, fretting and fretting corrosion-- is an important and complex element of tribology which is not well understood. Fretting is defined as wear occurring between

two surfaces having oscillatory or vibratory motion of small amplitude. Fretting corrosion is defined as the type of fretting damage which occurs when the debris produced is a chemical reaction product between constituents of the surface and the environment [1,2]. Although various mechanisms have been proposed, fretting and fretting corrosion are still not well understood.

One fundamental unknown is the magnitude and distribution of surface temperatures generated by friction during fretting and fretting corrosion. However, as stated previously, no direct measurements of surface temperatures produced during fretting have ever been made. At Virginia Polytechnic Institute and State University, experimental research has been carried out over a period of several years not only in the area of surface temperature measurements, but also in the area of fretting corrosion [3-5].

It was felt that knowledge of the surface temperatures produced during oscillating contact could shed light not only on mechanisms of fretting wear and fretting corrosion, but on possible ways to alleviate these problems. Thus, the research documented in this thesis was initiated to study the surface temperatures generated during oscillating contact between solids. In particular, relatively simple fretting situations were studied.

To study fretting in lieu of fretting corrosion, materials had to be selected that are relatively nonreactive in an air environment. Therefore, ceramic materials including zirconium oxide (zirconia), aluminum oxide (alumina), tungsten carbide, and sapphire were selected. These materials are inert in air and also have properties that could possibly lead to high surface temperatures. The properties of these materials are shown in Table 1. In particular, zirconia has a thermal conductivity of 2.00 watts/m K which is approximately 1/24th the thermal conductivity of 1040 steel. (Note, the thermal conductivity of 1040 steel is 48 watts/m K.) Therefore, heat generated at the surface of a zirconia test specimen will not be readily conducted into the specimen. In contrast, tungsten carbide has a thermal conductivity of 102 watts/m K which is more than twice the conductivity of 1040 steel. Furthermore, sapphire has a thermal conductivity of 41 watts/m K, which is approximately equal to the conductivity of steel. Therefore, based solely on thermal conductivity considerations, one can hypothesize that a zirconia-on-sapphire experiment should produce higher surface temperature rises than a tungsten carbide-on-sapphire experiment.

Table 1: Properties of Four Ceramic Materials							
MATERIAL	HARDNESS (N/m ²)	MODULUS OF ELASTICITY (N/m ²)	DENSITY (kg/m ³)	SPECIFIC HEAT J/(kg K)	THERMAL CONDUCTIVITY watts/(m K)	THERMAL DIFFUSIVITY (m ² /s)	POISSON'S RATIO
Sapphire	1.77(10) ¹⁰	3.65(10) ¹¹	3.98(10) ³	4.20(10) ²	4.18(10) ¹	2.50(10) ⁻⁵	2.00(10) ⁻¹
Alumina	1.08(10) ¹⁰	3.08(10) ¹¹	3.69(10) ³	1.05(10) ³	1.13(10) ¹	2.93(10) ⁻⁶	2.40(10) ⁻¹
Zirconia	1.05(10) ¹⁰	2.05(10) ¹¹	5.73(10) ³	4.00(10) ²	2.00	8.73(10) ⁻⁷	2.30(10) ⁻¹
Tungsten Carbide	1.27(10) ¹⁰	6.41(10) ¹¹	1.49(10) ⁴	2.05(10) ²	1.02(10) ²	3.34(10) ⁻⁵	2.60(10) ⁻¹
Sources for Material Properties Specified Above							
Sapphire - Ref. [21]							
Alumina - properties specified by manufacturer: (Grade 25 Alumina) Industrial Tectonics, Inc. Dexter, Michigan							
Zirconia - properties specified by manufacturer: (Nilcra Partially Stabilized Zirconia, Mechanical Strength Grade) Nilcra Ceramics, Inc. Elmhurst, Illinois							
Tungsten Carbide - properties specified by manufacturer except as noted below: (Grade 25 Tungsten Carbide, Material No. TC 44A) Industrial Tectonics, Inc. Dexter, Michigan (specific heat and thermal conductivity are from Ref. [97])							

However, other material properties such as hardness, modulus of elasticity, heat capacity, and density are also factors in surface temperature generation. Therefore, temperature rises are difficult to predict without using theoretical models such as those discussed in references [6-10]. Even these models have certain shortcomings since the real area of contact between two surfaces must be predicted and utilized appropriately. As a consequence, well-planned experimental techniques must be used to properly evaluate surface temperatures generated during oscillating contact.

To alleviate the problems associated with high surface temperatures and the resulting wear, lubricants are usually used. In fact, surface temperatures are believed to play an important role in the formation of protective antiwear films. For instance, zinc dialkyldithiophosphate (ZDDP) is a commonly used antiwear additive that forms protective films by chemically reacting *with* a surface [1]. Surface temperatures are believed to play an important role in the initiation of this chemical reaction. Another method of protective film formation is the tribopolymerization method proposed by Furey [11,12]. In this process, a potential polymer forming compound is first dissolved, dispersed, or mixed at low concentration in a carrier fluid which is usually a hydrocarbon. Due to high surface temperatures generated by friction, and possibly the spontaneous emission of electrons from freshly exposed surfaces [12], a thin protective polymeric film is formed *on* and between the surfaces. This film is formed only when required as dictated by the interfacial temperature level. Because of this, viable measurements of surface temperatures are desperately needed to aid in the design of lubricants.

1.2 Present Research at VPI&SU

The experimental research documented in this thesis represents a continuation of research at Virginia Polytechnic Institute and State University to measure surface temperatures generated during oscillating contact. In fact, results of preliminary investigations can be found in reference [13]. The initial research on surface temperatures generated during fretting was carried out by H.

Ghasemi [14,15]. In this research, an oscillating contact system centered around a scanning infrared microscope was designed, fabricated, and tested. This microscope can be used to measure radiance emitted from areas as small as $17\text{ }\mu\text{m}$ in diameter. Therefore, it is an effective tool for measuring surface temperatures generated at discrete, microscopic contact points.

Initial research at Virginia Tech on the subject of surface temperature generation was performed under dry sliding contact conditions. This research also used the infrared microscope in an experimental system designed by J. M. Wiggins [16]. The geometry for this sliding system consisted of a rotating sapphire disk and stationary test specimen. Various experimental investigations were carried out using the following materials loaded against the rotating sapphire disk: polymers, graphite, iron, copper, and silver [17-22]. The results of these investigations showed the effects of load, friction, and velocity on surface temperature. Furthermore, the results documented in the Master of Science thesis by C. A. Rogers [21] showed the effect of macroscopic subdivision of contact area on surface temperature for the system of copper sliding on sapphire. In the Master of Science thesis by S. C. Moyer, the effect of oxide formation was studied for the system of pure iron sliding on sapphire. All the research performed using the sliding system is summarized by Furey and Rogers in reference [5]. A discussion of the capabilities and limitations of the experimental system and infrared microscope can be found in reference [4].

The research in the oscillating contact regime is part of a research program funded by the National Science Foundation [23]. This research contains both experimental and theoretical portions. The experimental portion is under the direction of Dr. M. J. Furey, and is the focus of the research discussed in this thesis. The theoretical portion is under the direction of Dr. B. Vick, and involves the use of a numerical solution method developed by S. J. Foo [9,10]. Initial results of this dual research effort can also be found in reference [13].

1.3 Objectives of this Study

Fundamental information about the nature of surface temperatures generated during oscillating/fretting contact is of vital importance to the field of tribology. Furthermore, information about the temperature distribution across a contact region is also required. By using this information, inferences can be made about the size, location, and distribution of real contact areas. The magnitude and nature of frictional forces at the interface are also required to adequately compare experimentally measured surface temperature rises with theoretical predictions. In keeping with these general goals, the specific objectives of this research are as follows:

1. To measure surface temperatures generated during oscillating/fretting contact.
2. To carry out this study using ceramic-on-ceramic systems.
3. To measure instantaneous fluctuations in surface temperature over a single cycle.
4. To modify an existing numerical technique for calculating surface temperatures from radiance data. This numerical technique was originally developed by C. A. Rogers [21], and modifications have since been made to allow for the expedient calculation of surface temperatures.
5. To develop and utilize a technique for measuring instantaneous cycle-to-cycle friction forces as a function of time.
6. To develop and utilize a numerical method for calculating instantaneous velocity data from the output of an accelerometer.
7. To compare instantaneous cycle-to-cycle surface temperature data with instantaneous friction force and velocity data.

8. To examine the surface temperatures, friction forces, and velocity data in the frequency domain using Fourier transform techniques. Autospectral densities are presented along with cross spectral densities. From this information, phase differences between surface temperature, friction force, and velocity can be obtained.
9. To develop and utilize a method for measuring the emissivity of ceramic surfaces both before and after an experiment.
10. To study the effects of load, frequency, and vibration amplitude on surface temperatures generated by friction.
11. To compare surface temperature rises for various ceramic-on-sapphire systems.
12. To examine possible correlations between surface temperatures, heat generation rates, and wear.
13. To measure surface temperatures as a function of position in the geometric contact region. From this information, inferences can be made about the size, location, and distribution of real contact areas during the experiment.
14. To examine the worn surfaces of the test specimens using optical macrographs and scanning electron micrographs.
15. To compare experimental measurements of surface temperatures with theoretical predictions by Foo and Vick [9,10].

2. LITERATURE REVIEW

2.1 Theoretical Review [13,23]

The theoretical prediction of surface temperatures resulting from frictional heating was initiated with the pioneering works of Blok [8,25,26,27] and Jaeger [7]. Both of these authors employ an analytical solution for the temperature distribution due to a point source to construct the solution for a uniformly distributed heat source over a single contact patch on the surface of a semi-infinite medium. In order to partition the frictional heat between sliding bodies, Blok [8] first calculated the temperature distribution for stationary and moving sources subject to a uniform heat flux. The total heat flux was then partitioned such that the maximum temperatures on the two surfaces was the same. Jaeger [7], instead of matching maximum temperatures, matched the average temperatures of the two surfaces to determine the division of frictional heat. Another approximation was suggested by Archard [6] who proposed that the average interfacial temperature rise is the harmonic mean of the average rises if each surface received all the heat flux. In a recent paper [24], Archard extended his formulation to allow an estimation of temperature distribution at subsurface regions as well as at the surface.

In order to eliminate the need to approximate the division of frictional heat, Ling [28,29] evoked the condition that all points of intimate contact must have the same surface temperature. This leads to a singular integral equation for the heat partition function and shows that the correct partitioning function is not constant but varies with both position within the real contact area and with velocity. The technique suggested by Ling has been extended to problems with finite geometry for some practical situations involving rotating disks [30] and bearings [31,32]. Analytical solutions using the integral transform technique were developed for these problems in finite regions with a single area of contact.

The effect of multiple contacts has been studied by several investigators. A stochastic approach [33,34] was used in which a number of small contact spots were generated in a random manner over a nominal contact area. The resulting flash temperatures at the contact spots were found to be much higher than those elsewhere on the surface. Marscher [35] studied the effect of multiple interacting heat sources in a one-region problem. The problem of two solids with different bulk temperatures and multiple contacts was investigated by Barber [36] who used Jaeger's point heat source method and approximation for the partition of frictional heat.

The analytical treatment of surface temperatures has also been extended to include the effect of lubricants and third-body layers between the sliding surfaces. Lai and Cheng [37] considered lubricated sliding with rough contact where the surface roughness was generated numerically. The results show that scuffing is correlated with high temperature asperities which are above the material softening temperature. Another interesting analysis was performed by Ryhming [38] who assumed that all frictional heat was produced within a third-body layer between the two sliding bodies.

A variety of other analyses have employed analytical techniques [39-41] to study effects such as convective cooling from the noncontacting portions of the surface [39], and the effect of a Hertzian distribution of heat flux over a contact patch [40].

Numerical methods have also been used for the analysis of surface temperatures, especially for sliding bodies of complex shape. Both finite differences [42-44] and finite elements [45-48] have been employed. In order to accurately calculate the large temperature gradients in the vicinity of contact areas, the finite difference technique requires an excessively fine grid, resulting in long

computer times and excessive storage. As a result, the finite element technique seems more suited to these types of problems using a fine mesh in the region of contact and a coarser mesh elsewhere. Despite the general applicability of the finite element technique, problems with numerical oscillations and inaccuracies can occur if the Peclet number is too high [47]. Note that the Peclet number is typically defined as follows [6]:

$$Pe = \frac{(V_{ave})(r)}{2 \chi}$$

where,

Pe = Peclet number

V_{ave} = average velocity

χ = thermal diffusivity, (m^2/sec)

The finite element technique was applied by Kennedy et al. [45-49] to analyze a variety of situations of interest, including disk brakes, bearings, and gas seals. The recent work of Rashid and Seireg [44] models the effect of both surface film layers and lubricant films between the sliding bodies. The results show that both these effects can significantly influence surface temperatures.

Since both analytical and numerical techniques have advantages and disadvantages, an interesting hybrid technique has been proposed by Colin and Floquet [50]. It makes use of a finite element method in only the stationary component, which is usually the member of most complex geometry, and uses the integral transform technique in the simpler-shaped moving component. The initial results with the methods are quite promising. A comparison of analytical and numerical methods was presented by Floquet [51]. He points out that analytical techniques can present substantial advantages over numerical methods in accuracy and computational time, but analytical methods are difficult to apply to complex geometry.

As a whole, these surface temperature analyses have shown that the most important factors governing surface temperature magnitudes are the rate of heat generation, sliding velocity, thermal properties of the contacting materials, and the true nature of the real area of contact. The first three of these factors can generally be specified. However, the size, shape, and distribution of the actual contact spots and the influence of any third bodies, including oxide films and wear debris, is seldom known with certainty. All these factors and their complicated relationship with surface temperature require more study. In particular, the influence of an oscillating velocity has not been investigated since almost every study considers a constant sliding velocity.

The boundary integral equation method (BIEM) is a relatively new numerical technique for the analysis of thermal problems. It was first applied by Rizzo and Shippy [52] for the solution of transient heat conduction problems. Other approaches were proposed and utilized by Chang, Shaw, Kuroki, Sherget, Brebbia, and Onishi [53-57].

Recently, a variation of the BIEM has been used by Dr. B. Vick and S. J. Foo at Virginia Polytechnic Institute and State University to predict surface temperatures generated during oscillating/fretting contact [9,10,13]. This variation of the BIEM uses a full-space moving Green's function as the fundamental solution. This differs from the standard BIEM in which the stationary diffusion Green's function is used. The complete description of the new BIEM method along with an error analysis and results is documented in references [9,10]. This general theoretical model includes the important complexities of the frictional heating problem, and is both accurate and efficient. The general features of this theoretical model are as follows:

- Arbitrary sliding velocity, including oscillating and unidirectional motion.
- Any arbitrary contact area. Usually rectangular patches are used to approximate the true contact area.
- The spatial and time development of the division of frictional heat and temperature rise.
- Arbitrary regions with any thermal properties and geometry.

Some representative results are displayed in Figs. 1 and 2. Figure 1 shows the effect of various sliding velocities on the total fraction of heat received by the moving region, designated as region 2, and the dimensionless mean surface temperature rise of the contact area versus dimensionless time. The cases shown are for oscillating, unidirectional, and stationary velocity where

$$v(t) = v_m \cos(\omega t), \text{ oscillating}$$

$$v(t) = v, \text{ unidirectional}$$

$$v(t) = 0, \text{ stationary}$$

In the oscillating case, ω is the frequency, x_m is the amplitude of oscillation and $v_m = x_m \omega$ is the maximum velocity. In order to make a meaningful comparison, the total frictional heat is the same in all cases, thus $v = (2/\pi)v_m$, and the equivalent amount of heat is artificially input to the stationary case. All cases have been nondimensionalized with respect to the velocity parameters associated with the oscillating case and the thermal properties of the moving region. The results in Fig. 1 are for regions with identical material properties with a single square contact of dimensions $2a$ by $2a$, and a Peclet number, $Pe = 10$ where α_2 is the thermal diffusivity of the moving region-2. Figure 1 displays oscillating results for both a large amplitude, small frequency case ($x_m/a = 1$) and a small amplitude, high frequency case ($x_m/a = 0.1$).

The oscillatory case produces peak temperatures which are higher than even the stationary case with the same thermal energy input. Since the material properties are identical, the frictional heat is divided evenly in the stationary case. The oscillatory and unidirectional cases display the role of velocity in the distribution of frictional heat. The motion causes heat to be convected away from the contact area, thus decreasing the effective thermal resistance in the moving region and allowing the moving region to receive a higher percentage of the frictional heat. The fretting case shows that for relatively low amplitude/high frequency oscillations, the mean temperature oscillates about the temperature rise produced by a stationary heat source.

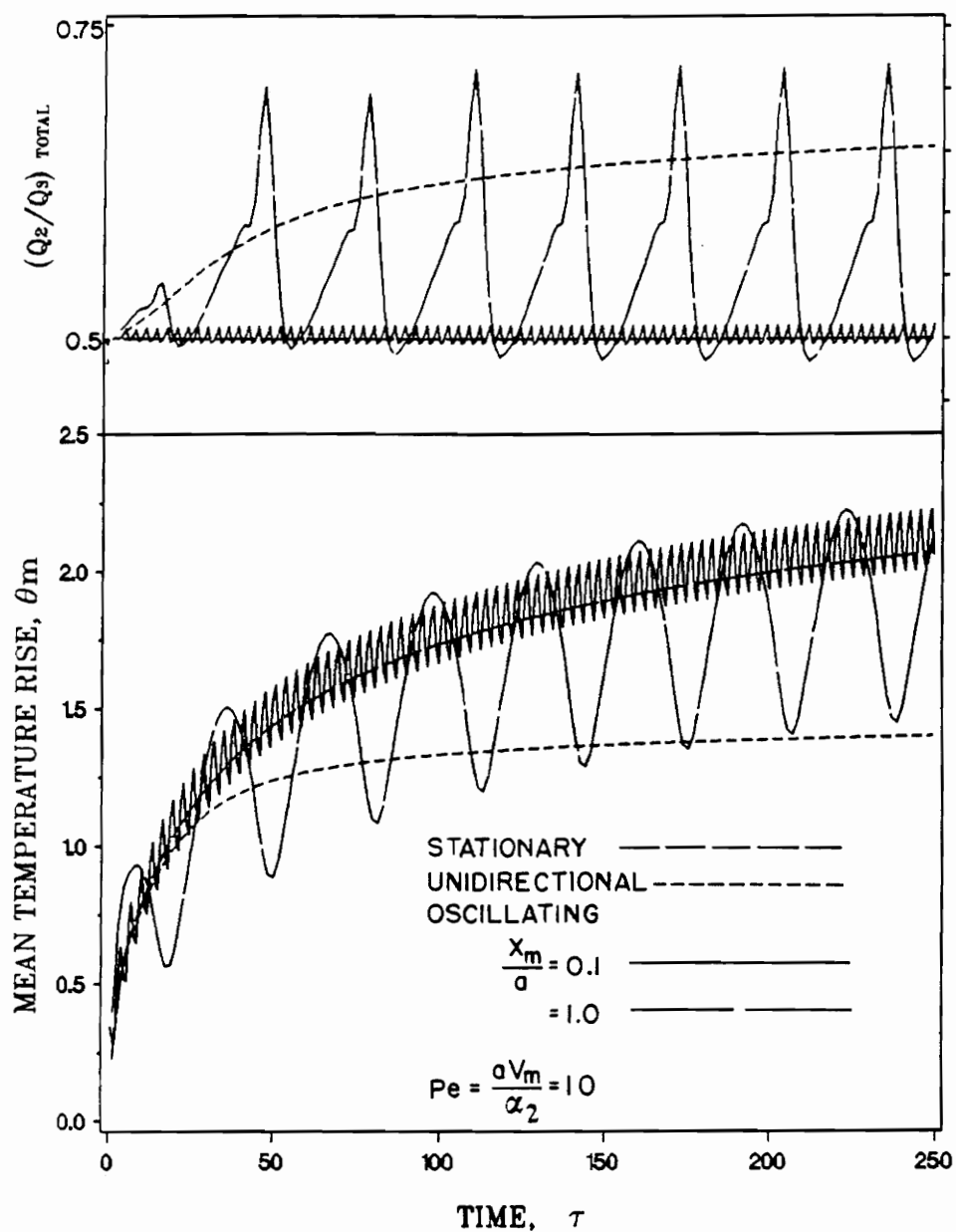


Figure 1 : The Theoretical Effect of Velocity on Heat Distribution and Temperature Rise [13]

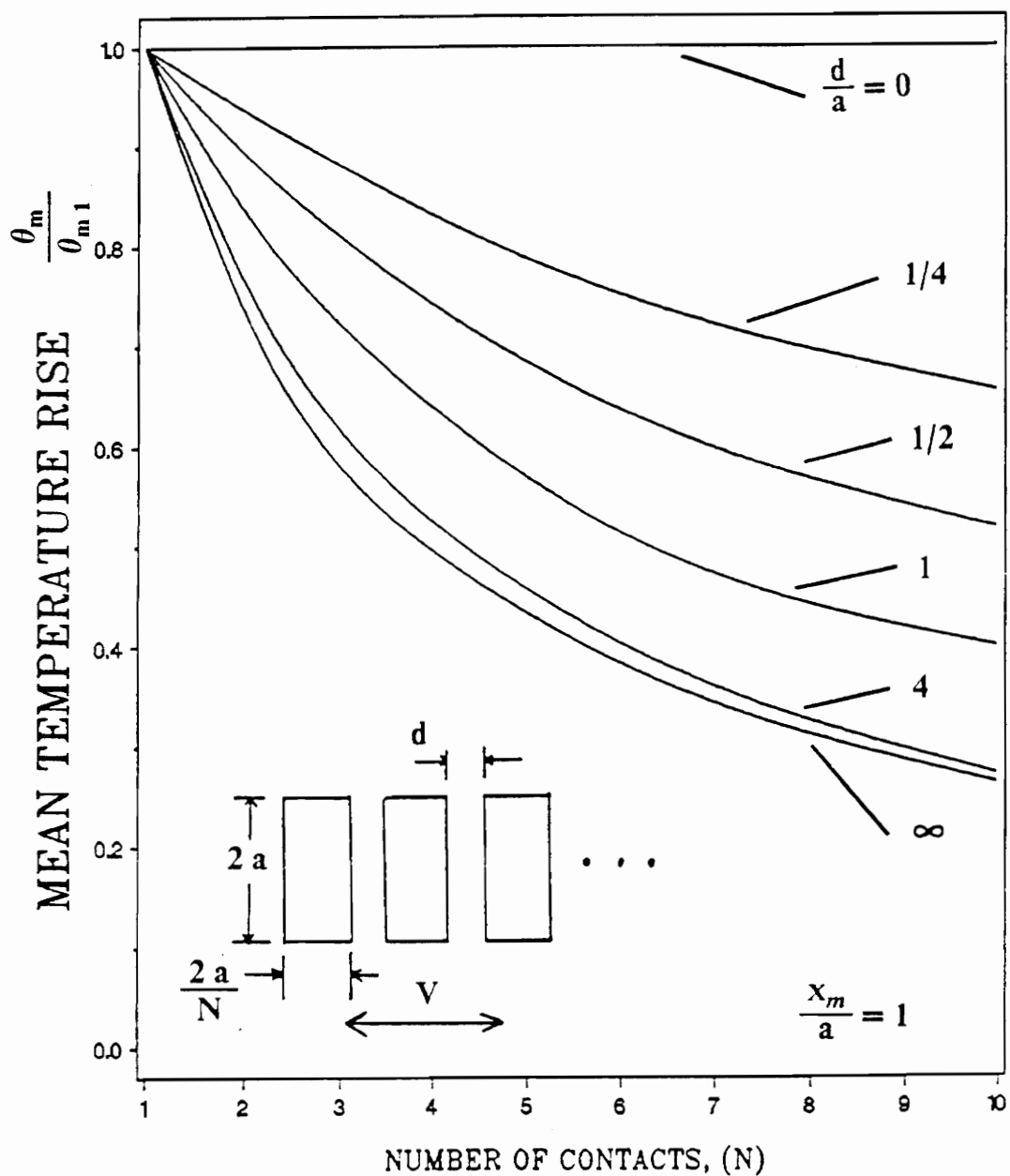


Figure 2: The Theoretical Effect of the Number and Spacing of Multiple Contacts [13]

Figure 2 is presented to show the effect of multiple contacts. The results display the effect of the number of contacts, N , the spacing between the contacts, d , and the orientation of the contacts. the results are referenced to the single square contact case where the total area is a square patch of dimensions $2a$ by $2a$ for each case. The vertical axis represents the ratio of the mean surface temperature θ_m to the surface temperature with a single square contact, θ_{m1}

Figure 2 is for divided contact areas oriented in the direction of motion. The effect of spacing and number of contacts is quite important. The curves for $d/a \rightarrow \infty$ represent infinite spacing or no thermal interaction between the contact patches. However, for a spacing of approximately $d/a = 4$ or less there is significant interaction between the heat patches. Simply taking N patches with no interaction can significantly underestimate the mean surface temperature rise. Results for contact patches oriented perpendicular to the direction of motion give results similar to Fig. 2, but with somewhat less thermal interaction between patches.

2.2 *Experimental Review*

The experimental measurement of surface temperatures between two sliding or oscillating materials is not a straightforward process. Many techniques have been employed to attempt these measurements yet few have been completely successful.

Early attempts were made at surface temperature measurement by using embedded thermocouples [58,59,60]. Since these thermocouples are not located at the surface, an average bulk temperature is actually obtained. Furthermore, the holes required to position the thermocouples interrupt the flow of heat. Also, because the contact surface is constantly being altered due to wear, the position of the thermocouple constantly changes with respect to the surface of the test specimen.

An alternative to the embedded thermocouple technique is the dynamic or Herbert-Gotwein thermocouple. This technique has been used successfully by Shore [61] and Furey [62]. A dynamic

thermocouple is created when two specific dissimilar metals such as steel and constantan are in sliding contact. Surface temperatures generated at the interface are therefore proportional to the electromotive force across the contact region. The measurements made by Furey [62] showed that average and transient temperatures were much less than those predicted using Archard's theories [6]. This difference could be due to the fact that the dynamic thermocouple is not measuring peak surface temperatures. Instead, it is probably measuring an average surface temperature based on the number of contacts at a given time. Uetz and Sommer [63] extended the utility of a dynamic thermocouple by comparing its results with phase changes of the test specimens.

Other types of surface temperature measurements have been attempted including the use of pressure-temperature transducers [64] and thin film transducers. However these devices interfere with the surface characteristics. Quinn and Winer [65] have used photographic methods to record visible hot spots on surfaces, and Quinn [66] has used x-ray diffraction techniques to correlate surface temperatures with the formation of oxide wear debris.

Perhaps the most appropriate surface temperature measurement technique is the use of infrared devices. For this method to work, one of the materials must be transparent to infrared radiation. The infrared device is positioned above this transparent material, and directly measures energy generated at the interface. Unlike the embedded thermocouple technique, the infrared method does not alter the flow of heat. Furthermore, instead of measuring the bulk temperatures of the materials, the infrared technique actually measures the temperature *at* the interface.

Pioneering efforts were made in this area by Parker and Thomas in 1948 [67]. In their work, an infrared sensitive photoconductive cell was used to measure temperatures at the interface of a brake shoe and drum. Bowden and Tabor also pursued infrared measurement techniques as early as 1954 [68]. They used a lead sulfide cell to measure surface temperatures generated at the interface of a pin and quartz disk. Other researchers, including Chao, Li, and Trigger [69], also used lead sulfide cells to measure the temperature distribution at the blank surface of a cutting tool. However, these measurements did not include the use of a transparent material. Instead, small holes were drilled through a work piece, and the temperature of the cutting tool was measured as it passed over the holes.

In a series of pioneering studies by Winer, et al. [70-73], a Barnes Infrared Radiometric Microscope was used to measure surface temperatures in dry sliding contact, and fluid temperatures in elastohydrodynamic films. The results of this research have led to a better understanding of temperatures developed in lubricated, high contact stress systems. In a recent article [74], Winer discussed the use of an infrared scanning camera to measure surface temperatures in a sliding ceramic-on-ceramic contact. This scanning camera can measure surface temperatures in 100 μm diameter areas. For the silicon nitride-on-sapphire system used, temperatures as high as 2700 C were observed for an 8.9 N load and sliding speed of 1.53 m/s. In this study, the magnitudes and rapid transients of the temperatures are believed to play a significant role in the friction and wear of the ceramic materials [74].

Although many researchers have measured temperatures generated during sliding contact, there are few researchers who have measured surface temperatures generated during oscillating/fretting contact. Kennedy, et al. [75] recently discussed a project that involved the study of surface temperatures generated during oscillating contact. In this research, a Barnes model RM-50 infrared micro-imager was used. This device has a very large 6350 μm x 6350 μm target area. The surfaces consisted of a sapphire disk and titanium alloy coated with molybdenum disulfide. This coating was chosen because it has a readily determined emissivity value [75]. For a 1000 N normal load, 10 Hz frequency, and 500 μm peak amplitude, temperature rises of only 14 C were measured.

In 1973, research was initiated at Virginia Polytechnic Institute and State University to study surface temperatures generated during sliding contact. This research centers around the use of a Barnes RM-2A infrared microscope that can be used to scan a surface for high temperature rises. This infrared measurement instrument has microscopic target spot diameters of 17 μm or 36 μm depending on the objective lens selected. Note, these target spot diameters are significantly smaller than those listed for the infrared instruments discussed in references [74] and [75]. Therefore, temperature rises can be measured at discrete contact points within the larger geometric contact region.

The experimental sliding system centered around the infrared microscope was designed by J. M. Wiggins [16] and fabricated at Virginia Polytechnic Institute and State University. Initial experiments were performed using various polymers sliding on sapphire [17,18]. Other materials used

in this system include graphite, pure iron, copper, and silver sliding on sapphire [19-22]. The results of these investigations showed the effects of load, friction, and velocity on surface temperature. Furthermore, C. A. Rogers [21] showed the effect of macroscopic subdivision of contact area on surface temperature for the system of copper sliding on sapphire. In the Master's thesis by S. C. Moyer [20], the effect of oxide formation was studied for the system of pure iron sliding on sapphire. All the research performed using the sliding system is summarized by Furey and Rogers in reference [5]. A discussion of the capabilities and limitations of the experimental sliding system and infrared microscope can also be found in reference [4].

In recent years, the experimental system at Virginia Polytechnic Institute and State University was modified to facilitate oscillating/fretting contact experiments. This modification was made by H. Ghasemi, and is discussed in references [13-15]. Other modifications to the experimental system include the installation of an advanced computerized data acquisition system. This system was coupled to the infrared microscope by S. Jayaram [76,77] and can be used for the acquisition, analysis, and display of infrared radiance. Detailed radiance maps of a contact region can be made and instantaneous surface temperatures can be calculated. By using the new experimental and data acquisition systems, fundamental information about the nature of surface temperatures generated during oscillating/fretting contact can be obtained. In fact, preliminary results can be found in references [13,14]. In reference [14], Furey and Ghasemi discuss surface temperatures generated during the fretting of polymeric coated steel spheres on sapphire. In reference [13], Furey, et al. discuss the theoretical prediction and experimental measurement of surface temperatures generated during oscillating/fretting contact. The experimental section of reference [13] summarizes zirconia-on-sapphire results that are also contained within the present thesis. This experiment was performed using a normal load of 40 N, frequency of 195 Hz, and peak-to-peak amplitude of 290 μm . Under these test conditions, temperature rises as high as 112 K were measured with variations of 50 K in less than two thousandths of a second.

2.3 *Review of Ceramic Tribology*

Although the emphasis of this thesis is surface temperatures generated during oscillating contact, the friction and wear characteristics of the ceramic test specimens are discussed in Section 4 and compared to measured temperature rises. Therefore, a short summary of the current literature in ceramic tribology is pertinent to this investigation.

Ceramic tribology is a relatively new area, and current applications include bearings, sliding surfaces, bushings for pumps handling corrosive liquids, high temperature ball and roller bearings, dies and seal rings, and diesel engine components [74,78]. However, almost all of the pertinent tribological data on ceramics has been generated using relatively simple sliding or rolling test configurations. Furthermore, much of the data obtained on ceramic tribology is either strictly qualitative or consists of only a few data points [79]. Although some research has been performed using low frequency (and low speed) reciprocating test apparatus [80,81,82,78], no data has been obtained for the oscillating/fretting situations discussed in the present thesis.

A recent review of ceramic tribology as a whole is presented by Cranmer [79]. This review contains a thorough reference section, and summarizes basic friction and wear models for ceramic materials, as well as analytical techniques for characterizing the materials. Cranmer [79] also summarizes basic wear and friction data for various ceramics sliding against other ceramics or metals. Although viable surface temperature data is currently unavailable for ceramic systems, Cranmer [79] does recognize the need for "real-time data analysis" of bulk temperatures as well as flash temperatures caused by friction. In his discussion of needs and opportunities in ceramic tribology, Cranmer also notes that many ceramic materials being considered for tribological applications are developmental materials with properties that change from lot-to-lot, if not from piece-to-piece.

In a recent paper by Braza, et al. [83], mechanical failure mechanisms in ceramic sliding and rolling contacts are reviewed. Fundamentals of ceramic wear are examined, and a methodology for describing wear mechanisms is presented. Definitions of ceramic wear modes are also proposed by

Braza, et al. to clarify usage terminology. As shown in Table 2, the following wear modes are defined: chipping, spalling, grain pullout, and polishing.

A short review of thermal effects on ceramic wear is also presented by Braza, et al. [83]. Although little research has been performed in this specific area, the effect of surface temperatures on spalling has been theoretically examined by Thouless [84]. Frictional heating of the surface of ceramic materials can cause the surface temperatures to be much higher than the bulk temperature due to the low thermal conductivity of ceramics. The difference in temperature between the surface and bulk will produce larger compressive stresses parallel to the surface. Localized buckling can occur above subsurface cracks, creating a spall as the crack propagates to the surface [83].

Since a large portion of the experimental work presented in this thesis was performed using a zirconia-on-sapphire system, it is worthwhile to discuss any research performed in this area. Although no specific investigations have been performed for the zirconia-on-sapphire system, tribological investigations for zirconia-on-zirconia systems have been reported [80,81]. In the research by Ishigaki, et al. [81], the effects of sliding speed on wear rate and friction were studied, and the effects of humidity were also included. In addition, a discussion of phase transformations as a result of high surface temperatures was presented. This subject was also discussed by Aronov [80]. As a result of Aronov's experimental investigation, a phenomenological model was developed to explain surface temperature effects on phase transformations and wear of zirconia. Additional information on the tribology of zirconia ceramics can be found in references [79,83,85,86,87].

Table 2 : Wear Modes for Ceramic Materials [83]	
Chipping	Formation of chips from transgranular cracks normal to sliding surface. For a microchip, the chip size is smaller than the grain size or several microns or less in size.
Spalling	Flakes produced primarily by subsurface lateral cracking approximately parallel to the sliding direction and sliding surface. In large spalls, the crack extends across many grains.
Grain Pullout	Primarily intergranular fracture where one or two grains are removed at a time.
Polishing	Smoothing of surface due to removal of material or by plastic deformation (burnishing).

3. EXPERIMENTAL TECHNIQUE

3.1 Overview of Test Apparatus

The basic contact geometry is shown in Fig. 3, and consists of a spherical test specimen loaded against an oscillating sapphire disk. An infrared microscope shown in Fig. 4 is positioned above the sapphire disk, and focused at the interface between the disk and specimen. Since frictional mechanisms at the interface cause the dissipation of radiant energy, and the sapphire disk is capable of transmitting this energy, the infrared microscope can be used to effectively measure the amount of radiant energy generated when the sapphire disk rubs against the test specimen.

Section 3.2 describes how surface temperatures are calculated from these radiant energy measurements, and also includes a summary of the operational theory of the infrared microscope. An important aspect of this temperature measurement technique is the need to know accurate emissivity values for the test specimen. In fact, any infrared system used for temperature measurement purposes requires emissivity values for the material(s) being studied. Therefore, a device for measuring the emissivity of spherical test specimens was fabricated and utilized as described in Section 3.3.

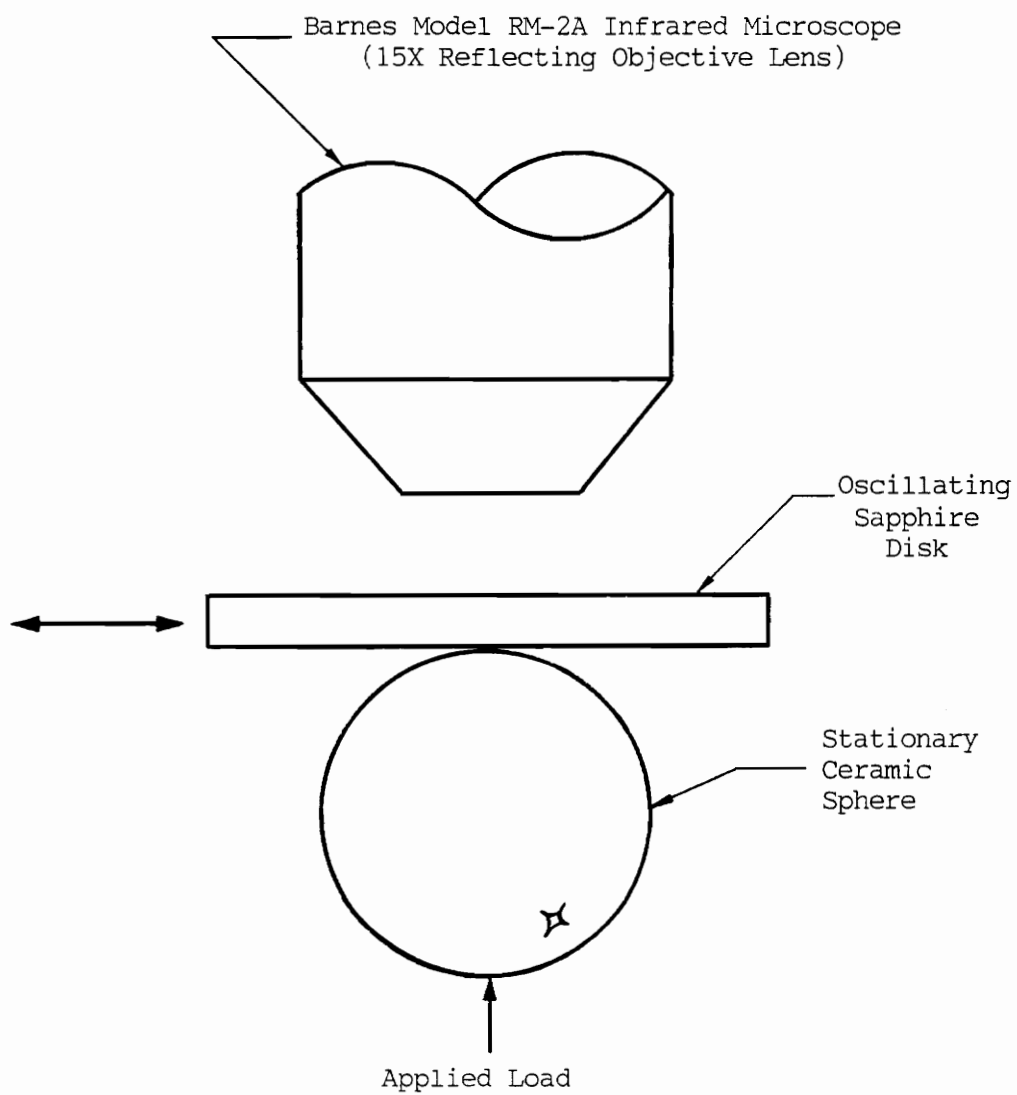


Figure 3 : Basic Contact Geometry for the Oscillating Contact System

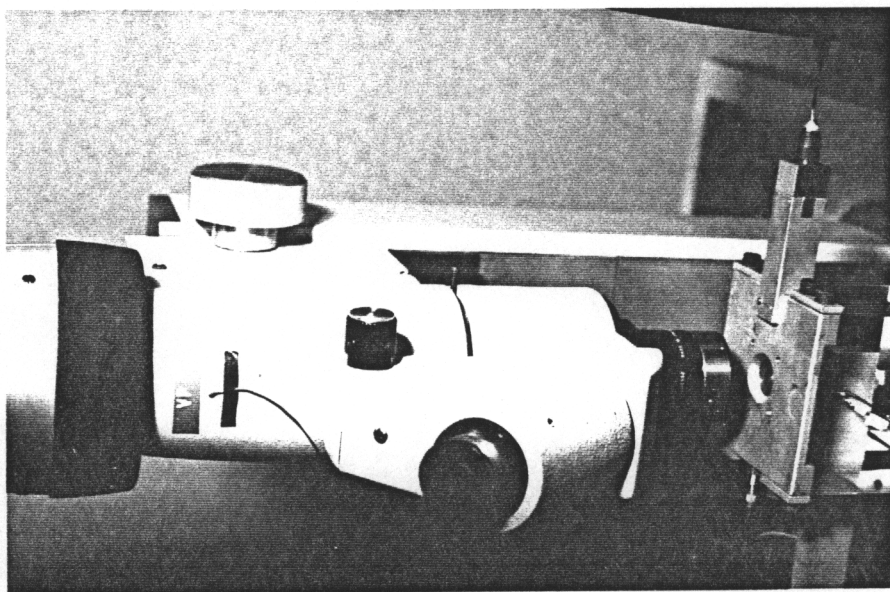
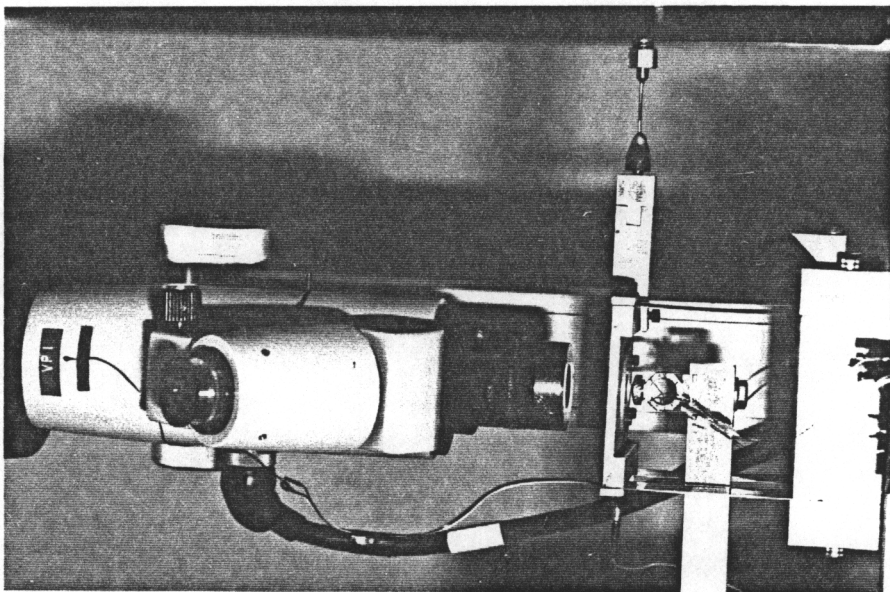


Figure 4 : The Oscillating Contact System

In addition to accurate emissivity values, accurate ambient temperature values are also required when infrared systems are used. This necessity is described in Section 3.2, and the actual method used for measuring ambient temperatures is described in Section 3.4.

To facilitate surface temperature measurements as a function of position, the infrared microscope is mounted on a precision x-y table. The position of the microscope can be controlled to the nearest 0.0001 in. using vernier type micrometers; or, to the nearest 0.001 in. using two linear variable differential transducers (LVDT's) mounted on the table. The calibration of these LVDT's is described in Appendix C. This appendix also contains a detailed picture of the x-y table and associated LVDT's.

The oscillatory motion of the sapphire disk is created by mounting the disk in a plate supported by four thin metal foils, and coupling the plate to an electromagnetic shaker. This configuration is shown in Figs. 4 and 5, and was developed by H. Ghasemi as described in reference [15]. As shown in Fig. 6, the shaker is manufactured by Vibration Test Systems, and is connected to a Wavetek wave generator and Tecron amplifier. Thus, the sapphire disk can be oscillated sinusoidally at various frequencies and amplitudes as controlled by the wave generator and amplifier, respectively. Even though the frequency and amplitude can be varied independently, the maximum attainable amplitude decreases as the frequency is increased. This relationship is shown in Fig. 7 and Table 3. Note that the continuous curve shown in Fig. 7 is only intended to show a trend for the data in Table 3. There are certain frequencies (such as 300 Hz) that are completely unusable due to natural harmonic frequencies present in the system. Table 3 also shows the maximum velocities for the shaker system and the maximum heat generation rates for a 40 N normal load. As frequency is increased, a decreasing trend is observed for velocity and rate of heat generation.

The amplitude and velocity data shown in Table 3 were obtained using the accelerometer installed on the edge of the sapphire disk's mounting plate. This accelerometer is manufactured by PCB Piezotronics and is shown in Figs. 4 and 5. A more detailed description of the method used to obtain velocity and amplitude measurements from the accelerometer data can be found in Sec-

tion 3.5 and Appendix D. Another measurement device shown in Figs. 4 and 5 is the strain ring used to measure frictional forces and normal loads.

Eight semiconductor strain gages are mounted on this ring to measure these forces as described in Section 3.6. Friction measurements made using this ring are based on the statistically determined calibration equations shown in Appendix B.

Data from all the measurement devices discussed so far are recorded simultaneously using an FM tape recorder, and subsequently sampled using a chart recorder, oscilloscope, or analog-to-digital converter connected to a computer. A schematic diagram of the entire data acquisition system is shown in Fig. 8. Components of this system can also be seen in Fig. 9. More information about the data acquisition system can be found in Section 3.7 and reference [77]. The experimental procedure used for acquiring data with this system is delineated in Section 3.8; and the test conditions used for performing experiments are described in Section 3.9.

After an experiment, the worn surfaces were examined using a Leitz-Wild Photomicroscope and a Jeoul Scanning Electron Microscope. The photomicroscope is shown in Fig. 10. This device includes of a binocular tube and a photographic tube. The binocular tube is used by an operator to view stereoscopic images of a sample. The photographic tube is used in taking photographic or video pictures of a sample. Samples can be magnified up to 80X when the phototube is used. Scanning electron microscopy (SEM) is an imaging process that can be used to examine surfaces at extremely high magnifications. In fact, in this study, surfaces were magnified up to 3300 times. Even at low magnifications, images produced using SEM contain more surface details than images produced using a regular light microscope.

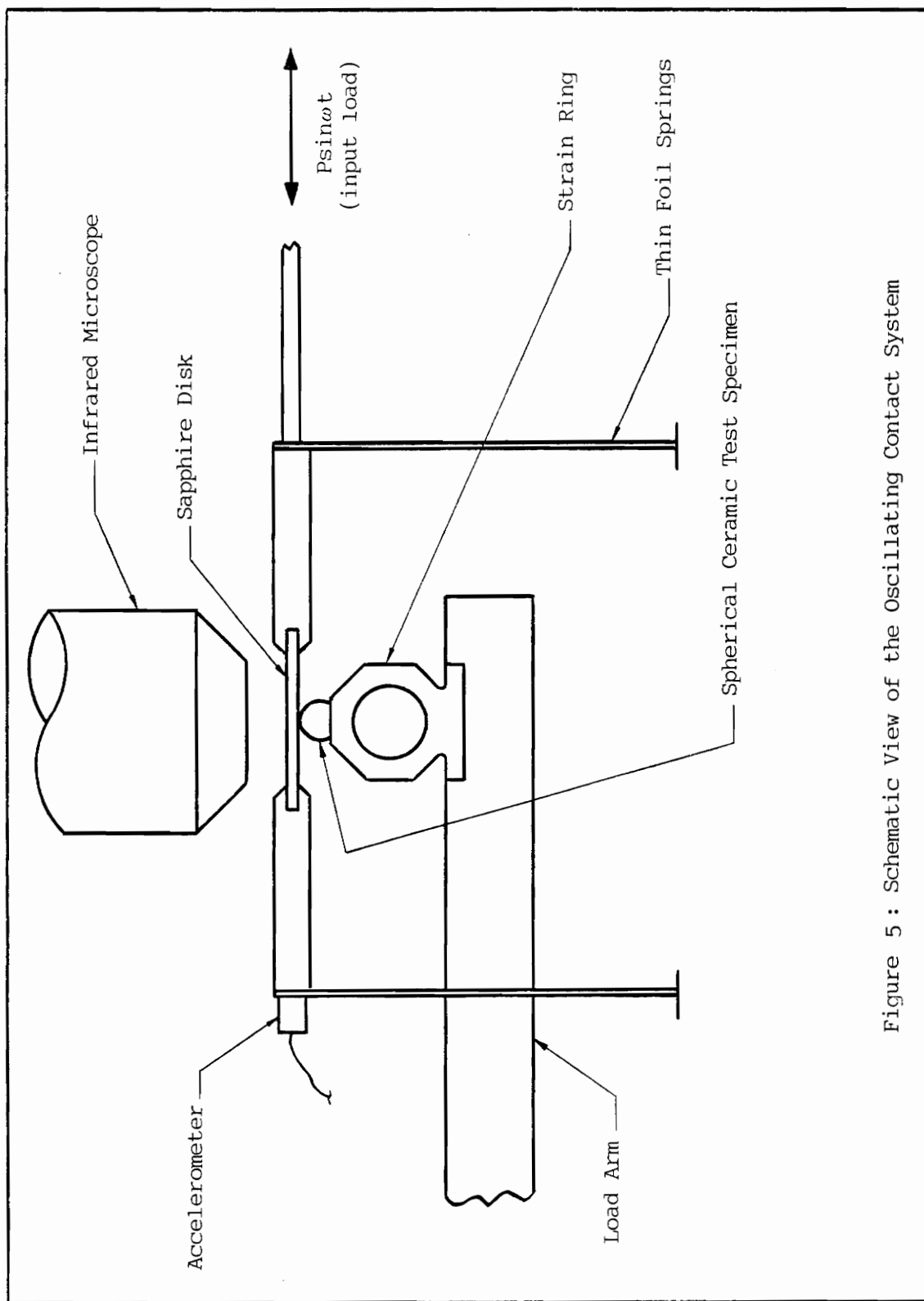


Figure 5 : Schematic View of the Oscillating Contact System

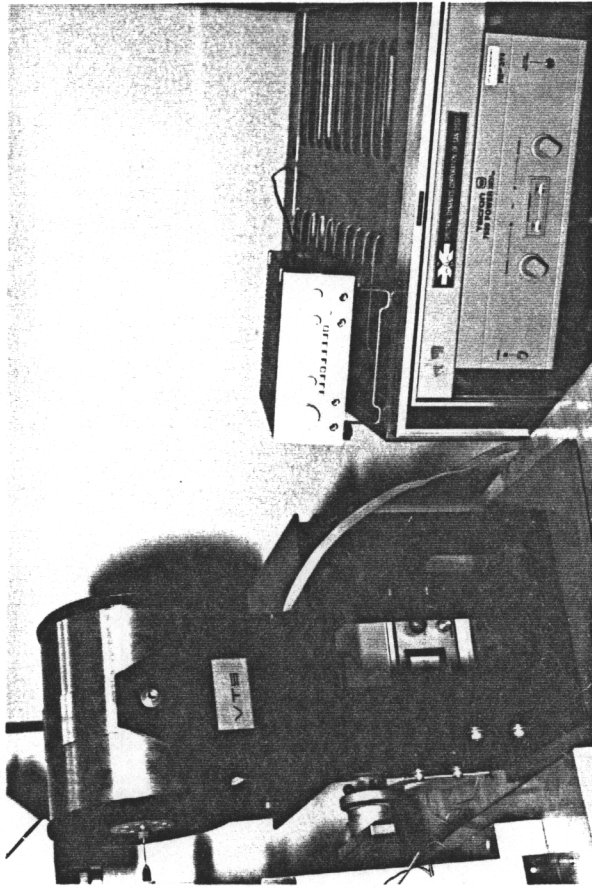


Figure 6: The Electromagnetic Shaker, Function Generator, and Amplifier

Table 3: Usable Amplitude and Frequency Ranges for the Oscillating Contact Test Apparatus

FREQUENCY (HZ)	AMPLITUDE RANGE (micrometers)	MAXIMUM VELOCITY RANGE (mm/s)	AVERAGE VELOCITY RANGE (mm/s)	$\dot{Q}/f =$ (4 N)($V_{\max}$) (watts) §	$\dot{Q}/f =$ (40 N)($V_{\max}$) (watts) §
50	27.9 - 2190	8.74 - 687	5.56 - 437	0.0350 - 2.75	0.350 - 27.5
100	10.9 - 870	6.87 - 546	4.37 - 347	0.0275 - 2.18	0.275 - 21.8
150	5.50 - 398	5.20 - 375	3.31 - 239	0.0208 - 1.50	0.208 - 15.0
200	2.74 - 230	3.43 - 289	2.18 - 183	0.0137 - 1.16	0.137 - 11.6
350	0.90 - 73.0	1.96 - 161	1.24 - 102	0.0078 - 0.64	0.078 - 6.44
400	0.69 - 57.5	1.72 - 144	1.09 - 91.7	0.0069 - 0.58	0.069 - 5.76
500	0.50 - 25.9	1.56 - 81.2	0.99 - 51.7	0.0062 - 0.33	0.062 - 3.25
600	0.48 - 24.2	1.82 - 91.1	1.16 - 58.0	0.0073 - 0.36	0.073 - 3.64

§ --- $\dot{Q}/f$ is defined as the maximum rate of heat generation per unit coefficient of friction

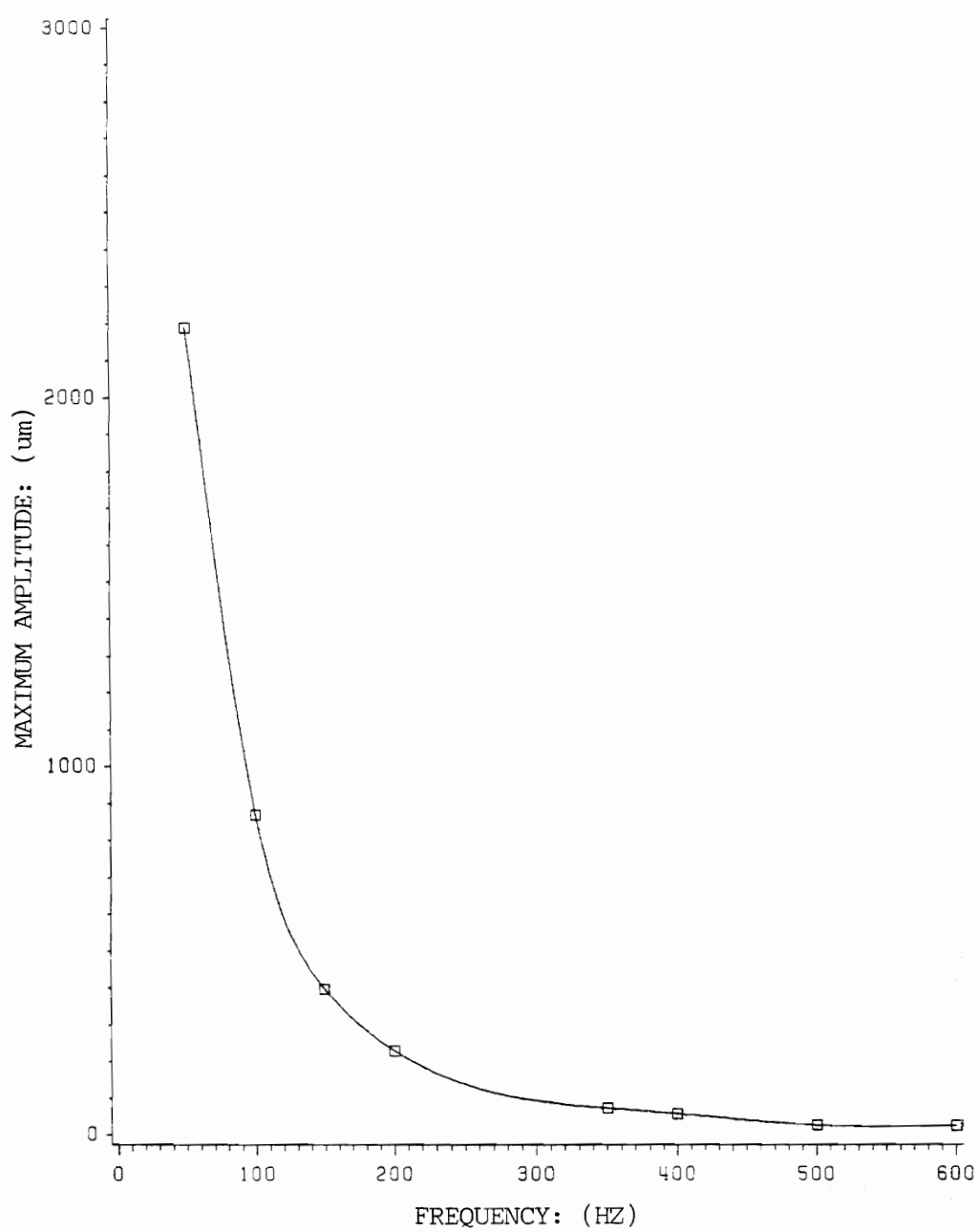


Figure 7 : Amplitude and Frequency Limits
for the Oscillating Contact System

3.2 *The Measurement of Surface Temperature*

3.2.1 Overview of the Infrared Microscope

All objects at temperatures greater than absolute zero emit electromagnetic energy in the form of infrared radiation.

This energy is generated by the vibration and rotation of charged particles within a substance. As the temperature of a substance increases, this molecular activity also increases and more infrared radiation is released. The infrared region of the electromagnetic spectrum is generally defined as the wavelength interval between 0.72 and 1000 μm as shown in Fig. 11. For convenience, this infrared region is subdivided into three separate regions: the near infrared between 0.72 and 1.5 μm , the intermediate infrared between 1.5 and 6.0 μm , and the far infrared between 6.0 and 1000 μm . The Barnes Engineering Model RM-2A Infrared Radiometric Microscope operates in the intermediate infrared region. Specifically, its liquid nitrogen cooled indium antimonide detector responds to infrared radiation emitted in the wavelength interval 1.8 to 6.2 μm . This interval can be seen in Fig. 12 which shows the spectral emissive power of a blackbody at different temperatures. Note that both the infrared microscope's region, and the visible region of the spectrum are shown.

Simplified functional diagrams of the infrared microscope are shown in Figs. 13a and 13b. Infrared and visible energy from the target specimen enter the microscope through the objective lens. Once inside the microscope, the visible energy is reflected by a germanium dichroic optical element into a visible channel which operates like a normal light microscope. The infrared energy is in turn transmitted through the germanium element into the infrared channel where it impinges on the indium antimonide detector. A tuning fork chopper is placed in front of the detector and is designed so that target radiation and reference radiation are alternately incident on the infrared detector. In effect, the tuning fork alternately opens and closes the aperture at the detector housing entrance and modulates the radiation incident on the detector. Note that the reference radiation

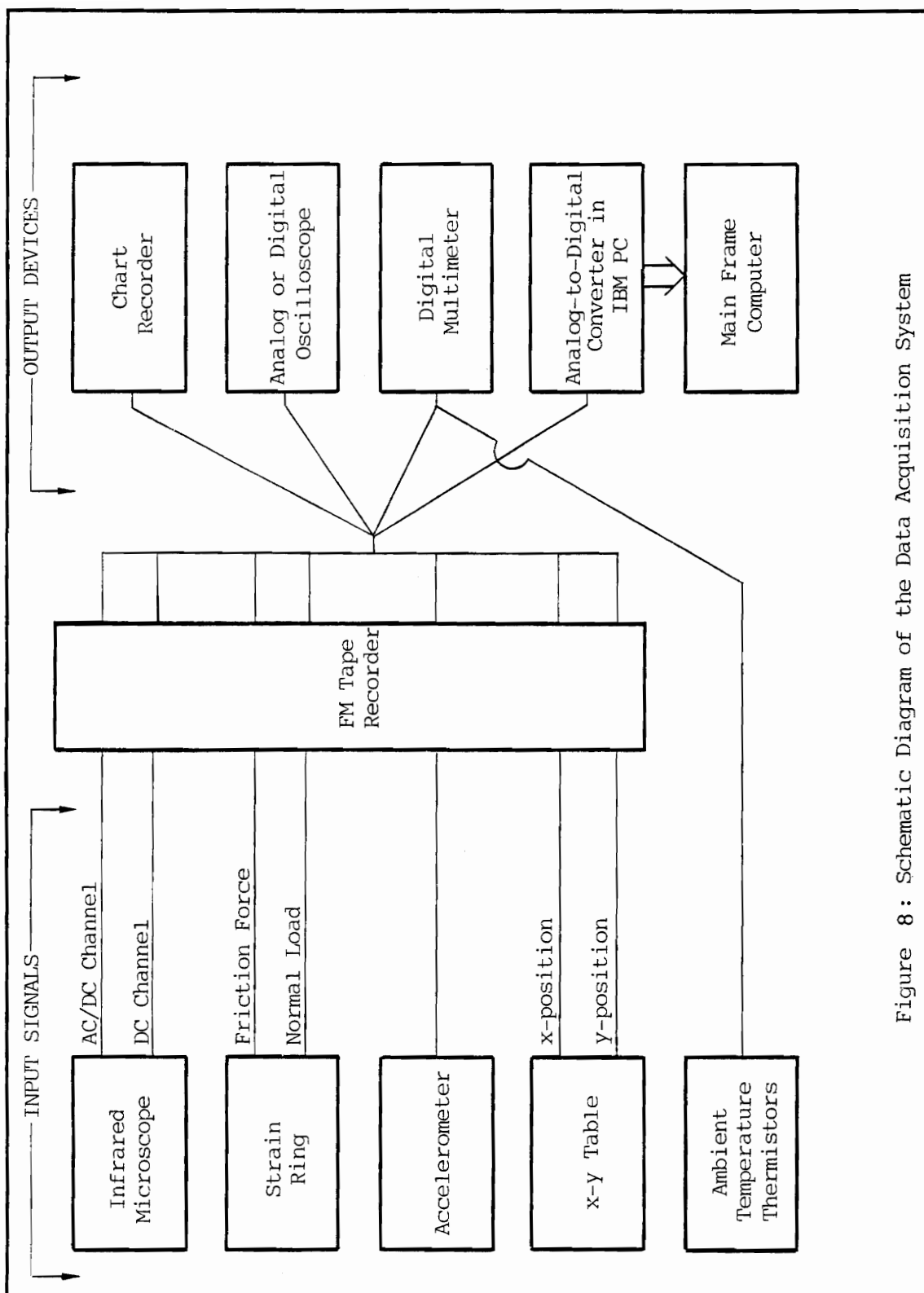


Figure 8 : Schematic Diagram of the Data Acquisition System

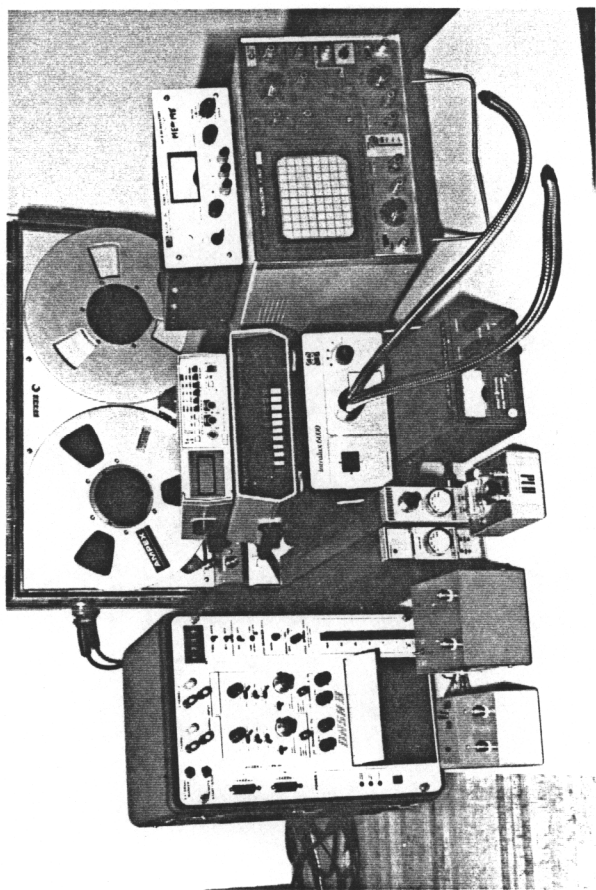


Figure 9 : Components of the Data Acquisition System

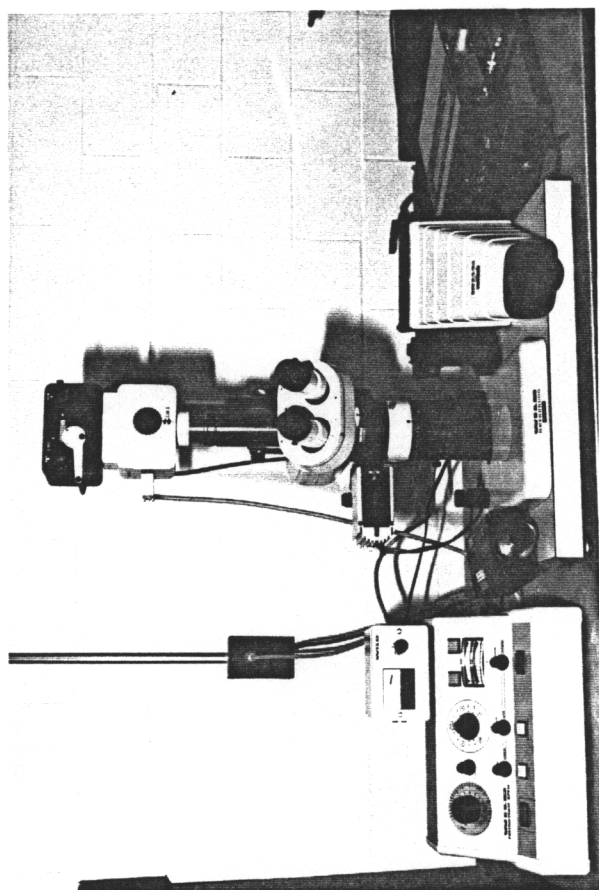


Figure 10: The Leitz - Wild Photomicroscope

observed by the detector is emitted by the blades of the chopper when the aperture is closed. This is a significant aspect of the microscope's design that will be discussed in Section 3.4. By modulating the incident radiation in this manner, an AC electrical signal is produced by the detector which is easier to amplify than a DC signal. As shown in Figure 13a, this AC signal passes through a preamplifier where it is amplified to an amplitude and impedance level suitable for transmission through a cable to the control unit.

At the control unit, the AC preamplifier signal can either be processed by the circuits in the control unit; or, it can be made available at an output jack, thus bypassing these circuits.

The latter method of operation is called the AC mode, and allows for the observation of rapidly occurring thermal transients. However, determination of temperature levels associated with these AC transients is difficult because the signal is still modulated by a 1200 Hz carrier (or chopping) frequency created by the tuning fork chopper. In the DC mode of operation, the signal from the microscope is amplified by the control unit, and this 1200 Hz carrier frequency is removed by the demodulator circuitry. After demodulation, the signal is filtered, and a DC voltage is produced which is proportional in magnitude to the difference between the target and reference radiation. In addition to the AC and DC modes of operation, a third mode of operation is available called the AC/DC mode. In this mode, the last filter used to process the DC electrical signal is bypassed. Thus, the impedance on the output signal is reduced, and the AC/DC mode of operation produces a higher voltage output than the DC mode of operation. Also, the AC/DC mode can be used simultaneously with either the DC mode or AC mode of operation. Since it is difficult to interpret the signal produced from the AC mode of operation, the DC and AC/DC modes of operation were used throughout the course of this work.

The infrared microscope at Virginia Polytechnic Institute and State University is equipped with either a 15X or 36X objective lens. The characteristics of these objective lenses are shown in Table 4. Due to clearance problems associated with the oscillating contact test apparatus, use of the 36X objective proved to be futile since it has a working distance of only 0.315 in. (8.0 mm). This places the lens of the 36X objective too close to the sapphire disk for focusing purposes, since it is impossible to get the required amount of light into the contact region. Figure 14a shows that

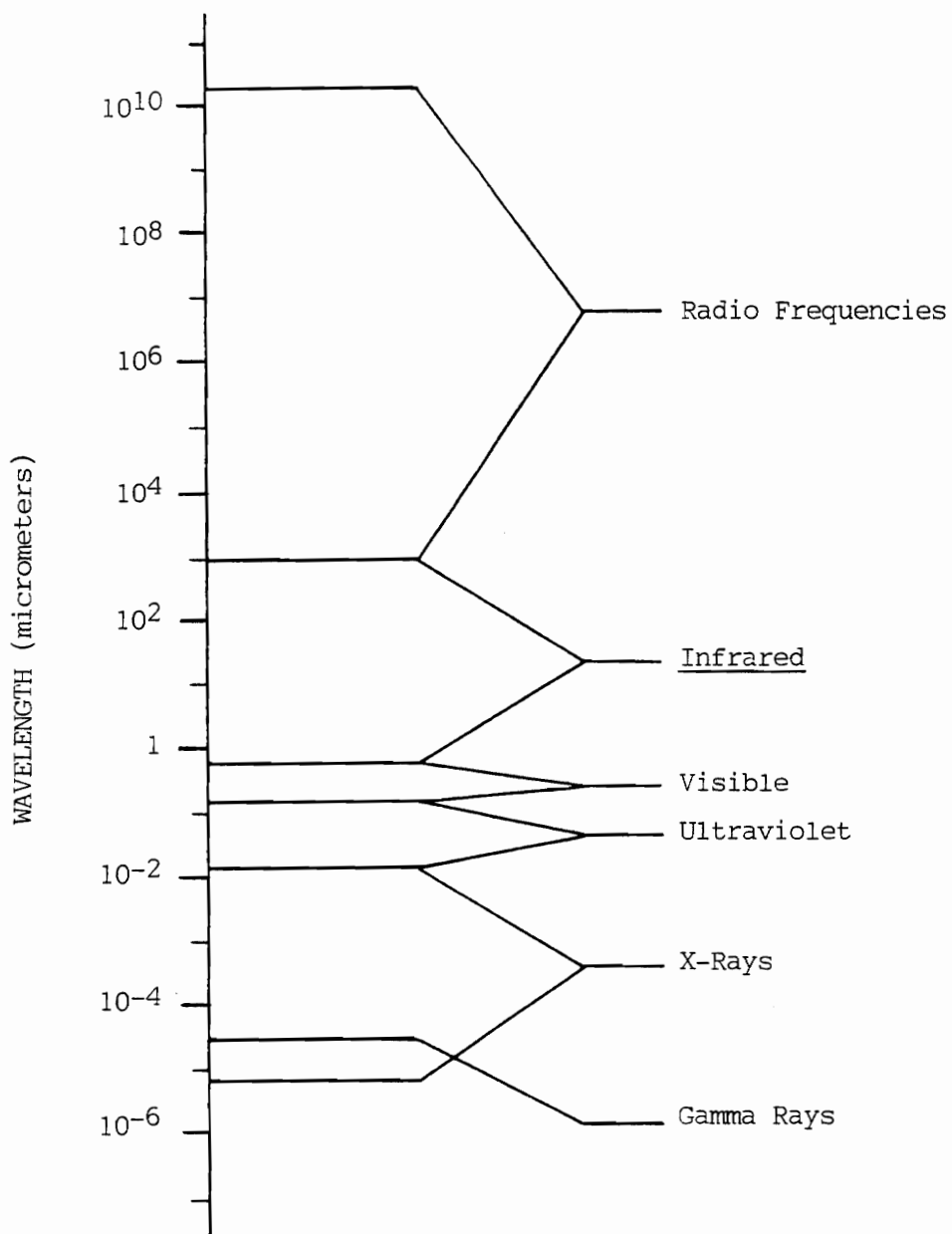


Figure 11 : The Electromagnetic Spectrum

BLACKBODY SPECTRAL INTENSITIES

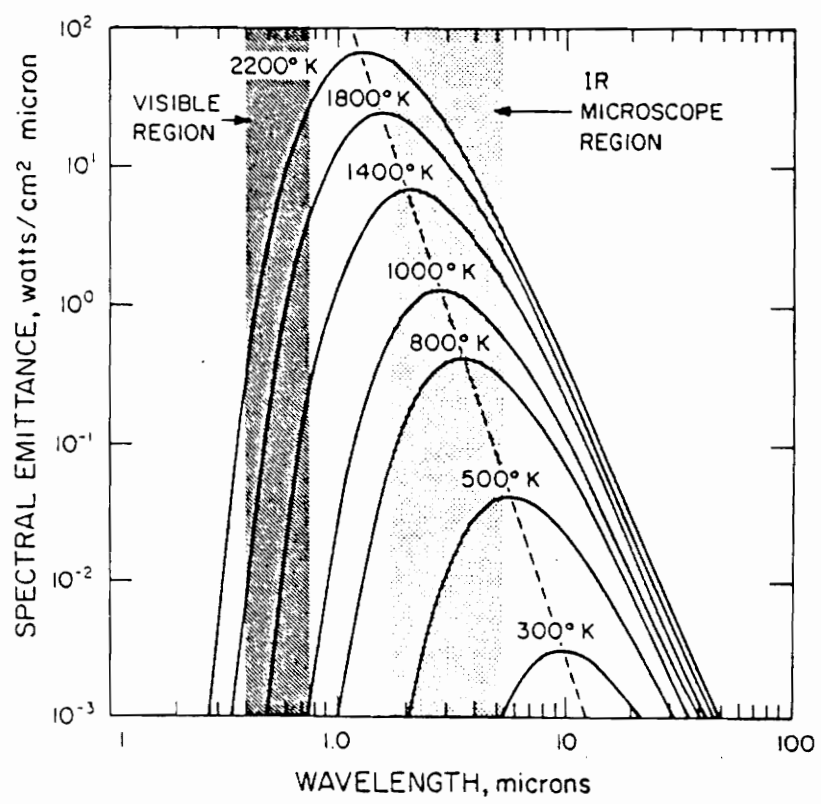


Figure 12: The Spectral Emissive Power of a Blackbody [4]

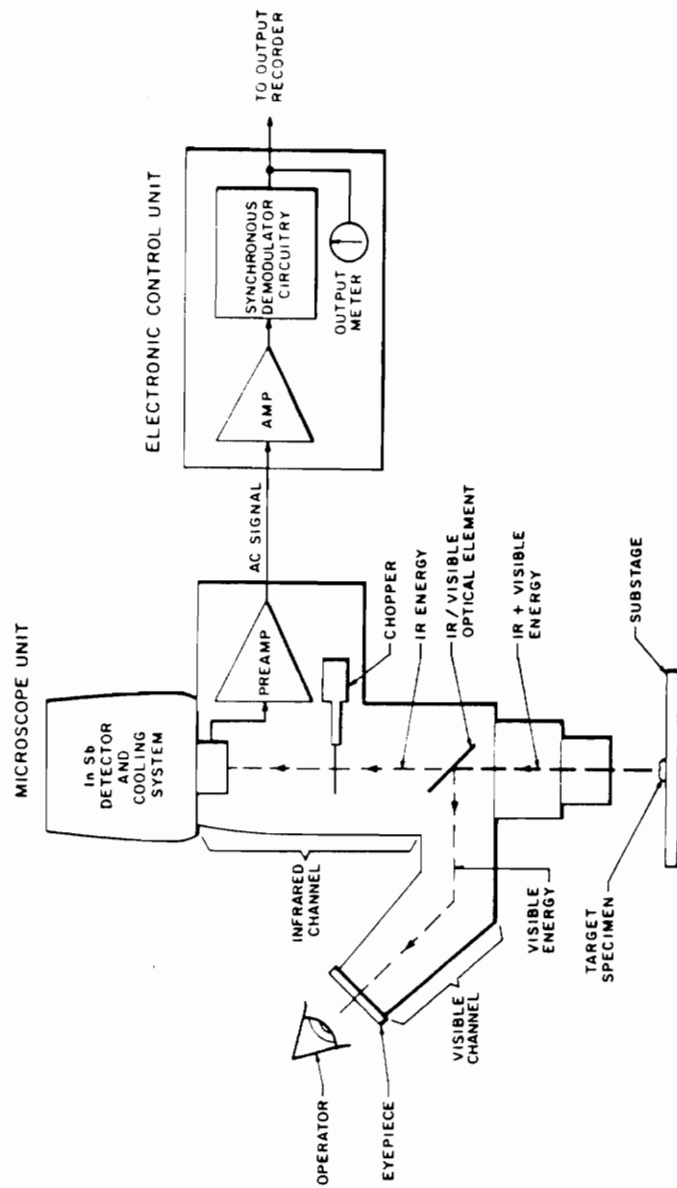


Figure13a: Simplified Functional Diagram of the Barnes RM-2A Infrared Microscope [88]

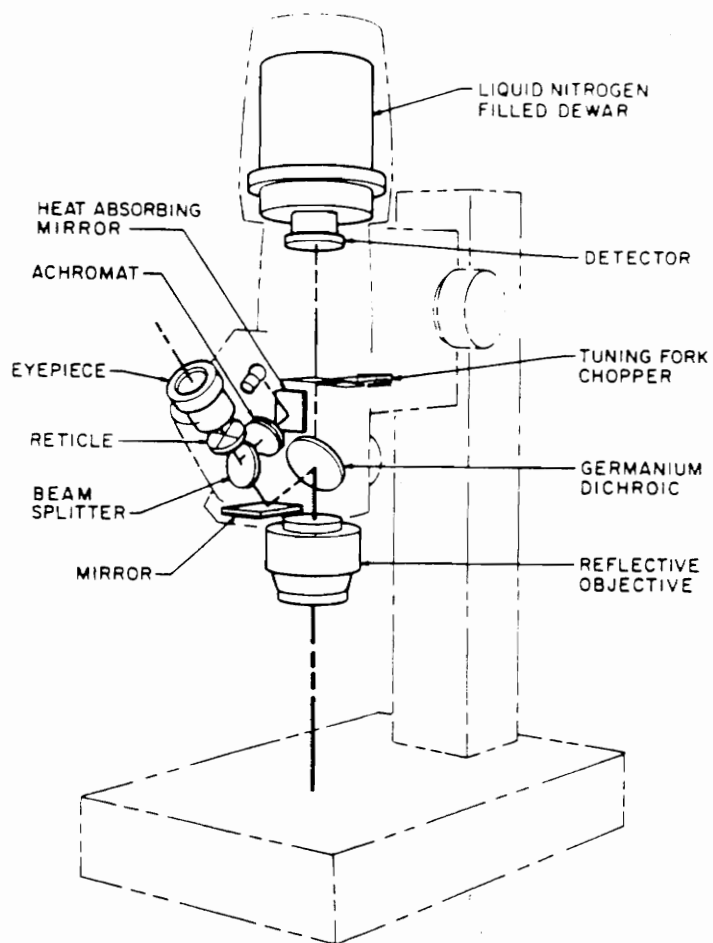


Figure 13b: Three-Dimensional Schematic View of the Barnes RM-2A Infrared Microscope [88]

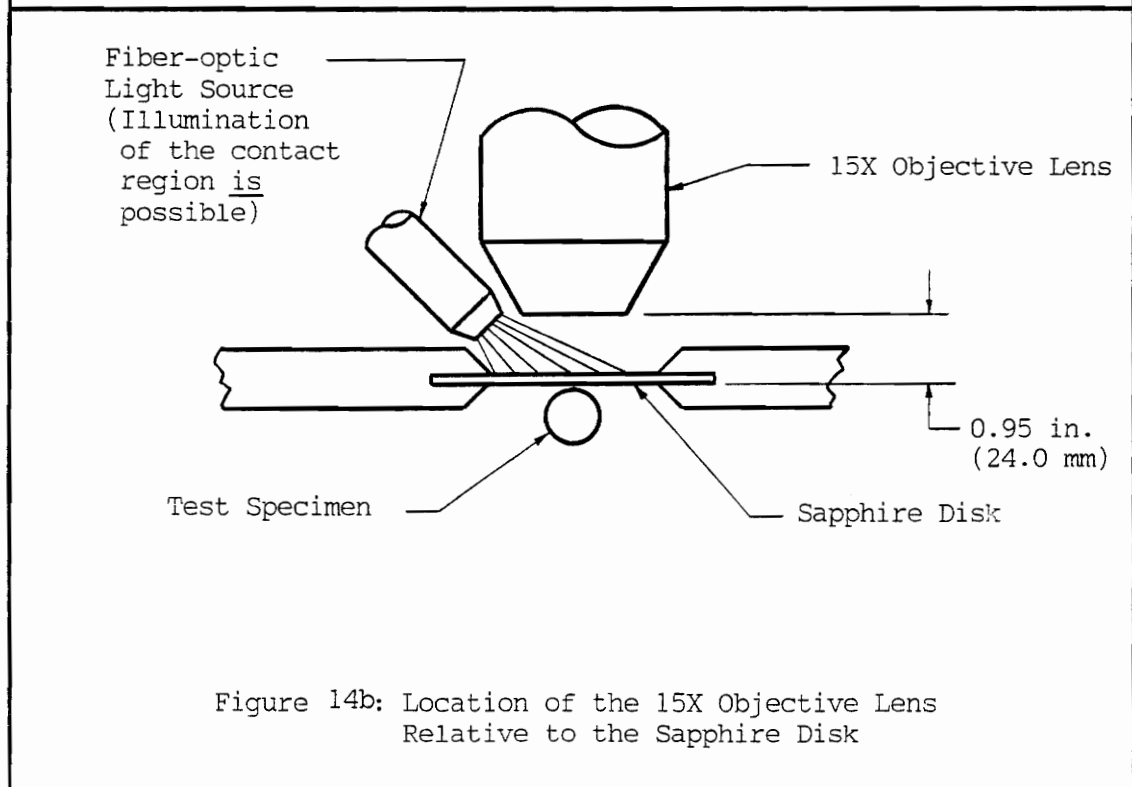
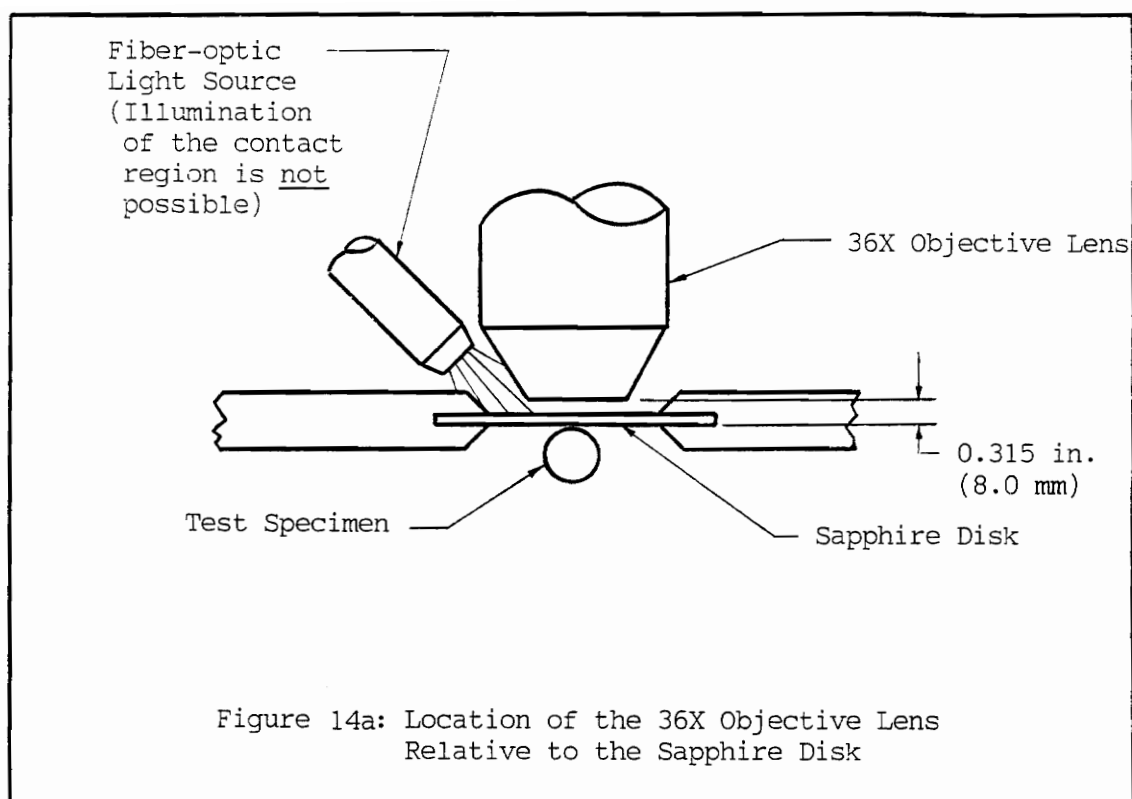
the 36X objective lens is actually within a recessed portion of the test apparatus compared to the 15X objective shown in Fig. 14b. Therefore, the 15X objective which has a working distance of 0.95 in. (24 mm), and an infrared target spot size of $35.6\ \mu\text{m}$ was used during all the experiments presented in this thesis.

Since the target spot diameter is only $35.6\ \mu\text{m}$ for the 15X objective, contact regions formed between the sapphire disk and spherical test specimens can be effectively scanned. As an example, Fig. 15a compares the $35.6\ \mu\text{m}$ diameter target spot size with the elastic contact area formed between a $\frac{1}{4}$ in. diameter zirconia sphere and sapphire disk under 20 N and 40 N loads.

This figure also compares the $35.6\ \mu\text{m}$ target spot size with the apparent contact area after a two-minute experiment performed under the following test conditions: normal load = 20 N, frequency = 195.3 Hz, peak-to-peak amplitude = $260\ \mu\text{m}$. Note that there is a large increase in apparent contact area after only two minutes. This makes scanning more appropriate as time progresses, since there is more area to scan as time progresses. However, scanning is still possible during the initial phases of an experiment since the target spot size is smaller than the initial elastic contact area.

For tungsten carbide-on-sapphire, the elastic contact area shown in Fig. 15b is only slightly smaller than for the zirconia-on-sapphire case. However, as shown in Figs. 15a and 15b, the apparent contact area for tungsten carbide-on-sapphire is smaller than the apparent area for the zirconia-on-sapphire case. Even though this difference appears to be significant, scanning is again still possible during a tungsten carbide experiment since the target spot size is smaller than either the elastic area or apparent contact area after a two-minute experiment. Compared to the $35.6\ \mu\text{m}$ target spot diameter used in this study, large target spot diameters of $100\ \mu\text{m}$ and $\sim 7165\ \mu\text{m}$ were used in earlier infrared studies of surface temperatures generated during frictional processes [74,75]. Therefore, use of the Barne's Infrared Microscope represents a significant improvement in the ability to study surface temperatures generated in small, microscopic regions.

Table 4 : Characteristics of the Barnes RM-2A Infrared Microscope (Ref. [88])		
	15 X Objective	36X Objective
Diameter of Target Spot - Infrared Channel	0.0014 in. (35.6 μm)	0.0007 in. (17.8 μm)
Total Magnification - Visual Channel	150X	360X
Working Distance	0.95 in. (24.0 mm)	0.315 in. (8.0 mm)
Numerical Aperture	0.28	0.65
Focal Length	0.51 in. (13.0 mm)	0.21 in. (5.3 mm)



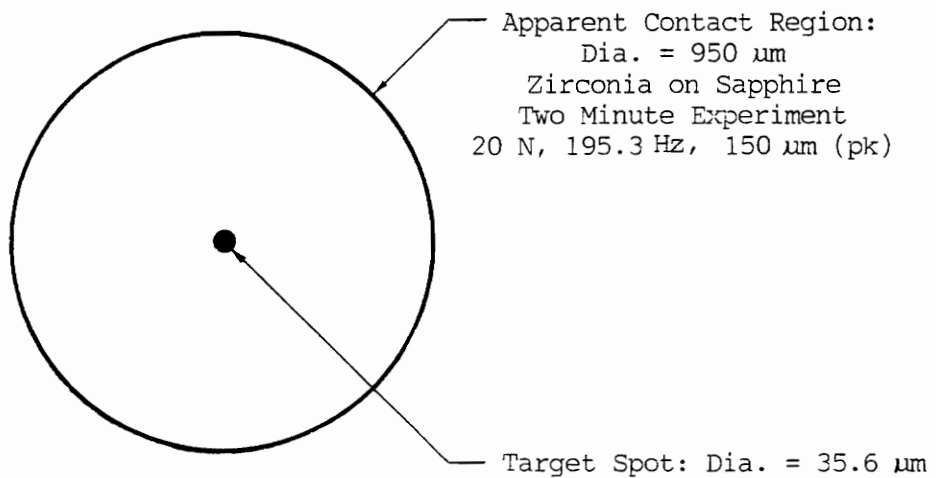
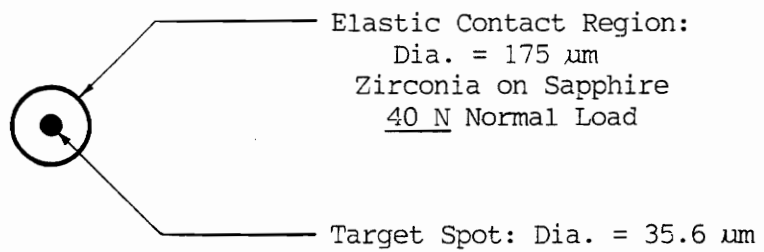
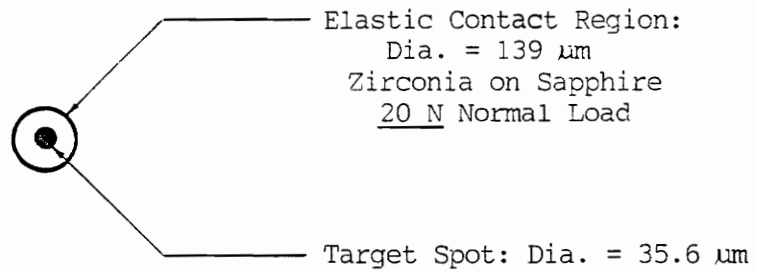


Figure 15a: Comparison of Target Spot Size and Contact Regions
for Zirconia on Sapphire

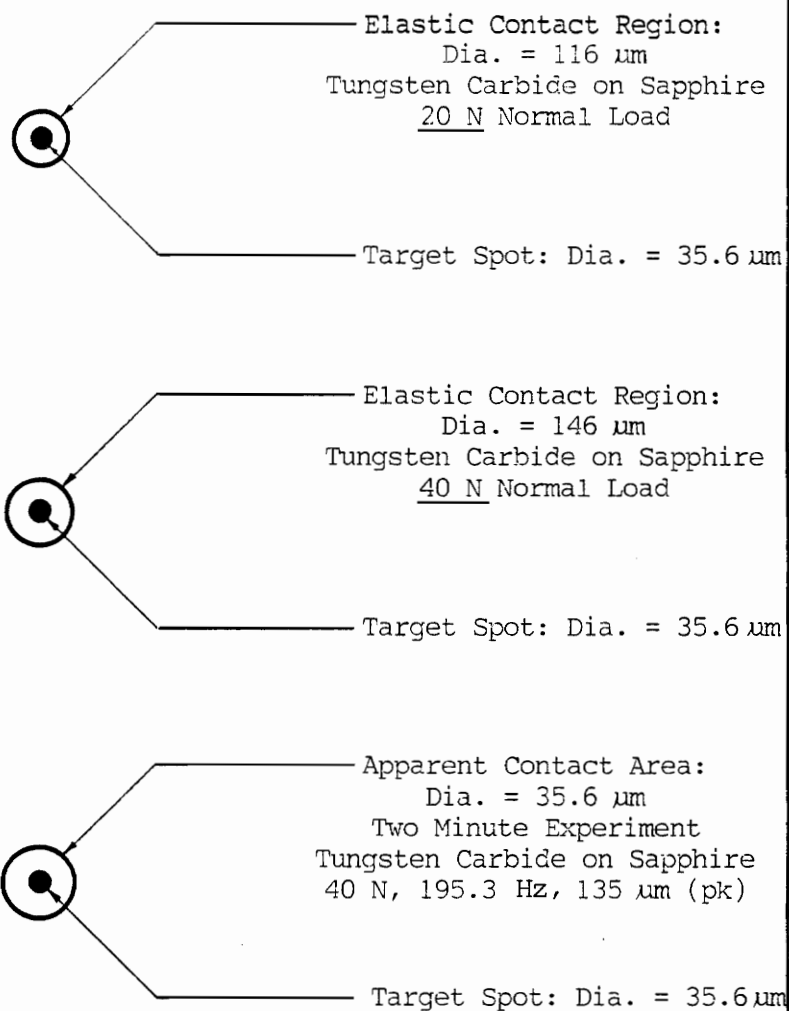


Figure 15b: Comparison of Target Spot Size and Contact Regions for Tungsten Carbide on Sapphire

3.2.2 Basic Operational Theory of the Infrared Microscope [88]

As stated in the previous section, infrared energy is generated by the motion of charged particles in a substance, and the amount of infrared energy released by a substance increases with temperature. However, different substances at the same temperature radiate different amounts of infrared energy depending on their emissivities. This term, emissivity, is used to describe the radiating efficiency of a substance, and can be defined as follows:

Emissivity is the ratio of the energy radiated by a substance to the energy radiated by a blackbody at the same temperature.

A blackbody has an emissivity of 1.0, and can be defined as follows:

A blackbody is an idealized material which is a perfect emitter and absorber of diffuse infrared energy.

As a corollary to this definition, it can be said that no substance at a given temperature can radiate more infrared energy than a blackbody at the same temperature. In short, real substances have emissivities less than 1.0. Mathematically, the emissivity of a substance can be written as follows:

$$\varepsilon_t = \frac{N_t}{N_{bt}} \quad (1)$$

where,

ε_t - emissivity of the target

N_t - radiance† emitted by the target

N_{bt} - radiance of a blackbody at the same target temperature

† The term radiance is defined as the radiation power emitted into a unit solid angle from a surface unit area. The units of radiance used in this thesis are watts/(cm² steradian).

The amount of radiance received by the infrared microscope is equal to the radiance emitted by the target plus the background radiance reflected by the target:

$$N^*_{TOTAL} = N_t + \rho_t N_o \quad (2)$$

where,

N^*_{TOTAL} = total radiance collected from the target

N_t = radiance emitted by the target

ρ_t = reflectivity of the target

N_o = radiance emitted by an ambient background

In reference [21], Rogers accounted for the presence of the sapphire disk between the microscope and the test specimen by determining two attenuation factors defined below:

n_1 = the fraction of emitted radiation from the test specimen that leaves the top surface of the sapphire disk, and is received by the infrared microscope

n_2 = the fraction of ambient radiation received by the infrared microscope that is reflected from the top surfaces of the test specimen and sapphire disk

The derivations for these attenuation factors will be summarized in the next section. When n_1 and n_2 are substituted into Eq. 2, the expression for total radiance collected from the target can be written as follows:

$$N_{TOTAL} = n_1 N_t + n_2 N_o \quad (3)$$

where,

N_{TOTAL} = total radiance collected from the target taking into account the presence of the sapphire disk

As stated in the previous section, the detector alternately sees radiation from the target, and radiation from the blades of the tuning fork chopper located in front of the detector. Therefore, the electrical output from the microscope is proportional to the difference between total radiance collected from the target, and radiance from the ambient upper cavity of the infrared microscope. This expression is shown below:

$$E = k(N_{TOTAL} - N_o) \quad (4)$$

where,

E = voltage output from the infrared microscope

k = proportionality constant

The proportionality constant k is obtained by calibrating the microscope using a blackbody source. This calibration technique is described in Appendix A. Calibration curves for the infrared microscope are also shown in this appendix.

By substituting Eq. 3 into Eq. 4, the expression for radiance emitted by the target can be written as follows:

$$N_t = (E(1/k) + N_o(1 - n_2))/n_1 \quad (5)$$

By defining "1/k" as the calibration constant "C", Eq. 5 can be rewritten as shown below:

$$N_t = (EC + N_o(1 - n_2))/n_1 \quad (6)$$

When Eq. 1 is substituted into Eq. 6, an expression for the radiance emitted by a blackbody at the target's temperature can be written as follows:

$$N_{bt} = (EC + N_o(1 - n_2))/n_1 \epsilon_t \quad (7)$$

Prior to showing how temperature is calculated from this expression, the radiation analysis described in reference [21] should be summarized. This analysis provides expressions for the attenuation factors n_1 and n_2 .

3.2.3 Summary of Radiation Analysis

This section summarizes the radiation analysis performed by C. A. Rogers in reference [21]. Before commencing a discussion of this analysis, certain concepts and terms must be introduced. Figure 16 shows how a monochromatic ray of radiant energy is reflected and refracted when it strikes a smooth transparent surface located in a vacuum. The angles shown in this figure are called the angle of incidence, θ_1 , and the angle of refraction, θ_2 . A constant known as the index of refraction is defined below in terms of θ_1 and θ_2 :

$$\eta = \frac{\sin \theta_1}{\sin \theta_2} \quad (8)$$

where,

θ_1 = angle of incidence

θ_2 = angle of refraction

η = index of refraction for a transparent material in vacuum

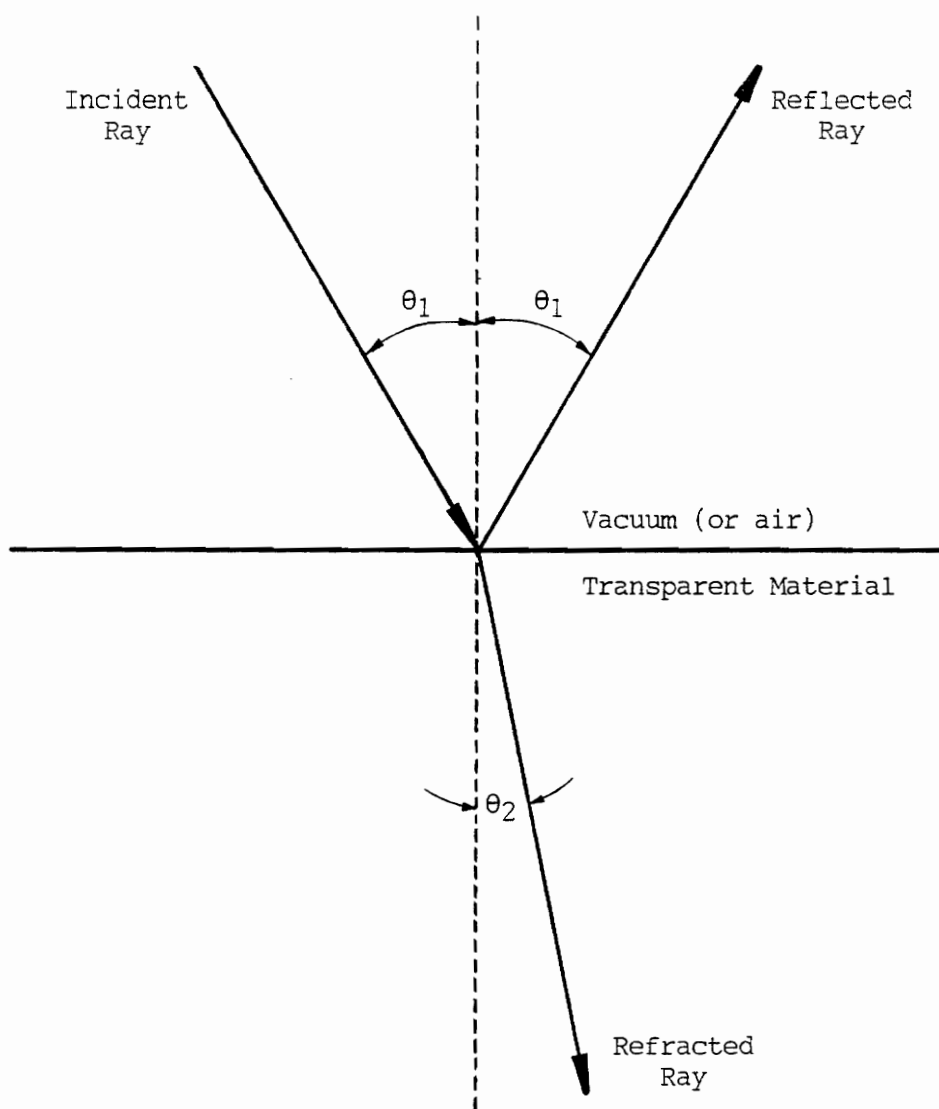


Figure 16: Reflection and Refraction of a Ray
at the Surface of a Transparent Material

As shown in Fig. 16, not all of the radiant energy striking a transparent material is refracted. Some of this energy is reflected. Fresnel's formula, shown below, is an expression that accounts for the fraction of radiant energy reflected at an interface between two materials with indices of refraction η_1 and η_2

$$r = \frac{(\eta_1 - \eta_2)^2}{(\eta_1 + \eta_2)^2} \quad (9)$$

where,

r = fresnel reflection coefficient

η_1 = index of refraction for material no. 1

η_2 = index of refraction for material no. 2

Since air has an index of refraction of nearly unity, Eq. 9 reduces to the following for an air-sapphire interface:

$$r_s = \frac{(\eta_s - 1)^2}{(\eta_s + 1)^2} \quad (10)$$

where,

r_s = fresnel reflection coefficient for an air-sapphire interface

η_s = index of refraction for an air-sapphire interface

Calculation of r , using Eq. 10 is actually not straightforward. As shown in Fig. 17, the index of refraction, η_s , is a function of wavelength in the spectral range of the microscope. Based on this observation, an index of refraction equal to 1.65 was selected by Rogers [21]. Therefore, the fresnel

reflection coefficient can be determined to be 0.0602. This value for r_r is used throughout the course of this work.

When radiant energy impinges on the surface of a translucent material, that energy is partially transmitted, partially reflected, and partially absorbed by the material. In general, the sum of the fractions of transmitted, reflected, and absorbed energy levels must equal one as shown below:

$$\tau + \rho + \alpha = 1 \quad (11)$$

where,

τ = transmissivity -- fraction of energy transmitted through the material

ρ = reflectivity -- fraction of energy reflected by the material

α = absorptivity -- fraction of energy absorbed by the material

For a perfectly opaque material that cannot transmit radiant energy, Eq. 11 reduces to the following:

$$\rho + \alpha = 1 \quad (12)$$

Equations 11 and 12 contain the absorptivity term, α , that is related to emissivity, ϵ , by Kirchoff's law. This law states that at a given wavelength, the fraction of energy absorbed by a substance is equal to the fraction of energy emitted by a substance:

$$\alpha_\lambda = \epsilon_\lambda$$

Since the infrared microscope used in this research detects radiant energy levels over a finite wavelength interval, an assumption known as the gray body assumption can be invoked. This assumption can be stated as follows: For a nonblack body in radiative equilibrium with an isothermal enclosure, $\alpha = \epsilon$. In this assumption, neither α nor ϵ are functions of wavelength. Upon application of Kirchoff's law and the gray body assumption, Eqs. 11 and 12 can be written as follows:

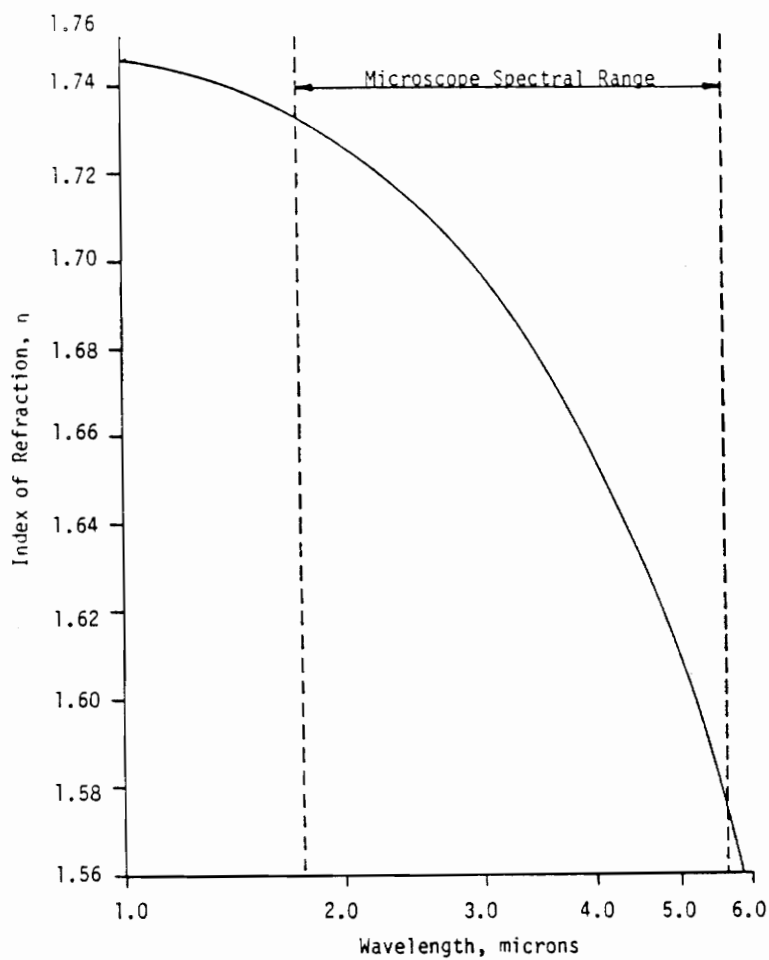


Figure 17: Index of Refraction as a Function of Wavelength

- for a material that partially transmits, reflects, and emits radiant energy,

$$\tau + \rho + \varepsilon = 1 \quad (13a)$$

- for an opaque material,

$$\rho + \varepsilon = 1 \quad (13b)$$

- for a translucent material,

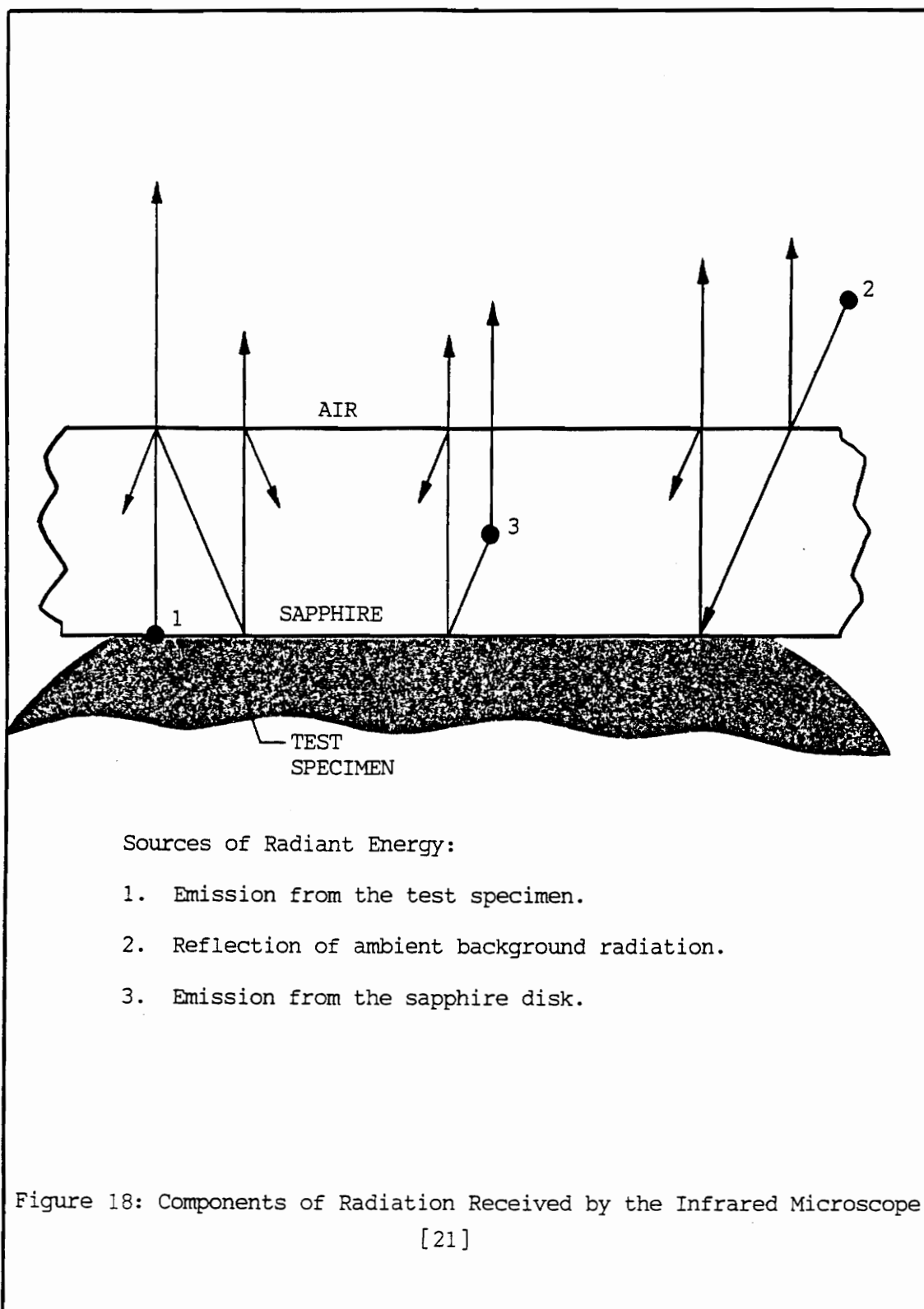
$$\varepsilon = 1 - \tau \quad (13c)$$

As shown in Fig. 18, the components of radiation received by the infrared detector can be attributed to the following three sources of radiant energy.

1. Emission from the test specimen and subsequent transmission through the sapphire disk.
2. Reflection of ambient background radiation off the sapphire disk and test specimen.
3. Emission from the sapphire disk itself.

As discussed in reference [21], emission from the sapphire disk itself is negligible compared to the amount of radiant energy released at the interface between the oscillating disk and test specimen. Therefore, only the first two sources of radiant energy are accounted for in the radiation analysis.

The attenuation factor, n_1 , associated with emission from the test specimen and transmission through the sapphire disk, is determined by using a ray-tracing analysis originally presented in reference [21]. This analysis is depicted in Fig. 19, and begins by considering the emission of a unit amount of radiant intensity from the test specimen. A fraction of this energy τ is transmitted through the sapphire, and $(1 - \tau)$ is absorbed by the disk. Due to a fresnel reflection at the top of the disk, a fraction τr_s is reflected back into the disk, and $\tau(1 - r_s)$ passes out of the surface of the disk. The fraction of reflected radiant intensity τr_s that is retransmitted through the disk is $\tau^2 r_s$.



Since the test specimen is opaque and has a reflectivity $\rho_t = 1 - \epsilon_t$, the fraction of radiant intensity reflected off this surface is $\tau^2 r_s \rho_t$. Subsequently, a fraction of this energy $\tau^3 r_s \rho_t$ is retransmitted through the disk and $\tau^2 r_s \rho_t (1 - \tau)$ is absorbed by the disk. Again, due to a fresnel reflection at the top of the disk, a fraction of energy $\tau^3 r_s^2 \rho_t$ is reflected back into the disk, and $\tau^3 r_s \rho_t (1 - r_s)$ passes out of the surface of the disk. As this analysis continues, it can be seen that the sum of the fractions leaving the top surface of the sapphire disk is n_1 :

$$\begin{aligned} n_1 &= \tau(1 - r_s) + \tau^3 r_s \rho_t (1 - r_s) + \tau^5 r_s^2 \rho_t^2 (1 - r_s) + \dots \\ &= (1 - r_s) \tau (1 + r_s \rho_t \tau^2 + r_s^2 \rho_t^2 \tau^4 + \dots) \end{aligned} \quad (14)$$

where,

n_1 = The fraction of emitted radiation from the test specimen that leaves the top surface of the sapphire disk, and is received by the infrared microscope.

τ = transmissivity of the sapphire disk

r_s = fresnel reflection coefficient for an air-sapphire interface

ρ_t = reflectivity of the test specimen (for opaque materials, this equals $1 - \epsilon_t$)

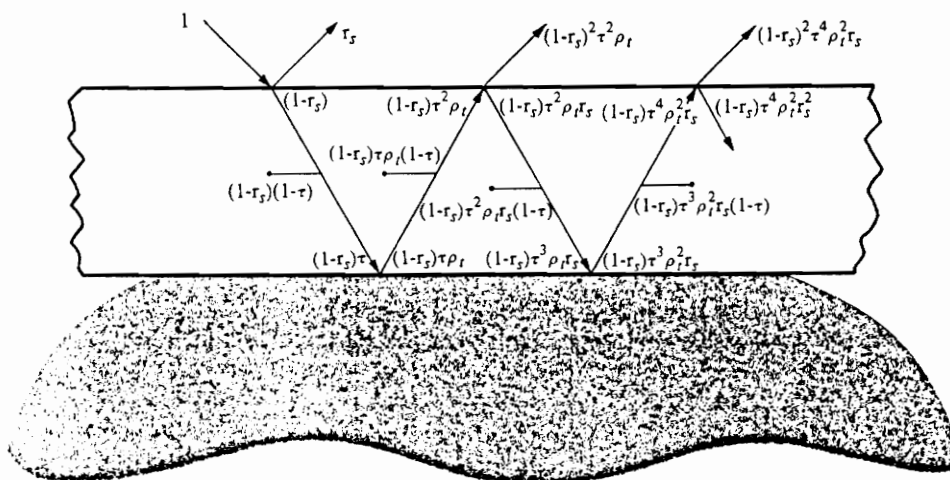
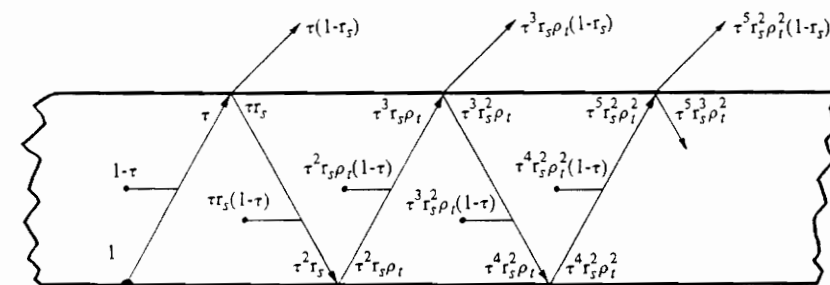


Figure 20: Ray Tracing Analysis for Ambient Radiation Reflected off the Test Specimen [21]

In reference [21], Rogers showed that the third term is close to zero. Therefore, n_1 can be written as follows:

$$n_1 = \tau(1 - r_s) + \tau^3 r_s \rho_t (1 - r_s) \quad (15)$$

The second attenuation factor, n_2 , accounts for the reflection of ambient radiation off the sapphire disk and test specimen. Figure 20 depicts the ray tracing analysis used to find this attenuation factor which is written below [21]:

$$\begin{aligned} n_2 &= r_s + \rho_t (1 - r_s)^2 \tau^2 + \rho_t^2 (1 - r_s)^2 r_s \tau^4 + \dots \\ &= r_s + [\rho_t (1 - r_s)^2 \tau^3 (1 + \rho_t \tau^2 + \rho_t^2 \tau^4 + \dots)] \end{aligned} \quad (16)$$

where,

n_2 = the fraction of ambient radiation received by the infrared microscope that is reflected from the top surfaces of the test specimen and sapphire disk

Higher order terms beyond the third term in this series were shown to be negligible [21], and n_2 can be written as follows:

$$n_2 = r_s + \rho_t (1 - r_s)^2 \tau^2 + \rho_t^2 (1 - r_s)^2 r_s \tau^4 \quad (17)$$

In the expressions for n_1 and n_2 shown in Eqs. 15 and 17, it is evident that there is a need to know the transmissivity of the sapphire disk, τ . This information is provided in the next section.

3.2.4 Determination of the Internal Transmissivity of the Sapphire Disk

Figure 21 depicts the ray tracing analysis for an air-sapphire-air system. In this analysis, it was shown that the fraction of radiant energy transmitted through the sapphire disk is equal to the following [21]:

$$T = \tau(1 - r_s)^2(1 + r_s^2\tau^2 + r_s^4\tau^4 + \dots) = \tau \frac{(1 - r_s)}{(1 + r_s)} \frac{(1 - r_s^2)}{(1 - r_s^2\tau^2)} \quad (18)$$

where,

T = external transmittance -- fraction of radiant energy transmitted through the sapphire disk

r_s = fresnel reflection coefficient for sapphire

τ = internal transmissivity of the sapphire disk

Since the last term, $(1 - r_s^2) / (1 - r_s^2\tau^2)$, is close to unity, it is neglected, and the following equation can be written to determine the internal transmissivity of the sapphire disk:

$$\tau = T \frac{1 + r_s}{1 - r_s} \quad (19)$$

The experimental technique for determining the external transmittance of an unused sapphire disk is described in Appendix I. Results are discussed in Section 4, and the average external transmittance, T , of an unused sapphire disk was determined to be 0.830. Since r_s was determined to be 0.0602 in Section 3.2.3, Eq. 19 can be used to calculate an internal transmissivity, τ , of 0.936.

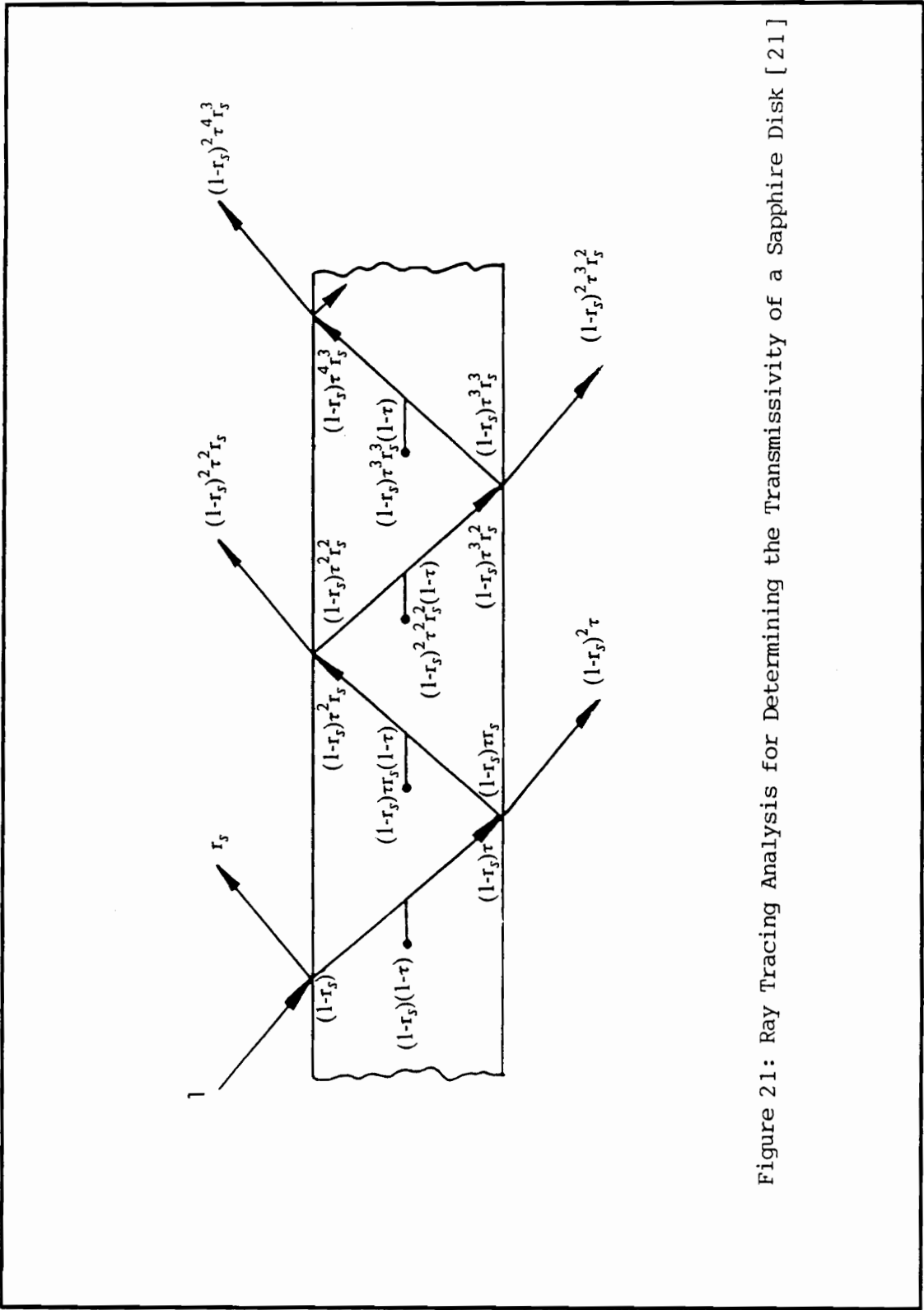


Figure 21: Ray Tracing Analysis for Determining the Transmissivity of a Sapphire Disk [21]

3.2.5 Calculation of Surface Temperature

A computer program shown in Appendix F is used to calculate surface temperatures when the following information is supplied as input:

- the electrical output from the infrared microscope
- an emissivity value for the test specimen
- the transmittance of the sapphire disk
- the reference level voltage output from the microscope obtained before an experiment
- the ambient temperature of the microscope

The procedure used is to first calculate the radiance being emitted by the test specimen. This is accomplished using Eq. 7 shown below. This equation was derived in Section 3.2.2.

$$N_{bt} = (EC + N_o(1 - n_2))/n_1\epsilon_t \quad (7)$$

where,

N_{bt} = radiance of a blackbody at the temperature of the target.

E = relative voltage output from the infrared microscope

C = calibration constant determined in Appendix A

N_o = radiance emitted by an ambient background

n_1 = the fraction of emitted radiation from the test specimen that leaves the top surface of the sapphire disk, and is received by the infrared microscope

n_2 = the fraction of ambient radiation received by the infrared microscope that is reflected from the top surfaces of the test specimen and sapphire disk

ε_t = the emissivity of the test specimen.

The radiance level determined by Eq. 7 can also be referred to as the experimentally determined blackbody radiance, N_{exp} . This terminology will be used throughout the rest of this discussion.

The objective of the computer program is to determine the surface temperature that corresponds to N_{exp} . Prior to discussing how this is actually accomplished, the following relationship must be introduced and explained.

$$N_{beff}(T) = B \int_{1.8}^{6.2} \frac{R(\lambda)}{R_{peak}} I_{b\lambda}(\lambda, T) d\lambda \quad (20)$$

where,

N_{beff} = effective blackbody radiance (actual blackbody radiance to which the detector responds); the units for radiance are watts/(cm² steradian)

$I_{b\lambda}(\lambda, T)$ = monochromatic blackbody radiant intensity - units: watts/(cm² steradian μ m)

$R(\lambda)$ = spectral response of the infrared microscope

R_{peak} = peak spectral response of the infrared microscope

B = a microscope constant specified by Barnes Engineering to be 13.50, [21]

N_{beff} accounts for the fact that the Barnes infrared microscope does not have ideally flat spectral response, transmission, or reflection characteristics. Furthermore, it accounts for the fact that the spectral bandwidth of the microscope is not 0 to infinity; but 1.8 - 6.2 μm . Values of N_{beff} have been computed by Barnes Engineering for various temperatures as shown in Appendix H.

One of the integrands in Eq. 20 is the monochromatic blackbody radiant intensity $I_{b\lambda}(\lambda, T)$. This term is also known as Planck's blackbody radiation distribution function as defined below:

$$I_{b\lambda}(\lambda, T) = \frac{c_1}{\lambda^5 (e^{c_2/\lambda T} - 1)} \quad (21)$$

where,

$I_{b\lambda}(\lambda, T)$ = monochromatic blackbody radiant intensity - units: watts/(cm^2 steradian μm)

λ = wavelength in micrometers

c_1 = $1.1909(10)^{-20}$ watts cm^2 / ster

c_2 = $14.388(10)^{-3}$ m K

As shown in Eq. 20, $I_{b\lambda}(\lambda, T)$ is multiplied by the normalized spectral response of the infrared microscope's detector, $R(\lambda)/R_{\text{peak}}$. This function is shown in Fig. 22. Upon examination of this figure, it can be seen that the microscope's indium antimonide detector has higher response characteristics at the center of its spectral bandwidth than at the extrema of its bandwidth.

Now that N_{beff} and N_{exp} have been defined, the method of surface temperature calculation can be explained. In simple terms, the computer program calculates N_{beff} at selected temperatures until a temperature T^* is found that equates N_{beff} to N_{exp} . This temperature T^* is the desired surface temperature. Mathematically, a function $f(T)$ is set-up in the computer program as shown below:

$$f(T) = N_{\text{exp}} - N_{\text{beff}}(T) \quad (22a)$$

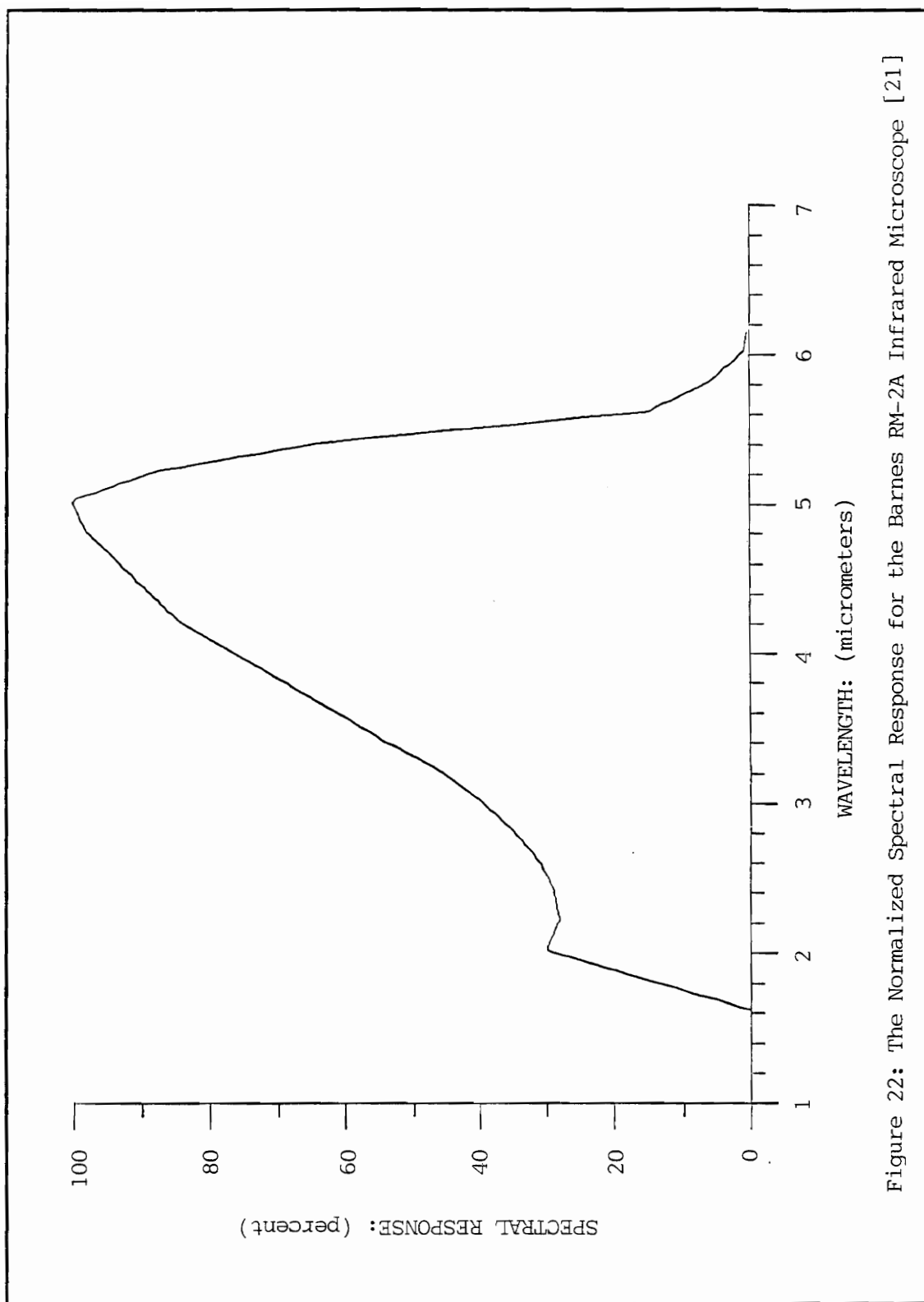


Figure 22: The Normalized Spectral Response for the Barnes RM-2A Infrared Microscope [21]

substituting Eq. 20 into Eq. 22a yields the following:

$$f(T) = N_{\text{exp}} - B \int_{1.8}^{6.2} \frac{R(\lambda)}{R_{\text{peak}}} I_{b\lambda}(\lambda, T) d\lambda \quad (22b)$$

substituting Eq. 7 and Eq. 21 into Eq. 22b yields the final relationship for $f(T)$:

$$f(T) = (EC + N_o(1 - n_2))/n_1 \varepsilon_t - B \int_{1.8}^{6.2} \frac{R(\lambda)}{R_{\text{peak}}} \frac{c_1}{\lambda^5 (e^{c_2/\lambda T} - 1)} d\lambda \quad (22c)$$

As shown in Eq. 22c, when the function $f(T) = 0$, N_{beff} is equal to N_{exp} , and the surface temperature T^* has been found. By expressing the problem in this manner, Newton's method for finding the roots of a function can be used effectively to find the surface temperature T^* that corresponds to $f(T^*) = 0$. More information about the computer program can be found in the documentation for the program listed in Appendix F.

3.3 *The Measurement of Emissivity*

As described in the previous section, surface temperatures can be effectively calculated from the radiant energy levels detected by the infrared microscope. However, the emissivity of the test specimen must be measured, or obtained from the literature. For the work described in this thesis, emissivity measurements were made using the specimen heater shown in Figs. 23 and 24. A ¼ inch or ½ inch diameter test specimen is placed inside the heater, and a small black spot is painted on the surface of the specimen using a fine-haired brush.

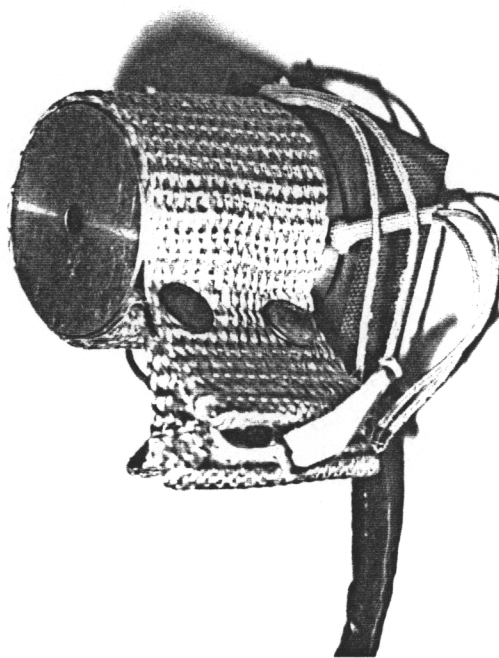
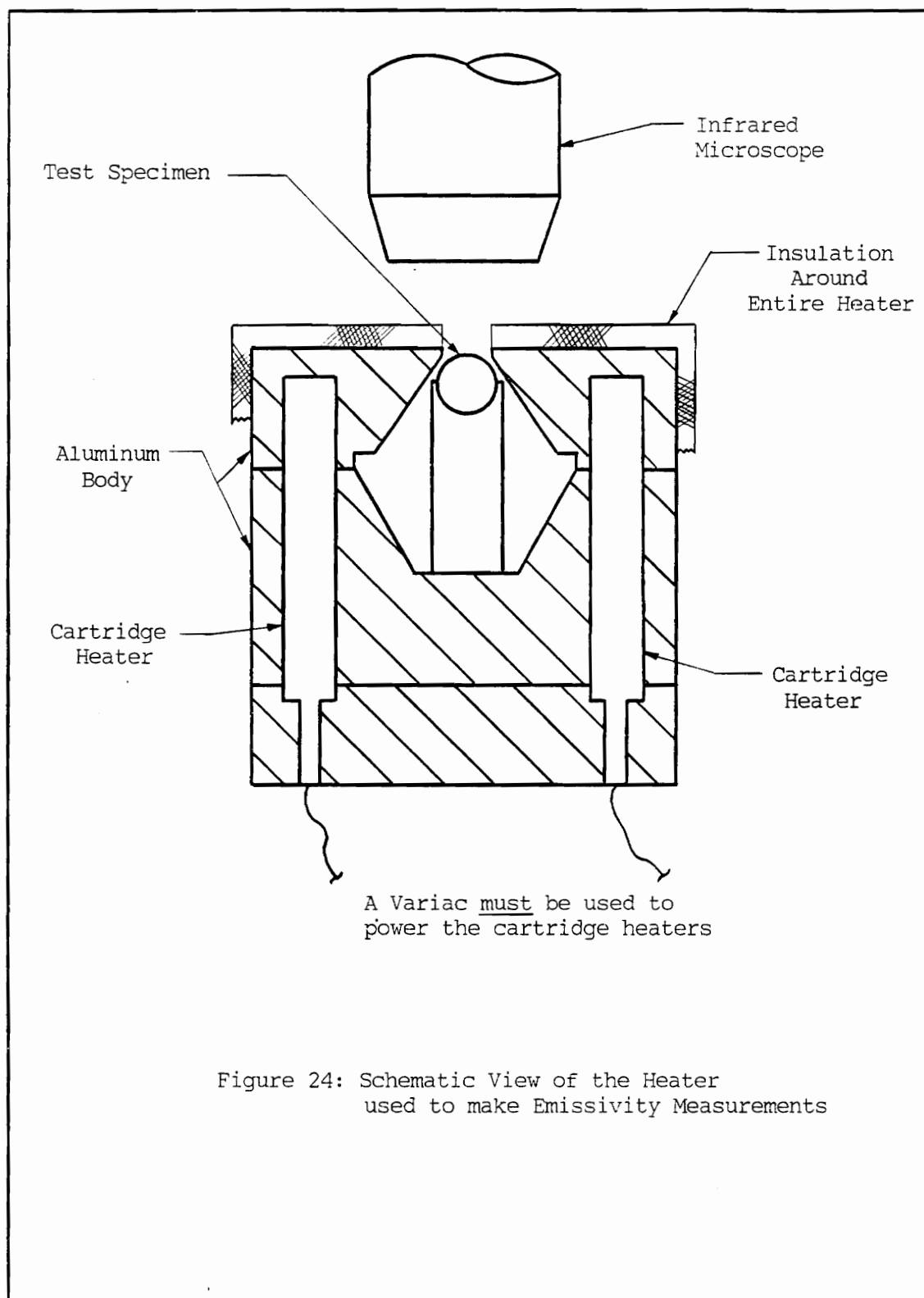


Figure 23: Heater for Measuring the Emissivity of Test Specimens



The paint used is assumed to have an emissivity in the range 0.90-0.95, since an ideal blackbody has an emissivity of 1.0. It is a flat black enamel manufactured by Testors Inc.. Emissivity measurements are made by first heating the specimen to a desired temperature, and then measuring radiance levels from the black and unpainted areas. The emissivity of the test specimen is then calculated using the equation shown below:

$$\varepsilon_t = (\varepsilon_p) \frac{\text{Radiance from the Unpainted Area}}{\text{Radiance from the Painted Area}}$$

where,

ε_t = emissivity of the test specimen

ε_p = emissivity of the paint $\sim(0.90-0.95)$

This experimental technique of emissivity measurement can be used to show the effect (if any) of temperature on the emissivity of a test specimen. Furthermore, it can be used to make emissivity measurements before and after an experiment. This is important because emissivity is expected to increase as surface roughness increases. Also, emissivity has been shown to increase when certain types of oxides are formed on the surface as a result of wear [20]. However, oxidation is not a factor in this research since the ceramic materials used as test specimens are inert in an air environment.

3.4 The Measurement of Ambient Temperature

Recall from Section 3.2 that the voltage output from the infrared microscope is proportional to the difference between total radiance collected from the target, and radiance from the ambient upper cavity of the infrared microscope.

Eq. 4 shows this relationship, and is written below:

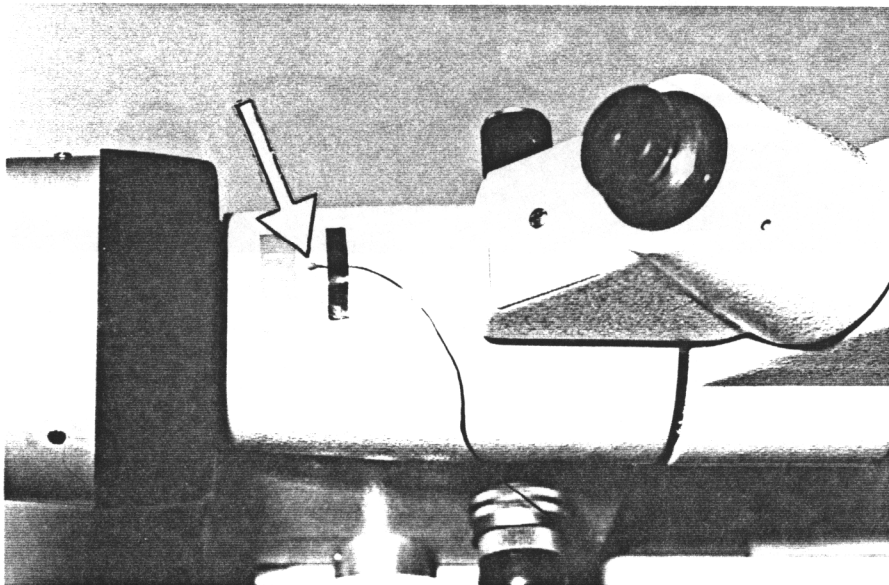


Figure 25 : The Omega #44204 Linear Response Thermistor

$$E = k(N_{TOTAL} - N_o) \quad (4)$$

where,

E = voltage output from the infrared microscope

k = proportionality constant

N_{TOTAL} = total radiance collected from the target

N_o = radiance emitted by an ambient background

Thus, to determine the total radiance collected from the target (and the surface temperature of the target), the ambient radiance emitted from the upper cavity of the microscope must be measured. In past work, this was done by simply measuring the air temperature in the vicinity of the microscope and converting this temperature to radiance using the graphs in Appendix H. In lieu of using this method of ambient radiance determination, a thermistor shown in Fig. 25 was obtained to more accurately measure the temperature of the microscope's upper cavity. Then, the ambient radiance that corresponds to this temperature was calculated using the equation shown below. This equation is incorporated into the program listed in Appendix F.

$$N_o(T_o) = B \int_{1.8}^{6.2} \frac{R(\lambda)}{R_{peak}} \frac{c_1}{\lambda^5 (e^{c_2/\lambda T_o} - 1)} d\lambda \quad (23)$$

where,

N_o = ambient background radiance

T_o = ambient temperature

Other terms in Eq. 23 are defined in Eqs. 20 and 21.

The thermistor produces a voltage output that is linearly related to temperature when it is connected in the electrical circuit shown in Fig. 26. Calibration equations were provided with the thermistor as shown below. These calibration equations are for the Omega no. 44204 linear response thermistor. Equation 24 can be used to determine temperatures in degrees celsius, and Eq. 25 can be used to determine temperatures in degrees fahrenheit.

$$V_o = (0.00563179)V_i T_C + (0.0192439)V_i \quad (24)$$

$$V_o = (0.0031289)V_i T_F + (0.09232)V_i \quad (25)$$

where,

V_o = voltage output from the thermistor circuit

V_i = voltage input to the thermistor circuit

T_C = temperature in degrees celsius

T_F = temperature in degrees fahrenheit

As shown in Fig. 27, the accuracy of this thermistor is approximately ± 0.18 F (± 0.10 C) at 75.0 F (23.9 C). The thermistor is less accurate at 30 F (-1 C) and 100 F (38 C) as shown in Fig. 24. However, it is only used to measure ambient temperatures between 68 F (20 C) and 80 F (27 C). Therefore, its accuracy is more than adequate for the purpose of measuring the ambient temperature of the infrared microscope. Furthermore, it is a marked improvement over the former method of ambient temperature (and ambient radiance) measurement.

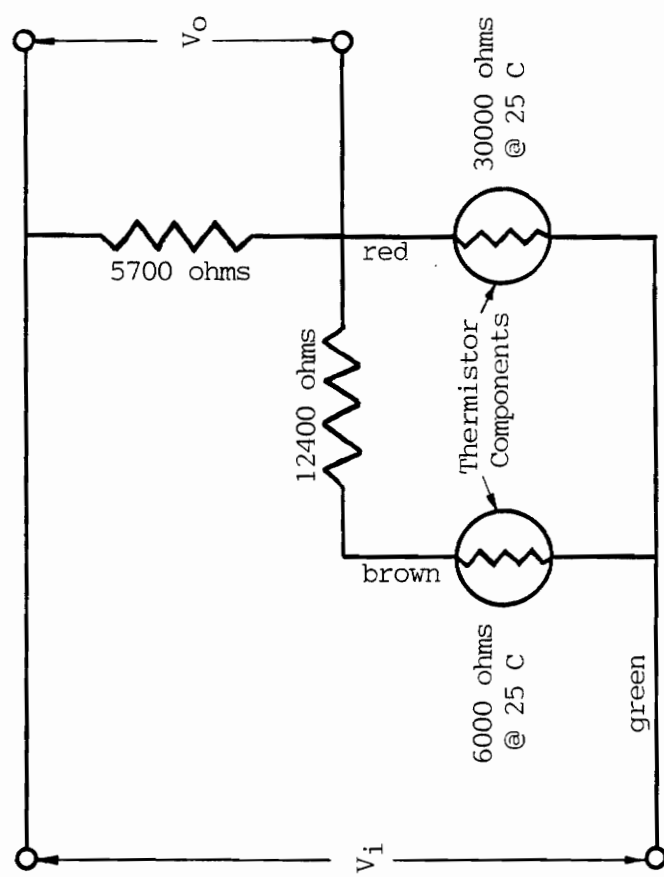


Figure 26: Circuit Design for the Omega #44204 Linear Response Thermistor

The maximum error at any point is the algebraic sum of the thermistor manufacturing tolerances plus the linearity deviation, a fixed network behavior. Since the linearity deviation is a known quantity, it may be eliminated from the error statement by consulting the linearity deviation curve at the temperature in question, and making the appropriate adjustment.

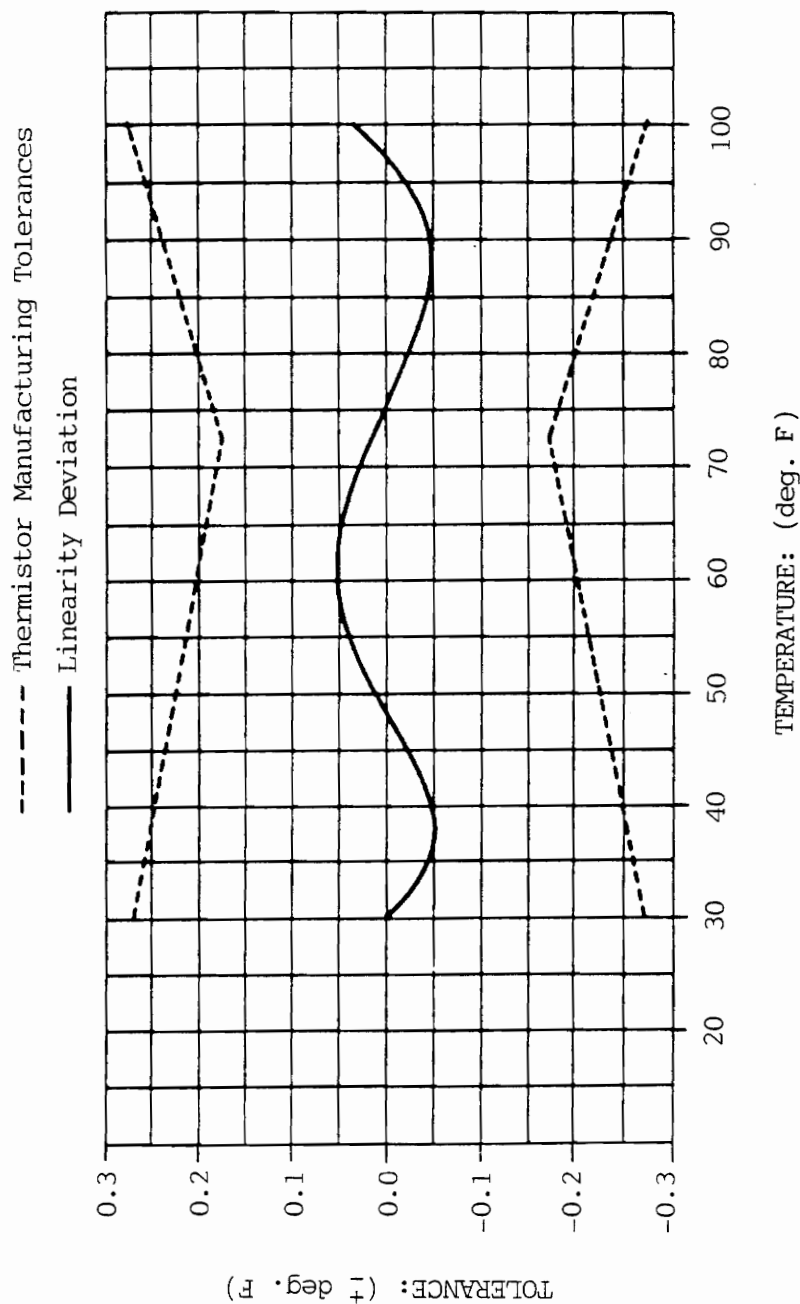


Figure 27: Confidence Intervals for the Omega #44204 Thermistor

3.5 *The Measurement of Acceleration, Velocity, and Amplitude*

Figure 28 shows an accelerometer installed on the end of the sapphire disk's mounting plate. This accelerometer is used to measure the frequency of vibration and acceleration of the sapphire disk. From these measurements, the disk's velocity and amplitude of vibration can also be calculated. The purpose of this section is to describe how this is accomplished. But first, the characteristic equation for the oscillating contact system should be introduced.

As described previously, the sapphire disk is oscillated sinusoidally using an electromagnetic shaker connected to an amplifier and wave generator. The sinusoidal force imposed on the system can be written as $P\sin(\omega t)$ where P is the peak force on the system, ω is the radial frequency in radians/second, and t is time in seconds. This sinusoidal force acts on a system mass, M , that consists of the sapphire disk, its support structure, and the accelerometer. The product of this mass, M , and the acceleration of the system, $a(t)$, constitutes the inertial resistance to the sinusoidal driving force. Another system force that opposes $P\sin(\omega t)$ is due to the foil springs that support the sapphire disk's mounting plate. These foil springs have a certain stiffness, k , that resists $P\sin(\omega t)$ with a characteristic force per unit meter of deflection. The actual spring force that opposes the driving force is equal to $kx(t)$; where $x(t)$ is the amplitude of vibration. Frictional forces, $F_r(t)$, at the interface between the test specimen and disk also resist the driving force. In summary, the equation below characterizes the system's overall resistance to the sinusoidal driving force $P\sin(\omega t)$:

$$Ma(t) + kx(t) + F_r(t) = P \sin(\omega t) \quad (26)$$

Equation 26 is often referred to as the characteristic equation of motion. It is a second-order nonhomogeneous differential equation that has the following steady-state solution:

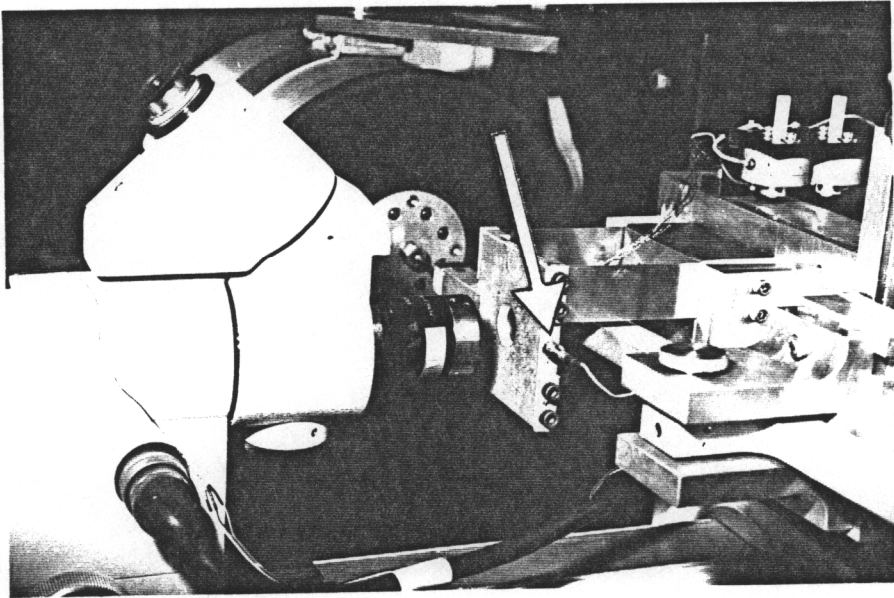


Figure 28: The PCB Piezotronics Accelerometer

$$x(t) = A\sin(\omega t + \phi) \quad (27)$$

where,

$x(t)$ = amplitude of vibration as a function of time

A = peak amplitude of vibration

ω = excitation frequency in radians/second

ϕ = phase difference between the sinusoidal input force and the resulting amplitude of vibration

When Eq. 27 is differentiated twice with respect to time, equations for velocity and acceleration are obtained:

$$v(t) = \omega A \cos(\omega t + \phi) \quad (28)$$

$$a(t) = -\omega^2 A \sin(\omega t + \phi) \quad (29)$$

where,

$v(t)$ = velocity as a function of time

ωA = peak velocity in m/s

$a(t)$ = acceleration as a function of time

$-\omega^2 A$ = peak acceleration in m/s^2

As shown by Eqs. 27-29, the velocity and amplitude of vibration can be obtained by integrating acceleration data measured using the accelerometer. As described in Appendix D, Fast

Fourier Transform (FFT) techniques can be employed to actually perform these integrations. In this manner, discrete velocity data can be obtained as a function of time.

As shown in Fig. 29, estimates of the peak velocity and peak amplitude can be made by first displaying the acceleration signal on an oscilloscope. Then, the peak acceleration, $\omega^2 A$, can be divided by ω to obtain an estimate of the peak velocity, ωA . Or, the peak acceleration can be divided by ω^2 to obtain an estimate of peak amplitude, A .

3.6 The Measurement of Friction

Friction measurements were made using an octagonal strain ring shown in Fig. 30. This strain ring also serves as the holder for the test specimen, and was developed using concepts first presented by Cook and Rabinowicz in reference [89]. As shown in Fig. 30, tangential loads are imposed on the ring due to frictional forces at the ceramic-ceramic interface. These loads cause measurable strains in the ring at points 5, 6, 7, and 8 in Fig. 30. Semiconductor strain gages are mounted at these points, and they produce a voltage output that is proportional to the induced strains. Therefore, by calibrating the gages with imposed tangential loads, frictional forces at the interface can be measured. This calibration procedure is described in Appendix B.

Semiconductor strain gages are also mounted at points 1, 2, 3, and 4 in Fig. 30. These gages are positioned to measure normal loads imposed on the ring. However, since a constant normal load is applied to the ring, output from these four gages is not particularly pertinent to this study.

A close-up picture of one of the semiconductor strain gages is shown in Fig. 31. The gages are manufactured by Micro Gage Inc., and are sold in matched sets of four. They are chemically milled, ultra thin strips of monocrystalline silicon oriented in the [1,1,1] crystallographic direction. As shown in Fig. 32, the eight gages mounted on the strain ring are connected into two wheatstone bridges. The tangential channel is comprised of gages no. 5, 6, 7, and 8. The normal channel is comprised of gages no. 1, 2, 3, and 4.

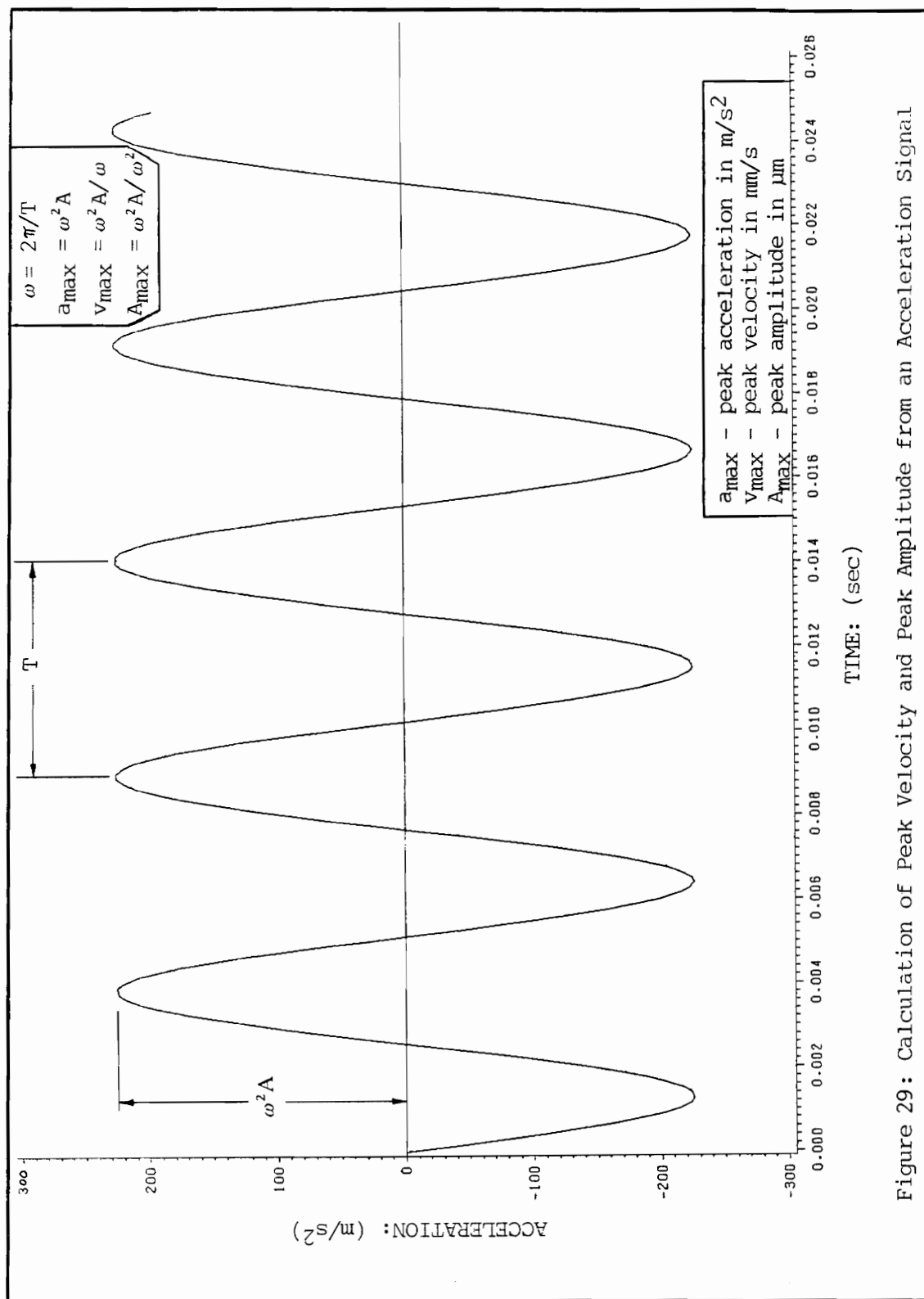


Figure 29: Calculation of Peak Velocity and Peak Amplitude from an Acceleration Signal

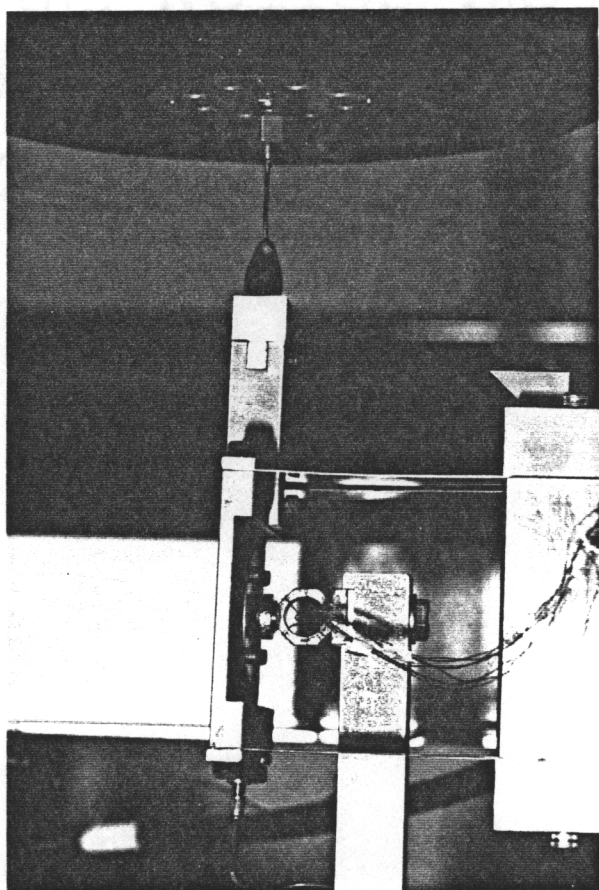


Figure 30: The Strain Ring

Model 916
Semiconductor Strain Gage
manuf. by Micro Gage Inc.
Resistance: 500 ohms
Gage Factor: 140



0.060 in.

Figure 31 : A Semiconductor Strain Gage - Micro Gage Inc.

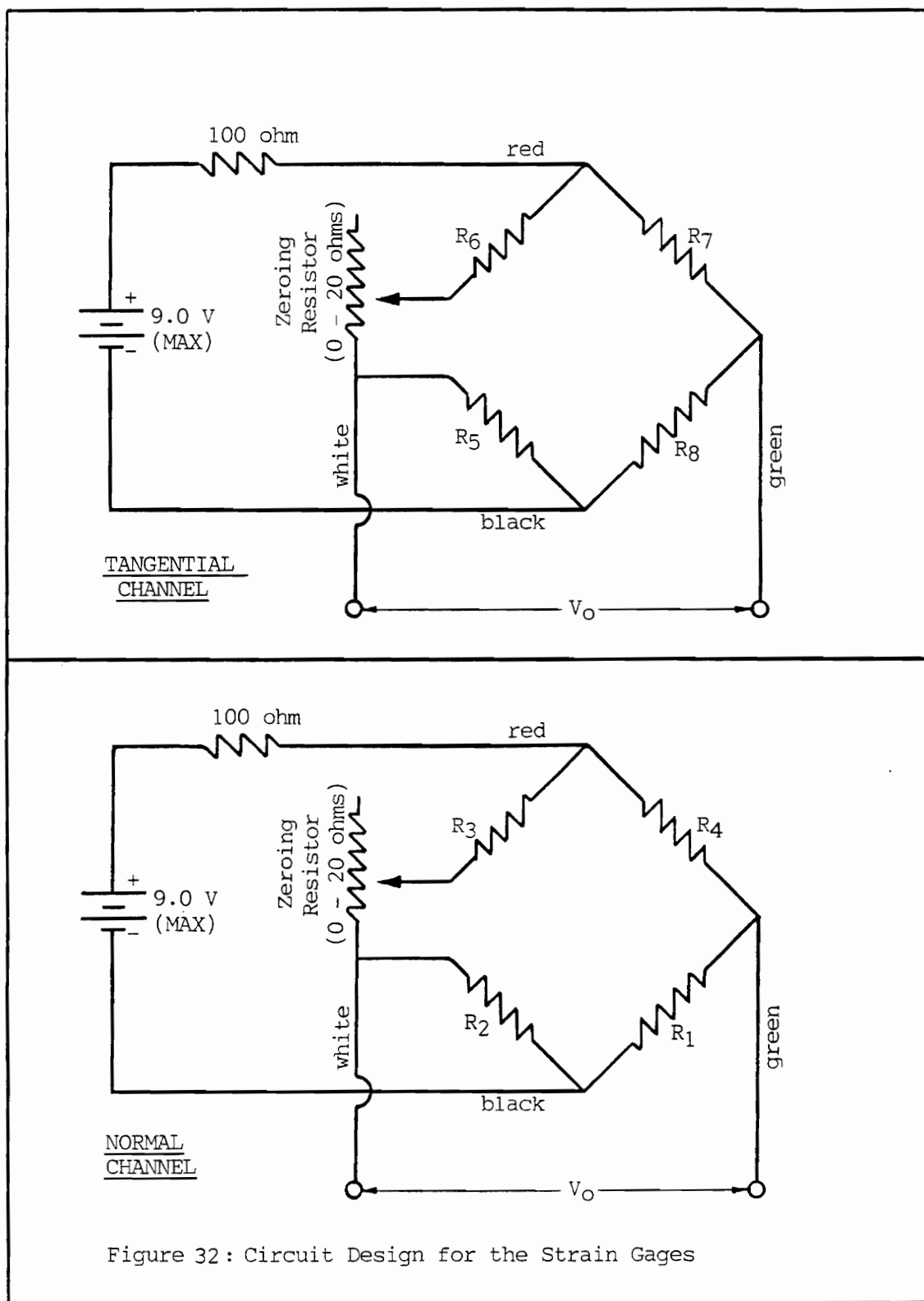


Figure 32 : Circuit Design for the Strain Gages

A 9.0 volt electromotive force is applied across each bridge using a DC power supply. Voltage output from each bridge is monitored as shown in Fig. 32. This output is a function of the input voltage, and is also a function of each gage's resistance to current flow. However, a gage's resistance changes by an amount ΔR when it is placed in strain. Equation 30 shows this relationship between ΔR and an induced strain:

$$\frac{\Delta R}{R} = (G.F.)(\epsilon) \quad (30)$$

where,

ΔR = change in resistance of a gage due to an induced strain.

R = resistance of an unstrained gage

G.F. = gage factor

ϵ = induced strain (change in length per total length)

An external variable resistor (zeroing resistor) is installed in each bridge as shown in Fig. 32. These resistors are used to compensate for differences in the resistances of the gages. As stated previously, the gages are purchased from the manufacturer in matched sets of four. This means that their resistances are essentially equal prior to installation. However, when they are installed, their resistances do not remain equal. These differences in resistance arise from compressive stresses that are induced when the gages are glued to the ring. Thus, each wheatstone bridge is said to be in an "unbalanced state". The zeroing resistors are then used to "balance" each bridge, and obtain a reference voltage of zero volts.

The equation below expresses the voltage output from the tangential channel of the strain ring relative to the input voltage:

$$\frac{V_{oT}}{V_i} = \left[\frac{R_z + (R_6 + \Delta R_6)}{R_z + (R_6 + \Delta R_6) + (R_5 + \Delta R_5)} \right] - \left[\frac{(R_7 + \Delta R_7)}{(R_7 + \Delta R_7) + (R_8 + \Delta R_8)} \right] \quad (31)$$

where,

V_{oT} = output voltage from the tangential channel

V_i = input voltage (9.0 volts)

R_z = resistance of the zeroing resistor (0 - 20 Ω)

R_5, R_6, R_7, R_8 = resistance of each unstrained strain gage

$\Delta R_5, \Delta R_6, \Delta R_7, \Delta R_8$ = changes in the resistance of each gage as defined by Eq. 30

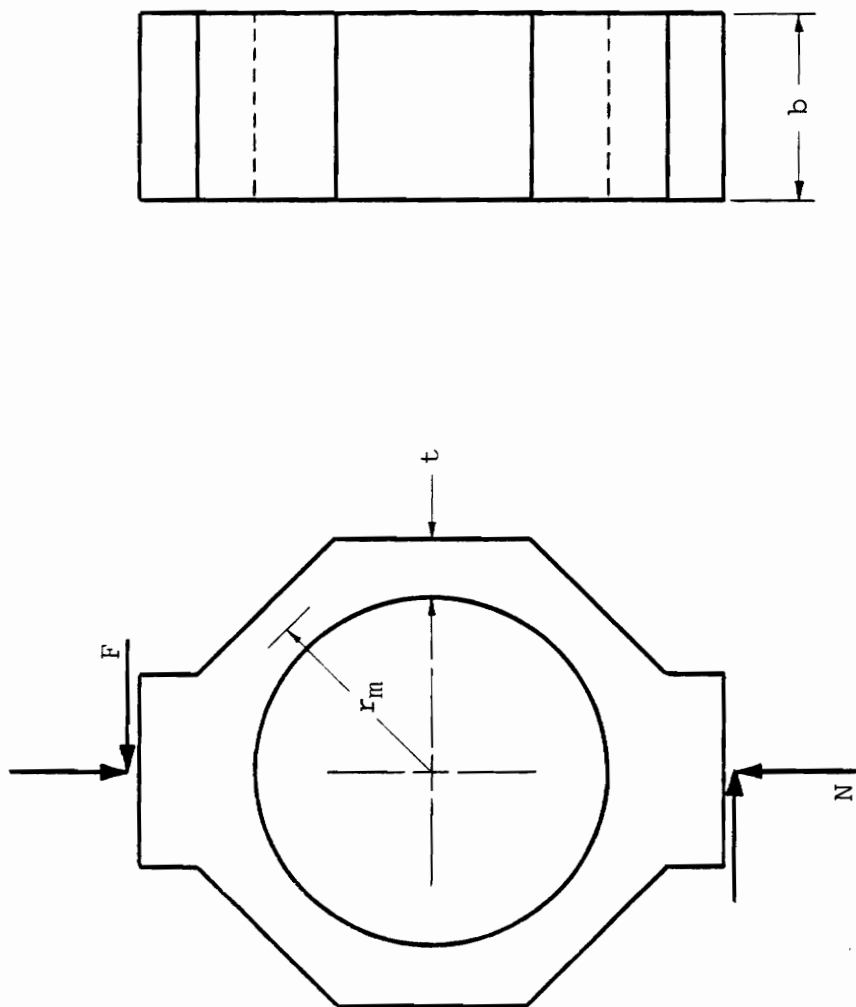
Since $V_i, R_z, R_5, R_6, R_7,$ and $R_8,$ stay constant during an experiment, the only change in voltage output comes from the induced strains on each gage. These strains cause the changes in resistance, ΔR , and are directly proportional to the applied tangential load on the ring. Cook and Rabinowicz determined the following empirical relationships between induced strain and applied load. The geometric terms shown in these equations are defined in Fig. 33.

$$\epsilon_{50} = 1.4 \frac{Fr_m}{Ebt^2} \quad (32)$$

$$\epsilon_{90} = 0.7 \frac{Nr_m}{Ebt^2} \quad (33)$$

where,

ϵ_{50} = strain on a gage mounted at $\theta = 50$ degrees. These gages are positioned to measure a tangential force, F .



F: Tangential Force due to Friction
N: Normal Load

Figure 33: Geometric Terminology for the Strain Ring [89]

ϵ_{90} = strain on a gage mounted at $\theta = 90$ degrees. These gages are positioned to measure a tangential force, N.

E = modulus of elasticity

Deflection equations were also determined by Cook and Rabinowicz. These are given below:

$$\delta_F = 3.7 \frac{Fr_m^3}{Ebt^3} \quad (34)$$

$$\delta_N = 1.0 \frac{Nr_m^3}{Ebt^3} \quad (35)$$

where,

δ_F = horizontal deflection due to a tangential force, F

δ_N = vertical deflection due to a tangential force, N

In lieu of calculating strains on the ring using Eqs. 32 and 33, the ring was calibrated using techniques described in Appendix B. Calibration equations and confidence intervals can also be found in this appendix. Fig. 34 shows calibration curves obtained for the tangential channel. This figure shows that the output from the gages changes significantly with room temperature. This is a common characteristic of semiconductor strain gages and is described in reference [90]. To account for this characteristic, all experiments were performed at 72 F. At this temperature, the output from the tangential channel is approximately 1 millivolt per newton. Furthermore, as shown in Fig. 34, the voltage output at 72 F is higher than the output at 80 F. To monitor the ambient temperature of the strain ring, a thermistor was placed in the vicinity of the strain ring. This thermistor is similar to the one described in Section 3.4.

An important design characteristic of the strain ring is the separation of normal and tangential channels. In other words, when a tangential force is applied to the ring, the electrical output from

the normal channel should be zero. The converse relationship should also be true. When a normal force is applied to the ring, electrical output from the tangential channel should be zero.

Since separation of channels is an **ideal** characteristic of strain rings, it is important to know the **real** effect of one channel on the other.

Tables 5 and 6 show these effects, and can be described as follows:

- Table 5 shows voltage output from the normal and tangential channels when a *normal force* is applied to the strain ring.
- Table 6 shows voltage output from the tangential and normal channels when a *tangential force* is applied to the strain ring.

First, Table 5 will be discussed. Ideally, the output from the tangential channel should be zero when a normal force is applied. For the real case, Table 5 shows that there is a small signal in the tangential channel when a normal force is applied. However, by using the zeroing resistor, output from the tangential channel can be rezeroed after application of a normal force to the ring. Therefore, during an experiment, output from the tangential channel is only due to frictional effects at the interface; the effect of normal load is "zeroed-out".

Table 6 shows the effect of a tangential load on the normal channel. Ideally, the output from the normal channel should be zero when a tangential force is applied. However, output from the normal channel is 17 mv when a 40 N tangential load is applied. As shown in Table 5, a 40 N normal load only produces 18 mv in the normal channel. This means that the normal channel's response to a tangential force is about the same as its response to a normal force. Since output from the normal channel is rezeroed after a normal load is applied, the normal channel indicates mainly tangential loads during an experiment. This is not surprising since the normal load is in fact constant. As a consequence, only output from the tangential channel of the strain ring is utilized in this thesis.

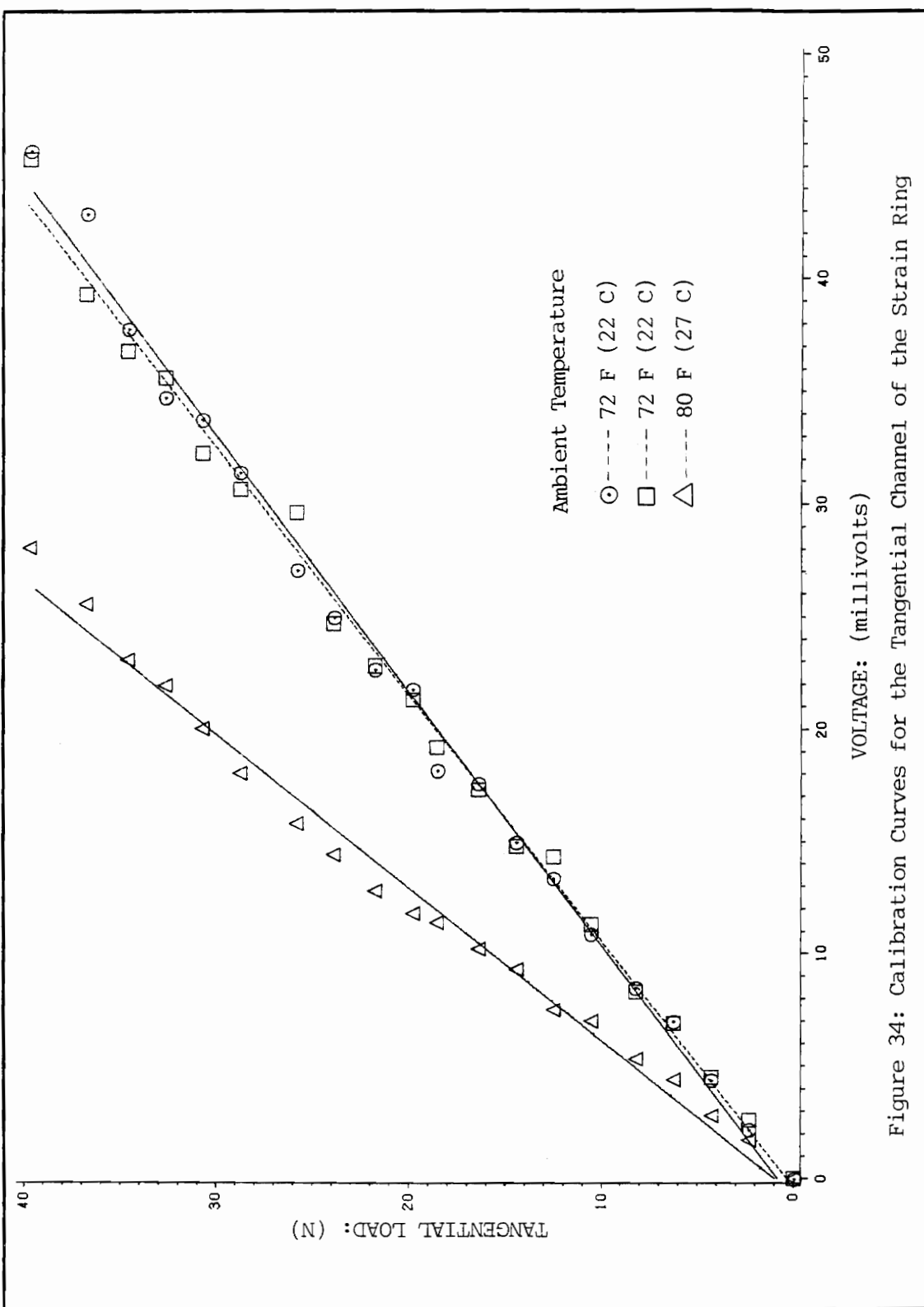


Figure 34: Calibration Curves for the Tangential Channel of the Strain Ring

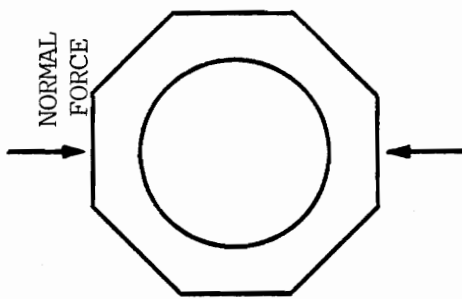
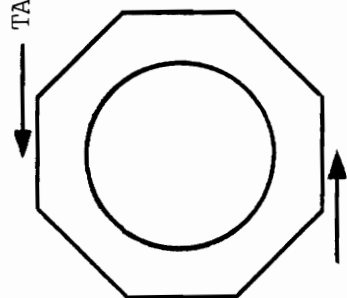
Table 5 : Electrical Output from the Two Channels of the Strain Ring when a <u>Normal Force</u> is Applied				
NORMAL FORCE (N)		NORMAL CHANNEL (millivolts)	TANGENTIAL CHANNEL (millivolts)	
0		0.	0.1	
10		4.3	0.7	
20		8.9	1.6	
30		13.	2.8	
40		18.	3.8	

Table 6 : Electrical Output from the Two Channels of the Strain Ring when a <u>Tangential Force</u> is Applied				
TANGENTIAL FORCE (N)		TANGENTIAL CHANNEL (millivolts)	NORMAL CHANNEL (millivolts)	
0		0.	0.	
10		11.	4.2	
20		21.	7.5	
30		32.	12.	
40		45.	17.	

3.7 *The Data Acquisition System*

Figure 8 is a schematic diagram of the data acquisition system used to store, monitor, and display data from the measurement devices discussed in previous sections. Perhaps the most important piece of equipment used in this data acquisition system is the FM "reel-to-reel" magnetic tape recorder. Its primary function is to receive and store up to seven signals from various measurement devices used during an experiment. These signals can subsequently be "played-back" on a chart recorder or oscilloscope. In addition, the analog signals can be converted to digital signals using the analog-to-digital converter located in an IBM personal computer, [76,77]. Data can then be stored on floppy disks, and transferred to mainframe computers for further processing.

The FM tape recorder is shown in Fig. 35. Some specifications for this tape recorder are shown below:

usable voltage range: -1.4 volts to 1.4 volts

flat frequency response: 20 Hz - 10 KHz

One aspect of the FM tape recorder that was initially addressed in reference [77] is the attenuation factors associated with each of the recorder's channels. This means that the output signal from the FM tape recorder is not the same as the input signal. Therefore, the FM tape recorder was calibrated using the technique described in Appendix E. Results from this calibration are also shown in this appendix, along with regression equations that can be used to correct for the attenuation of the input signals. These regression equations are included in a computer program used to process the data when it is sampled from the tape recorder.

The signals monitored by each channel are shown below:

- 1 - Radiance from the AC/DC channel of the infrared microscope

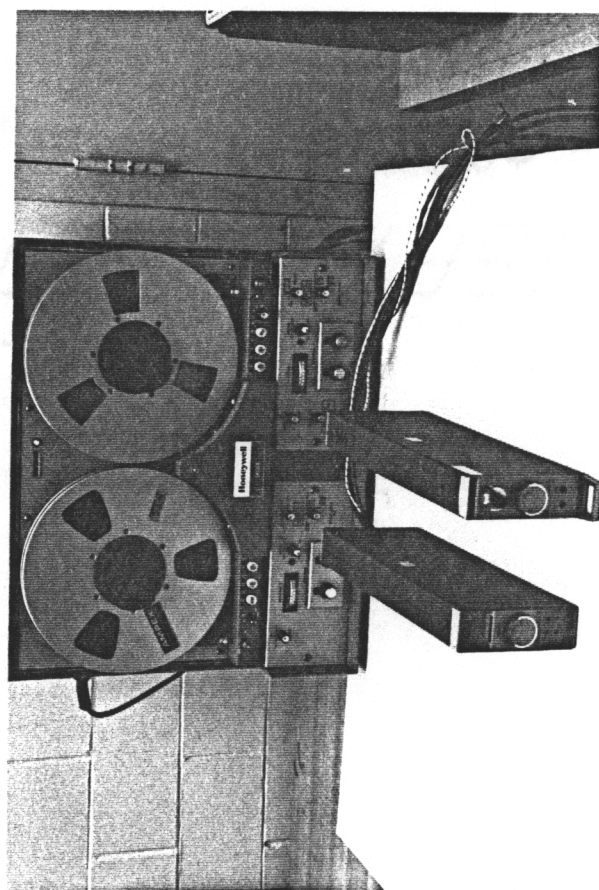


Figure 35: The FM Tape Recorder and Hewlett-Packard Amplifiers

- 2 - X position of the infrared microscope
- 3 - Y position of the infrared microscope
- 4 - Output from the normal channel of the strain ring
- 5 - Output from the accelerometer
- 6 - Radiance from the DC channel of the infrared microscope
- 7 - Output from the tangential channel of the strain ring, (friction)

3.8 Experimental Procedure

Due to the complexity of the instrumentation and measurement devices used in this research, the delineation of a repeatable experimental procedure is extremely important. This procedure is discussed in the following paragraphs.

Prior to beginning an experiment, the surfaces of the ceramic specimens are ultrasonically cleaned using methanol and hexane. Methanol is used to remove any inorganic species present on the surface whereas hexane is used to remove any organic species present on the surface. To be more specific about the cleaning procedure, the ceramics are first placed in a bath of methanol and ultrasonically cleaned for five minutes. After rinsing the specimens with methanol, they are placed in a bath of hexane and ultrasonically cleaned for another five minutes. After rinsing with hexane, the specimens are cleaned again with methanol. The sapphire disks are also cleaned in this manner.

After installing the sapphire disk and test specimen, the specimen is loaded against the sapphire disk. Then, the contact region is located using the optical channel of the infrared microscope. An external light source must be used to find this contact region since the light source in the microscope

is too dim. Furthermore, the contact region is actually located by finding the Newton ring patterns associated with the contact region, see Fig. 36.

Once the contact region is located, the microscope is focused at the interface and positioned at the center of the Newton ring patterns. At this time, the x and y LVDT's are zeroed using the threaded rods attached to the x-y table. In this way, the coordinate system for scanning becomes a cartesian system with the origin at the center of the contact region. Figure 37 shows the relationship between the cartesian axes, and the location of the shaker and microscope.

Now that the infrared microscope has been positioned over the contact region, the dewar flask can be filled with liquid nitrogen, and the microscope can be turned on. In addition to the microscope, the rest of the instrumentation is turned on and allowed to warm-up for at least one-half hour. During this period, the ambient temperatures of the microscope and strain ring are monitored using thermistors. As described previously, the strain ring's output is a function of ambient temperature. Therefore, the laboratory is kept at 22 C to ensure that the calibration equations for the strain ring are correct. The ambient temperature of the microscope is usually about 1 - 2 C less than the ambient temperature of the strain ring. This can be attributed to the 77 K liquid nitrogen filled dewar located on the microscope. Even though this dewar is insulated from the rest of the microscope's body, it does affect the temperature of the microscope's upper cavity.

After recording the ambient temperatures of the ring and microscope, the strain ring output is zeroed. Then, the FM tape recorder is turned on to record reference voltage levels from all the measurement devices. After 30 seconds, the oscillation of the sapphire disk is initiated by turning up the vibration amplitude of the electromagnetic shaker. Next, the position of the microscope over the test specimen is checked to ensure that it is still at the center of the contact region. If it is not, the microscope is repositioned at the center. After the sapphire disk has oscillated for one minute, the microscope's target spot is moved over the contact region as shown in Fig. 38. After a total of two minutes, the motion of the sapphire disk is stopped. The FM tape recorder is allowed to run for another 30 seconds to measure the cooling response at the interface.

After an experiment, the test specimen is carefully removed and stored for future surface analysis. The sapphire disk is removed and cleaned using the procedure described previously.

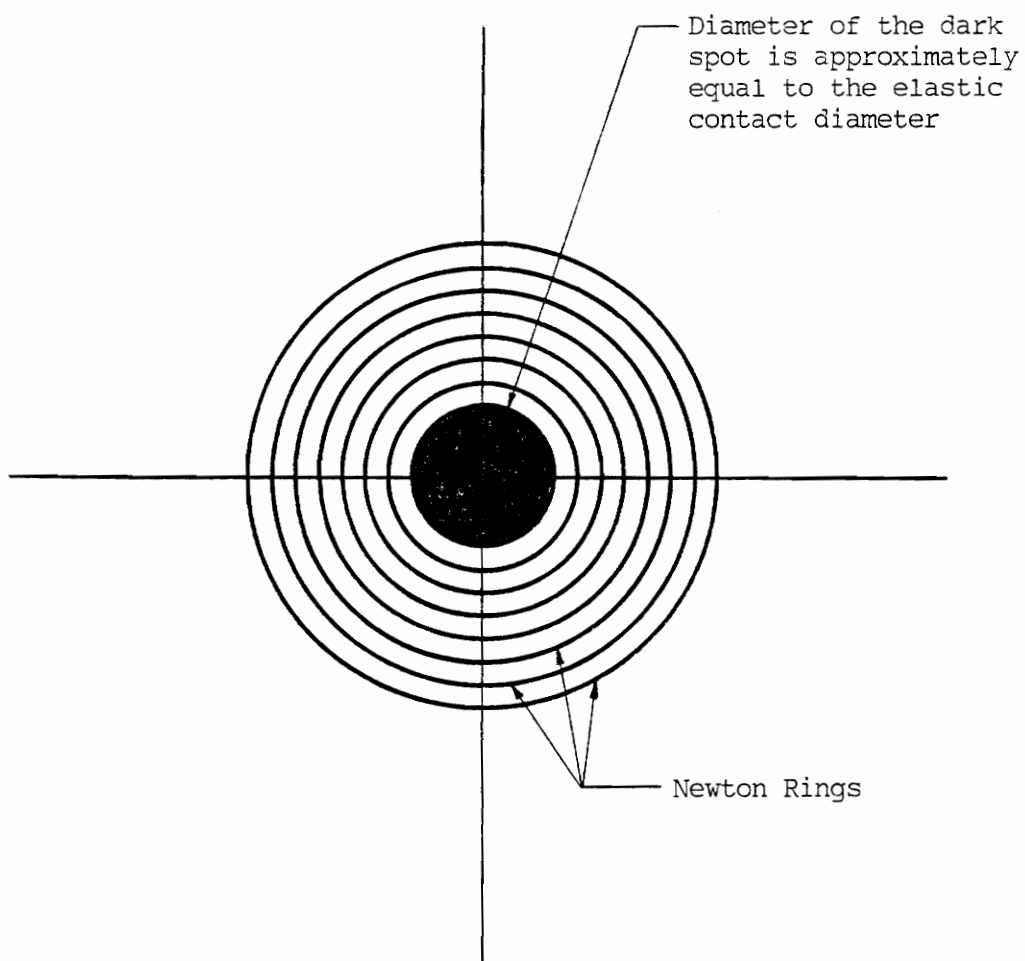


Figure 36: Arrangement of Newton Rings at the Contact Region Before an Experiment

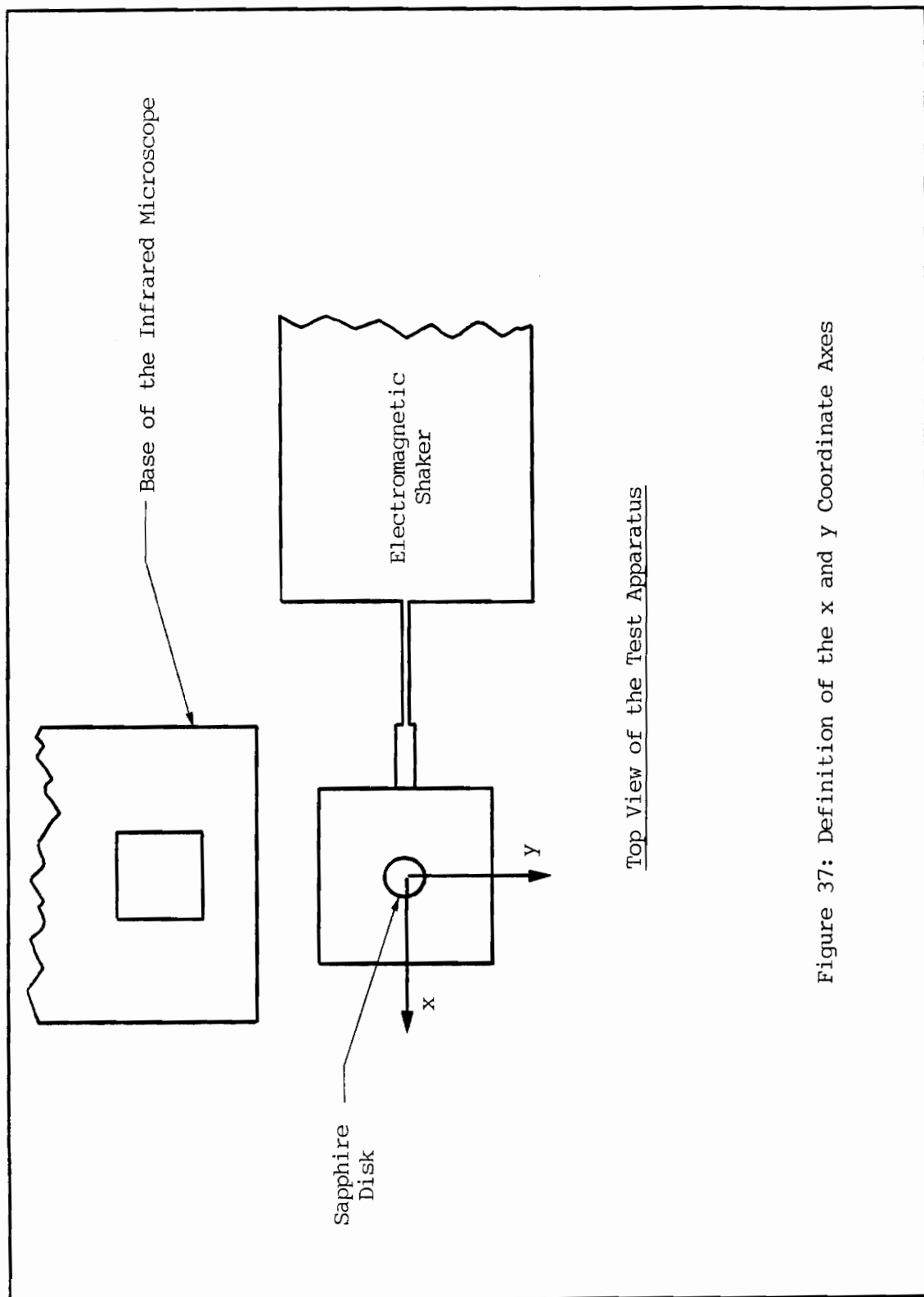


Figure 37: Definition of the x and y Coordinate Axes

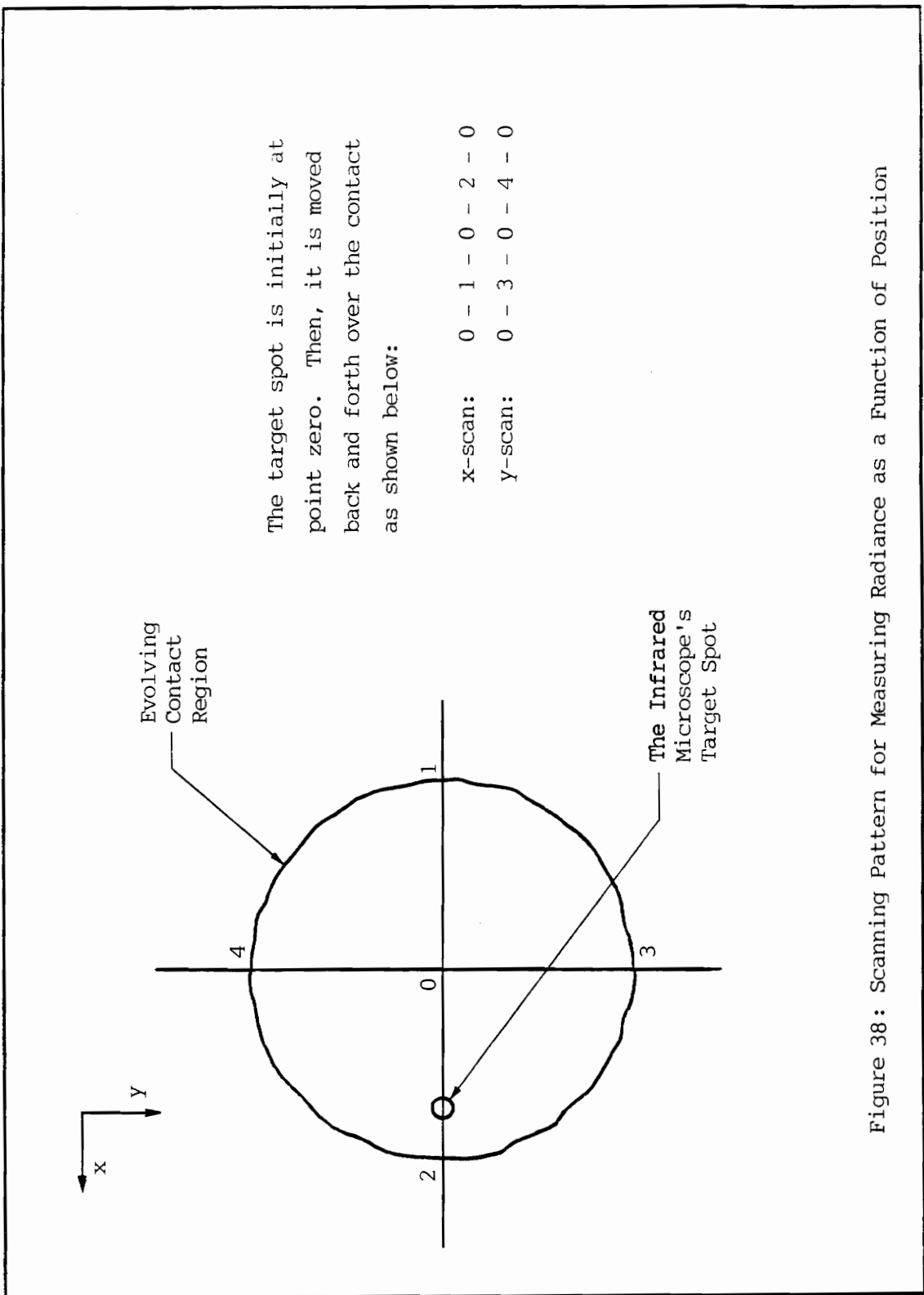


Figure 38: Scanning Pattern for Measuring Radiance as a Function of Position

A large amount of material transfer and/or wear usually occurs on the sapphire disk. Therefore, a different contact region must be selected if the disk is used for another experiment.

3.8 Test Conditions

All experiments were performed under dry, unlubricated conditions. The zirconia-on-sapphire experiments were performed under the following test conditions:

DISK: sapphire

BALL: zirconia

LOADS: 20 N and 40 N

FREQUENCIES: 100 Hz and 195 Hz

INITIAL AMPLITUDES: 65 μm and 130 μm (peak)

TIME PERIOD FOR EXPERIMENTS: two minutes

All possible combinations of loads, frequencies, and amplitudes were used, yielding a total of eight experiments. Replicate experiments were performed for the high frequency-high amplitude cases at both loads. In addition, replicate experiments were performed as required when certain problems with the test apparatus and data acquisition system yielded questionable data.

As summarized below, experiments were also performed using four different materials. To generate the highest velocity, high frequencies and amplitudes were used for these experiments. Also, loads of 20 N and 40 N were used for comparison purposes.

DISK: sapphire

BALL MATERIALS: zirconia, tungsten carbide, alumina, sapphire

LOADS: 20 N and 40 N

FREQUENCY: 195 Hz

INITIAL AMPLITUDE: 130 μm (peak)

TIME PERIOD FOR EXPERIMENTS: two minutes

All possible combinations of materials, loads, frequency, and amplitude were used yielding a total of eight experiments. Replicates were performed for the zirconia experiments, and initial experiments had to be performed for the other three materials to determine amplification requirements. However, data from these initial experiments were not adequately captured on the FM tape because inappropriate amplifier settings were used.

4. RESULTS AND DISCUSSION

4.1 Emissivity Results

Prior to discussing surface temperature results, the emissivities measured for the different materials will be presented. The procedure for measuring emissivity is summarized in Section 3.3, and all emissivity data presented in the following paragraphs are statistical summaries of the large data sets that can be found in Appendix J. Also, two different assumptions were made with regard to the emissivity of the black spot: 0.90 and 0.95. Therefore, two emissivity values were calculated for each set of measurements made.

Emissivity results for zirconia will be presented in detail, since the majority of the experiments summarized in this thesis were performed using this material. In addition, emissivity measurements made before and after a zirconia-on-sapphire experiment will be discussed. The “after-experiment” emissivity measurements will show the effect of surface roughness on the emissivity of the material. Emissivity results will also be presented for the other materials used in this work: tungsten carbide, alumina, and sapphire. Lastly, transmissivity results obtained for the sapphire disk will be presented. The procedure for making transmissivity measurements is discussed in Appendix I. Transmissivity measurements were performed both before and after an experiment.

4.1.1 Emissivity Measurements for Zirconia

Before performing any zirconia-on-sapphire experiments, initial emissivity measurements were made using unworn zirconia test specimens. These initial emissivity measurements were made at fifteen temperature levels ranging from 36 C to 76 C. In this temperature range, the emissivity of the zirconia test specimen does not change appreciably. Therefore, an average emissivity value was calculated for each of the two black spot emissivity assumptions. These averages are shown in Table 7 along with the 95% confidence intervals, and the standard deviations. The complete data set can be found in Table J-1 in Appendix J. For the two assumed black spot emissivities, average emissivities of $0.71 \pm .004$ and $0.68 \pm .004$ were calculated. Therefore, there is little difference between choosing a black spot emissivity of 0.95 or 0.90. Furthermore, the small range of the data, and the low standard deviations show that the effect of specimen temperature is negligible. For instance, assuming a black spot emissivity of 0.95, the standard deviation is only 0.0078, and the 95% confidence interval ranges from 0.706 to 0.714.

The emissivity of zirconia was also measured after an experiment to determine the effect of surface roughness on the emissivity of the test specimen. An optical macrograph of this test specimen is shown in Fig. 39. The zirconia wear scar shown in this figure was created during a one-minute experiment under the following test conditions: the normal load was 40 N, and the sapphire disk was oscillated at a frequency of 200 Hz with a peak amplitude of 130 μm . The procedure used to make emissivity measurements within the wear scar is nearly identical to the procedure described in Section 3.3. However, instead of just measuring radiance from the painted and unpainted (unworn) regions, radiance measurements were also made at points A, B, C, D, and E within the wear scar shown in Fig. 39. Measurements were made at temperatures ranging from 43 C to 65 C. Since the variation of emissivity with temperature is again small, the average emissivity was found for each position. These results are summarized in Table 8. This table also shows the 95% confidence intervals for each of the six measurement positions. These confidence intervals are shown graphically as dashed lines with an asterisk, *, locating the average emissivity calculated at each position.

Table 7 : Summary of Emissivity Results for an Unused Zirconia Specimen (see Table J-1 in Appendix J for the complete data set) (Temperature Range: 36 - 76 C)			
Assumed Emissivity of Black Spot	Number of Measurements	Ave. Emissivity ± 95% Confidence Interval	Standard Deviation
0.95	15	0.71 ± .004	0.0078
0.90	15	0.68 ± .004	0.0074

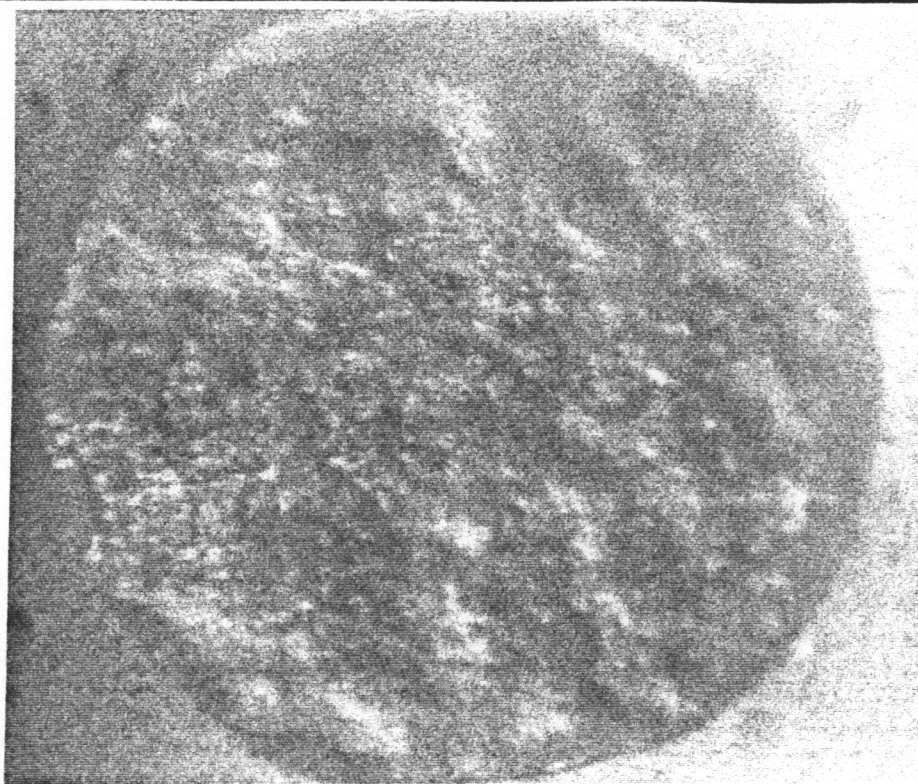


Figure 39a: Optical Macrograph of the Zirconia Test Specimen used for Emissivity Measurements

Major Diameter of Wear Scar = 851 μm

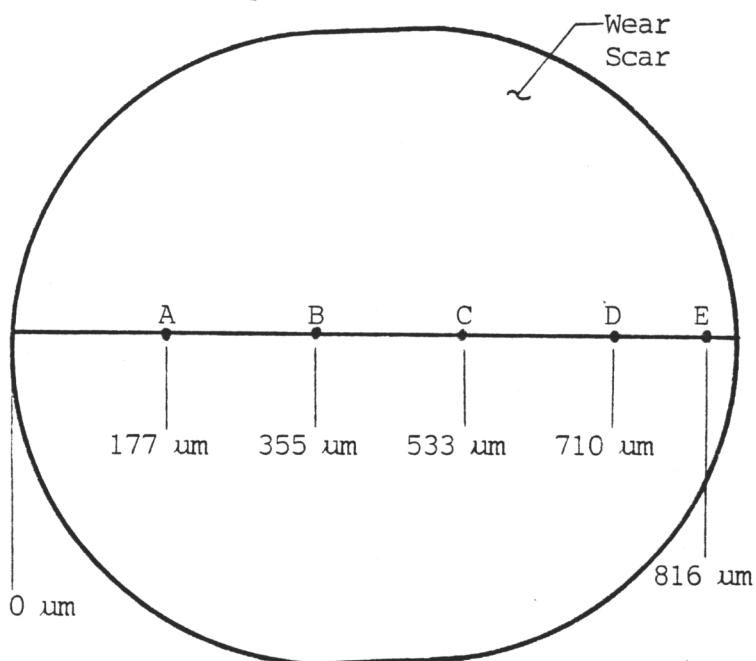
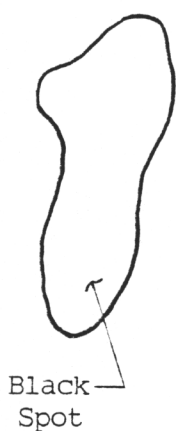


Figure 39b: Sketch of Contact Region Showing Points where Emissivity was Measured

Table 8: Summary of Emissivity Results for a Worn Zirconia Specimen (see Table J-2 in Appendix J for the complete data set) (Temperature Range: 43 - 65 C)			
Position of Microscope's Target Spot	Ave. Emissivity ± 95% Confidence Interval §	Standard Deviation	Individual 95% Confidence Intervals
Unworn Area	0.50 ± .02	0.020	(-----*-----)
Point A	0.54 ± .02	0.017	(-----*-----)
Point B	0.52 ± .02	0.021	(-----*-----)
Point C	0.54 ± .02	0.021	(-----*-----)
Point D	0.57 ± .02	0.013	(-----*-----)
Point E	0.51 ± .02	0.020	(-----*-----)
§ --- assumed emissivity of black spot is 0.90			(-----*-----) 0.500 0.525 0.550 0.575

The data summarized in Table 8 show that the lowest emissivity ($0.50 \pm .02$) was measured for the unworn area, and the highest emissivity ($0.57 \pm .02$) was measured for the worn area. Even though the overall spread of the distribution is small (< 0.1), there is some variation within the worn area of the specimen. In fact, the emissivity measured at point E is almost equal to the emissivity of the unworn area. Upon examination of Fig. 39, however, point E appears to be a relatively smooth area within the wear scar. When this fact is taken into account, the emissivity at point E is expected to be lower than the emissivities measured at the rougher areas of the wear scar.

To quantify the variation in emissivities measured at each of the positions, a simple one-way analysis of variance was performed to determine if there is a significant difference between the emissivities measured at each position. The result of the F-test performed in this analysis shows a 99.9% probability that the emissivities are different. This difference can be readily seen in Table 8. Even though the ranges of the confidence intervals in this table show some overlap, there are areas within the wear scar that have different emissivities. Furthermore, there is an obvious difference between the emissivity of the unworn area and the emissivity of certain points within the wear scar.

As an addition to the experiment described previously, more emissivity data was taken at the unworn area of the disk, and at point A within the wear scar. The temperature range was 43 C to 72 C, and emissivity increased by less than 0.1. Therefore, average values of emissivity were again calculated for each of the two positions based on black spot emissivities of 0.95 and 0.90, respectively. Table 9 summarizes this data. 95% confidence intervals are also shown in this table, and they show that there is a difference between the emissivity of the unworn area and the emissivity at point A within the wear scar. Assuming a black spot emissivity of 0.95, the average emissivity of the unworn area was determined to be $0.56 \pm .02$, while the average emissivity of the worn area was determined to be $0.60 \pm .02$.

As a final note to this summary of zirconia emissivity measurements, it should be pointed out that the experiment summarized in Table 7 shows an average "unworn" emissivity of 0.68 assuming a black spot emissivity of 0.90.

Table 9 : Summary of Emissivity Results for a Worn Zirconia Specimen (see Table J-2 in Appendix J for the complete data set) (Temperature Range: 43 - 72 C)				
Assumed Emissivity of Black Spot	Position of Microscope's Target Spot	Ave. Emissivity ± 95% Confidence Interval	Standard Deviation	Individual 95% Confidence Intervals
0.95	Unworn Area	0.56 ± .02	0.032	(-----*-----)
0.95	Point A	0.60 ± .02	0.039	(-----*-----)
0.90	Unworn Area	0.53 ± .02	0.031	(-----*-----)
0.90	Point A	0.57 ± .02	0.037	(-----*-----)
				0.50 0.55 0.60

This is significantly higher than the "unworn" emissivity shown in Table 8 which equals 0.50. Furthermore, the data used to calculate the average emissivity of 0.68 has a standard deviation of 0.0074. This is less than one half the standard deviation calculated for an emissivity of 0.50, ($\sigma = 0.020$). Therefore, there is obviously a source of variation in this type of emissivity measurement that has not been accounted for. Since the material and temperature ranges used to perform the two zirconia experiments are similar, the most probable source of variation is the thickness and roughness of the black paint used to simulate a blackbody source. More information on this subject can be found in the recommendations section of this thesis. In lieu of the fact that significantly different emissivities were measured for zirconia during separate experiments, two emissivities will be used when surface temperatures are calculated in Section 4.2. These emissivities represent the extrema of emissivities measured, and are equal to 0.71 and 0.51, respectively. (Note, 0.51 was chosen because it represents the lowest average emissivity measured for the worn area of the zirconia test specimen.)

The range of emissivities measured for zirconia (0.50 - 0.71) seem reasonable when compared to values found in the literature. As shown in Table 10, emissivities for zirconia are listed in reference [91] for the following temperatures: 0 K, 700 K, 1200 K, 2000 K, and 2800 K. These temperatures do not directly correspond to the 316 - 350 K range used for the experimental measurements. However, the measured emissivity values do compare well with the literature values. For instance, at 0 K, reference [91] lists the emissivity as 0.82. At 700 K, reference [91] lists the emissivity as 0.61-0.68; and, at 1200 K, reference [91] lists the emissivity as 0.4. The experimentally measured values range from 0.50-0.71 at 316 -350 K, and lie within the range of the literature values listed above. The comparison is not perfect, but emissivities for different kinds of zirconia are listed in Table 10. The zirconia used in this research is partially-stabilized, and might have slightly different properties than the other two types of zirconia listed in Table 10. However, the main constituents of zirconium and oxygen are present in all three types of zirconia, and any interstitial constituents such as stabilizing compounds are likely to have a negligible effect on emissivity. In conclusion, even though the comparison between the literature values and the values

presented herein is inexact, it does demonstrate that the experimentally measured emissivities for zirconia are in an appropriate range.

4.1.2 Emissivity Measurements for Tungsten Carbide

The emissivity of tungsten carbide was measured using unworn test specimens. The use of unworn specimens in lieu of worn tungsten carbide specimens is justified by the following reasons. First of all, it is important to know the emissivity of a material **before** running an oscillating contact experiment. This is due to the fact that the voltage output from the infrared microscope is proportional to the emissivity of the test specimen. Thus, a low emissivity material tends to produce a low voltage output, and an amplifier might be needed to adequately capture the data on FM tape. This is the case for tungsten carbide. Secondly, as will be shown in subsequent sections of this thesis, when compared to zirconia, the degree of surface degradation is substantially smaller for tungsten carbide. Since zirconia showed only a very small change in emissivity with wear, the effect of wear on the emissivity of tungsten carbide should be even smaller.

Two separate emissivity experiments were performed for tungsten carbide, and measurements were made at temperatures ranging from 36 C to 120 C. Both of these experiments showed a negligible effect of temperature on the emissivity of tungsten carbide. Therefore, average values of emissivity were calculated for each of these experiments. These averages are shown in Table 11, along with the 95% confidence intervals and standard deviations. The complete data sets for tungsten carbide can be found in Tables J-4 and J-5 of Appendix J. In reference to Table 11, average emissivities of $0.39 \pm .02$ and $0.36 \pm .03$ were obtained for each of the two data sets. (Note, these values were obtained assuming a blackbody emissivity of 0.90. If 0.95 is assumed, the measured emissivity of tungsten carbide increases by only 0.02.)

Since the emissivities for the two data sets have overlapping confidence intervals, it can be said that there is very little variation between the two data sets. This negligible variation in tungsten carbide emissivity is in sharp contrast with the large variation observed for zirconia. In fact, the

Table 10: Comparison with Literature Values - Zirconia Emissivity Results	
Experimentally Measured Emissivity	Emissivities for Zirconia from reference [91]
0.50 - 0.71 @ 316 - 350 K§	0.82 @ 0 K¶ 0.61 - 0.68 @ 700 Kε 0.4 @ 1200 K¶ 0.5 @ 2000 K¶ 0.25 - 0.4 @ 2800 Kε
ε --- plasma sprayed zirconia ¶ --- fully stabilized zirconia § --- partially stabilized zirconia	

zirconia emissivity measurements showed a variation of 0.21 between experiments; whereas tungsten carbide showed a variation of only 0.03. The difference could be due to the nature of the painted black spot used as a reference point.

The two data sets for tungsten carbide used the same "blackbody" reference point; whereas the two data sets for zirconia used different "blackbody" reference points. As will be discussed in the recommendations section, to facilitate accurate emissivity (and temperature) measurements, an alternative method to the "painted blackbody" might yield more repeatable results.

4.1.3 Emissivity Measurements for Alumina

The emissivity of alumina was measured using unworn specimens. The justification for using an unworn versus worn alumina specimen is the same as the justification described for tungsten carbide. Before conducting an oscillating contact experiment, the emissivity of the material must be known to determine if the voltage output from the infrared microscope will be high enough to facilitate recording the data on FM tape. Furthermore, both zirconia and alumina are oxides, and the small emissivity variation with wear recorded for zirconia should also be true for alumina. Twenty-two emissivity measurements were made using an alumina test specimen at temperatures ranging from 40 C to 150 C. The effect of temperature was negligible and average emissivities were calculated as shown in Table 12.

Assuming a black spot emissivity of 0.95, an average emissivity of 0.76 was calculated with a small confidence interval of only ± 0.02 . For a black spot emissivity of 0.90, the average emissivity of alumina decreases a little to 0.72 ± 0.02 . These results compare well with emissivity values found in the literature. Table 12 shows emissivity values for alumina at three different temperatures: 100 K, 1000 K, and 1600 K. The values of emissivity at these temperatures are 0.75, 0.53, and 0.41, respectively. The average emissivities measured in this research range from 0.72 - 0.76, and were determined in the 313 K - 423 K temperature range. It can be seen that the experimentally measured emissivities are close to the literature value of 0.75 specified for 100 K. Even though this

Table 11: Summary of Emissivity Results for Tungsten Carbide (see Tables J-4 & J-5 in Appendix J for the complete data set) (Temperature Range: 43 - 120 C)				
Data Set No. 1				
Assumed Emissivity of Black Spot	Number of Measurements	Ave. Emissivity $\pm$ 95% Confidence Interval	Standard Deviation	
0.95	11	0.41 $\pm$.02	0.031	
0.90	11	0.39 $\pm$.02	0.029	
Data Set No. 2				
Assumed Emissivity of Black Spot	Number of Measurements	Ave. Emissivity $\pm$ 95% Confidence Interval	Standard Deviation	
0.95	20	0.38 $\pm$.03	0.053	
0.90	20	0.36 $\pm$.03	0.050	

comparison is not exact, it demonstrates that the experimentally measured emissivity values for alumina are in the correct range.

4.1.4 Transmissivity Measurements for the Sapphire Disk

Prior to discussing how the emissivity of a *spherical* sapphire test specimen was calculated, the transmittance measurements for the sapphire *disk* will be presented. During an experiment, there is sometimes a great deal of degradation and/or material transfer to the sapphire disk. This fact is readily illustrated in Fig. 40. This figure depicts the surface of a sapphire disk after a one-minute zirconia-on-sapphire experiment. The normal load was 20 N, and the sapphire disk was oscillated at a frequency of 195 Hz with a peak amplitude of 130 μm . The white area in the center of the picture could represent transferred zirconia material and/or actual wear of the sapphire disk. Since the sapphire disk is transparent at the beginning of an experiment, this whitish area represents an increase in the opacity of the disk. Therefore, the transmittance of the sapphire disk is expected to decrease during an experiment with zirconia. To measure this decrease, the procedure described in Appendix I for transmittance measurements was used with a slight modification. Transmittance measurements were not only made in the unused area of the sapphire disk, but also within the contact region. Figure 40 depicts the points where these measurements were made. At point A, the microscope was focused on a less opaque area that will be referred to as the fringe area. At points B, C, and D, the microscope was focused on the opaque area.

Prior to making measurements within the contact region, measurements were made in the clear area to determine the disk's transmittance before an experiment. Measurements were made at temperatures ranging from 60 C to 110 C to determine if there is any effect of temperature on the transmittance of the disk. After performing the measurements in this temperature range, the effect of temperature on transmittance appeared to be insignificant. Therefore, an average transmittance was calculated for each of the five measurement points shown in Fig. 40. These averages are listed in Table 13 along with the standard deviations and 95% confidence intervals calculated for each

Table 12: Summary of Emissivity Results for Alumina (see Table J-6 in Appendix J for the complete data set) (Temperature Range: 40 - 150 C)			
Assumed Emissivity of Black Spot	Number of Measurements	Ave. Emissivity ± 95% Confidence Interval	Standard Deviation
0.95	22	0.76 ± .02	0.053
0.90	22	0.72 ± .02	0.050
Experimentally Measured Emissivity	Emissivities for Alumina from reference [91]		
0.72 - 0.76 @ 313 - 423 K	0.75 @ 100 K		
	0.53 @ 1000 K		
	0.41 @ 1600 K		

position. These confidence intervals are graphically depicted as dashed lines with asterisks, *, locating the average values. For the complete data set, see Table I-1 of Appendix I.

As shown in Table 13, the overall spread of the data is relatively small, i.e. 0.693 - 0.830. Furthermore, the variation at each of the measurement positions is small; confidence intervals as low as ± 0.004 were measured. Also, there appears to be a significant difference between the transmittance of the clear area of the disk, and the transmittance of the opaque area of the disk. For instance, the transmittance of the clear area of the disk was determined to be 0.830 ± 0.005 ; whereas the transmittance at point D was determined to be 0.693 ± 0.017 . Results from a simple one-way analysis of variance showed a 99.9% probability that there is a difference between the transmittance values measured at the five points shown in Fig. 40. This difference can easily be seen upon examination of the confidence intervals shown in Table 13.

The highest transmittance value is obviously in the clear area of the disk, and the lowest transmittance values are obviously in the opaque area of the disk. Also, there appears to be a great deal of transmittance variation within the opaque area of the disk. There is little difference between points A and B; but, there is more difference between points A & B and C & D. When Figure 40 is examined more closely, it is apparent that point A is located in the fringe, and points B, C, and D are located in the more opaque area of the contact region. A logical comparison of the transmittance measurements with Fig. 40 should yield the following relationships:

- The clear area of the disk has the highest transmittance, and points A through D can be arranged in decreasing transmittance as follows: $A > B > C > D$.
- The clear area of the disk is the most translucent, and points A through D can be arranged in increasing opacity as follows: $A < B < C < D$.

Although the confidence intervals in Table 13 show the first relationship quite clearly, it is difficult to visually see whether the increasing opacity from points A to D is indeed true. Point A is obviously less opaque than B, C, or D; but the differences between B, C, and D are less apparent.

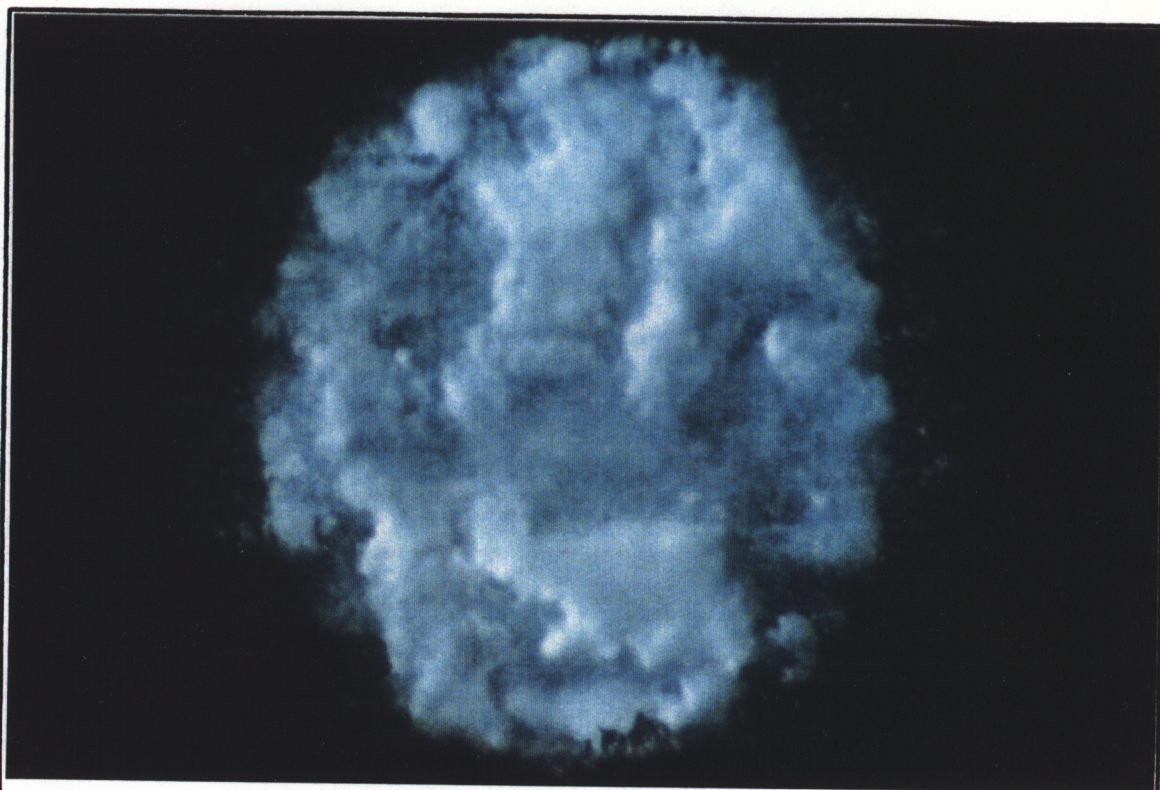


Figure 40a: Optical Macrograph of the Sapphire Disk used for Transmittance Measurements

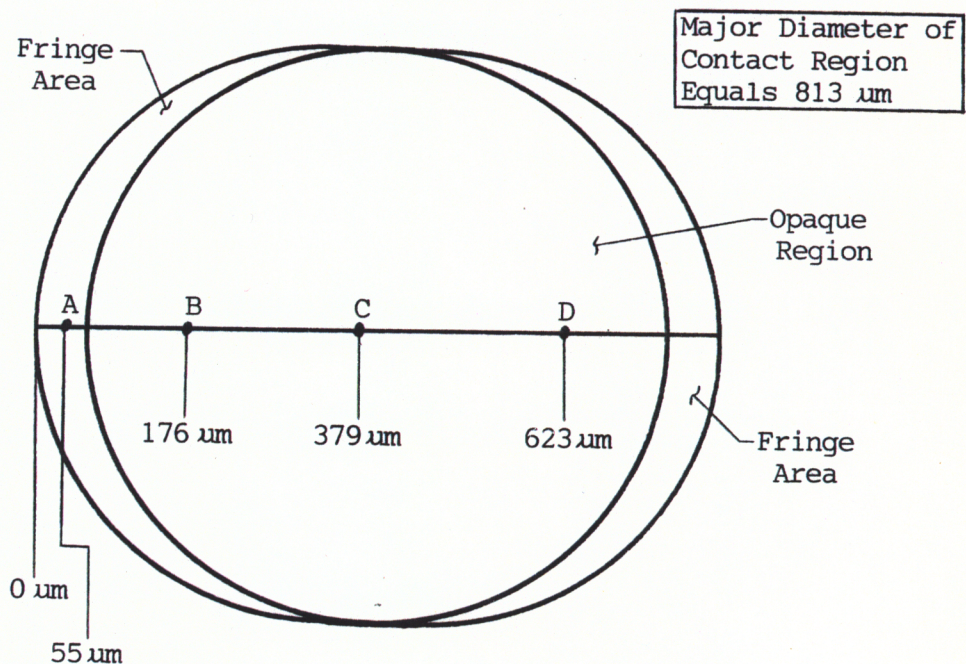


Figure 40b: Sketch of Contact Region Showing Points where Transmittance was Measured

Table 13: Summary of Transmittance Results for the Sapphire Disk (see Table I-1 in Appendix I for the complete data set) (Temperature Range: 60 - 110 C)			
Position of Microscope's Target Spot	Average Transmittance ± 95% Confidence Interval	Standard Deviation	Individual 95% Confidence Intervals
Clear Area	0.830 ± .005	0.0058	(*)
Point A	0.764 ± .005	0.0069	(*)
Point B	0.757 ± .004	0.0051	(*)
Point C	0.726 ± .006	0.0083	(*)
Point D	0.693 ± .017	0.0237	(*)

Perhaps the most important conclusion that can be made from these transmittance measurements is the following: during an experiment using zirconia-on-sapphire, the transmittance of the sapphire disk will decrease, and this decrease must be taken into account when surface temperature calculations are made. As shown in Table 13, the average transmittance of the unused area of the sapphire disk compares well with the average transmittance calculated in reference [21]. The two results are 0.854 and $0.830 \pm .004$, respectively. This close comparison shows that the method of transmittance measurement described in Appendix I is very accurate, and the results can be effectively used for surface temperature measurements.

As a completely independent check of these measurements, Figure 41 is presented. This figure shows the transmittance of a 1 mm thick sapphire disk for the wavelength interval 0.13 to $7.0 \mu\text{m}$. The flat portion of this curve shows that sapphire has a flat transmittance of approximately 0.85 in the wavelength interval 0.5 to $4.5 \mu\text{m}$. If the normalized spectral response function of the microscope is superimposed on the transmittance curve, one would observe that the microscope only detects radiation in the 1.6 to $5.5 \mu\text{m}$ spectral range. Furthermore, the spectral response function is approximately a normal distribution. Therefore, the microscope detects the greatest amount of incident radiation at the center of its distribution ($\sim \lambda = 3.6 \mu\text{m}$). As a result, most of the energy detected by the microscope is in the flat transmittance region of the sapphire disk. Since this flat region corresponds to a transmittance of ~ 0.85 , the comparison with the experimentally measured value of $0.830 \pm .004$ is more than adequate.

To calculate transmissivity from an external transmittance of 0.830, Eq. 19 is used. This equation was derived in Section 3.2.4:

$$\tau = T \frac{1 + r_s}{1 - r_s} \quad (19)$$

where,

T = external transmittance -- fraction of radiant energy transmitted through the sapphire disk
(measured to be $0.830 \pm .004$)

r_s = fresnel reflection coefficient for sapphire ($r_s = 0.0602$ as calculated in Section 3.2.3)

τ = internal transmissivity of the sapphire disk

Substituting the appropriate parameters into Eq. 19 yields a transmissivity of 0.936 corresponding to an external transmittance of 0.830. The transmissivity drops to 0.782 when an external transmittance of 0.693 is used in Eq. 19. The transmittance value of 0.693 represents the lowest average value obtained for the opaque region of the sapphire disk. This lower transmittance value is important, because the calculated surface temperatures will increase when lower transmittance values are assumed. Therefore, when surface temperatures are calculated for the zirconia-on-sapphire experiments, both transmittances will be used to estimate a range of surface temperatures.

4.1.5 Emissivity Calculations for the Sapphire Sphere

The emissivity of the spherical sapphire test specimen cannot be measured using the specimen heater described in Section 3.3. This is due to the fact that sapphire is a translucent material, and transmits infrared energy. Therefore, if a sapphire ball is placed in the specimen heater, the infrared microscope will detect energy emitted from within the heater and transmitted through the sapphire ball. Because of this, an alternative must be found for obtaining the emissivity of sapphire. The alternative chosen uses the transmittance measurements to calculate the emissivity. From the previous paragraphs, the transmissivity of an unused sapphire disk was calculated to be 0.936. Since the surface reflectivity, ρ_t , can be assumed to be zero for sapphire, the emissivity can be calculated from the simple relationship derived in Section 3.2.3:

$$\epsilon_t = 1 - \tau \quad (13c)$$

Note, this method of emissivity determination is common for translucent materials, and is discussed in references [92] and [93]. By using Eq. 13c, the emissivity of sapphire can be calculated

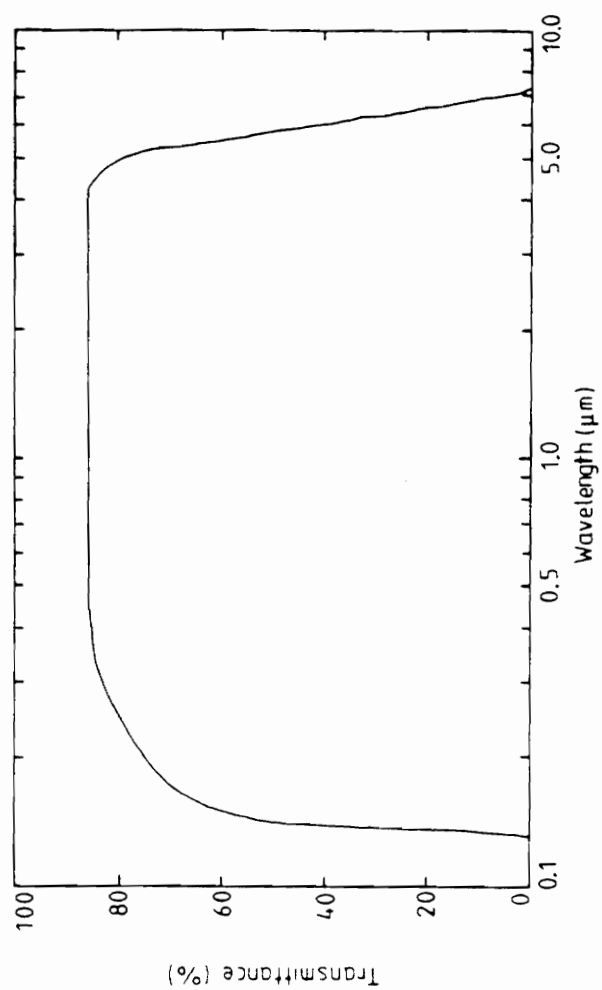


Figure 41: Transmittance of a 1 mm Thick Sapphire Disk as a Function of Wavelength [96]

to be 0.064. The value of 0.064 agrees well with the emissivity values found in the literature. Figure 42 shows the emissivity of sapphire over a wide wavelength. Recall from the previous discussion that the microscope has a normally distributed response function from 1.8 to 6.2 μm . Therefore, the emissivity of the sapphire disk should only be considered in this wavelength interval. As shown in Fig. 42, the lowest value of emissivity is less than 0.1 and occurs at the center of the microscope's spectral range. Since this is the area that corresponds to the peak spectral response of the microscope, the calculated emissivity of 0.064 compares fairly well with Fig. 42.

It should be pointed out that the emissivity of 0.064 corresponds to an unused sapphire ball, and doesn't account for the increase in opacity caused by wear and material transfer during an experiment. Furthermore, the surface reflectivity, ρ_t , at the sapphire-sapphire interface does not remain zero if the opacity increases. The assumption of $\rho_t = 0$ is in fact an approximation used to simplify the calculation of emissivity and subsequent calculation of surface temperature. More information about this assumption can be found in the recommendations section of this thesis.

4.2 *Zirconia-on-Sapphire Results*

4.2.1 Radiance Traces and Temperature Rises

Radiance traces for seven zirconia-on-sapphire experiments are shown in Fig. 43. Each trace has its own radiance scale, and a time scale is shown at the bottom for all seven experiments. All the experiments lasted for two minutes, and the experiment number, load, frequency, and amplitude are noted for each radiance trace. The test conditions listed for each experiment are summarized below:

- two loads - 20 N and 40 N

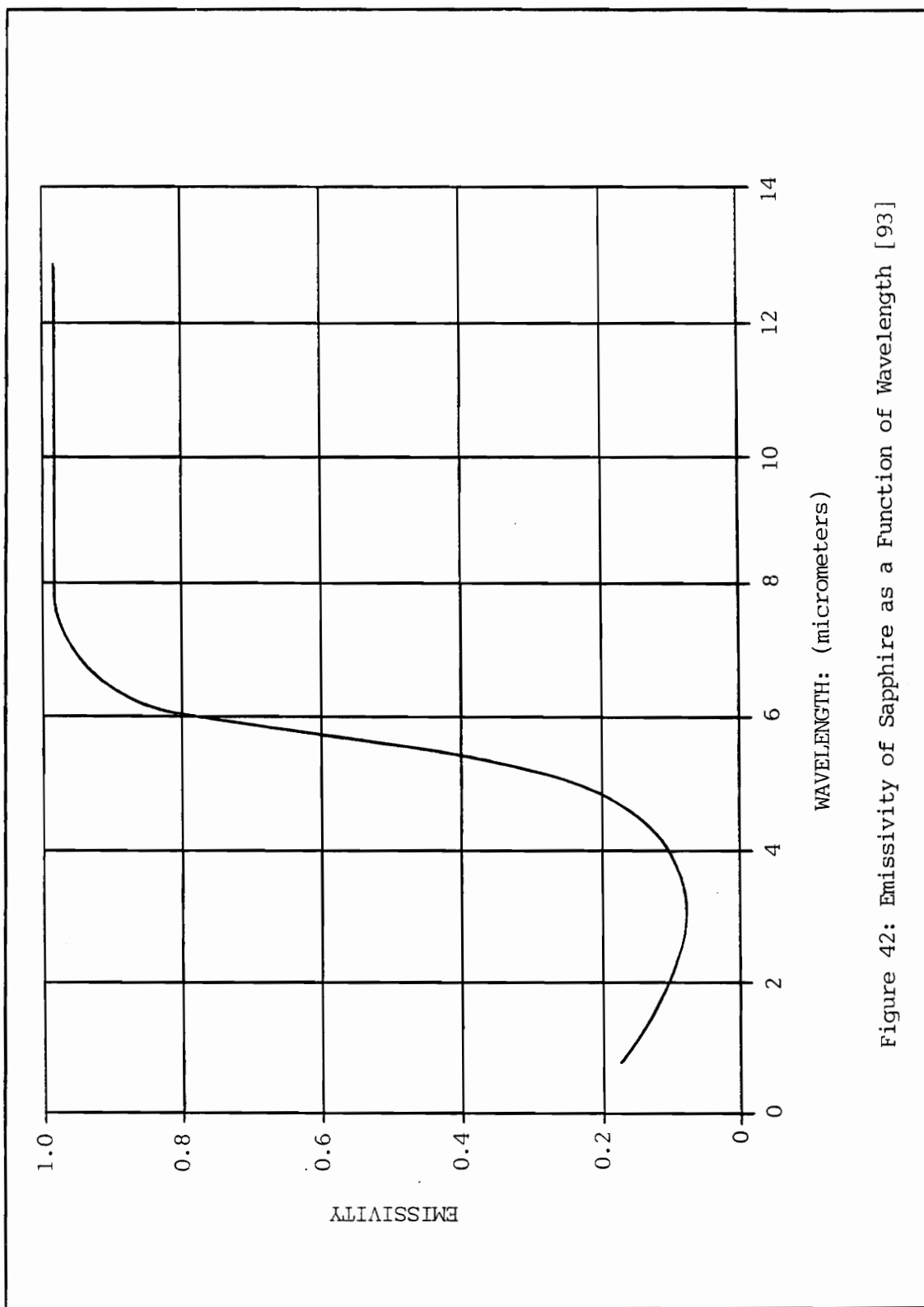


Figure 42: Emissivity of Sapphire as a Function of Wavelength [93]

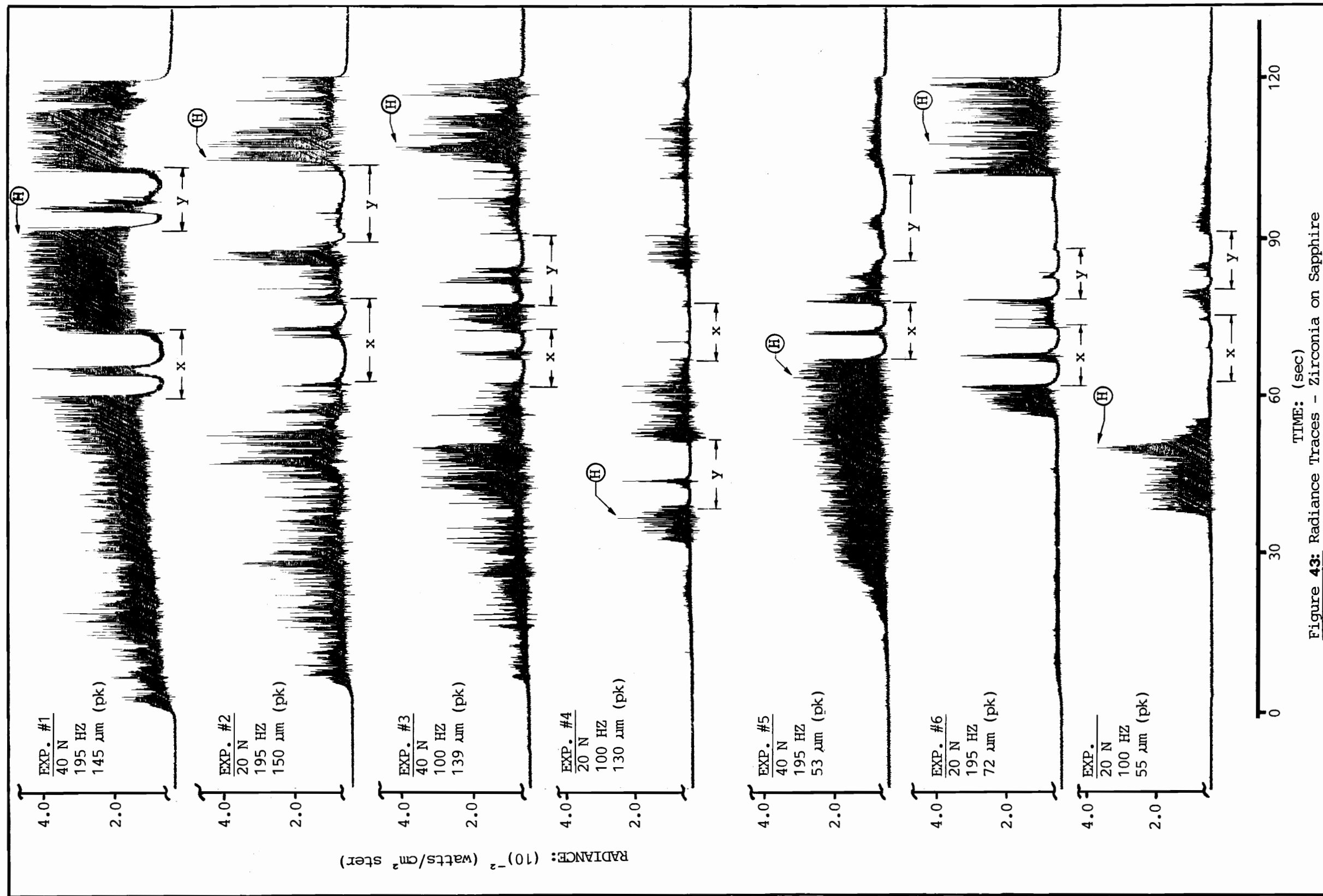


Figure 43: Radiance Traces - Zirconia on Sapphire

- two frequencies - 100 Hz and 195 Hz
- two amplitude ranges -

high range: 130 μm - 150 μm (pk)

low range: 36 μm - 72 μm (pk)

The amplitudes are listed in two ranges due to problems associated with keeping the amplitude constant between experiments. This variation in amplitude could be due to frictional effects that vary between experiments. Also shown in Fig. 43 are the time intervals during which the microscope was operated in a scanning mode. The letter "x" represents a scan in the x-direction, and the letter "y" represents a scan in the y-direction. The scanning pattern used is summarized in Fig. 38. For the x-direction scan, the microscope's target spot is initially positioned at the center of the contact region. Then, it is moved out of the contact region in a direction parallel to the motion of the sapphire disk. Next, the target spot is moved back across the contact region to the other side. Finally, the target spot is repositioned at the center of the contact region. The y-direction scan proceeds in the same manner as the x-direction scan, but the microscope's target spot is moved in a direction perpendicular to the motion of the sapphire disk. See Fig. 37 for the definition of the x and y coordinate axes.

For each experiment, the highest radiance levels are labelled with the letter "H". The temperature rises corresponding to each of these "HOT" points are shown in Fig. 44. As shown in the KEY for Fig. 44, two emissivity and transmittance values are represented. The solid lines represent average maxima and minima for low emissivities and transmittances of 0.51 and 0.70, respectively. By using this combination, the highest possible temperature rises are calculated. The dashed lines represent high emissivities and transmittances of 0.71 and 0.83, respectively. This combination yields the lowest possible temperature rises.

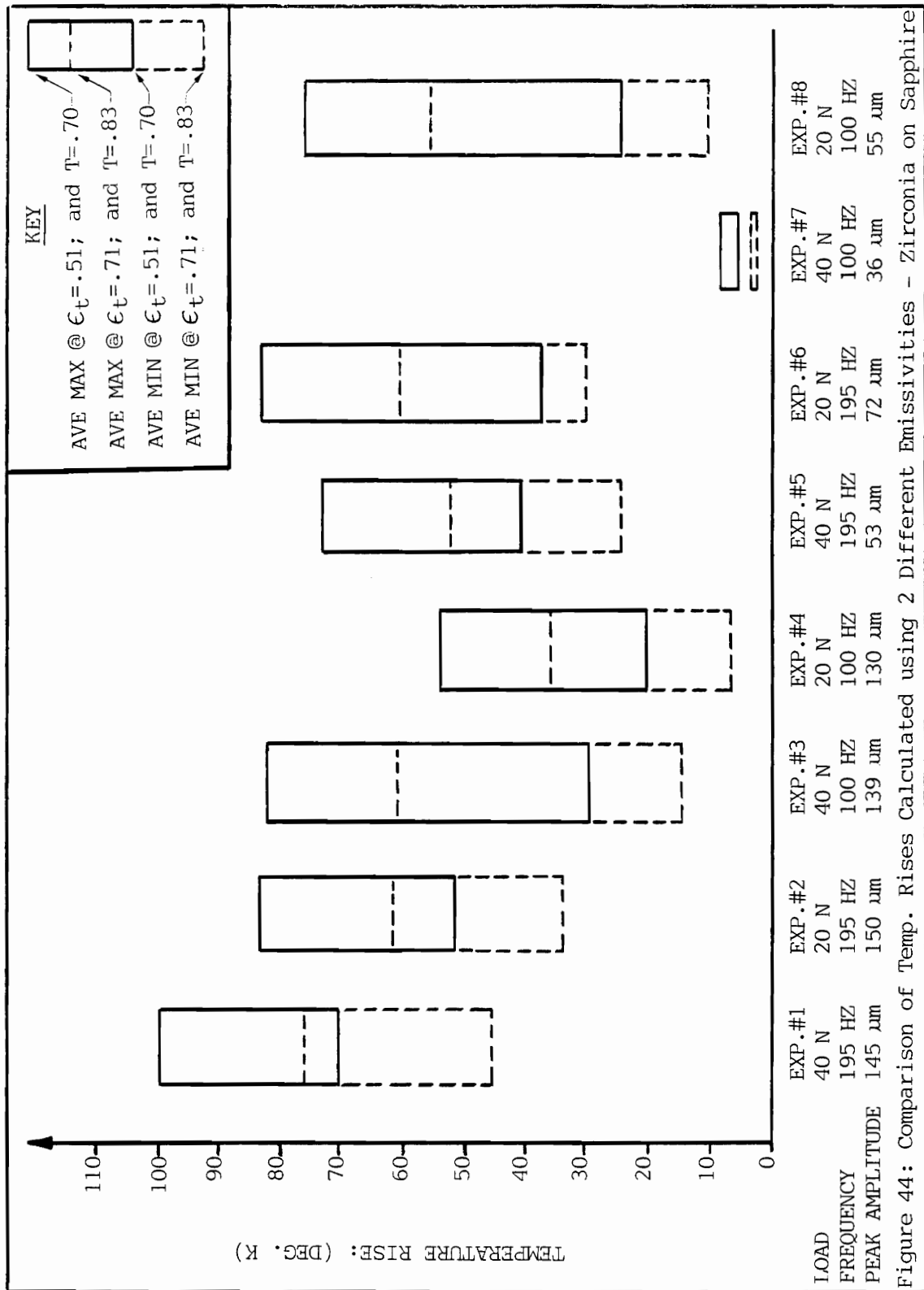
The average values shown in Fig. 44 are for 20 cycles of the temperature signal. This corresponds to a sample period of 0.05 seconds for experiments performed at 195 Hz, and 0.10 seconds

for experiments performed at 100 Hz. Note, as will be shown in later sections of this thesis, there are two temperature rises for every cycle of motion. Therefore, the predominant frequency of the radiance (and surface temperature) is twice the oscillation frequency. The data used to make Fig. 44 was sampled from the FM tape recorder using the digital data acquisition system. Samples were acquired at a rate of 8000 data points per second. This sampling rate is more than 20 times the highest predominant frequency detected by the infrared microscope. As a result, each cycle of radiance data is represented by more than 20 points. Instantaneous temperature rises corresponding to Figs. 43 and 44 will be presented in subsequent sections of this thesis.

4.2.1.a Radiance and Temperature Rises for Experiment 1

Experiment no. 1 represents the highest load, frequency, and amplitude used in any of the experiments: 40 N, 195 Hz, and 145 μm (pk). After initiation of the experiment, the radiance increased significantly and approached a quasi steady-state. Throughout the experiment, rapid fluctuations and high peaks in radiance occurred. In addition, both the average and peak-to-peak radiance levels increased. During the x and y scans, radiant energy was obtained as a function of position. A detailed analysis of the energy levels measured during scanning could conceivably show the location of real contact areas within the geometric contact region. High radiance levels would correspond to the location of real contact areas, and low energy levels would correspond to regions between real contact areas. This information will be presented in Section 4.2.5.

The highest radiance levels and corresponding temperature rises were detected at the center of the contact region after 90 seconds of relative motion. (See the H symbol in Fig. 43.) As shown in Fig. 44, average maximum temperature rises between 77 K and 100 K were measured depending on the emissivity and transmittance values selected. Furthermore, average peak-to-peak variations of 30 K were measured. Detailed analyses of this temperature data will be presented in the following sections. As an additional note, the cooling rate at the end of the experiment is quite re-



markable. When the motion of the sapphire disk is stopped, energy is rapidly dissipated out of the contact region.

4.2.1.b Radiance and Temperature Rises for Experiment 2

The second experiment shown in Fig. 43 was performed at the same frequency as Exp. 1. The amplitude of vibration was also approximately the same as Exp. 1's amplitude. However, the 20 N load used for Exp. 2 is only half the load used for Exp. 1. Therefore, the energy input for Exp. 2 should be half that of Exp. 1 if the coefficient of friction and velocity are constant. The character of Exp. 2's radiance trace is markedly different from Exp. 1's. For instance, the average radiance does not increase steadily during the experiment. Instead, it increases to a base level. However, superimposed on this base level of radiance are rapidly occurring peaks. In fact, these peaks correspond to temperature rises as high as 83 K. As shown in Fig. 44, this temperature rise corresponds to the lower emissivity of 0.51, and the lower transmittance of 0.70. If the higher emissivity and transmittance values are used, the maximum temperature rise becomes 62 K. Furthermore, average peak-to-peak temperature rises as high as 31 K were detected for Exp. 2. As shown in Fig. 44, this peak-to-peak variation for Exp. 2 is not significantly different from the peak-to-peak variation for Exp. 1. A more detailed assessment of this data will be presented in the next section.

4.2.1.c Comparison of Radiance and Temperatures for Experiments 1 and 2

As stated previously, the characteristics of the radiance traces for Exps. 1 and 2 are different. Experiment 1 is characterized by an average radiance level that increases throughout the experiment; whereas Exp. 2 is characterized by a base radiance level with rapidly occurring peaks superimposed on the base. To show that the characteristics of these two radiance traces are indeed different, the preliminary experiments performed under the same test conditions as Exps. 1 and 2 are presented in Fig. 45. These two preliminary experiments were performed for one minute, and parrot the na-

ture of the radiance traces for Exp. 1 and 2. The 20 N experiment shown in Fig. 45a has a base radiance level with peaks superimposed on it, and looks similar to Exp. 2's radiance trace shown in Fig. 43.

In contrast, the 40 N experiment shown in Fig. 45b has an increasing average radiance level with variations in radiance about the average. Furthermore, the 40 N experiment in Fig. 45b looks similar to Exp. 1 in Fig. 43. In summary, the characteristics of the radiance traces for Exps. 1 and 2 in Fig. 43 are indeed different as shown by the radiance traces depicted in Figs. 45a and 45b.

Now that the radiance traces representative of Exp. 1 and Exp. 2 have been shown to be different, it is important to discuss possible reasons why this is so. The simplest explanation is that the loads are different. Exp. 1 was performed using a 40 N load, and Exp. 2 was performed using a 20 N load. However, this inference is too superficial. Each load level affects the contact region differently causing the two different radiance traces. To facilitate this discussion, first consider that heat generation is the product of the friction coefficient, load, and velocity. Therefore, any variation in one of these quantities could cause fluctuations in the heat generation.

Since normal load and velocity remain relatively constant throughout the experiment, they cannot be the source of the fluctuations. Even the friction coefficient remains relatively constant for each of the two experiments. (Although Exp. 2 shows more variation in friction than Exp. 1, this variation is insignificant compared to the rapid fluctuations seen in the radiance; see Fig. 64.)

The only other source of variation is the real area of contact. More specifically, a source of variation could be present between the microscope's target spot location, and the real area of contact(s). Figures 46a and 46b show two possible arrangements of real contact areas. For Exp. 2, the real area of contacts could be a lot smaller than the microscope's target spot. Furthermore, these real areas might not be present all the time. As shown in Fig. 46a, if the target spot for Exp. 2 is positioned between a group of small fluctuating real areas, it will only detect the lower energy levels between these real areas. This lower level could be the base level observed for Exp. 2. The radiance peaks superimposed on this base level could be caused by real areas forming within the target spot area. This idea is depicted by the dashed lines shown in Fig. 46a. For Exp. 1, the real areas of contact could be larger than the microscope's target spot. This possibility is shown in Fig.

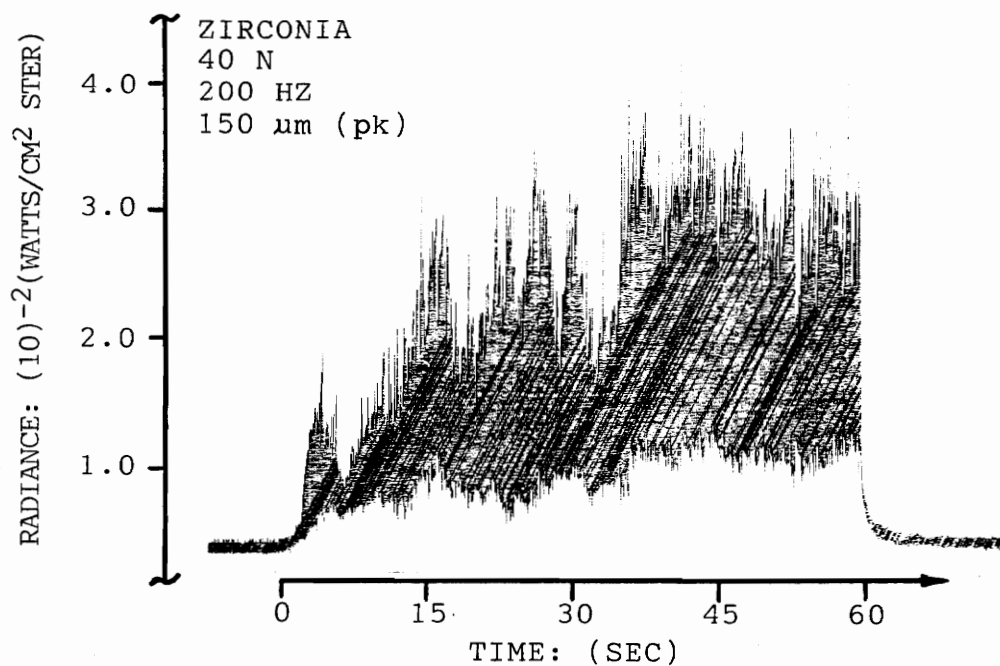


Figure 45b: Radiance Trace - One Minute Zirconia on Sapphire Experiment (40 N, 200 HZ, 150 μm (pk))

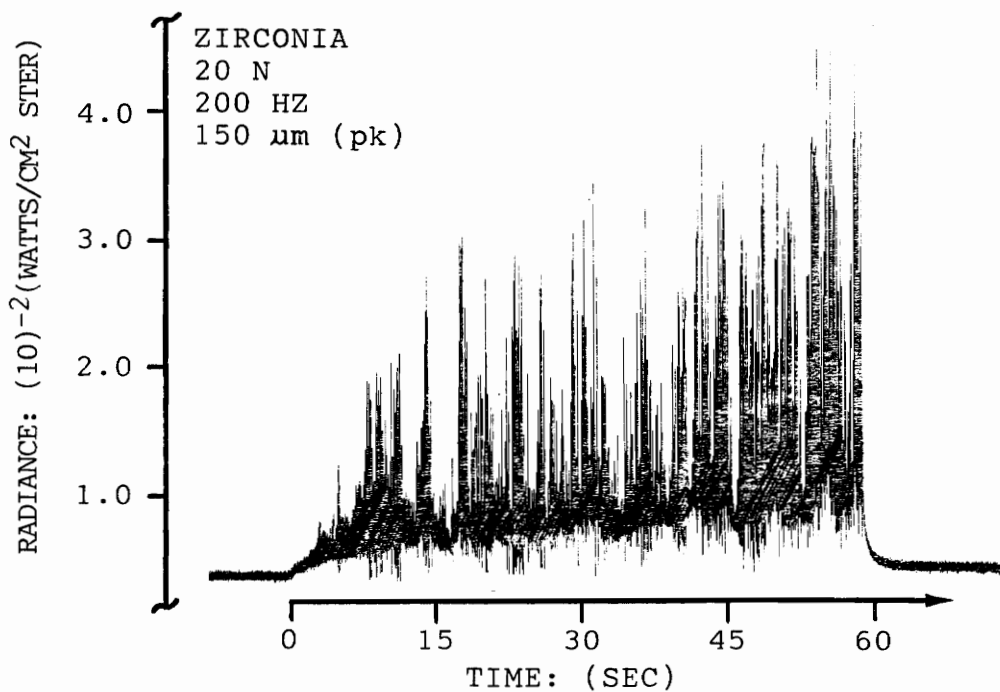


Figure 45a: Radiance Trace - One Minute Zirconia on Sapphire Experiment (20 N, 200 HZ, 150 μm (pk))

46b. For this case, the microscope is no longer detecting radiance from a low temperature region between real contact areas. Instead, it's detecting energy from a more uniform heat source. Therefore, the base radiance level observed for Exp. 2 would not be observed for Exp. 1.

However, one can argue that the average radiance level observed for Exp. 1 is really an increasing base level with radiance peaks superimposed on it. This would suggest that the multiple contact model is just as appropriate for Exp. 1 as it is for Exp. 2.

The two contact models shown in Fig. 46 are of greater significance when their role in surface temperature calculations is considered. For instance, if the multiple area model shown in Fig. 46a is considered, the surface temperatures calculated from the radiance trace would not be correct. Since the real area is smaller than the target spot, the microscope is detecting an average radiance from surrounding low energy areas as well as the real area. Therefore, the true temperature at the real area could be greater than the temperature calculated from the radiance data. This is not the case for Fig. 46b. For this case, the real area is larger than the target spot, and the surface temperatures calculated from the radiance are correct within the constraints of the emissivity and transmittance assumptions.

Although the simplistic models shown in Fig. 46 lend some insight to the cause of the differing radiance traces, they cannot be taken as conclusive models. For instance, the base level observed for Exp. 2 does not necessarily remain constant, and Exp. 1 contains rapid fluctuations in radiance that could be caused by fluctuating real areas of contact. In short, the experiments discussed herein cannot be explained entirely on the basis of relatively simple models. They should be characterized as random processes, and simple models should only be used to make inferences about the general nature of the data.

4.2.1.d Radiance and Temperatures for Experiments 3 - 8

In general, the other radiance traces shown in Fig. 43 can be broken up into three categories:

Type I - This type of radiance trace emulates the characteristics of Exp. 1.

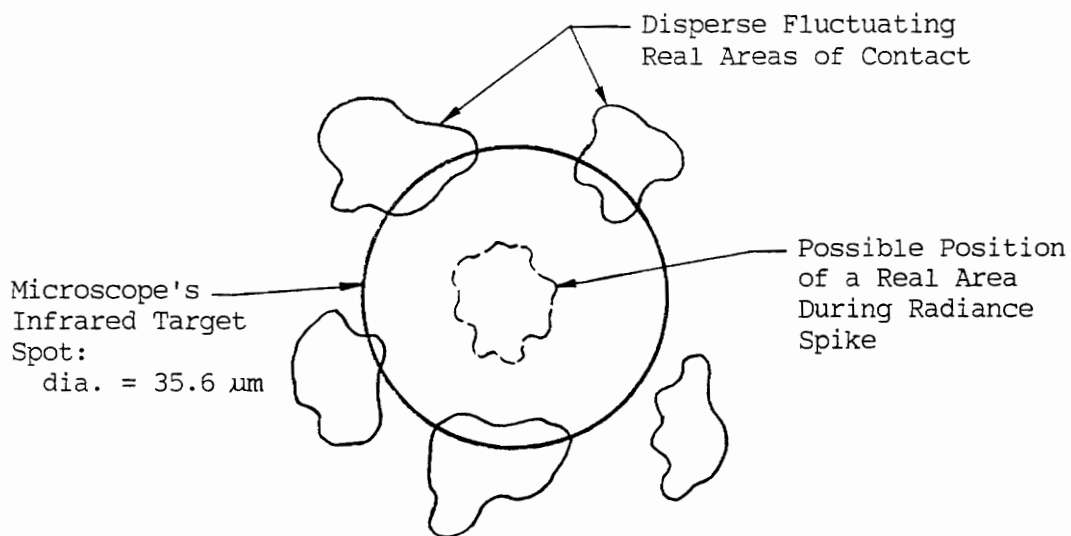


Figure 46a: Possible Arrangement of Real Contact Areas -
Multiple Contact Model

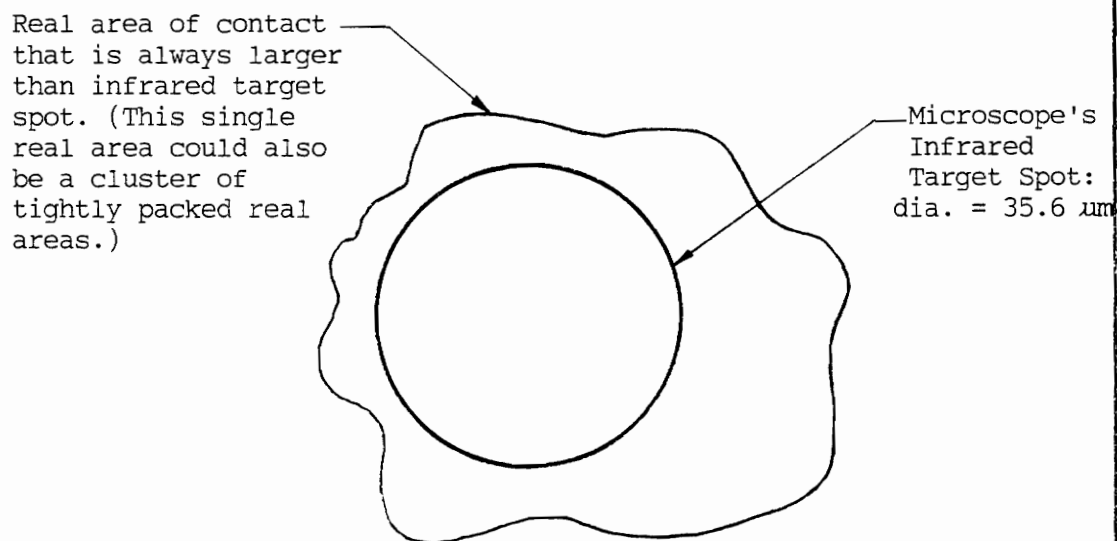


Figure 46b: Possible Arrangement of Real Contact Areas -
Single Contact Model

Type II - This second type of radiance trace emulates the characteristics of Exp. 2.

Type III - This last type of radiance trace contains characteristics that are similar to both Exp. 1 and Exp. 2. In other words, a Type III radiance trace contains characteristics of both Type I and Type II traces.

The only experiment that can be placed in the Type I category is Exp. 5. This experiment's radiance trace has an average value that increases significantly during the first minute of the experiment. Furthermore, there is an increasing peak-to-peak variation about the average during the first minute. In short, Exp. 5 emulates the characteristics of Exp. 1. This fact is not all that surprising since Exp. 5 was performed under test conditions that are nearly identical to Exp. 1's test conditions. The only difference lies in the amplitude. Experiment 5's amplitude is less than one half Exp. 1's amplitude. Experiment 5 emulates a Type I experiment for only the first minute. After the x-direction scan takes place, the radiance level drops to a lower average. This drop can be attributed to wear of the ball, and subsequent material transfer to the sapphire disk. The more material transfer to the disk, the lower the radiance detected by the infrared microscope.

Experiments 3 and 4 can be placed in the Type II category. They both have base radiance levels with peaks superimposed on them. As shown in Fig. 44, the maximum temperature rise for Exp. 3 ranges from 61 - 83 K depending on the emissivity and transmittance assumption. For Exp. 4, this range drops to 37 - 55 K. This drop in temperature is obviously due to the lower load of 20 N used for Exp. 4. Figure 44 also shows that the high frequency experiments (1 and 2) show higher temperatures than the low frequency experiments (3 and 4). This difference is expected because higher frequencies cause higher velocities, and higher rates of heat generation.

Since Exp. 6 emulates characteristics of Exp. 1 and Exp. 2, it can be categorized as a Type III radiance trace. The initial part of the radiance trace can be characterized as a base level of radiance without the radiance peaks seen in Exp. 2. This could be due to the location of the microscope's target spot between real areas of contact. Furthermore, the lack of radiance peaks could be due to a lack of real areas occurring within the target spot area. Just before the x-direction scan for Exp.

6, the average and peak-to-peak radiance suddenly increase. This increase is characteristic of Exp. 1 and is quite difficult to explain. One explanation for this sudden increase is the sudden formation of a real contact area in the vicinity of the target spot. This real area might partially or completely fill the target spot area, and cause the radiance to increase. Between the x and y scans, Exp. 6 takes on Type II characteristics again with radiance peaks superimposed on a base level. After the y scan, the base level without radiance peaks returns; and at the end of the experiment radiance peaks reappear. Although other processes could be occurring, the random formation and disappearance of real contact areas can again be associated with this behavior.

The last experiment shown in Fig. 43 is Exp. 8. At the start of this experiment, the increase in radiance is negligible. Then, at about 35 seconds into the experiment, there is a sudden increase in radiance that lasts for about 15 seconds. After this, the radiance drops again, and only increases slightly throughout the rest of the experiment. This behavior was seen in Exp. 6, and could be due to changes in the real area of contact.

As shown in Fig. 44, there is a seventh experiment with a temperature rise that is less than 10 K. Its radiance trace would be a flat line on the scales shown in Fig. 43. This experiment was performed at a load, frequency, and amplitude of 40 N, 100 Hz, and 36 μm (pk). It was repeated three times to verify that the temperature rise is indeed low. Compared to Exp. 8, which showed maximum temperature rises between 77 and 56 K, Exp. 7 is significantly different. Because Exp. 8 was performed using only a 20 N load, one would expect the temperature rise for Exp. 8 to be less than Exp. 7's rise. One possible explanation for this discrepancy is the difference in amplitude between Exp. 8 and Exp. 7. Experiment 8's amplitude was 55 μm , and Exp. 2's amplitude was 36 μm . Another possible explanation is the real area of contact fluctuations discussed previously. More information about Exp. 7 and Exp. 8 will be presented in the analysis of heat generation rates shown in Fig. 47.

4.2.2 Heat Generation Rates and Temperature Rises

Since the normal load, velocity, and friction coefficient are all measured quantities, frictional heat generation rates can be calculated as shown below:

$$\dot{Q}_{\max} = \mu W v_{\max} \quad (36)$$

$$\dot{Q}_{ave} = \mu W v_{ave}; \text{ where, } v_{ave} = \frac{2}{\pi} v_{\max} \quad (37)$$

$\dot{Q}$ = rate of frictional heat generation in watts

μ = coefficient of friction

W = normal load in newtons

v = velocity in meters/second

The results of frictional heat generation calculations are shown in Fig. 47 for the eight zirconia-on-sapphire experiments. As expected, Exp. 1 represents the highest rate of heat generation with maximum and average values of 7.1 and 4.5 watts, respectively. As shown in Fig. 47, Exp. 1 was performed at a high load, frequency, and amplitude. Exp. 2 was performed at roughly the same frequency and amplitude as Exp. 1; but the normal load used was only 20 N. Therefore, the heat generation rate for Exp. 2 is approximately half the heat generation rate for Exp. 1. Experiments 3 and 4 were performed at a low frequency of 100 Hz, and have heat generation rates that are less than 2.0 watts. Again, the 20 N experiment has a lower heat generation rate than the 40 N experiment.

The general diminishment of heat generation rates for Exps. 1 - 4 is also seen in the temperature rises. As shown in Fig. 44, temperature rises decrease from 100 K to 55 K for Exps. 1 - 4

assuming a low emissivity and transmittance. A correlation between heat generation rates and temperature rises is not present for Exps. 5 - 8. As shown in Fig. 47, the maximum heat generation rates decrease from 2.5 to 0.5 watts for Exps. 5 - 8. Furthermore, Exp. 5 was performed using a 40 N load, and shows a higher rate of heat generation than Exp. 6 which was performed using a 20 N load.

Since Exp. 5's rate of heat generation is greater than Exp. 6's rate, one would expect the temperature rise for Exp. 5 to be greater than the temperature rise for Exp. 6. Figure 44, however, does not show this relationship for Exps. 5 and 6. Instead, Exp. 5 shows a maximum temperature rise of only 74 K; whereas Exp. 6 shows a maximum temperature rise of 83 K. This discrepancy could be due to the position of the microscope's target spot relative to the location of real contact areas. In other words, the target spot for Exp. 5 might not have been located at the "hottest" real area of contact.

A lack of correlation also exists for Exps. 7 and 8. Although the heat generation rate for Exp. 7 is slightly greater than Exp. 8's heat generation rate, the temperature rise for Exp. 7 is much smaller than the rise for Exp. 8. The relationship between target spot location and real area location could again explain this discrepancy. However, this explanation should not be considered by itself. For instance, as will be shown in the next section, there is a strong correlation between temperature rise and wear for Exps. 7 and 8.

To facilitate understanding the relationship between temperature rise and heat generation, Fig. 48 is presented. This figure shows temperature rise as a function of heat generation. Average and maximum values are shown and all eight zirconia-on-sapphire experiments are represented. Although there is some variation in the data, a general nonlinear trend is observed in this plot. This nonlinear trend shows that at high rates of heat generation, high temperature rises are measured. For heat generation rates below 2.0 watts, there are some data points that follow the general nonlinear relationship. However, other data points show a correspondence between low rates of heat generation and high temperature rises. These data points could be regarded as random variations that simply do not follow the nonlinear curve. But, variables such as real area of contact must be taken into account when this assessment is made.

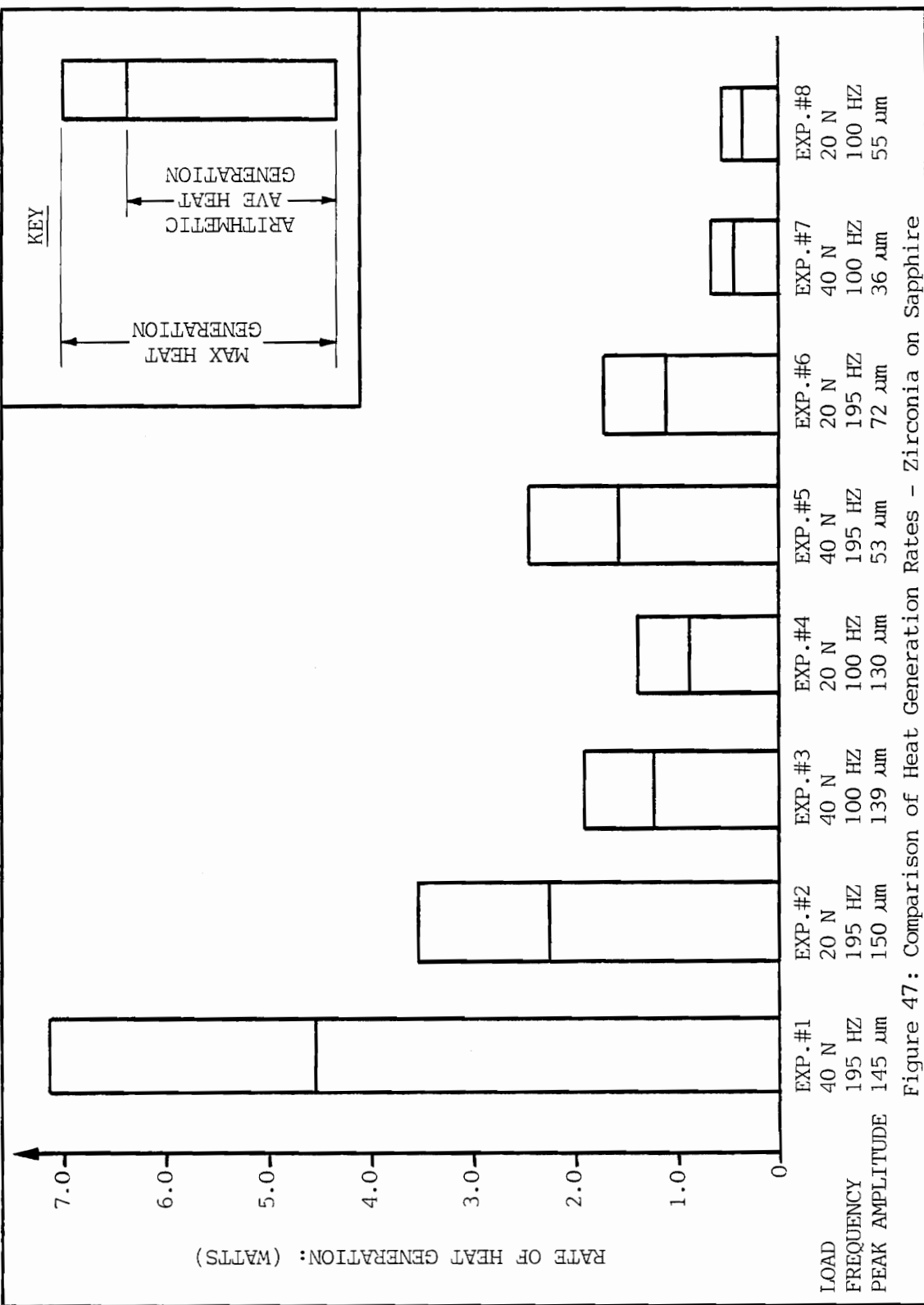


Figure 47: Comparison of Heat Generation Rates - Zirconia on Sapphire

4.2.3 Wear, Friction and Temperature Rises

Wear scar sizes for the zirconia test specimens are shown in Fig. 49. As defined in the KEY for this figure, major and minor diameters of the elliptical wear scars are shown.

(Exp. 6's wear scar is circular and has no major or minor diameters.) The largest wear scar diameters were measured for Exp. 1. Major and minor diameters of 953 μm and 914 μm were measured for this experiment. The smallest wear scar diameters were measured for Exp. 7. These diameters are 215 μm and 152 μm , respectively. When the wear scar diameters in Fig. 49 are compared to the temperature rises shown in Fig. 44, there appears to be a correspondence. For instance, the highest temperature rise and largest wear scar are both observed for Exp. 1. Also, the lowest temperature rise and smallest wear scar are both observed for Exp. 7. There is also a correspondence between wear and temperature for the other experiments.

This correspondence is even more predominant if the volume of debris removed from the spherical test specimens is considered. Fig. 50 shows these volumes divided by the total distance traveled by the sapphire disk. To approximate the volume of debris removed, the wear scar on the sphere is assumed to be a flat plane. Also, the wear scar is assumed to be perfectly circular. Therefore, the volume of debris removed is equal to the solid geometric segment of material removed from the sphere. As discussed in reference [94], the equation for this volume is:

$$V = \pi r^2(r - a) - \frac{\pi}{3}(r^3 - a^3); \quad \text{where, } a = \sqrt{r^2 - (d_w/2)^2} \quad (38)$$

V = volume of debris removed from sphere

r = radius of the sphere

d_w = diameter of the wear scar

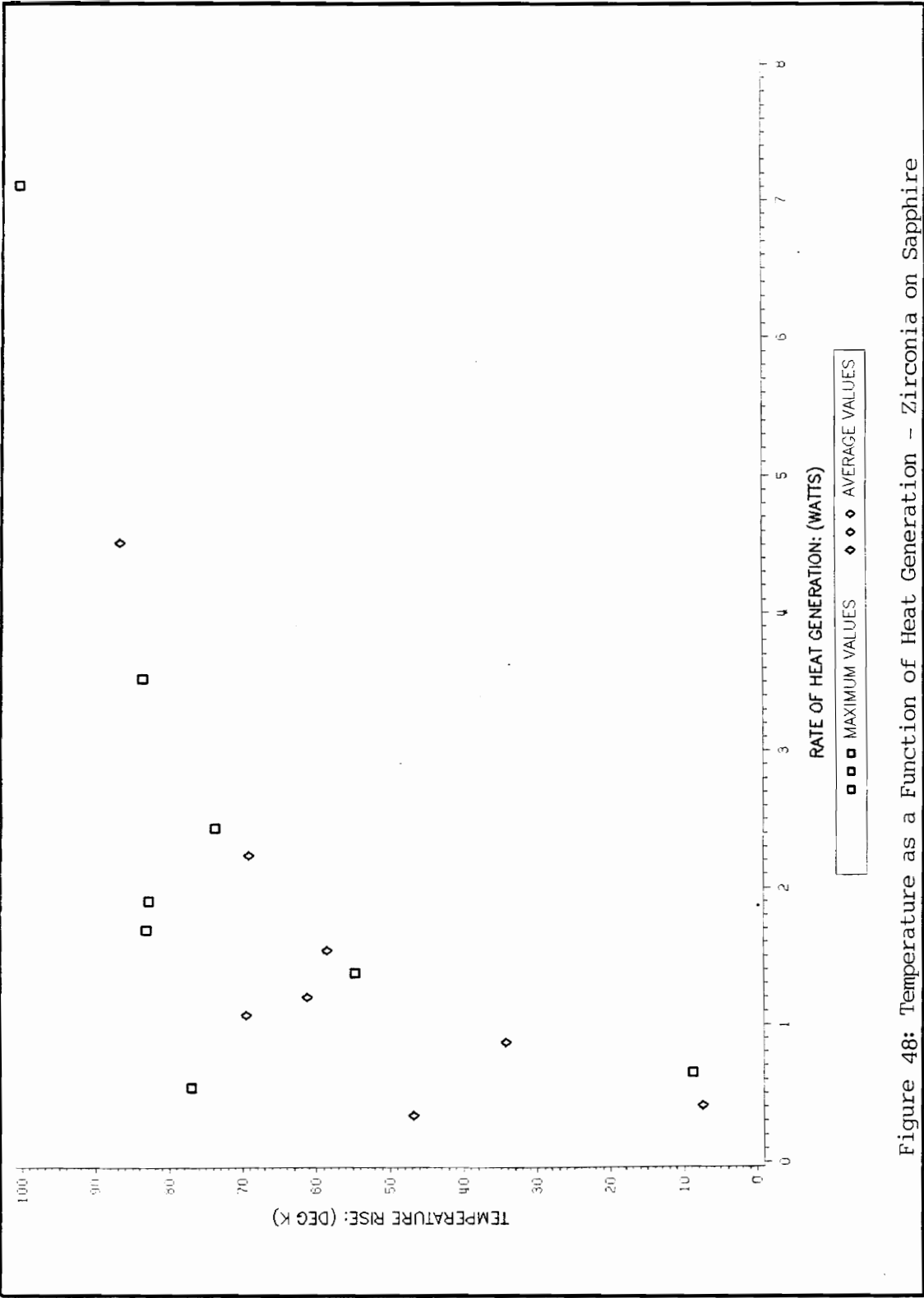


Figure 48: Temperature as a Function of Heat Generation - Zirconia on Sapphire

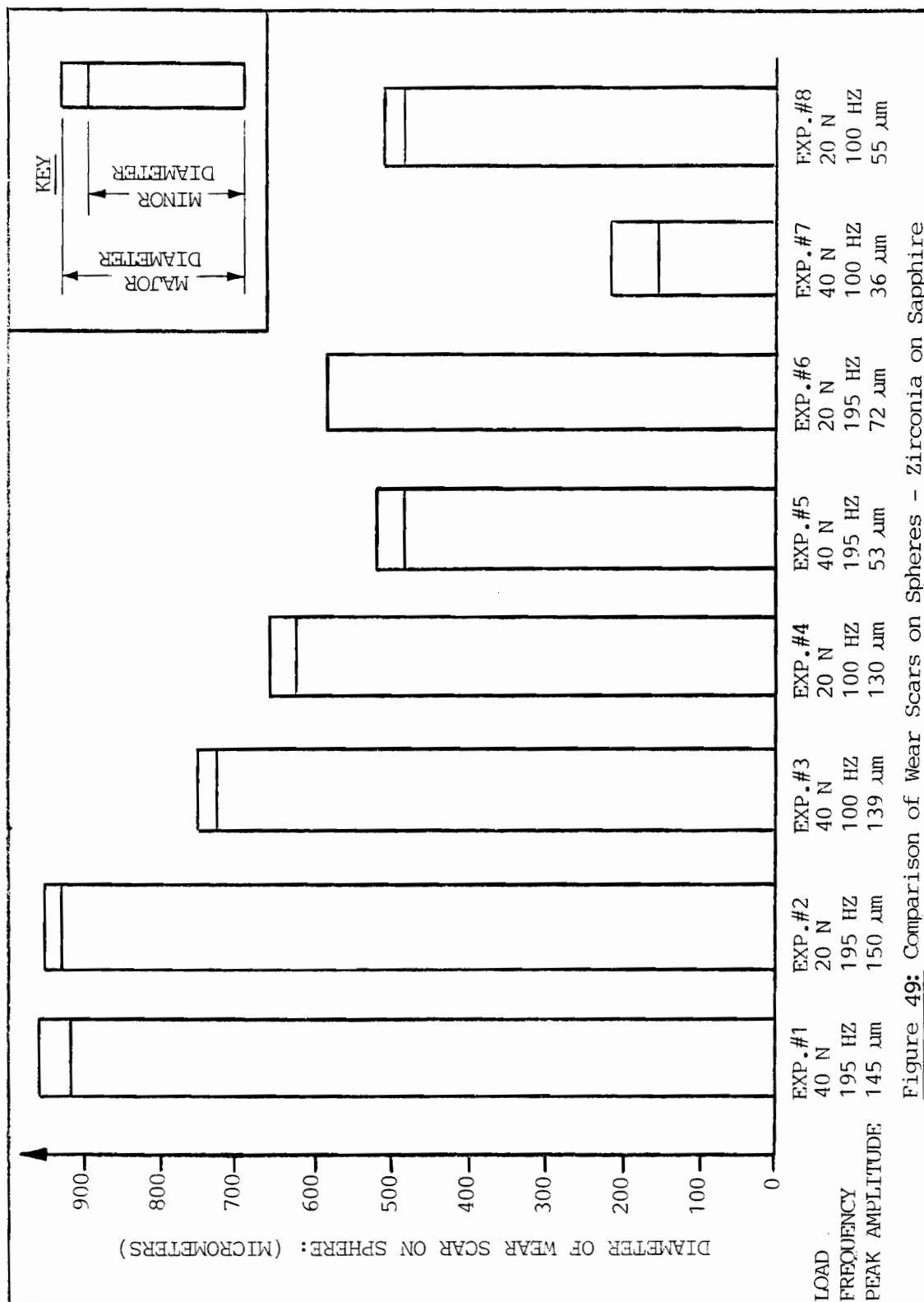


Figure 49: Comparison of Wear Scars on Spheres - Zirconia on Sapphire

Major diameters of the wear scars were used to calculate the debris volumes. Therefore, Fig. 50 represents an upper bound to the volume of debris removed.

If Exps. 1 - 4 are considered, the decreasing trend to the temperature data is also characteristic of the debris volumes shown in Fig. 50. This relationship is depicted in Fig. 51. Temperature rises and debris volumes are plotted as shown by the two vertical axes.

The squares represent temperature rises calculated for each experiment and the triangles represent debris volumes per sliding distance for each experiment. Figure 51 not only shows a decreasing trend for the wear and surface temperatures determined in Exps. 1 - 4, but also shows a relationship between wear and surface temperature for Exps. 5 - 8. For instance, if Exps. 5 - 8 are considered, the temperature rises can be listed in decreasing order as follows:

$$\#6 > \#8 > \#5 > \#7$$

The debris volumes can also be listed in decreasing order with the following result:

$$\#8 > \#6 > \#5 > \#7$$

The only discrepancy in this comparison lies with Exps. 6 and 8. However, the difference between the temperature rises for Exp. 6 and Exp. 8 is only 7 K. Therefore, the correspondence between temperature rise and debris volume is also excellent for Exps. 5 - 8.

The correspondence between temperature rise and specimen degradation is also seen when the contact regions on the sapphire disks are considered. These regions represent the major and minor diameters of the geometric contact regions formed on the sapphire disk, and are shown in Fig. 52. As will be shown in the following section, the sapphire disk's contact regions are formed by transference of zirconia material, and possibly wear of the disk itself. For Exps. 1 - 4, the decreasing trend to the temperature data shown in Fig. 44 is also prevalent for the disk's contact regions. Also, if Exps. 5 - 8 are considered, the temperature rises and contact regions can be listed in decreasing order as follows:

$$\#6 > \#8 > \#5 > \#7$$

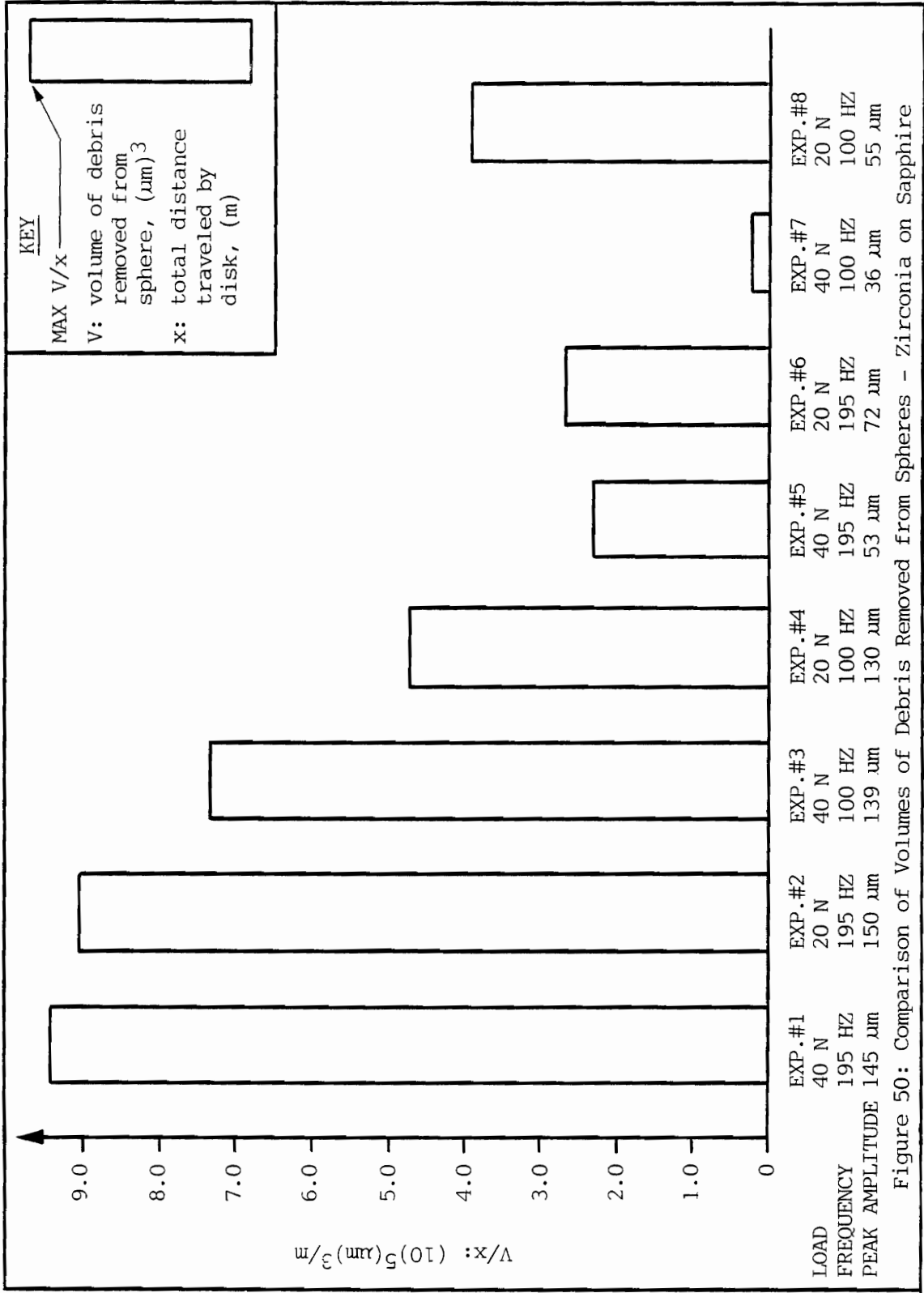


Figure 50: Comparison of Volumes of Debris Removed from Spheres - Zirconia on Sapphire

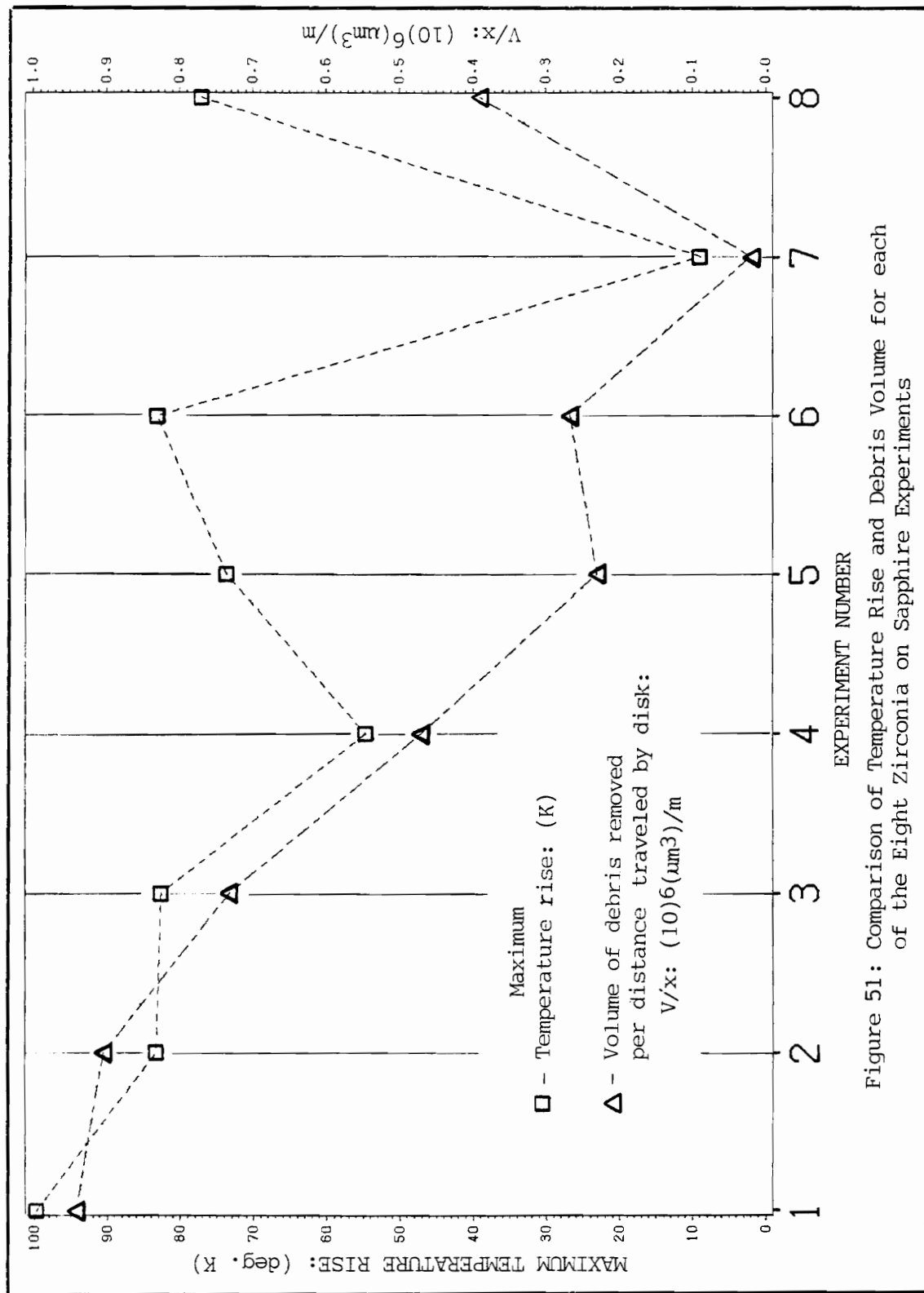


Figure 51: Comparison of Temperature Rise and Debris Volume for each of the Eight Zirconia on Sapphire Experiments

As a result, there also appears to be an excellent correspondence between temperature rises, and contact regions on the sapphire disk.

Since there appears to be a correlation between wear and temperature rise, it is worthwhile to plot wear as a function of temperature rise using the zirconia-on-sapphire data.

This plot is shown in Fig. 53 and represents debris volume per distance traveled as the ordinate axis, and temperature rise as the abscissa. This plot shows little relationship between wear and temperature. More specifically, no simple mathematical relationship can be developed from this data to accurately predict wear from temperature rise. However, the qualitative relationships discussed previously using bar charts should not be disregarded. Furthermore, ceramic wear can be related to surface temperature effects as discussed by Braza and Thouless [83,84]. They described how frictional heating of the surface of ceramic materials can cause the surface temperature to be much higher than the bulk temperature due to the low thermal conductivity of ceramics. This difference in temperature between the surface and bulk will produce large compressive stresses parallel to the surface. These compressive stresses lead to the formation of subsurface cracks that eventually propagate to the surface. As a result, wear particles defined as spalls are formed where high surface temperatures are present [83].

Friction coefficients for the zirconia-on-sapphire experiments are shown in Fig. 54. They were obtained by calculating the average maximum friction for 100 cycles. For the 195 Hz experiments, Fig. 54 shows friction coefficients that range from 0.94 - 1.0. At the lower frequency, 100 Hz, the friction coefficients range from 0.54 - 0.85. The cause of the friction difference between 100 Hz and 195 Hz is unknown. Since friction and wear are obviously unrelated for these experiments, wear cannot be used to explain this difference. Since the data used in Fig. 54 was obtained using a sampling rate of 4000 data points per second, cycle-to-cycle details of friction forces can be obtained. This information will be presented in the next section along with cycle-to-cycle details for temperature and velocity.

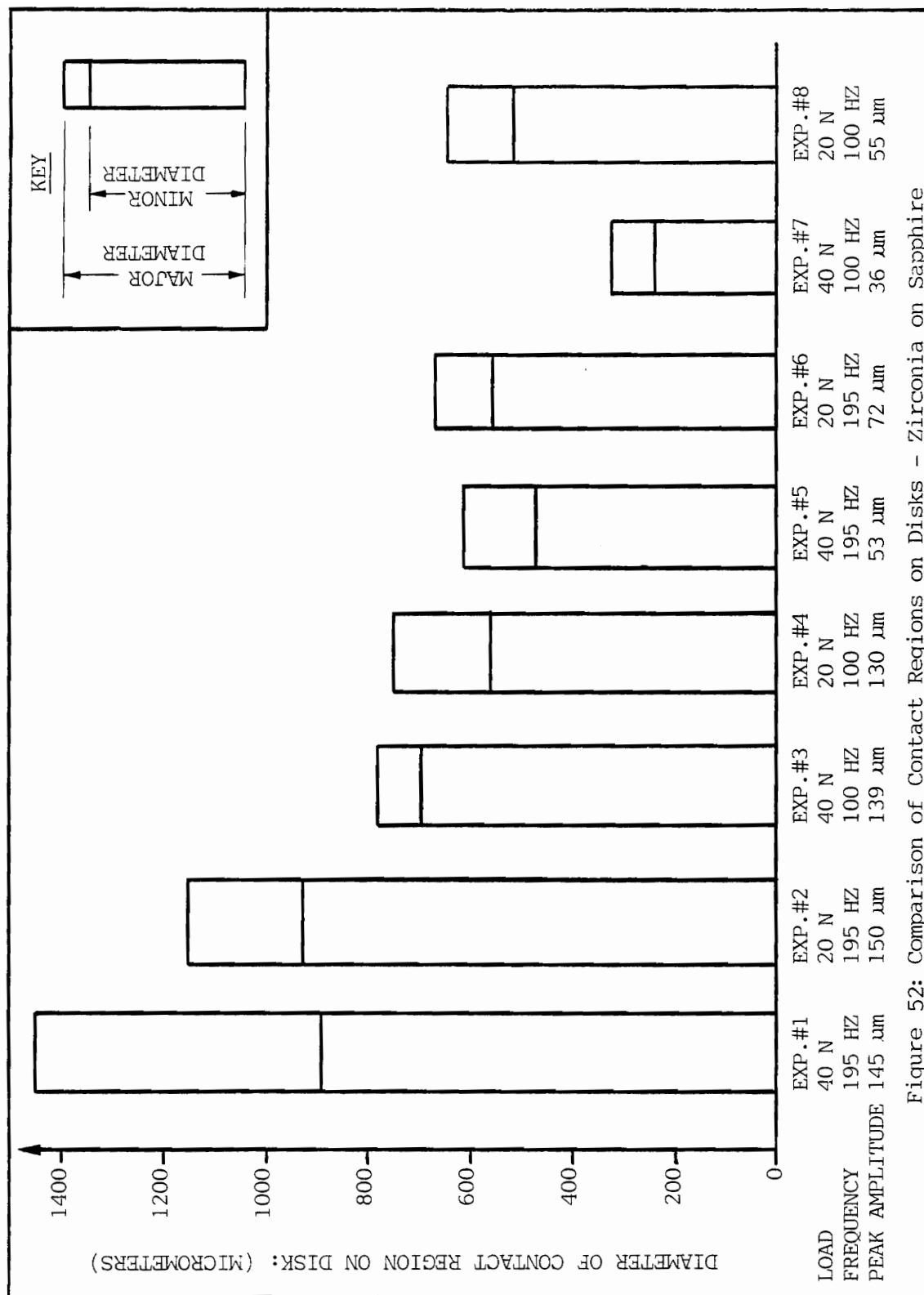


Figure 52: Comparison of Contact Regions on Disks - Zirconia on Sapphire

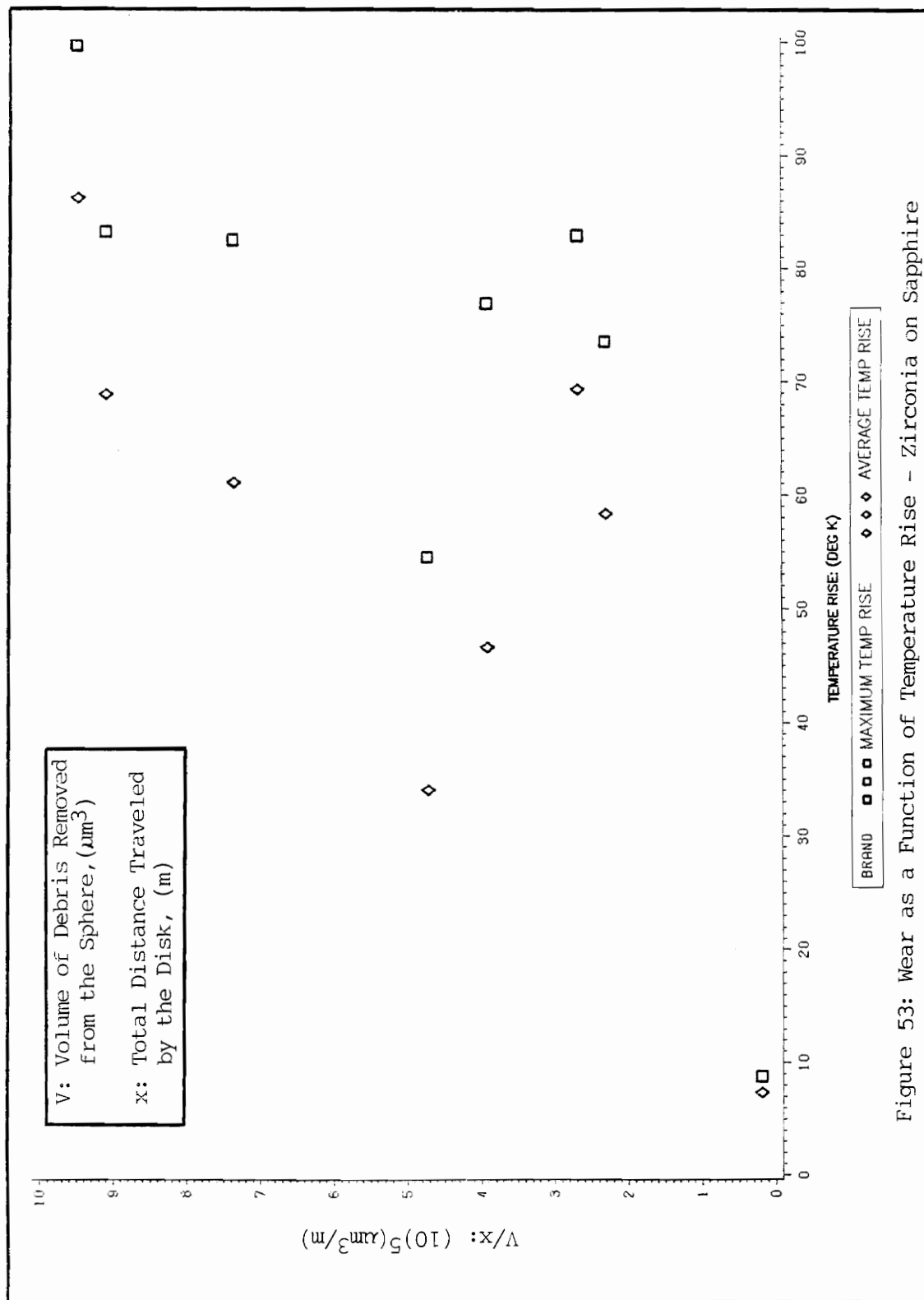


Figure 53: Wear as a Function of Temperature Rise - Zirconia on Sapphire

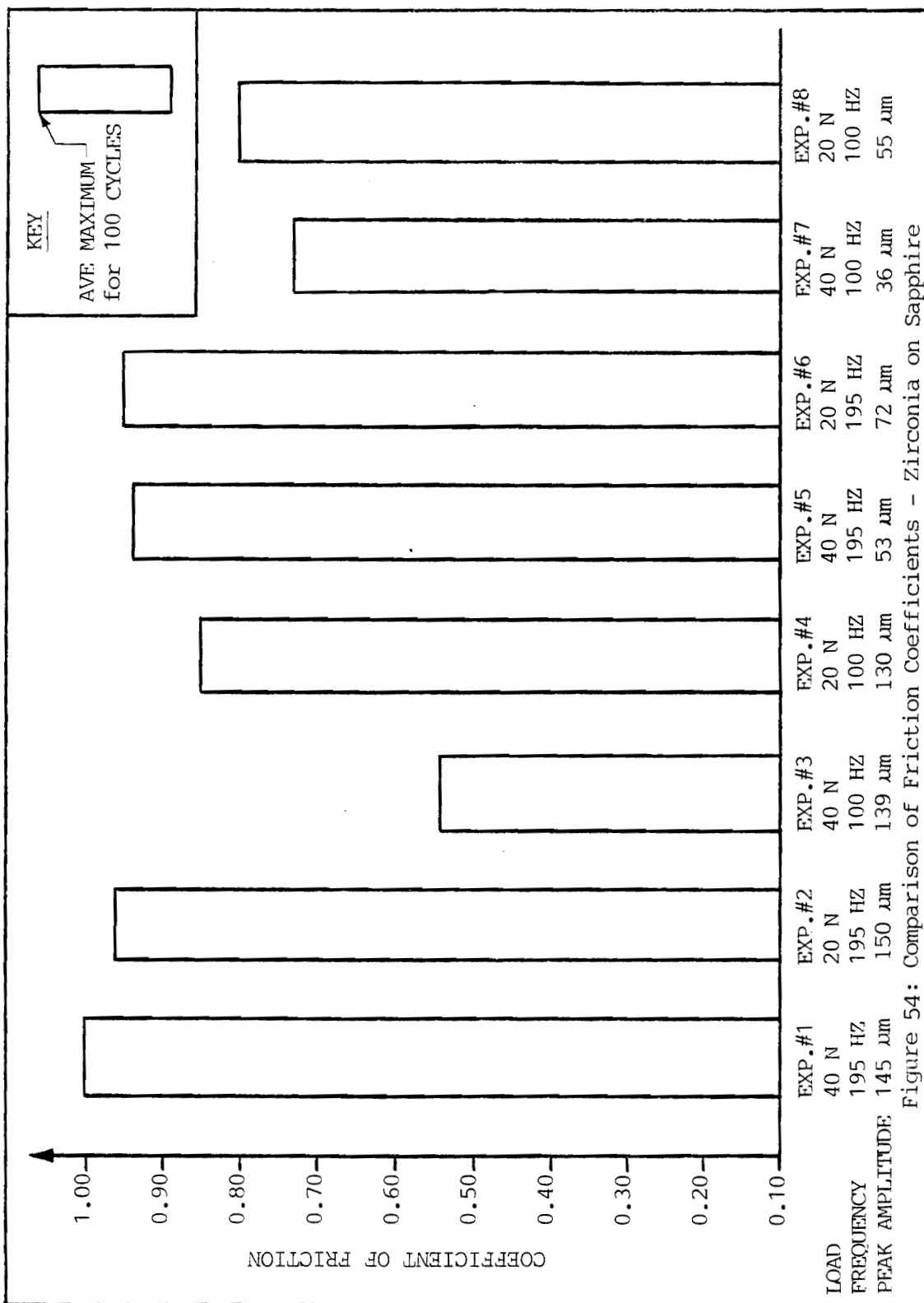


Figure 54: Comparison of Friction Coefficients - Zirconia on Sapphire

4.2.4 Cycle-to-Cycle Results - Zirconia-on-Sapphire

4.2.4.a Radiance and Temperature Rises in the Time Domain

Cycle-to-cycle results for a zirconia-on-sapphire experiment will be presented in this section. This experiment was performed using a 20 N load, 195 Hz frequency, and 150 μm (pk) amplitude. The radiance trace for this experiment is the second one shown in Fig. 43. This radiance trace is shown by itself on a larger scale in Fig. 55. Since the general characteristics of this experiment were described in the previous section, the purpose of this section is to focus on the cyclic details that occur in less than half a second. To capture these cyclic details, data was digitally sampled from the FM tape recorder at the 105 second mark shown in Fig. 55. Radiance data at this point is shown in Fig. 56. One hundred cycles of radiance are represented in this figure, and the total time period is 0.51 seconds. Rapid increases in radiance as high as $4(10)^{-2}$ watts/(cm^2 ster) are shown, and an average radiance of $2(10)^{-2}$ watts/(cm^2 ster) was calculated. Figure 56 also shows that peak-to-peak variations as high as $3(10)^{-2}$ watts/(cm^2 ster) occur in less than five thousandths of a second. At the 105.2 second point, the rapid fluctuations in radiance cease for approximately one tenth of a second, and a lower base level is predominant. This base level has an average value of approximately $1.5(10)^{-2}$ watts/(cm^2 ster), and could be caused by a temporary lack of high temperature real contact areas in the vicinity of the microscope's target spot. This phenomenon was discussed in section 4.2.1.c using the contact area models depicted in Fig. 46.

By using the computer program in Appendix F, the radiance data used to create Fig. 56 was converted to temperature rises. The lower emissivity and transmittance values of 0.51 and 0.70 were used to make this conversion. Figure 57 shows the resulting temperature rises. The general characteristics of the temperature rises in Fig. 57 appear to be similar to the radiance levels in Fig. 56. However, the scales on the ordinate axes are of course different. Temperature rises as high as 95 K are shown in Fig. 57, and an average value of 64 K was computed. Furthermore, an average maximum temperature rise of 79 K was determined.

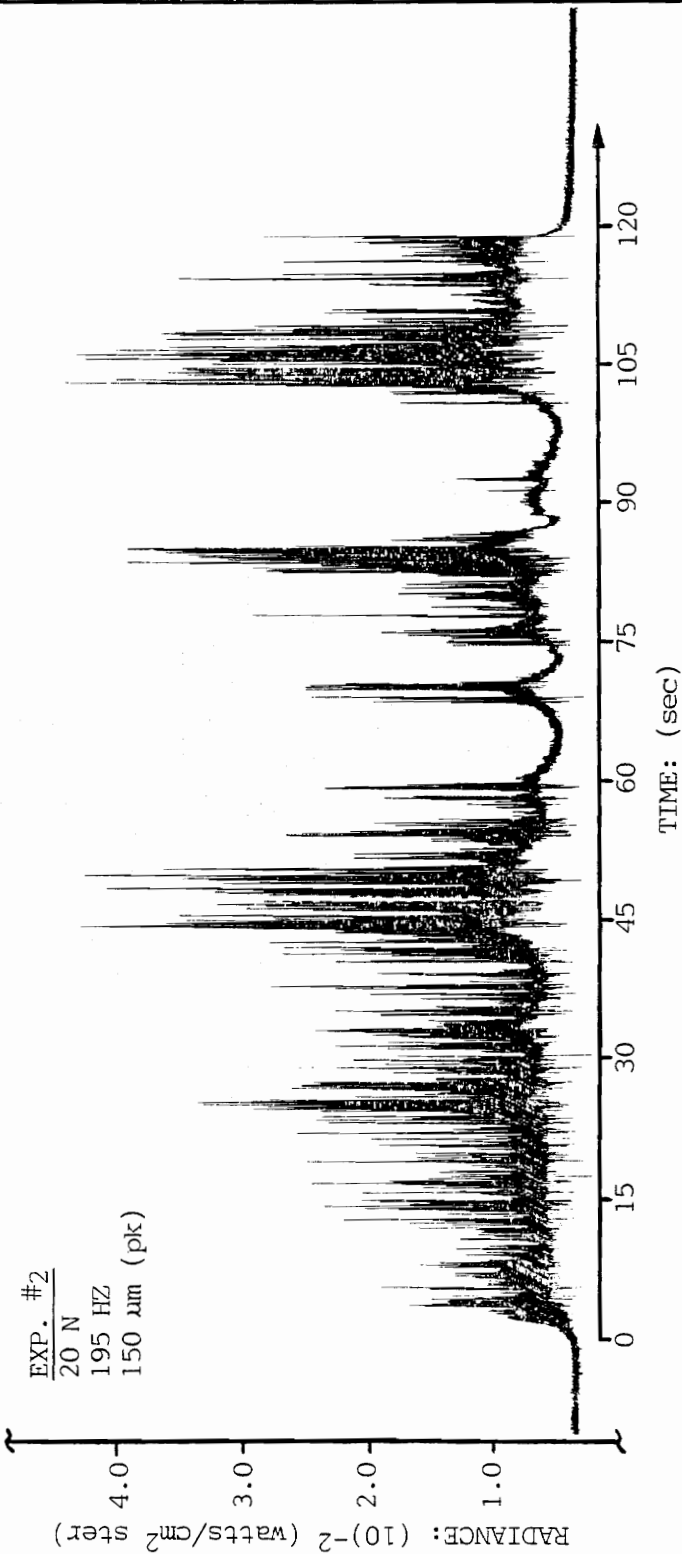
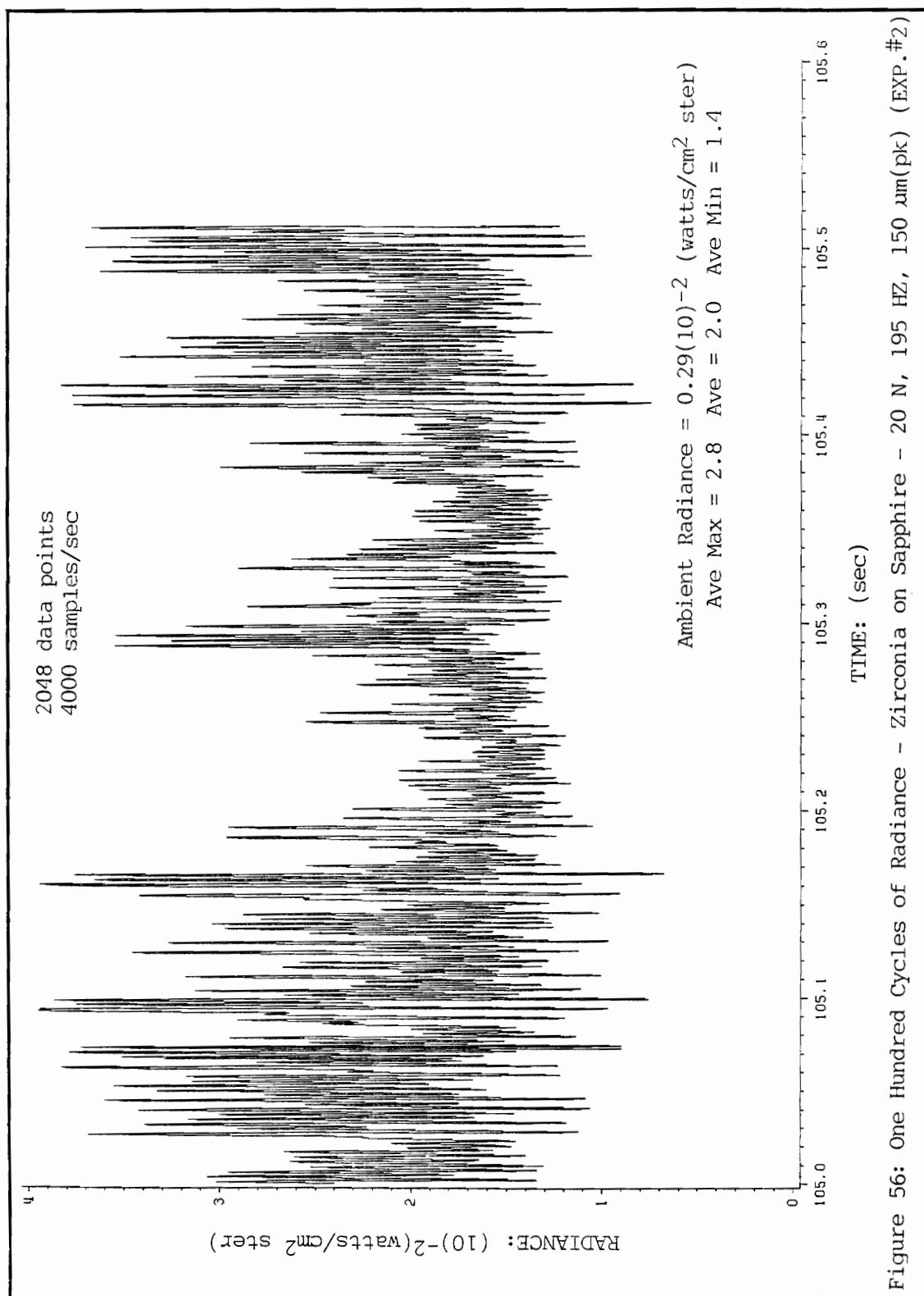


Figure 55: Radiance Trace - Zirconia on Sapphire - 20 N, 195 HZ, 150 um (pk) (EXP. #2)



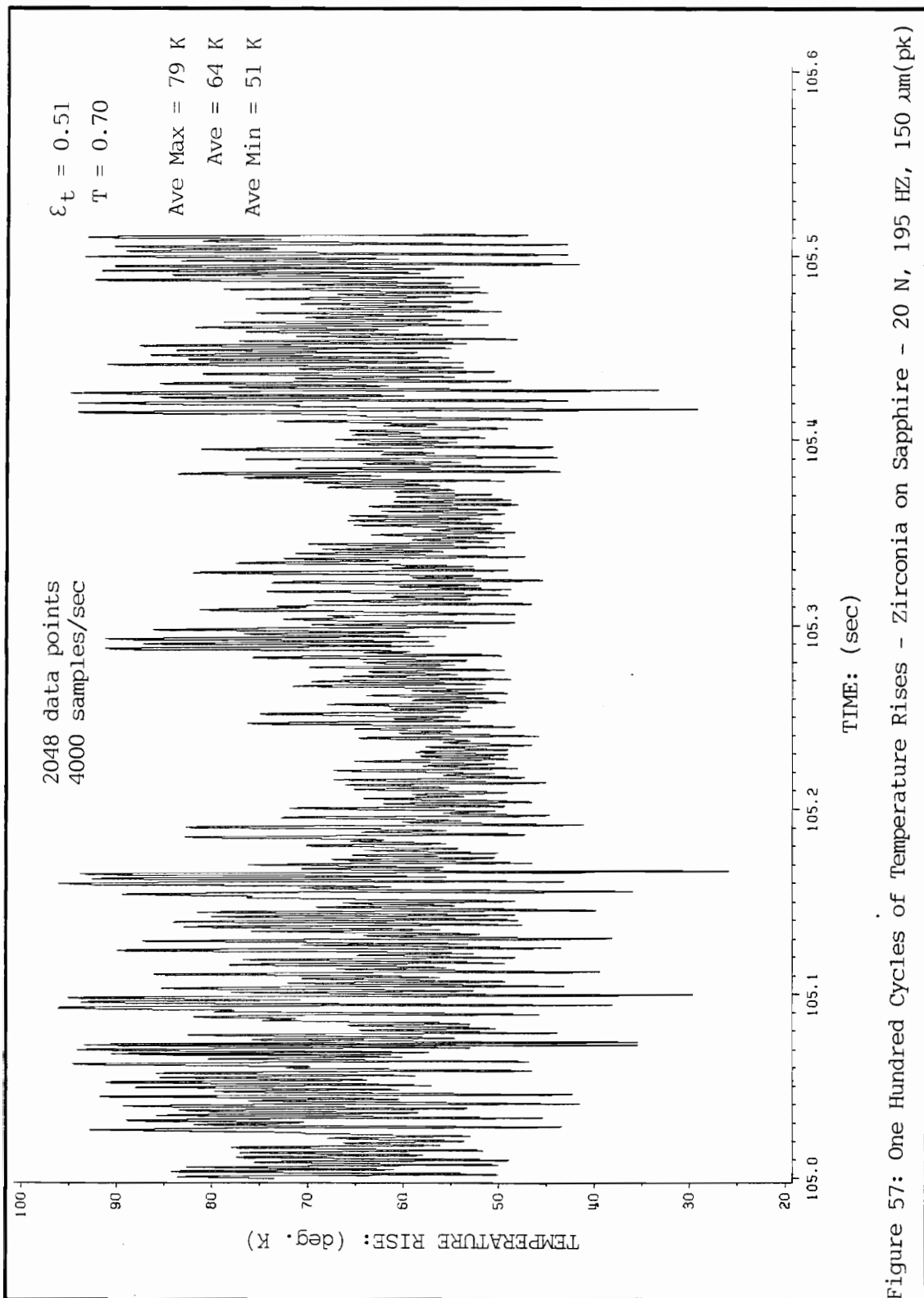
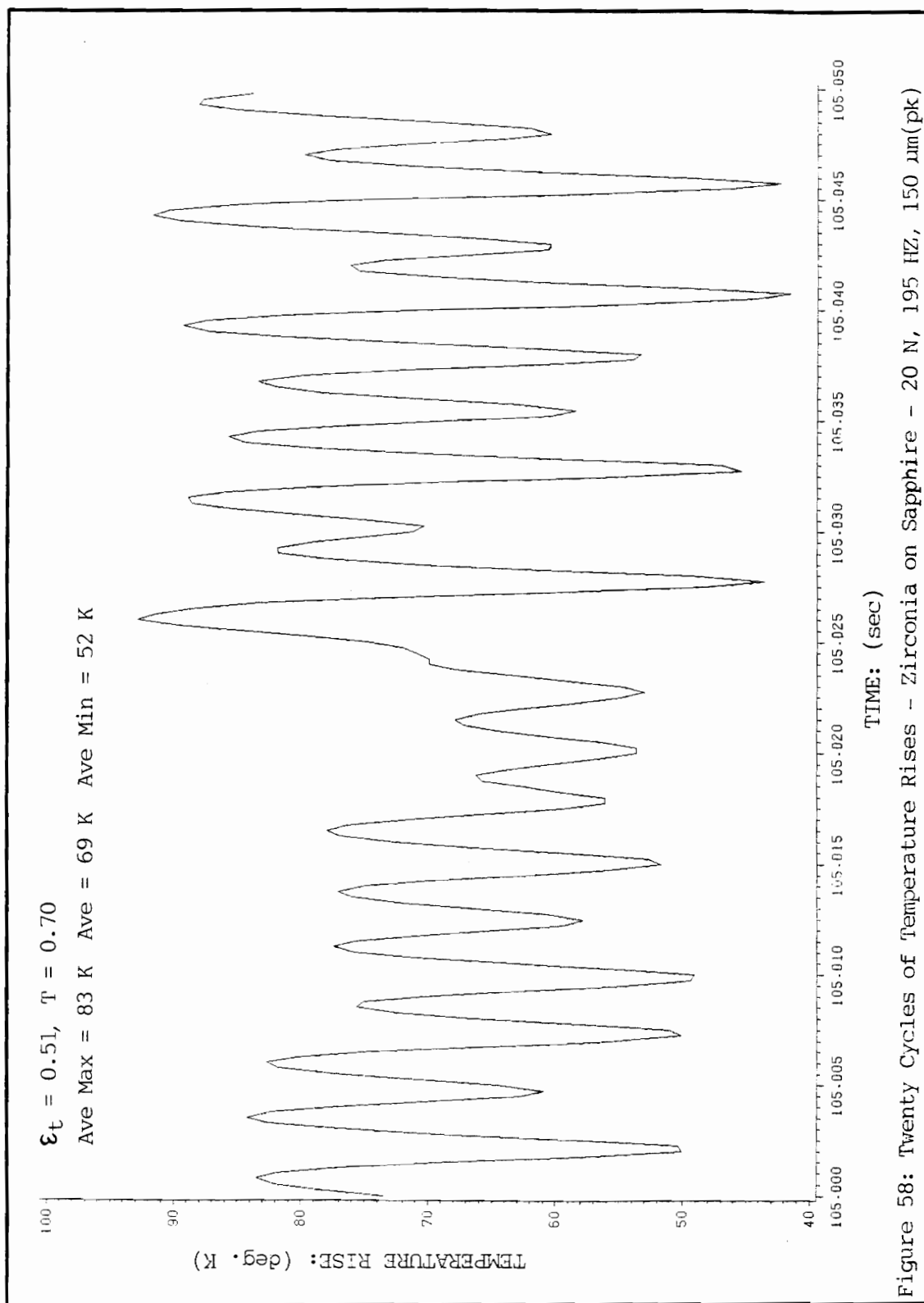


Figure 57 also shows that peak-to-peak temperature variations as high as 50 K occur in less than five thousandths of a second. In other words, in less than one cycle of motion there is a 50 K change in surface temperature between the zirconia sphere and sapphire disk.

High peak-to-peak variations in temperature are more apparent when only twenty cycles are plotted in Fig. 58. The sinusoidal nature of the temperature rises is also apparent. The predominant frequency of the temperature signal is 390.6 Hz. This is twice the oscillation frequency of 195.3 Hz, and means that there are two temperature peaks for every cycle of motion. At approximately 105.024 seconds, there appears to be a temperature peak missing! One explanation for this missing peak could be a sudden change in real contact area. Another explanation could be the sudden imposition of a relatively cool wear particle within the microscope's target spot. However, it is impossible to formulate a concrete explanation for this missing peak; (especially since the time period of this occurrence is less than five thousandths of a second.) In conclusion, the results shown in Fig. 54 represent direct measurements of instantaneous surface temperatures generated by friction during oscillating/fretting contact. To our knowledge, this has never been done before. These results dramatically demonstrate the capabilities of the experimental system used in this research.

4.2.4.b Temperature Measurements using the AC/DC and DC Channels

During an oscillating contact experiment, the FM tape recorder is used to monitor signals from two separate channels of the infrared microscope. The characteristics of the AC/DC and DC channels were discussed in Section 3.2.1. However, possible differences between these two channels have not been demonstrated. First of all, the DC channel has a frequency response of 400 Hz, and was installed in the microscope by the manufacturer. The AC/DC channel was installed at Virginia Tech, and has an unknown frequency response. However, the AC/DC channel's response should be higher than the DC channel's because a 400 Hz filter used in the DC channel is bypassed. Figure 59 shows radiance traces for the AC/DC and DC channels. Both voltage scales and radiance scales are shown in this figure.



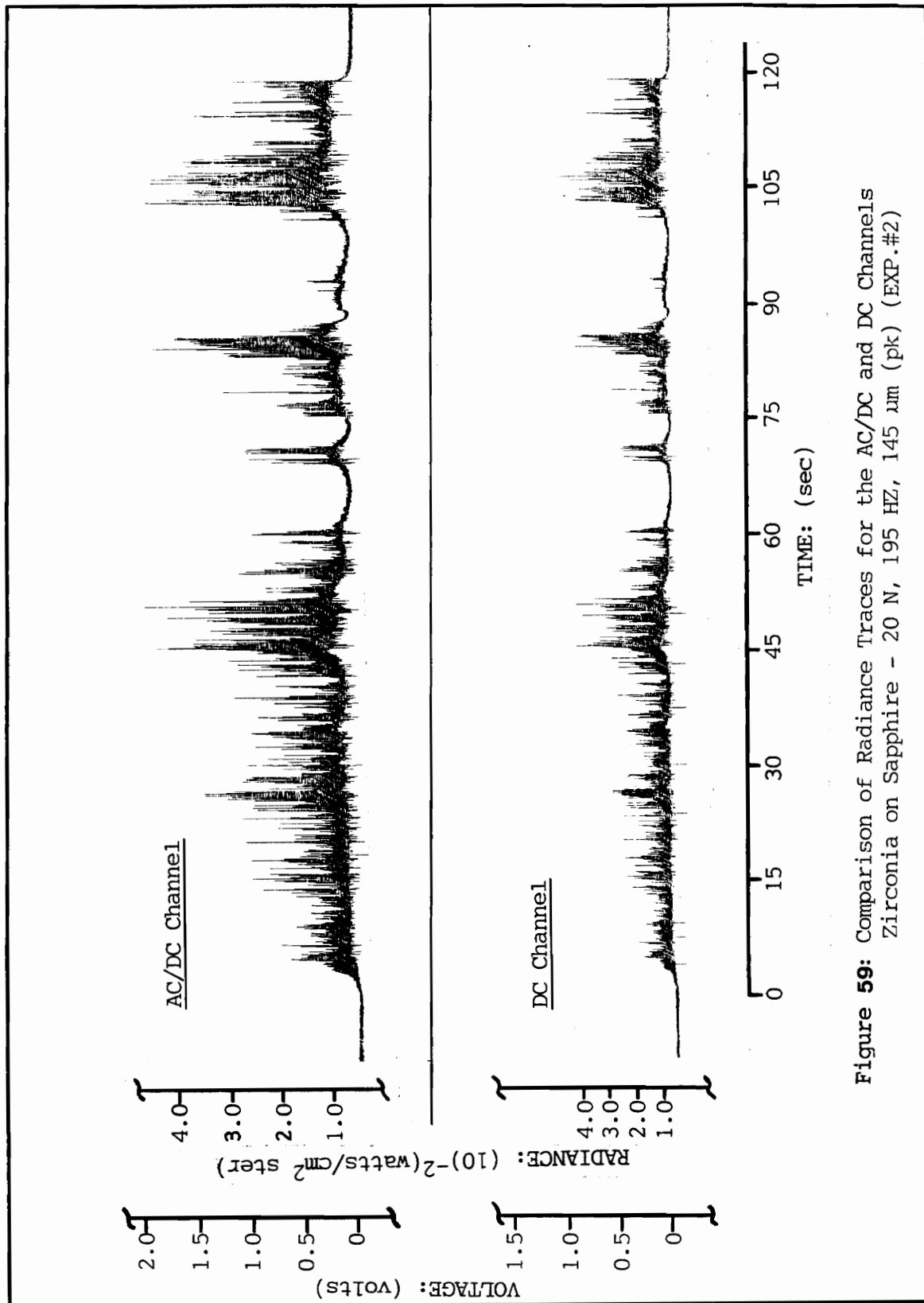


Figure 59: Comparison of Radiance Traces for the AC/DC and DC Channels
Zirconia on Sapphire - 20 N, 195 HZ, 145 μm (pk) (EXP.#2)

Since the voltage scales are the same for both the AC/DC and DC channels, it is obvious that the AC/DC channel has a higher voltage output than the DC channel. The DC channel's output is lower because of the presence of the 400 Hz filter. This filter not only brings the DC channel's frequency response down to 400 Hz, but it also increases the impedance causing the DC channel's voltage output to be lower. The radiance scales, on the other hand, are different for each channel. In fact, based on these scales, it would appear that the radiance measured using the two channels is nearly identical. An explanation for this similarity can be found by examining the microscope's calibration curves shown in Appendix A. The least squares equations associated with each of these curves are written below:

$$\text{AC/DC RADIANCE} = 8.02(10)^{-3}(\text{AC/DC VOLTS}) + 2.60(10)^{-3} \quad (39)$$

$$\text{DC RADIANCE} = 15.3(10)^{-3}(\text{DC VOLTS}) + 2.60(10)^{-3} \quad (40)$$

OR,

$$\text{AC/DC VOLTS} = 125.(10)^{-3}(\text{AC/DC RADIANCE}) - 3.24(10)^{-1} \quad (41)$$

$$\text{DC VOLTS} = 65.4(10)^{-3}(\text{DC RADIANCE}) - 1.70(10)^{-1} \quad (42)$$

Equations 39 and 40 are the calibration equations for predicting radiance from voltage. As shown above, these two equations can be rewritten to show voltage output as a function of radiance. The slopes of Eqs. 41 and 42 are $125(10)^{-3}$ for the AC/DC channel, and $65.4(10)^{-3}$ for the DC channel. Therefore, the voltage output from the AC/DC channel is approximately twice the voltage output from the DC channel.

When the radiance data for the AC/DC and DC channels is converted to temperature rises, there is a difference of approximately 5 K. Figure 60 shows this difference for the temperature plot discussed previously. The dashed line represents temperature rises measured using the DC channel. The solid line represents temperature rises measured using the AC/DC channel. Since the dashed line is slightly lower than the solid line, it is obvious that the DC channel slightly underestimates

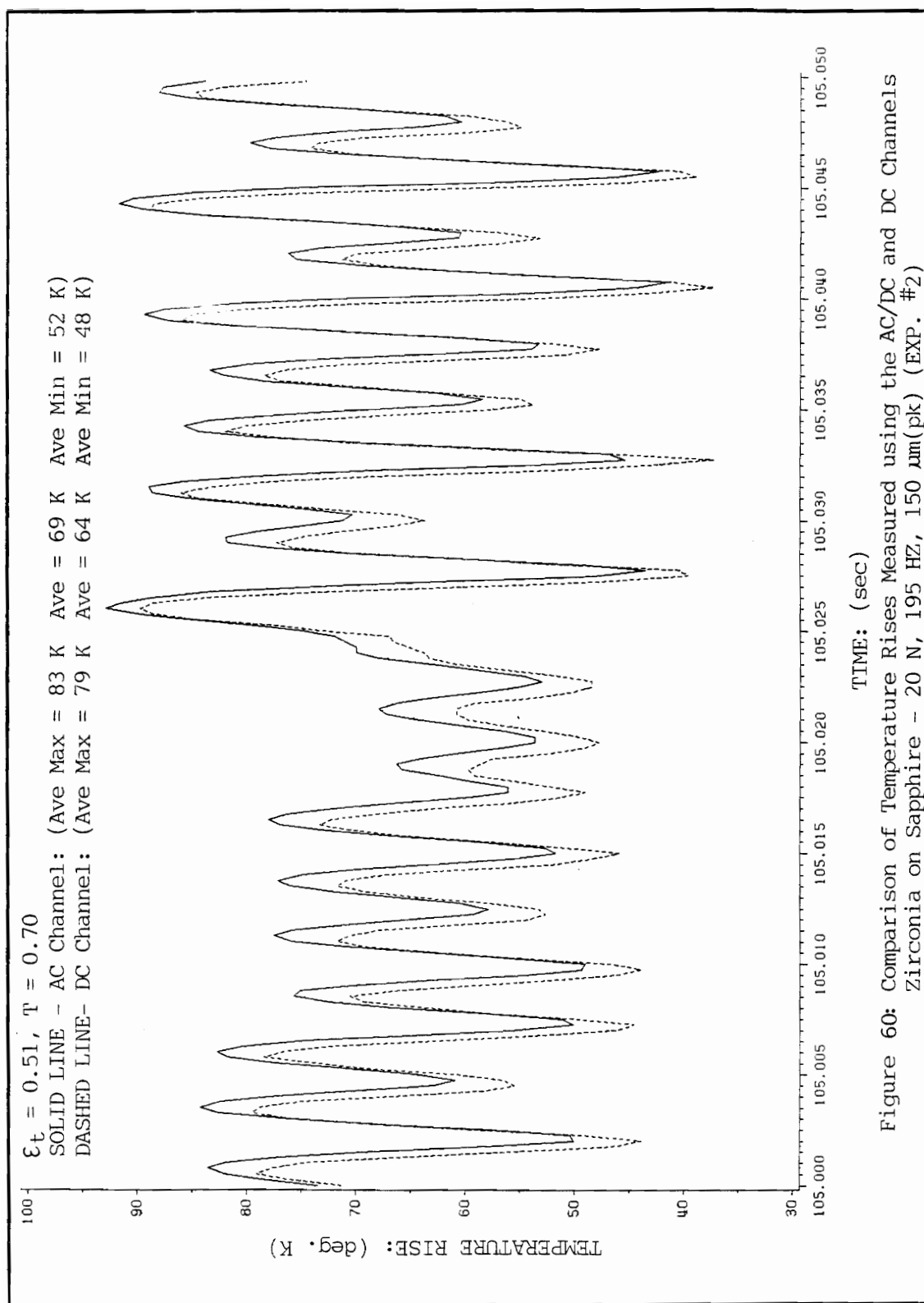
the temperature rise. The higher temperature rises measured using the AC/DC channel could be explained by an increase in frequency response.

However, the predominant frequency of the temperature rises is 390.6 Hz, which is slightly lower than the DC channel's 400 Hz frequency response. Therefore, temperature rises measured using the two channels should be nearly identical. An alternative explanation for the 5 K difference between the two channels is the variance associated with the calibration curves. Since the AC/DC channel has a slightly wider confidence interval than the DC channel, the variance associated with AC/DC temperature rises is greater. As a final note, the 5 K discrepancy between the two channels is less than the discrepancy associated with using different emissivities and transmittances. Recall that this discrepancy is approximately 15 - 20 K for emissivities and transmittances ranging from 0.51 - 0.71 and 0.70 - 0.82, respectively.

4.2.4.c Temperatures in the Frequency Domain - AC/DC and DC Channels

To determine the predominant frequencies associated with the temperature rises, the Fourier transform of the data was obtained, and the autospectral density was determined. This technique is described in Appendix D, and will only be summarized in the present discussion. Basically, the autospectral density of a signal tells us the frequency content of that signal. Also, it tells us the peak magnitude of the signal at each frequency. Figure 61a shows the autospectral density of the temperature rises shown in Fig. 57. These temperature rises were obtained using the AC/DC channel of the infrared microscope. The predominant frequency is 390.6 Hz, and is associated with the largest spike. Other frequencies are also contained within the temperature signal. For instance, peaks are also present at 195.3 Hz and 1.95 Hz. To determine the peak magnitude of the signal at 390.6 Hz, the autospectral density of 56 K²/Hz must be converted to Kelvin. This is done by simply multiplying 56 by the resolution in Hz, and taking the square root:

$$\sqrt{56 \frac{\text{K}^2}{\text{Hz}} \frac{(4000 \text{ samples/sec})}{(2048 \text{ samples})}} = 10\text{K(pk)}@390.6\text{Hz} \quad (43)$$

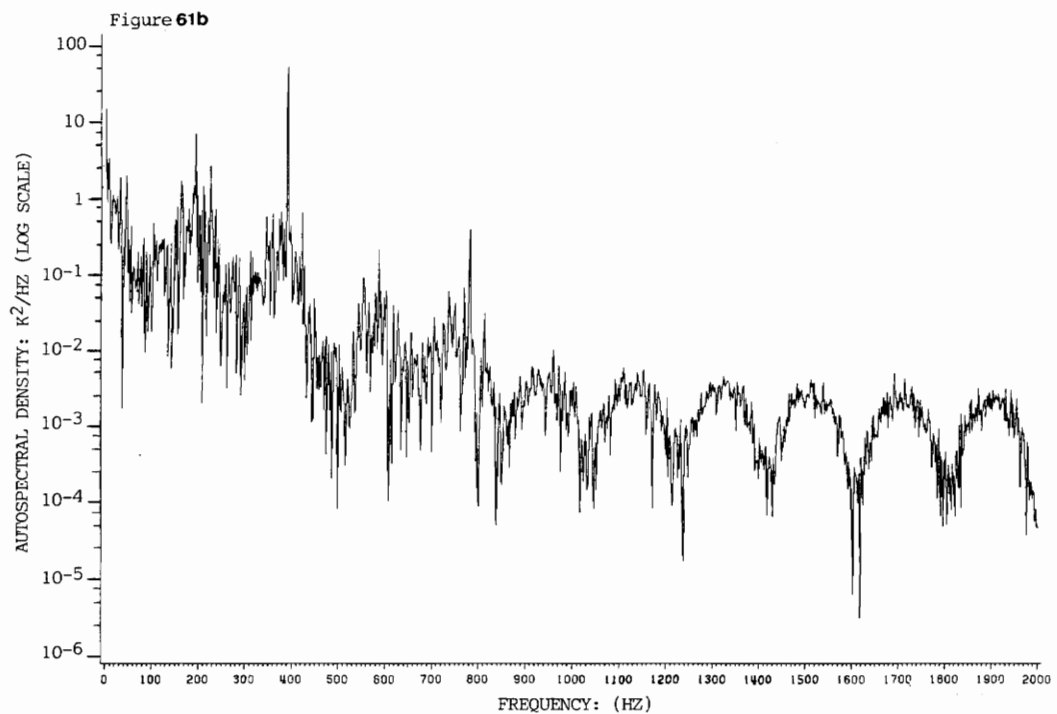
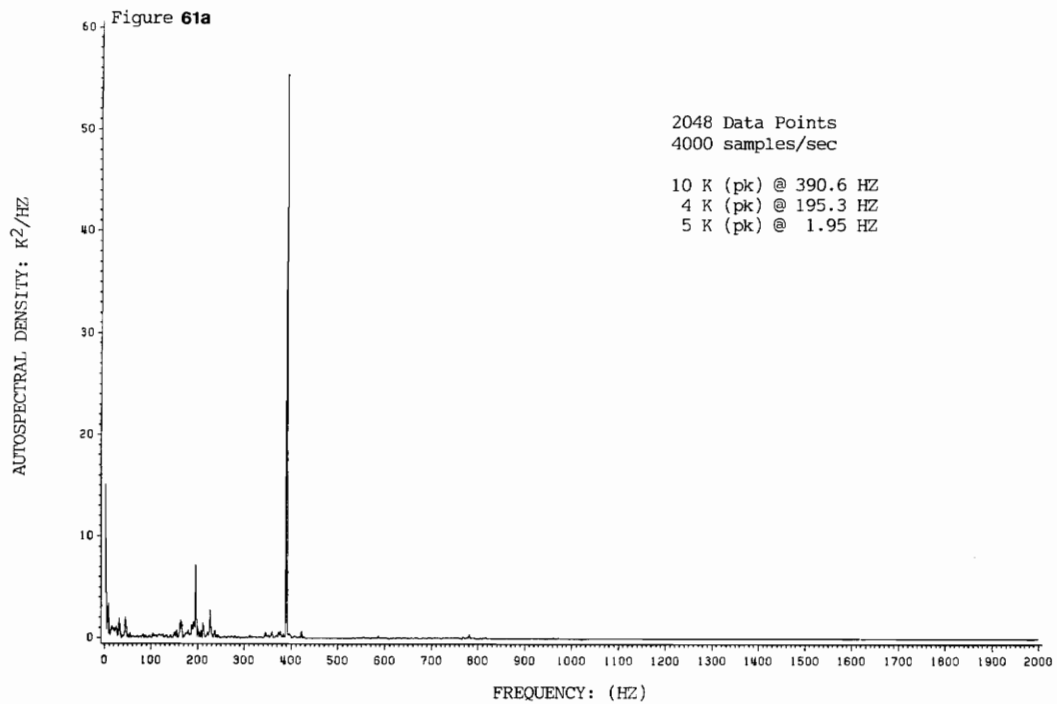


where,

$$\text{RESOLUTION (in Hz)} = \frac{\text{samples/sec}}{\text{samples}}$$

The 10 K (pk) temperature derived above is *not* a temperature rise above ambient. Instead, it is a measure of the temperature variation about an average value. Figure 62 illustrates this point. The other two predominant frequencies in Fig. 61a are 195.3 Hz and 1.95 Hz. The magnitudes at these frequencies are 4 K (pk) and 5 K (pk), respectively. Other frequencies present in the temperature signal become more apparent when the autospectral density is plotted on a log scale. This plot is shown in Fig. 61b. Higher frequencies at 585 Hz and 781 Hz are shown in this plot. Since 585 Hz and 781 Hz are multiples of the oscillation frequency (195.3 Hz), the peaks at these frequencies probably represent temperature rises generated at higher modes of vibrations. However, the magnitudes at these frequencies are less than 1 K, and do not contribute significantly to the temperature variation. At frequencies greater than 850 Hz, there are waveforms spaced at 200 Hz intervals. The cause of these waveforms is a mystery. They are present only in the AC/DC channel's logarithmic autospectra shown in Fig. 61b. The DC channel's logarithmic autospectra are shown in Fig. 63b, and the waveforms are not present. However, the predominant frequencies at 390.6 Hz, 195.3 Hz, and 1.95 Hz are present in the DC channel's autospectra. Furthermore, the DC channel is also detecting temperature rises at the higher frequencies of 585 Hz and 781 Hz.

Since neither the AC/DC nor DC channels contain significant frequencies above 781 Hz, one could hypothesize that no high frequency interfacial temperatures are generated. The question of interfacial temperature "jumps" was originally proposed by Blok in references [8,25]. In his hypothesis, Blok proposed that single asperity interactions could lead to the generation of extremely high temperatures since the real area of contact is microscopic. These high temperatures could be characterized as high frequency transients superimposed on the mean surface temperature. To measure these high frequency temperatures, the AC/DC channel's true frequency response would have to be obtained. With this information, one could conclude whether or not the lack of frequencies above 781 Hz is indeed due to a lack of high frequency temperature rises.



Figure's 61a&61b : Autospectral Density of Temperature Rises - (AC/DC CHANNEL)
Zirconia on Sapphire - 20 N, 195 HZ, 150 μm (EXP.#2)

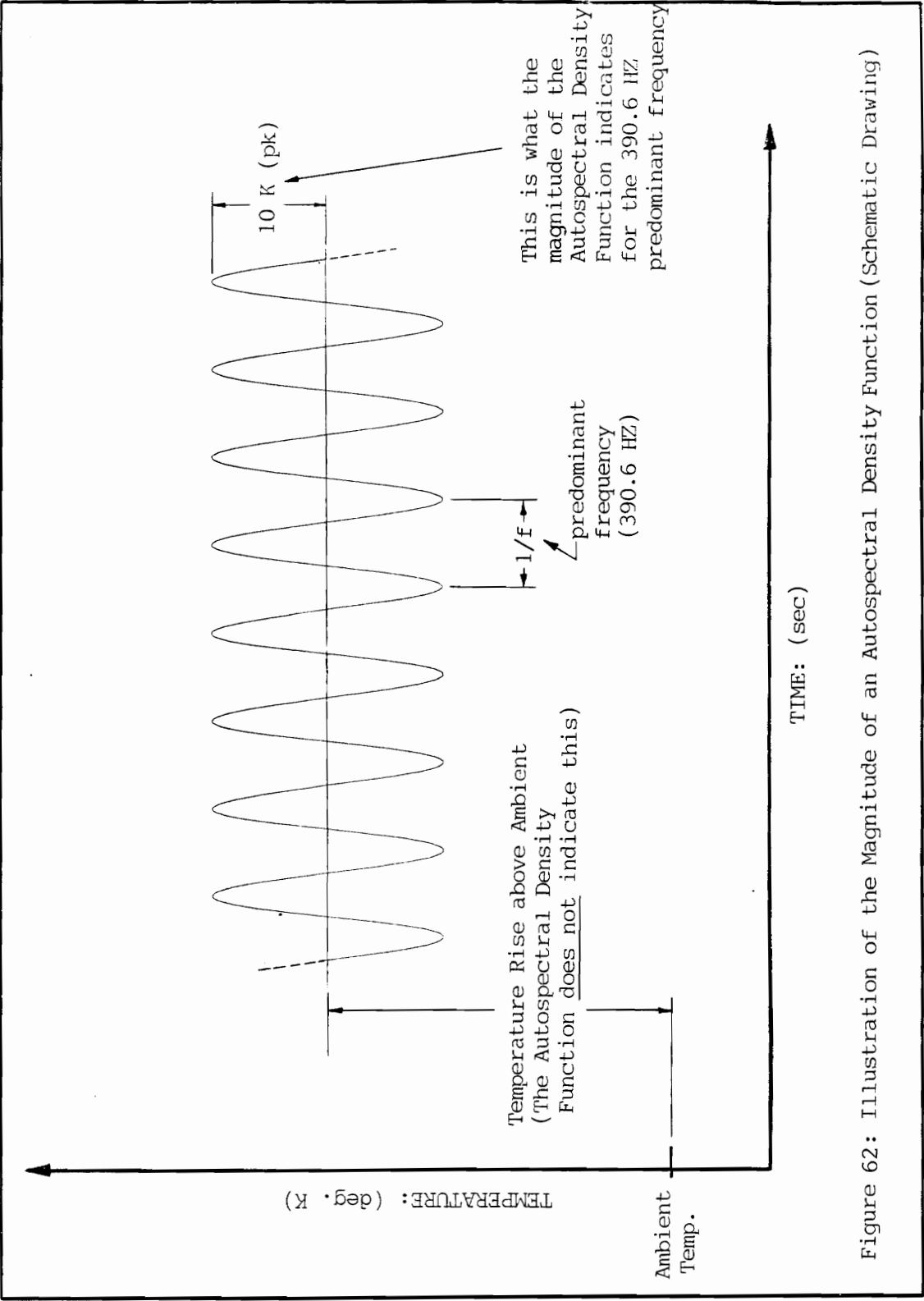
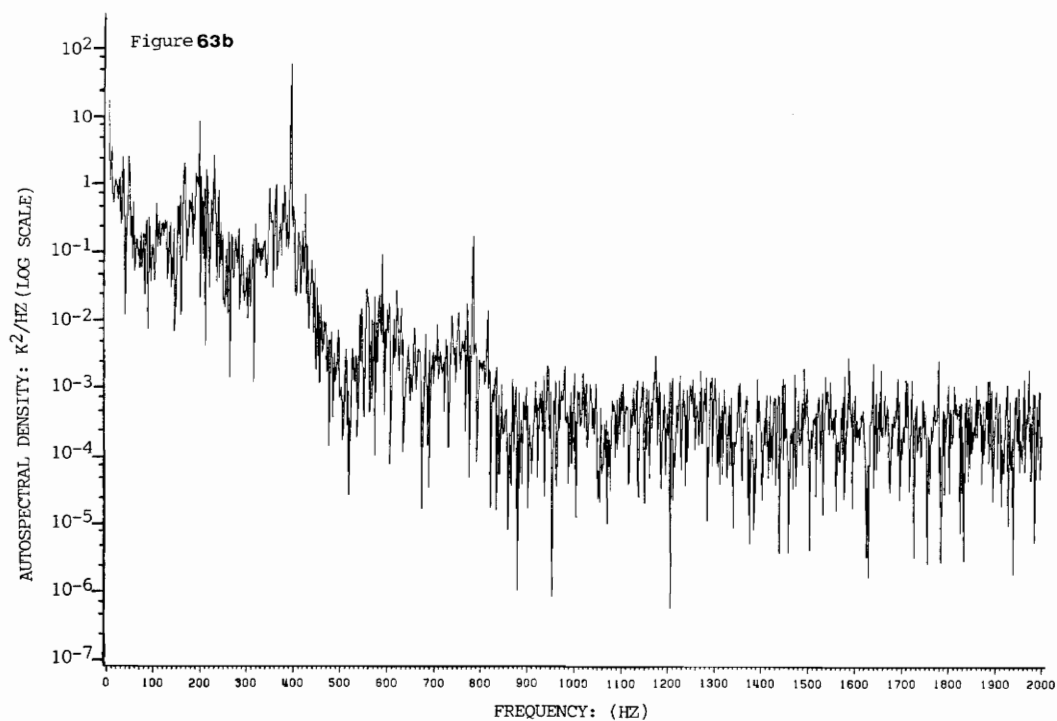
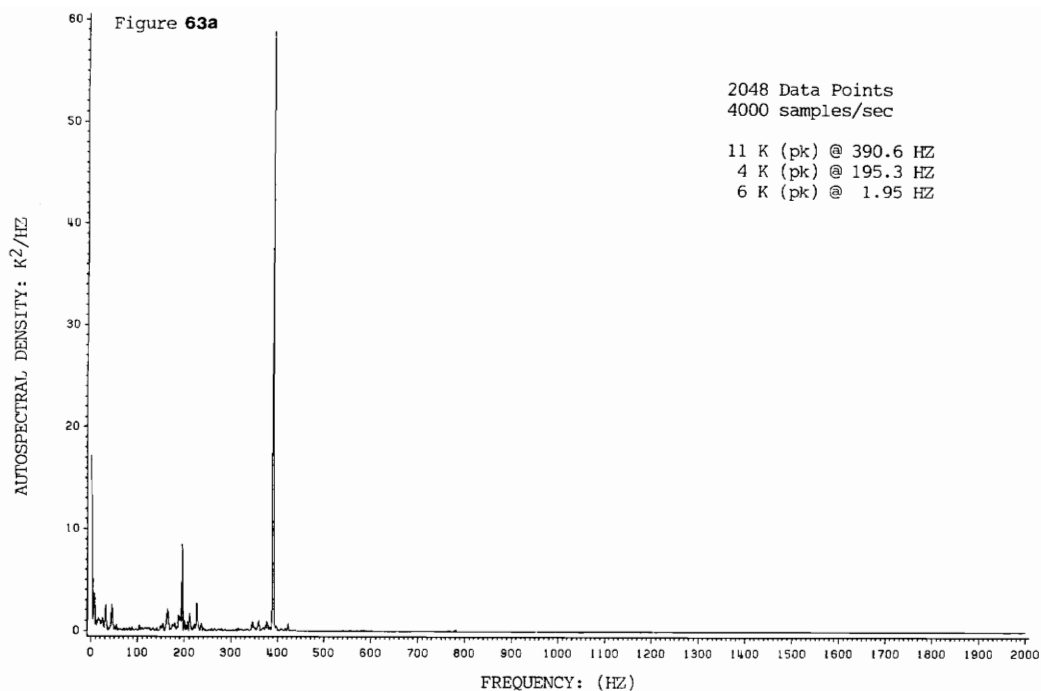


Figure 62: Illustration of the Magnitude of an Autospectral Density Function (Schematic Drawing)



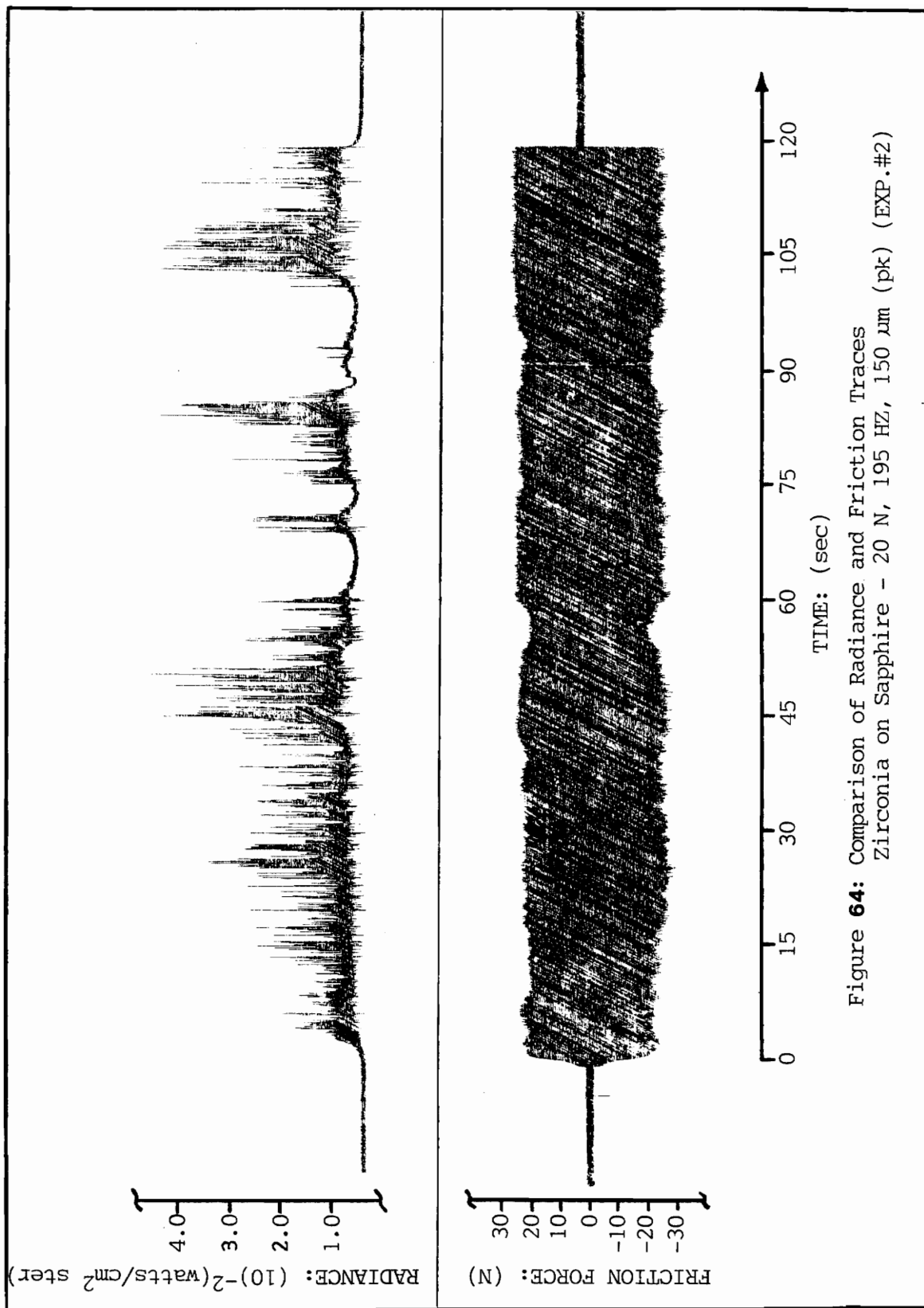
Figures 63a & 63b: Autospectral Density of Temperature Rises - (DC CHANNEL)
Zirconia on Sapphire - 20 N, 195 HZ, 150 μm (pk) (EXP.#2)

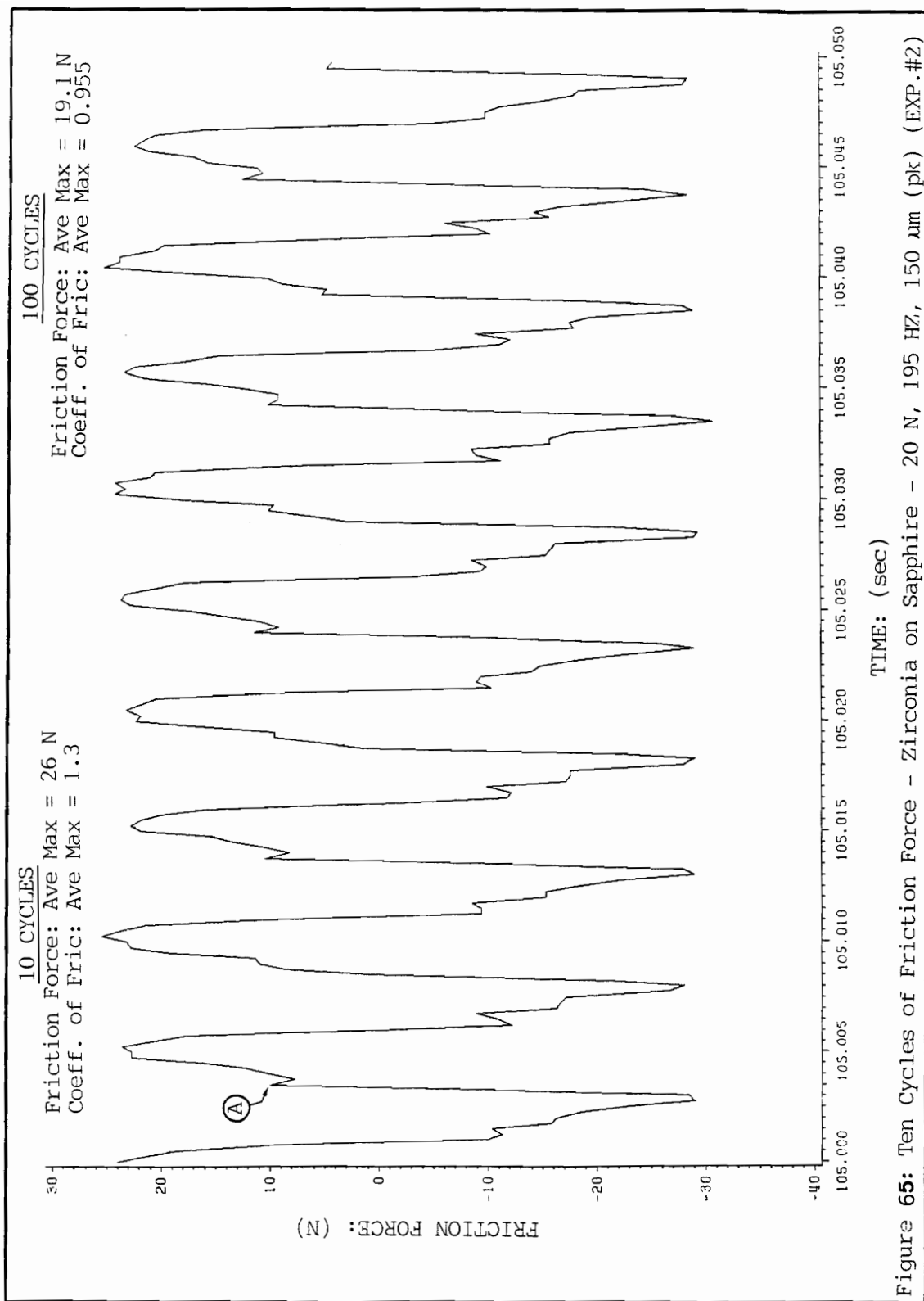
4.2.4.d Cycle-to-Cycle Details for Friction and Temperature

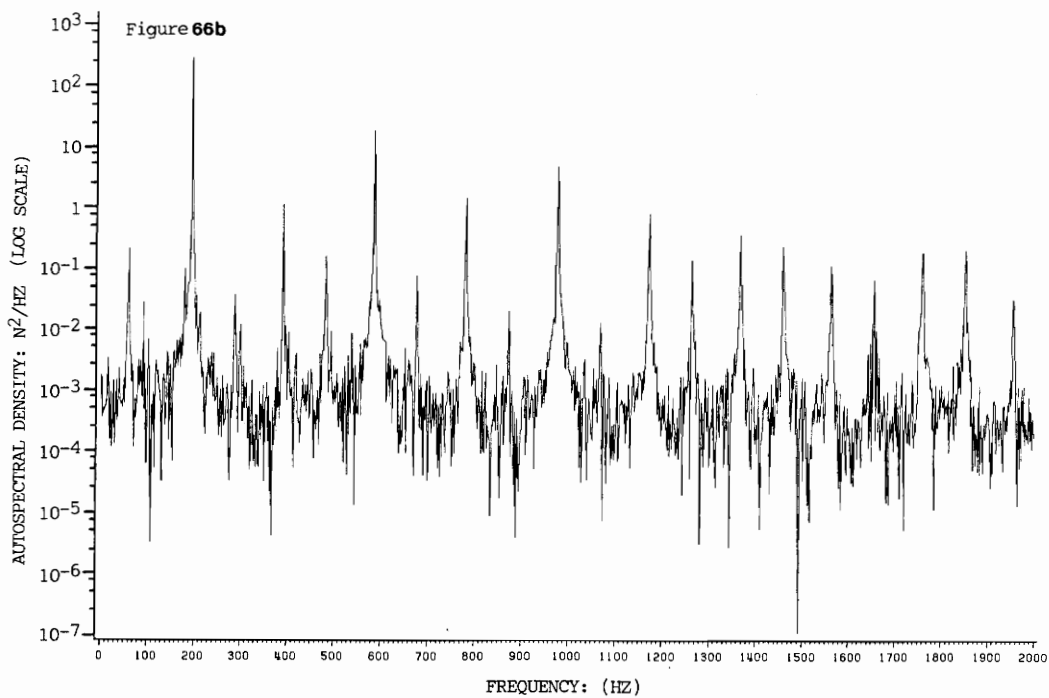
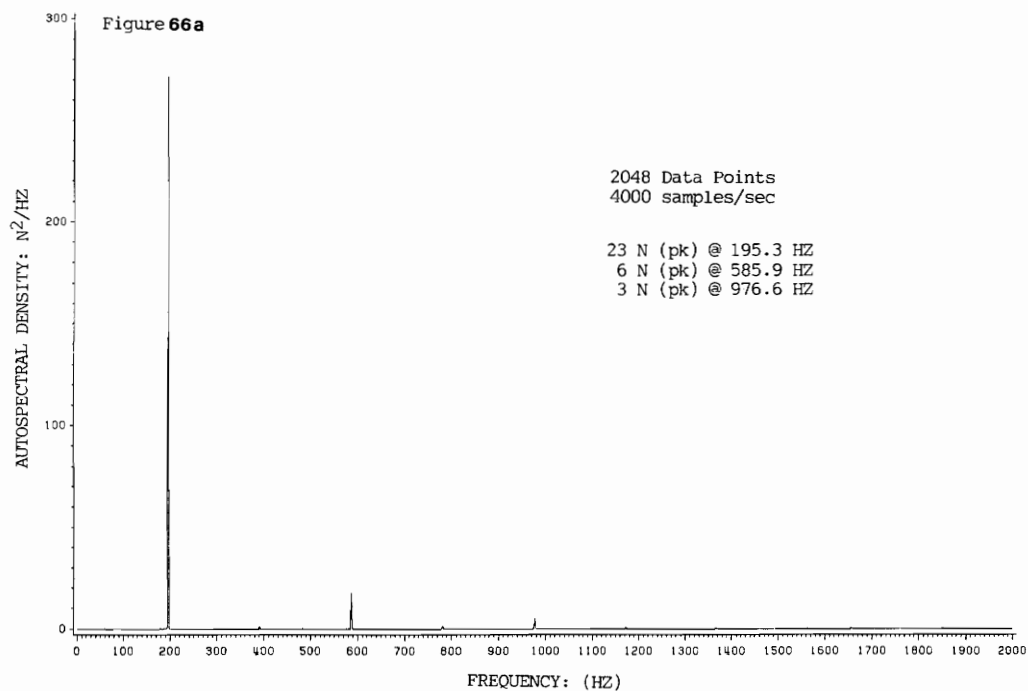
Figure 64 shows a radiance trace and friction trace for zirconia Exp. 2. Before the start of the experiment, the friction force is zero and the radiance is at an ambient level. When oscillation of the sapphire disk is initiated at 0 seconds, the friction force increases to an average peak level between 18 and 19 N. Since the normal load used was 20 N, this corresponds to a friction coefficient between 0.90 and 0.95. Note, friction force is a vector quantity. Therefore, when compared to a positive friction force, a negative friction force acts in the opposite direction. When friction is compared to radiance in Fig. 64, it is obvious that the initiation of friction coincides with an increase in radiance. Furthermore, when the friction ceases at the end of the experiment, the radiance decreases dramatically to an ambient level. There are also slight variations of friction force during the experiment. However, the peak level remains relatively constant, and the variations are not very significant.

At 105 seconds after the start of the experiment, 100 cycles of the friction force signal were sampled. Ten of the 100 cycles sampled are shown in Fig. 65. High peak values of friction force range from 24 - 28 N in this figure. Also, lower peaks seem to occur between 11 and 15 N. One of these lower peaks is designated by point A in Fig. 65. When all 100 cycles of the friction force signal are used, the average maximum friction force is determined to be 19.1 N. This corresponds to a friction coefficient of 0.955. Note, the 19.1 N average takes into account both the positive and negative vectorial directions. It is in fact the average of the peak friction forces measured for each direction.

Figures 66a and 66b show the autospectral density of the friction force signal. The predominant frequency of the signal is 195.3 Hz. At this frequency, the peak variation is 23 N. Other frequencies are also present. For instance, at 585.9 Hz, the peak variation is 6 N; and at 976.6 Hz, the peak variation is 3 N. Figure 66b shows the autospectral density of friction on a log scale. It shows that there are several high frequencies detected by the strain ring. From Fig. 66b one can conclude that the frequency response of the strain ring is at least 2 KHz. The addition of high frequency signals to the predominant 195.3 Hz signal could be due to additional modes of vibration.







Figures 66a & 66b : Autospectral Density of Friction Force
Zirconia on Sapphire - 20 N, 195 HZ, 150 μm (pk) (EXP.#2)

In fact, the 585.9 Hz spike shown in Figure 66a is three times the 195.3 Hz predominant frequency; and the 976.6 Hz frequency is five times the 195.3 Hz predominant frequency. However, their effect on the dynamic friction force is insignificant.

Now that the temperature and friction signals have been analyzed separately, correlations between the two signals will be obtained. To do this, the cross-spectral density of the two signals is calculated. This technique is used to obtain two pieces of information about the signals. First, it displays the frequency correlation between the two signals. In other words, the cross-spectral density of temperature and friction answers the following question: "What are the characteristic frequencies present in *both* signals?" Secondly, the cross-spectral density tells us the time delay or phase difference between the two signals. More specifically, the time delay at a given correlation frequency is obtained. A more complete discussion about cross-spectral density functions can be found in Appendix D.

Figure 67 shows the cross-spectral density of friction force and temperature. Since the absolute value of friction force is used, the two signals are highly correlated at 390.6 Hz. This is twice the 195.3 Hz oscillation frequency. The two signals are also correlated at 195.3 Hz, 585.9 Hz, and 781.2 Hz. The units for cross-spectral density in Fig. 67 are NK/Hz. Therefore, the highest friction force and temperature rise yield the highest cross-spectral density at a given frequency. In Fig. 67, the highest spike is obviously at 390.6 Hz. As a result, absolute friction forces operating at this frequency cause the highest temperature rises. The calculated time delay and phase differences at 390.6 Hz are also shown in Fig. 67. The time delay is -0.139 ms. The negative sign means that friction reaches a maximum before temperature. This -0.139 ms corresponds to a phase difference of -19.5 degrees or -0.340 radians. In fractions of a cycle, the phase difference is -0.054 cycles. Stated another way, friction reaches a maximum value five one hundredths of a cycle before temperature. In short, the 390.6 Hz components of temperature and friction reach a maximum value at approximately the same time.

The 0.054 cycle phase difference between temperature and friction is not obvious when the two signals are superimposed on each other. Figure 68 shows temperature plotted as a solid line and friction plotted as a dashed line.

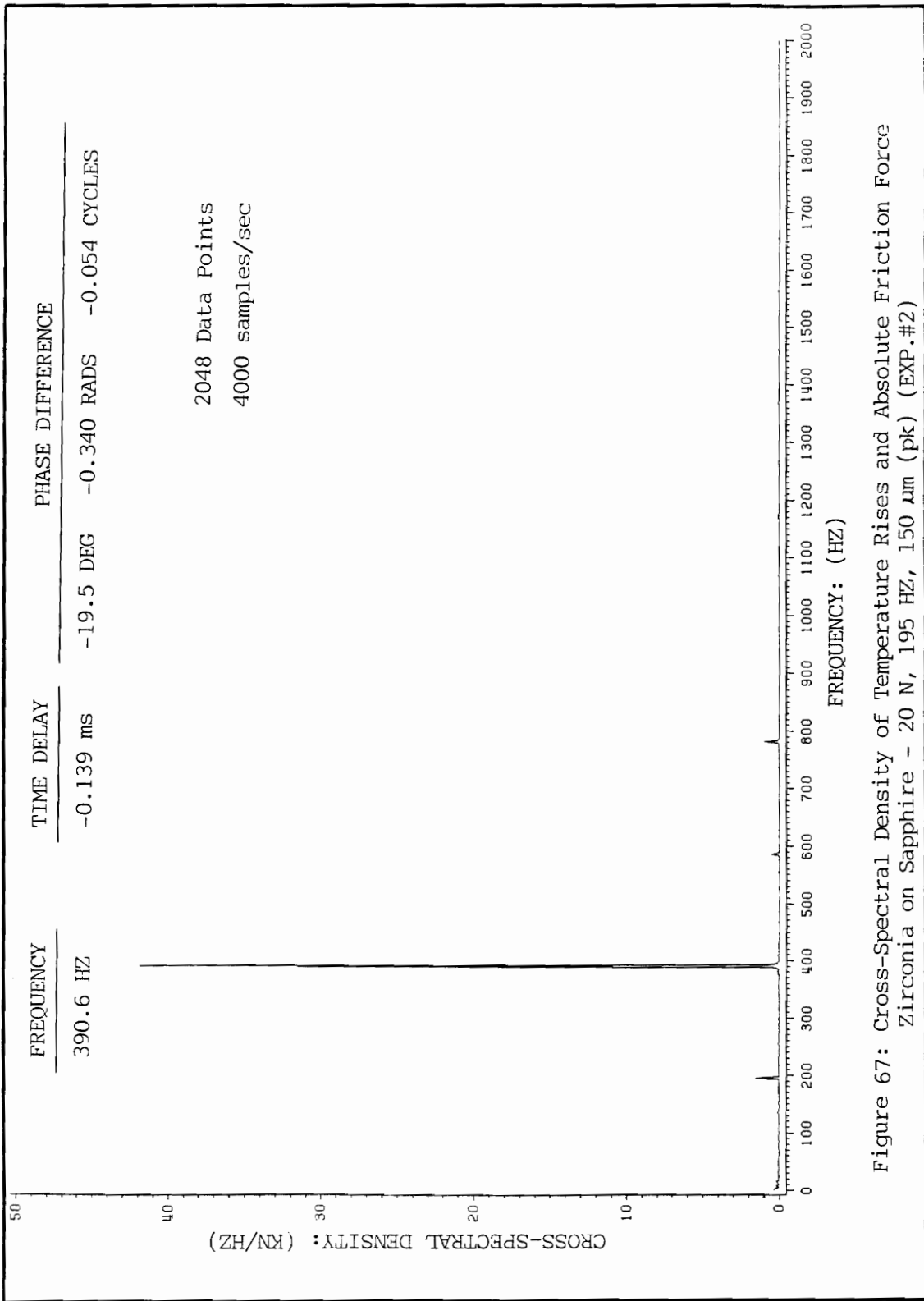


Figure 67: Cross-Spectral Density of Temperature Rises and Absolute Friction Force
Zirconia on Sapphire - 20 N, 195 HZ, 150 μ m (pk) (EXP.#2)

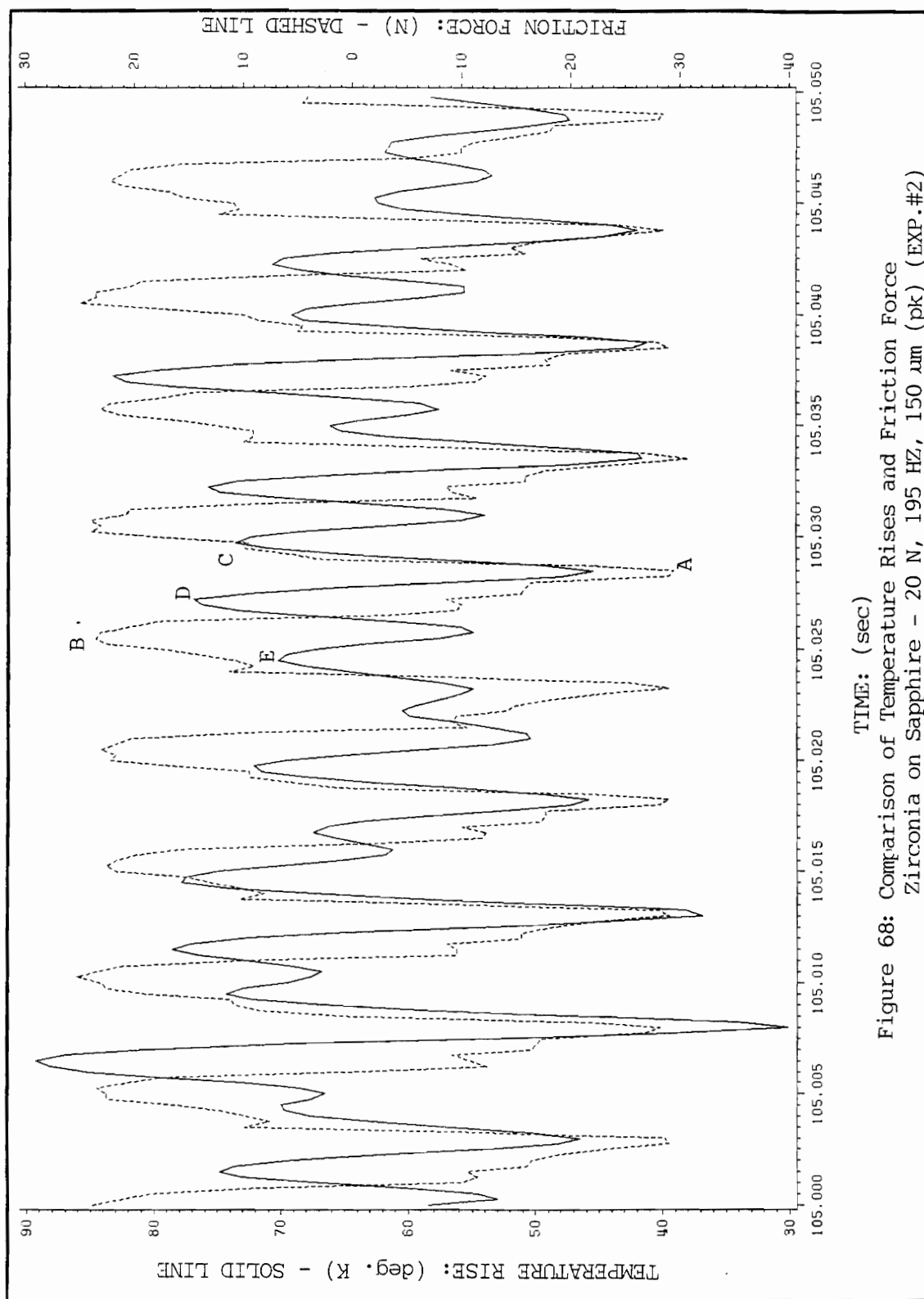


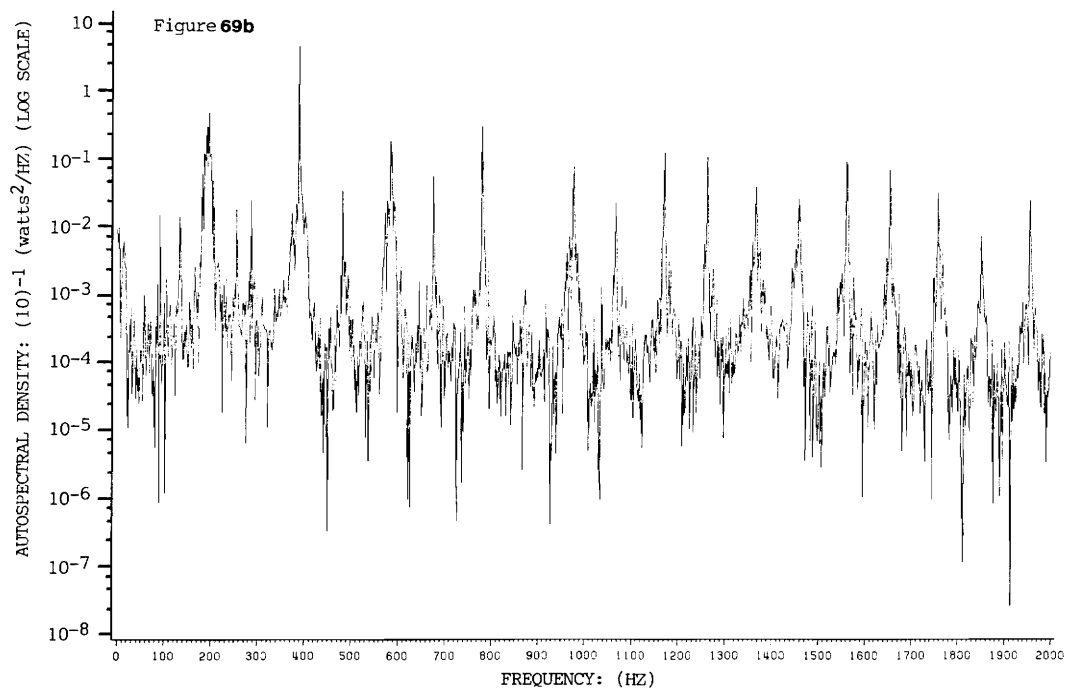
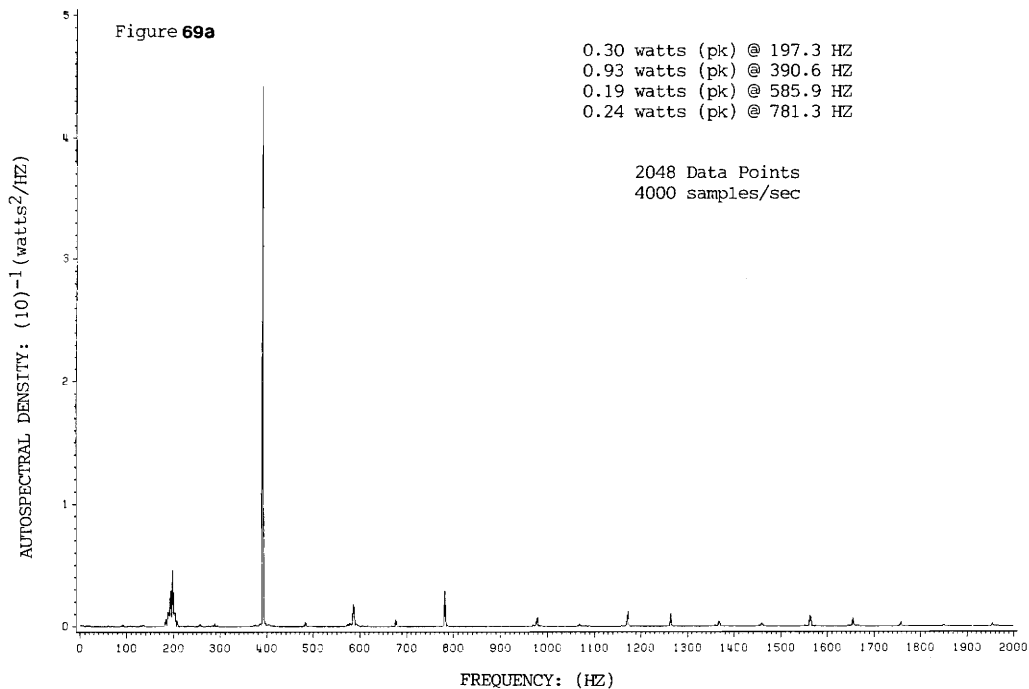
Figure 68: Comparison of Temperature Rises and Friction Force
Zirconia on Sapphire - 20 N, 195 Hz, 150 μ m (pk) (EXP.#2)

Since both signals contain more than one frequency, it is difficult to determine the phase difference by simply examining the figure. For instance, the negative maximum friction designated by point A in Fig. 68 seems to correspond to a minimum in temperature. However, it probably corresponds to one of two maximum temperatures designated by points D and C. The same inference can be made for the positive maximum friction force designated by point B. It corresponds to one of two maximum temperatures designated by points E and D. In light of these difficulties, the use of cross-spectral density functions to calculate phase differences is certainly a better approach. The frequencies contained within the signals are separated, and the phase difference is calculated for only the predominant frequency. As a final note, the data acquisition process causes the friction force signal to be shifted 0.125 ms to the left. Although this shift is negligible in Fig. 68, it is taken into account when the phase difference is calculated.

4.2.4.e Cycle-to-Cycle Details for Velocity and Temperature

Figures 69a and 69b show the autospectral density of the acceleration signal. Since the experiment was performed at 195.3 Hz, there is a predominant spike at this frequency. The magnitude of this spike corresponds to a peak acceleration of 227 m/s^2 . When the autospectral density is plotted on a log scale in Fig. 69b, higher frequencies become apparent. These higher frequencies suggest that there are different vibration modes present in the system. However, as shown in Fig. 69a, the magnitudes of these high frequency components are insignificant compared to the magnitude at 195.3 Hz.

By using the methods described in amplitude values can be obtained from the peak acceleration of 227 m/s^2 at 195.3 Hz. These values are 185 mm/s and $150 \text{ }\mu\text{m}$, respectively. Also, by using digital integration techniques described in Appendix D, cycle-to-cycle velocity values can be calculated from the acceleration signal. The result of this integration process is shown in Fig. 70. In this figure, acceleration is represented as a solid line, and velocity is represented as a dashed line. As expected, velocity is shifted 90 degrees with respect to acceleration.



Figures 69a & 69b : Autospectral Density of Heat Generation
 Zirconia on Sapphire - 20 N, 195 HZ, 150 μ m (pk) (EXP.#2)

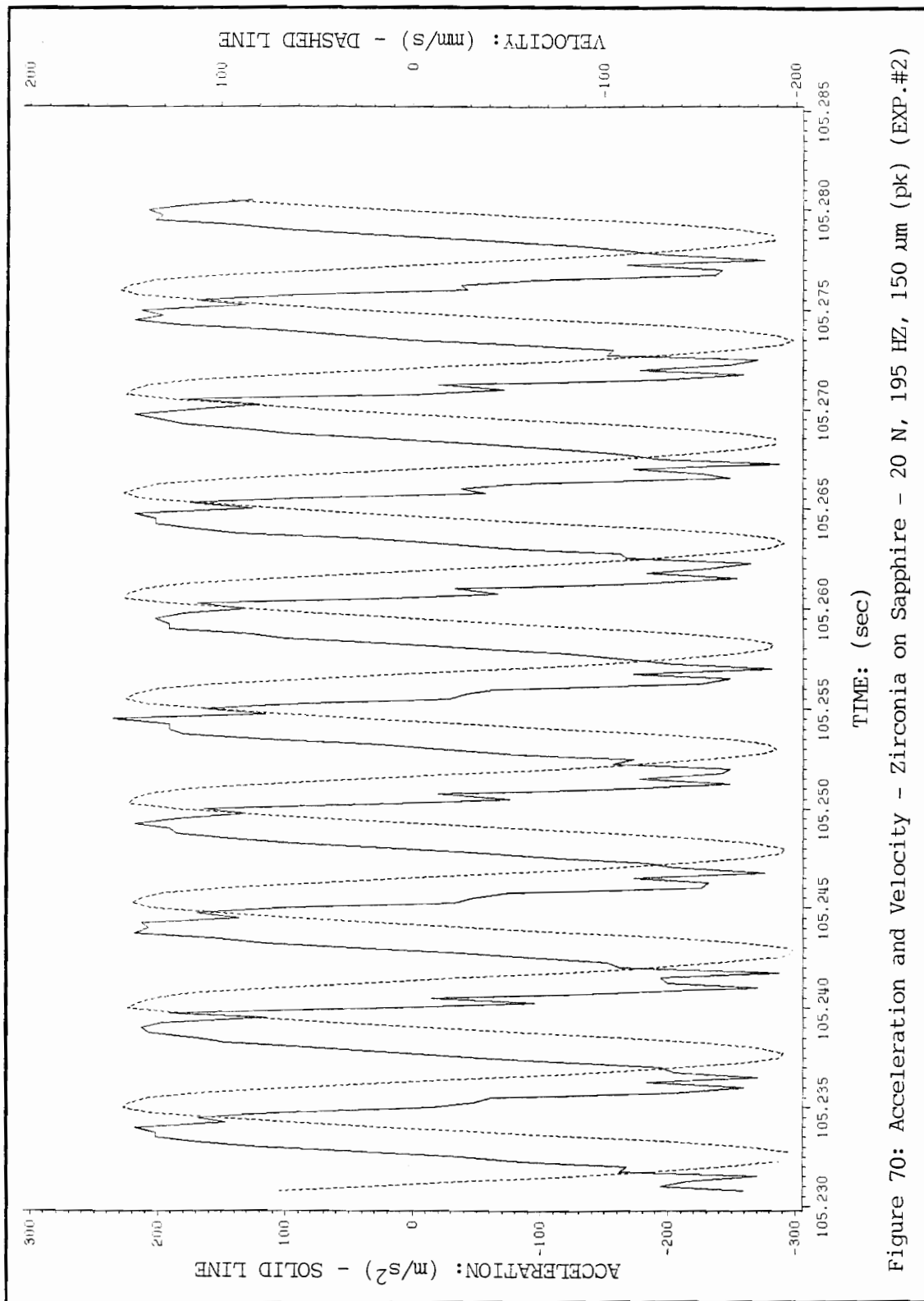


Figure 70: Acceleration and Velocity - Zirconia on Sapphire - 20 N, 195 HZ, 150 μm (pk) (EXP.#2)

It also appears smoother than the acceleration signal, i.e. velocity does not contain the high frequencies found in the acceleration signal. This lack of high frequencies in the velocity signal is due to the integration process which tends to "smooth" the data, and emphasize the predominant low frequency component(s). Because of this phenomenon, autospectral densities of velocity (and amplitude) contain less information than the autospectral density of acceleration. The high frequency peaks are reduced and the predominant low frequency peak is increased. Furthermore, successive integrations to obtain velocity and amplitude increase the amount of error in the resulting signal. In short, the autospectral density of the acceleration signal contains more valid information than the densities of the velocity and amplitude signals. As a result, only the acceleration autospectral density is presented in Figs. 69a and 69b.

The velocity signal shown in Fig. 70 can be used to determine the correlation between temperature and velocity. Figure 71 shows a temperature signal superimposed on a velocity signal. The temperature rise is represented as a solid line, and the peak-to-peak velocity is represented as a dashed line. There is an excellent correspondence between maximum temperatures and absolute maximum velocities. This suggests that temperature reaches a maximum at about the same time velocity reaches a maximum. If the absolute value of velocity is used, the correspondence with peak temperature is even more striking. This relationship is shown in Fig. 72. Although there is a slight phase difference, peak temperatures correspond to peak velocities. To measure this phase difference, the cross-spectral density of temperature and velocity is obtained. Figure 73 shows this density for temperature and absolute velocity. The highest peak is at 390.6 Hz with smaller peaks at 195.3 Hz and 781.3 Hz. At 390.6 Hz, the phase difference between the two signals is 37.7 degrees or 0.658 radians. In fractions of a cycle, the phase difference is 0.105 cycles. In other words, temperature reaches a maximum one tenth of a cycle before velocity. Although this represents an excellent correspondence, the fact that temperature reaches a maximum before velocity is counterintuitive. Since high velocities **cause** high temperatures, one would expect the velocity to reach a maximum before temperature. However, temperature rise is a function of pressure, velocity, and friction. Therefore, the interaction of all these parameters must be considered, and the positive 0.105 cycle phase difference between temperature and velocity is not unreasonable.

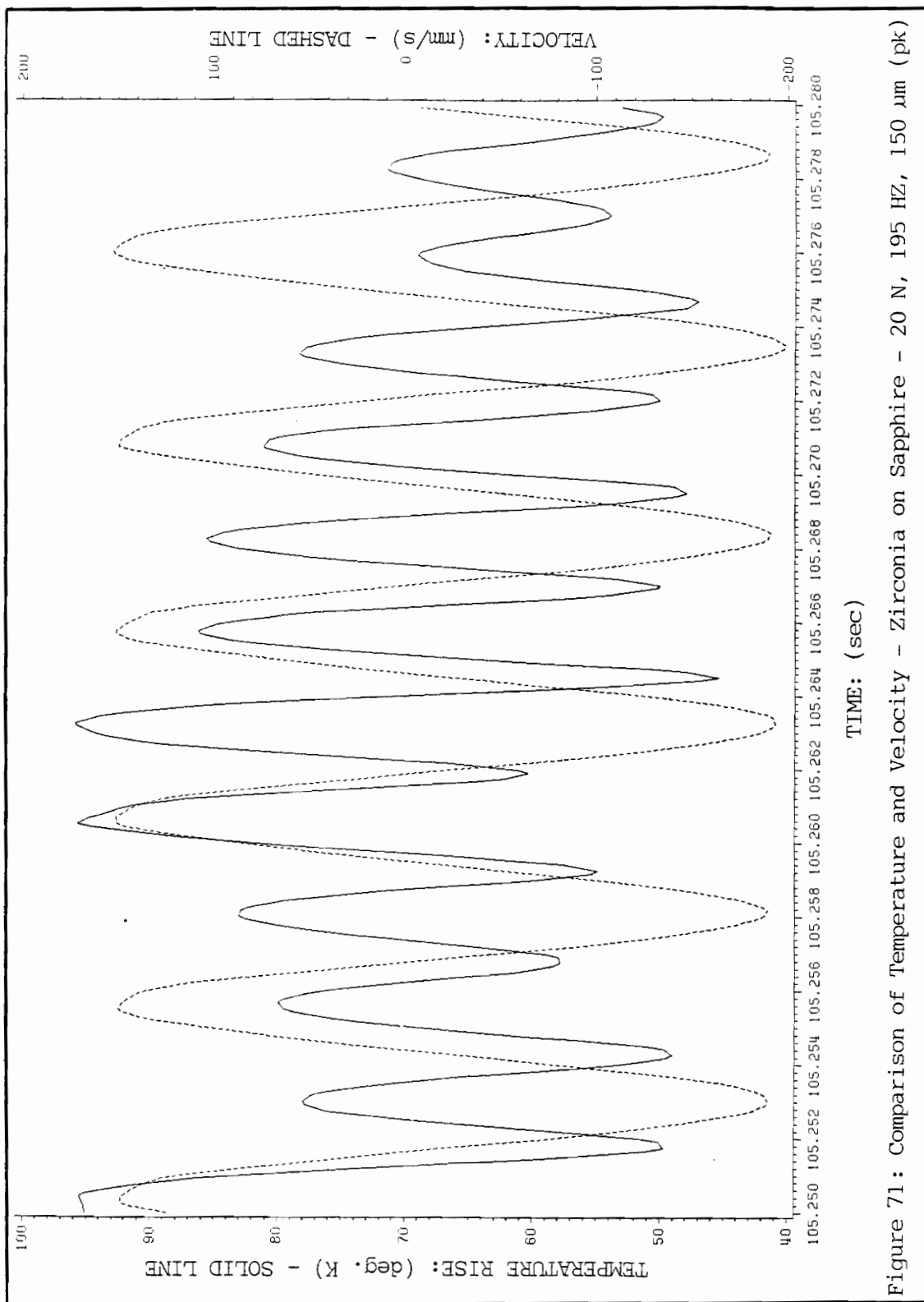


Figure 71: Comparison of Temperature and Velocity - Zirconia on Sapphire - 20 N, 195 HZ, 150 μ m (pk)

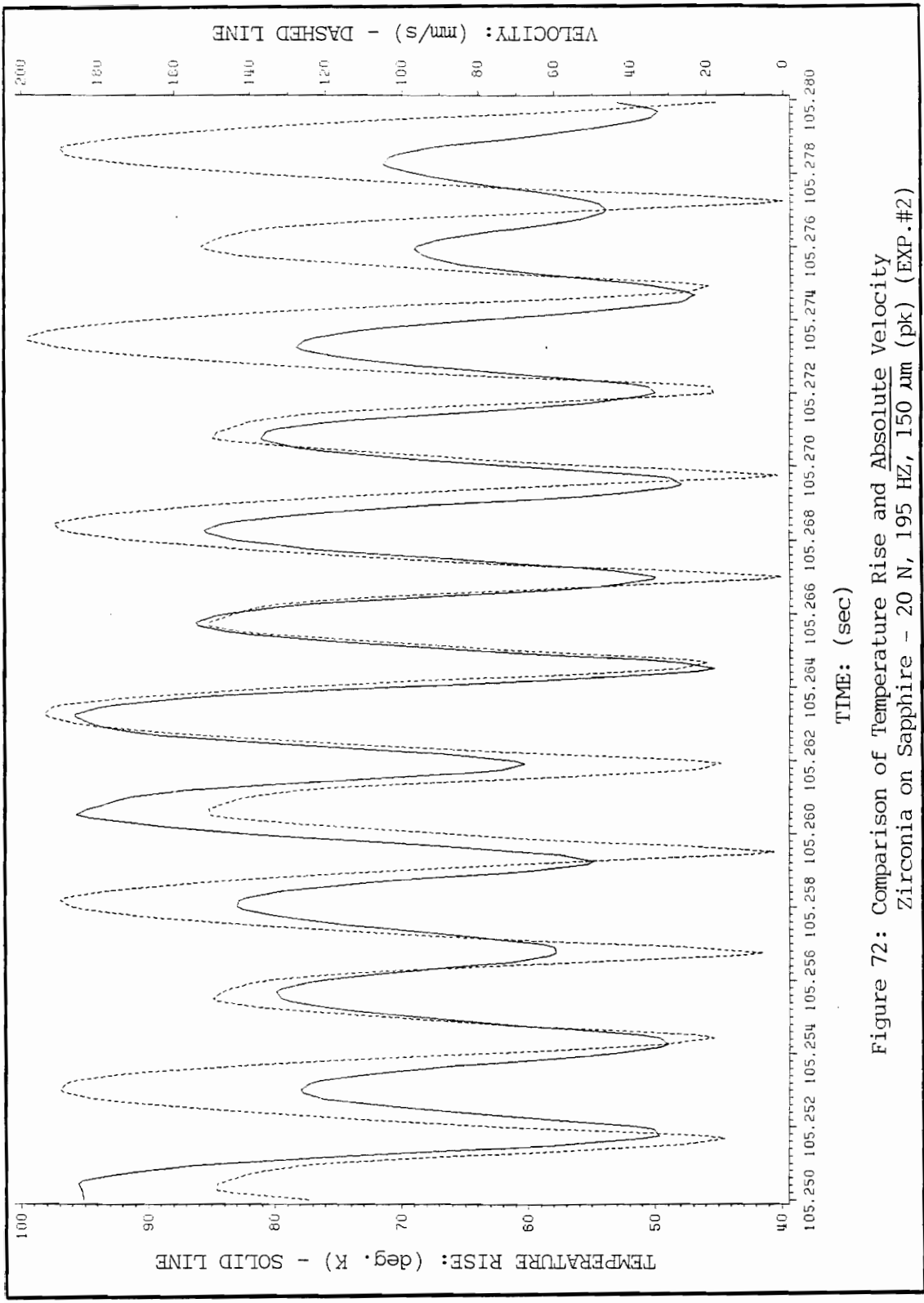


Figure 72: Comparison of Temperature Rise and Absolute Velocity
Zirconia on Sapphire - 20 N, 195 HZ, 150 μ m (pk) (EXP.#2)

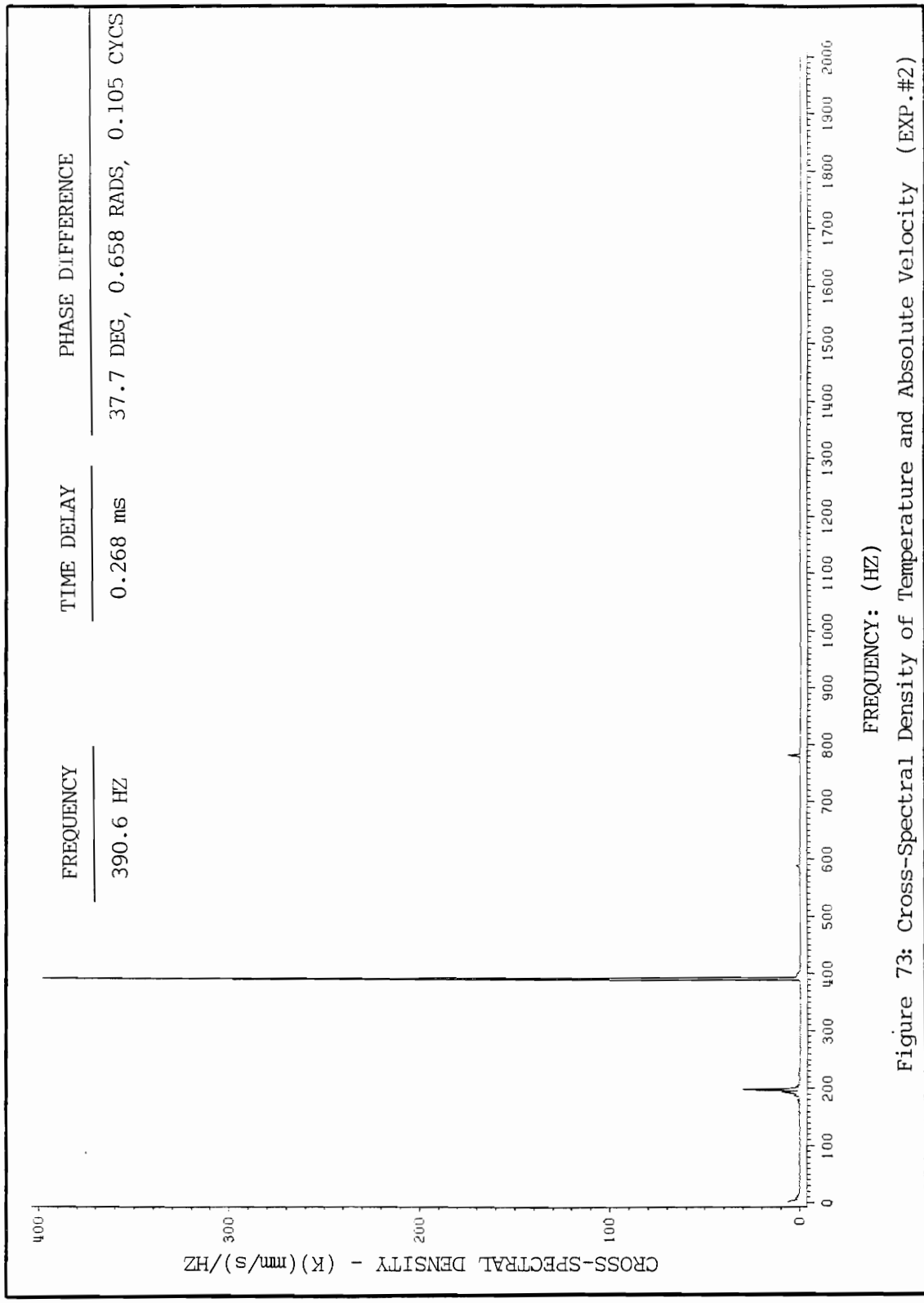


Figure 73: Cross-Spectral Density of Temperature and Absolute Velocity (EXP.#2)

4.2.4.f *Comparison of Friction and Velocity*

In addition to temperature-friction and temperature-velocity correlations, the correlation between friction and velocity is also important. Figure 74 shows a friction signal superimposed on a velocity signal. Friction is represented by a solid line and velocity is represented by a dashed line. The cross-spectral density of these signals is shown in Fig. 75. As expected, both of these signals contain a predominant 195.3 Hz frequency. In addition, the phase difference between friction and velocity is 136 degrees (0.378 cycles) at 195.3 Hz. This phase difference can be seen in Fig. 74. For instance, if friction and velocity were 180 degrees out of phase, they would both cross zero at the same time, and their peaks would oppose one another. However, since the phase difference is less than 180 degrees, velocity is shifted a little to the left in Fig. 74. The results shown in Figs. 74 and 75 agree well with theoretical expectations. In theory, the absolute velocity and absolute friction should reach a maximum at approximately the same time. This is indeed the case for the friction and velocity signals shown in Fig. 74.

Since the units for friction force are newtons, and the units for velocity are meters per second, the product of friction force and velocity yields the rate of frictional heat generated at the interface in watts. This multiplication process can be done for all the discrete points used to make Fig. 74. The result is a heat generation function shown in Fig. 76. From Fig. 76, the average maximum heat generation is 2.63 watts, and the overall average is 1.57 watts. As shown in Fig. 77a, if the autospectral density of heat generation is calculated, a predominant peak at 390.6 Hz is found. This corresponds with the predominant frequency of the temperature rises shown in Fig. 61. Figure 77a also shows that the highest peak-to-peak heat generation is 1.86 watts at 390.6 Hz. Other frequencies are also contained within the heat generation function, and their presence becomes more apparent when the autospectral density is plotted on a log scale. This relationship is shown in Fig. 77b. All the major peaks above 390.6 Hz correspond to multiples of 390.6. Therefore, they could represent heat generation at different modes of vibration. Furthermore, there is a spike at 197.3 Hz which is approximately equal to the sapphire disk's oscillation frequency. Although the presence of these other frequencies should not be disregarded, their contribution to heat generation is small.

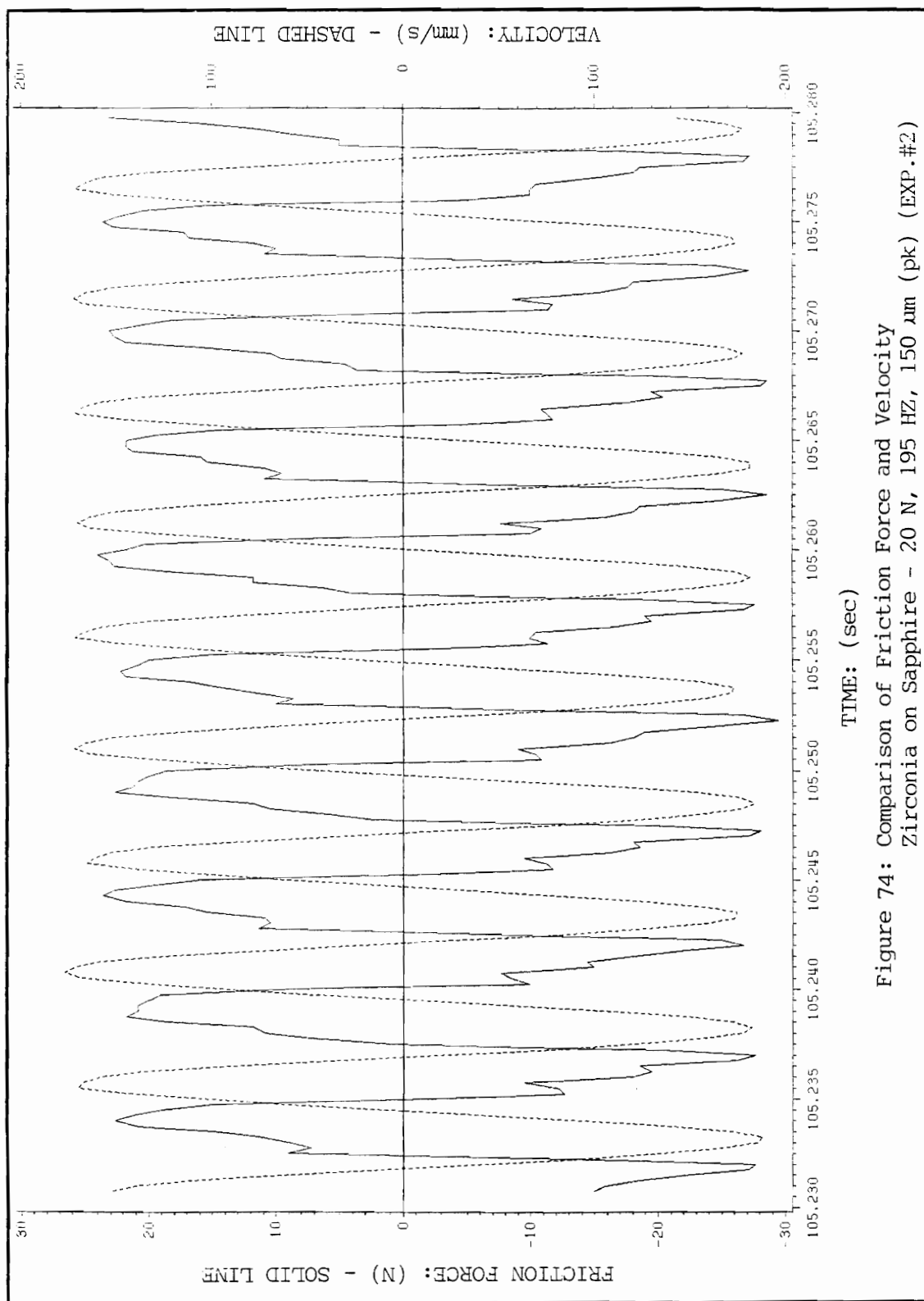
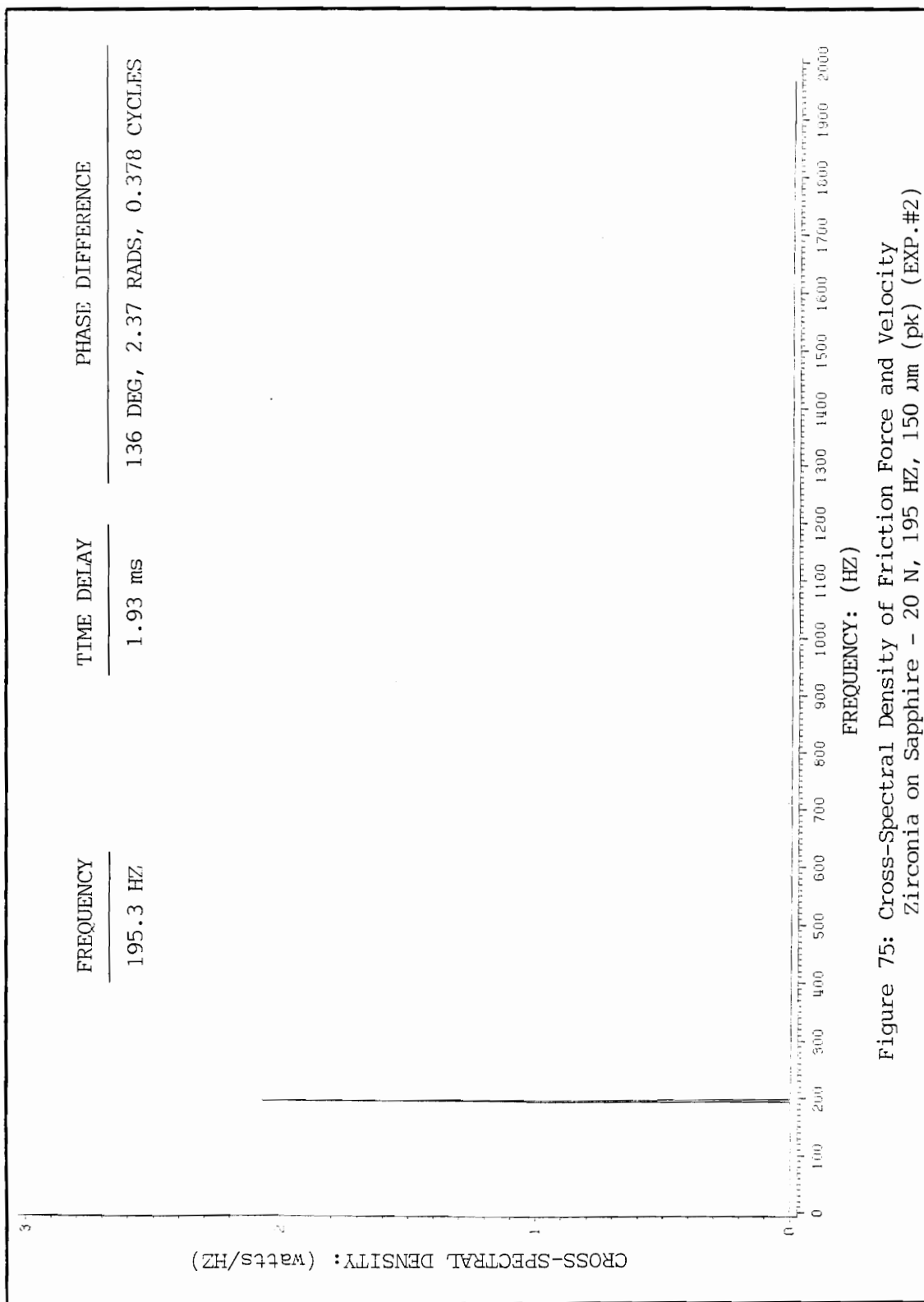


Figure 74: Comparison of Friction Force and Velocity
Zirconia on Sapphire - 20 N, 195 HZ, 150 μ m (pk) (EXP.#2)



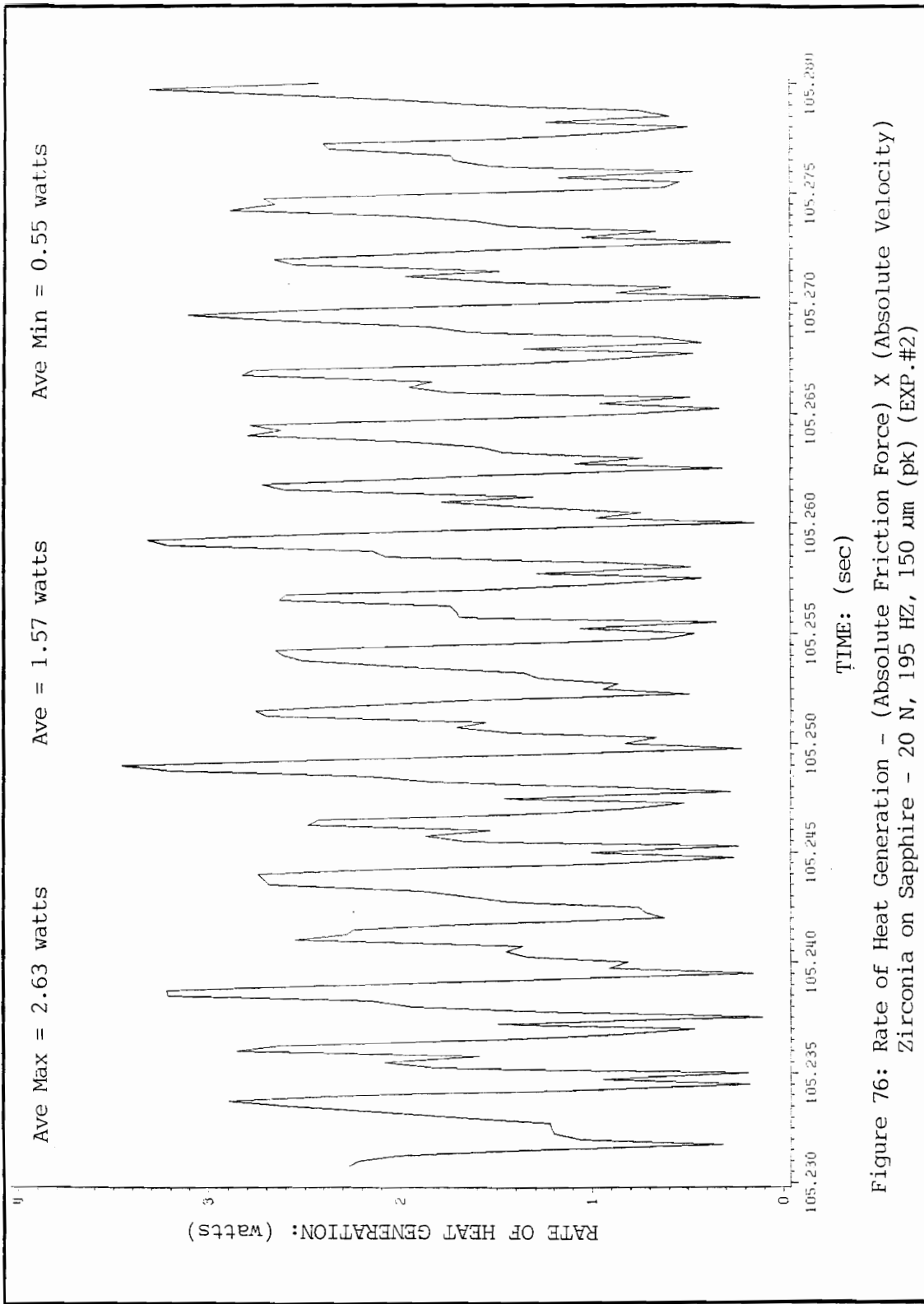
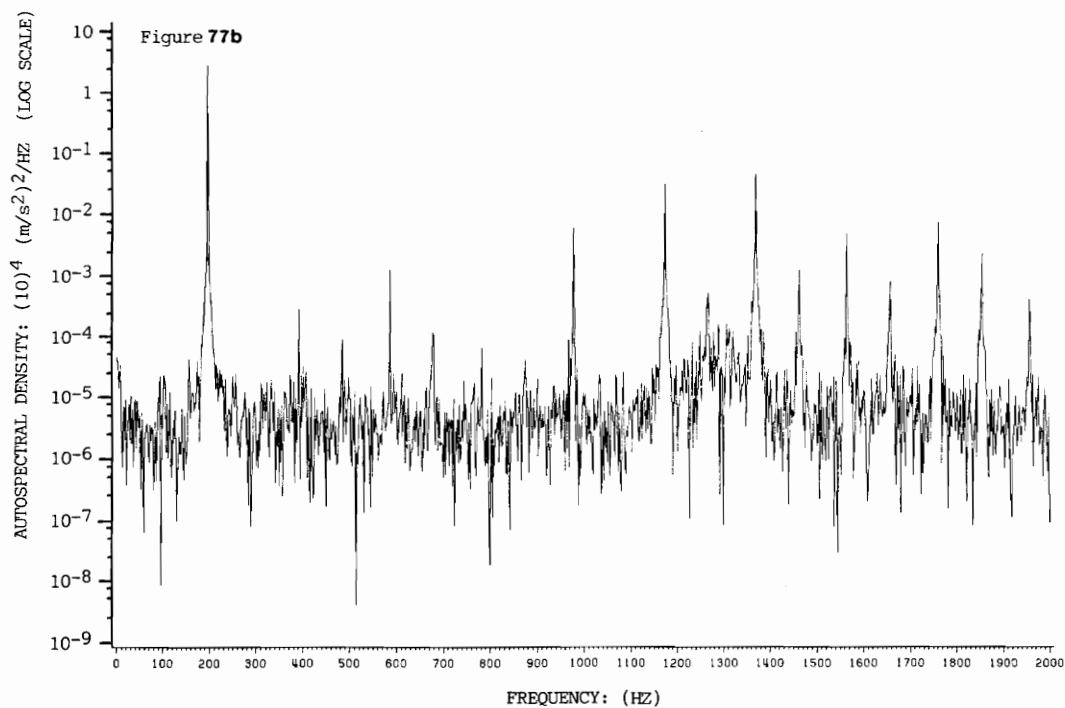
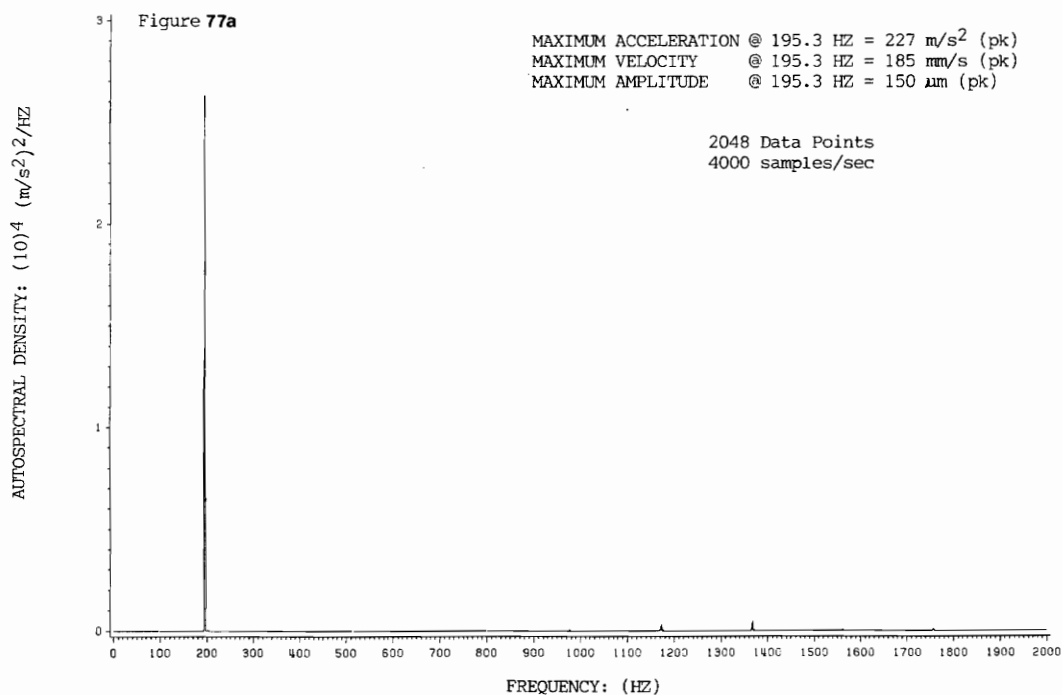


Figure 76: Rate of Heat Generation - (Absolute Friction Force) X (Absolute Velocity)
Zirconia on Sapphire - 20 N, 195 Hz, 150 μ m (pk) (EXP.#2)



Figures 77a & 77b: Autospectral Density of Acceleration
 Zirconia on Sapphire - 20 N, 195 HZ, 150 μm (pk)

As shown in Fig. 77a, almost all of the heat is generated at 390.6 Hz. As a result, the predominant frequency of the temperature signal is also 390.6 Hz.

4.2.5 Scanning Results - Zirconia-on-Sapphire

As shown in Fig. 43, the microscope is moved over the contact regions in the x and y directions. The procedure used to do this is summarized in Fig. 38. The x and y coordinate axes are defined in Fig. 37 with respect to the shaker and infrared microscope. Figure 78 shows an expanded view of the radiance trace during the x scan. Below this radiance trace is the actual trace from the x-position LVDT. At point A on this trace, the target spot is initially at the center of the contact region. At point B, the target spot is completely out of the contact region. Next, the target spot is passed back over the center of the contact region to point C. When the target spot gets to point D, it is again completely out of the contact region. Finally, the microscope is repositioned at the center of the contact region at point E. When the target spot is completely out of the contact region, the radiance drops to a low level. However, the radiance does not drop as low as the ambient radiance level. When the target spot is moved back over the center of the contact region, there are two predominant high radiance areas. These high radiance peaks could be associated with real areas of contact. However, the x-position data has certain regions where the position of the target spot is held constant. Therefore, the microscope is actually collecting radiance data from the same spot for more than one cycle.

To understand the true relationship between radiance and x-position, the data acquisition system was used to sample radiance and x-position data simultaneously. The radiance data was converted to temperature rises using the lower emissivity and transmittance values of 0.51 and 0.70. In this way, temperature rise can be plotted as a function of x-position. This relationship is shown in Fig. 80. The disjointed appearance of Fig. 80 relates to the sampling of more than one point at a given position. In fact, each vertical line in Fig. 80 represents multiple samples at discrete positions. The sloped lines represent movement from one position to another.

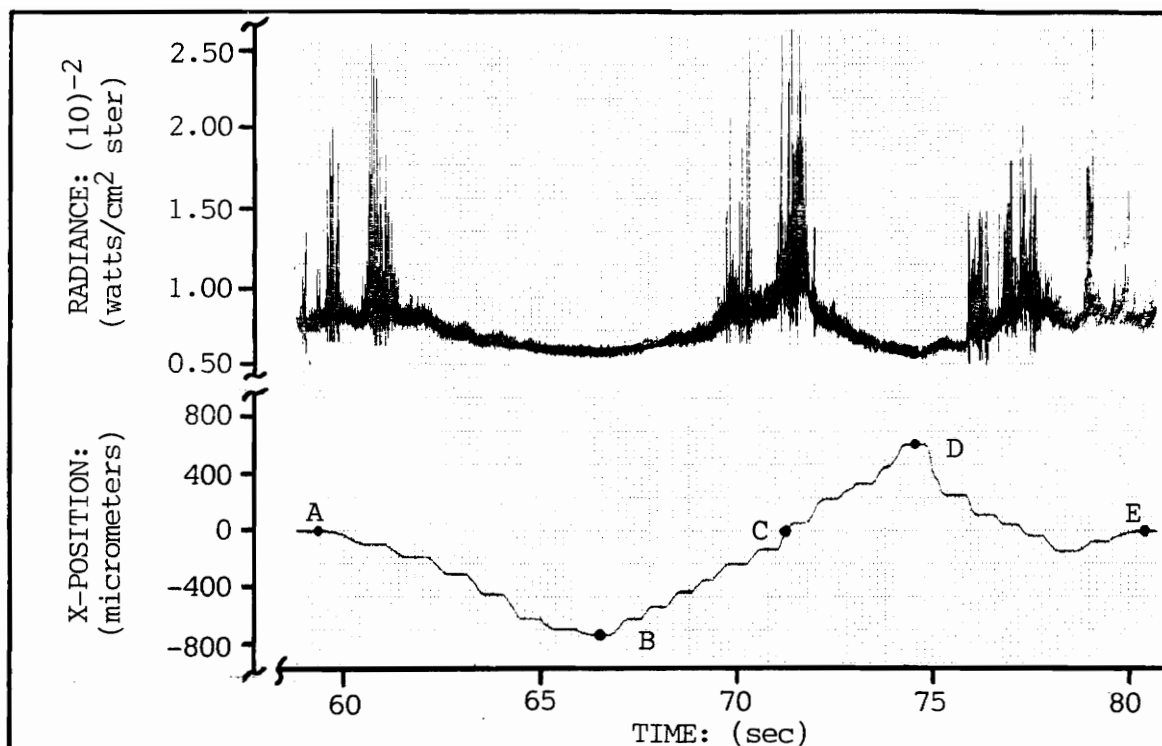


Figure 78: Comparison of Radiance and X-Position
Zirconia on Sapphire - 20 N, 195 HZ, 150 μ m (pk)

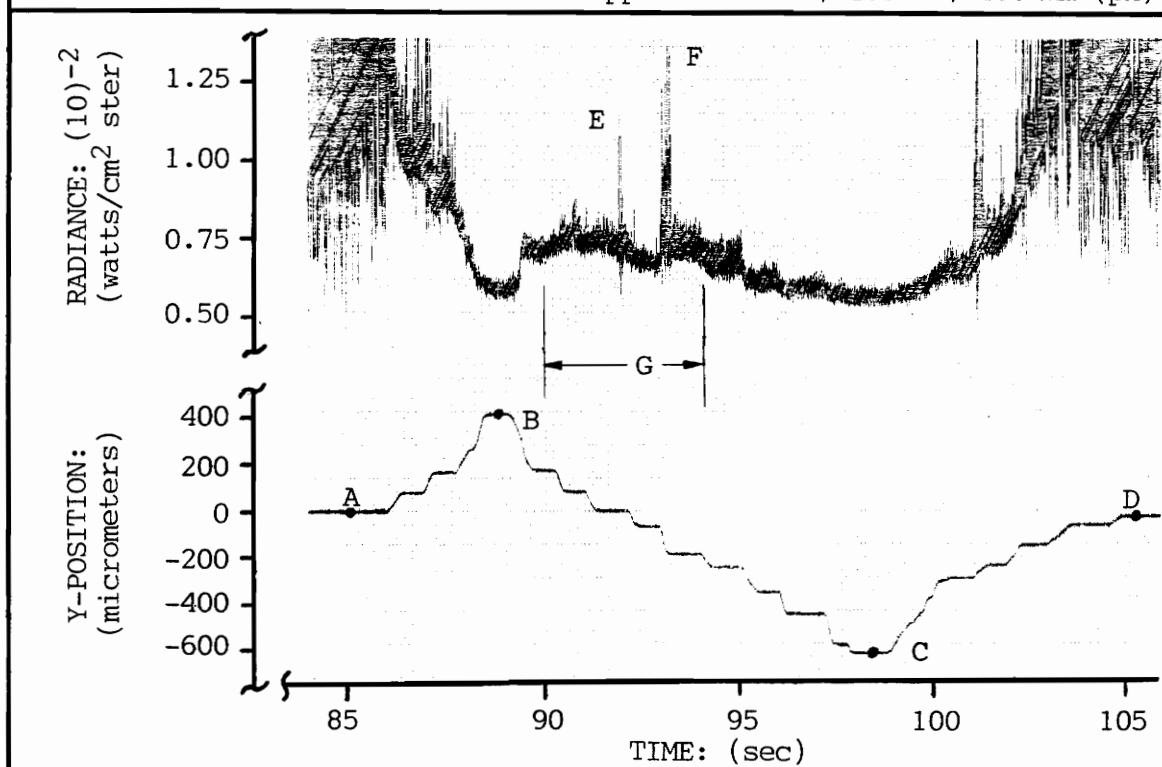
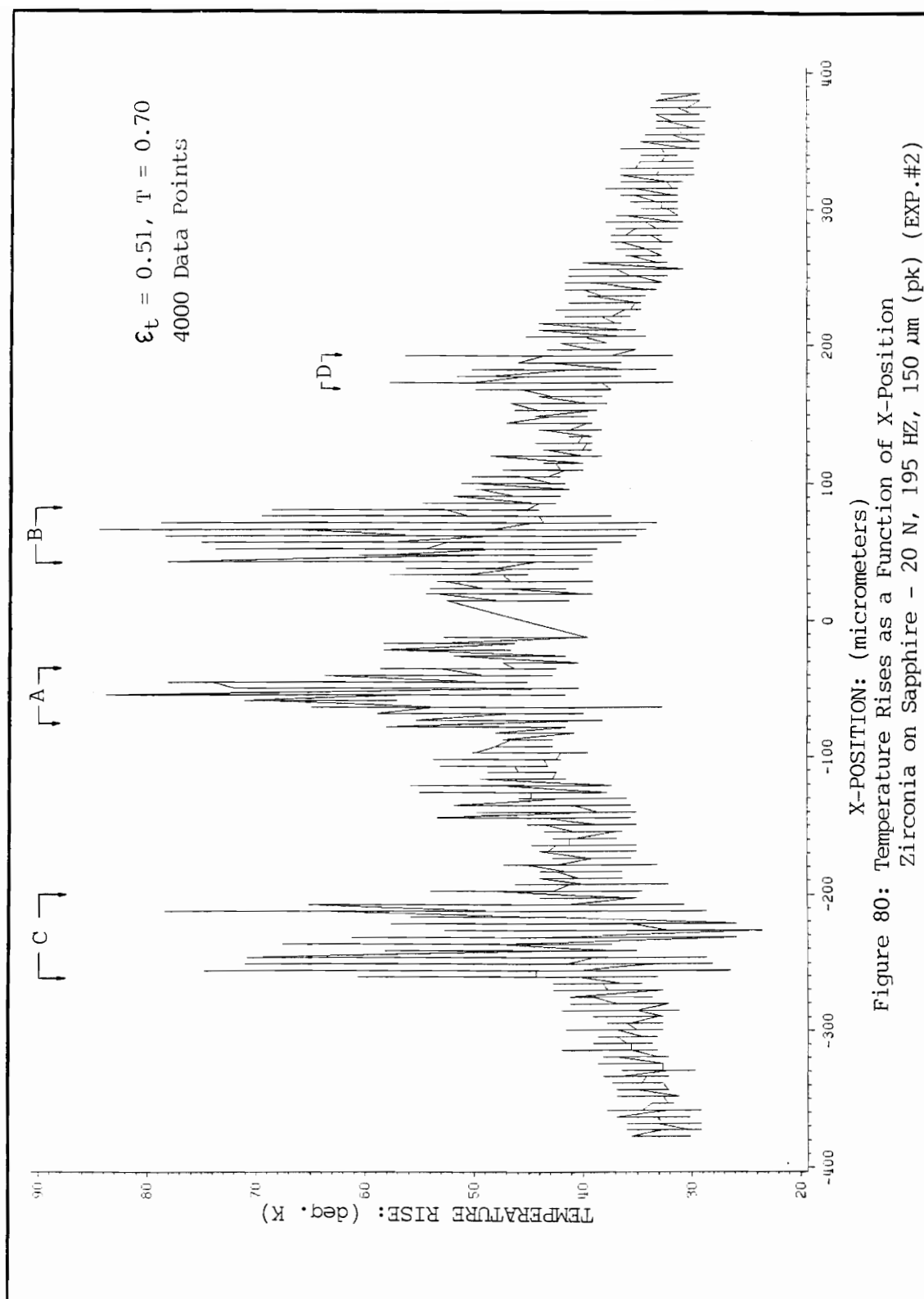


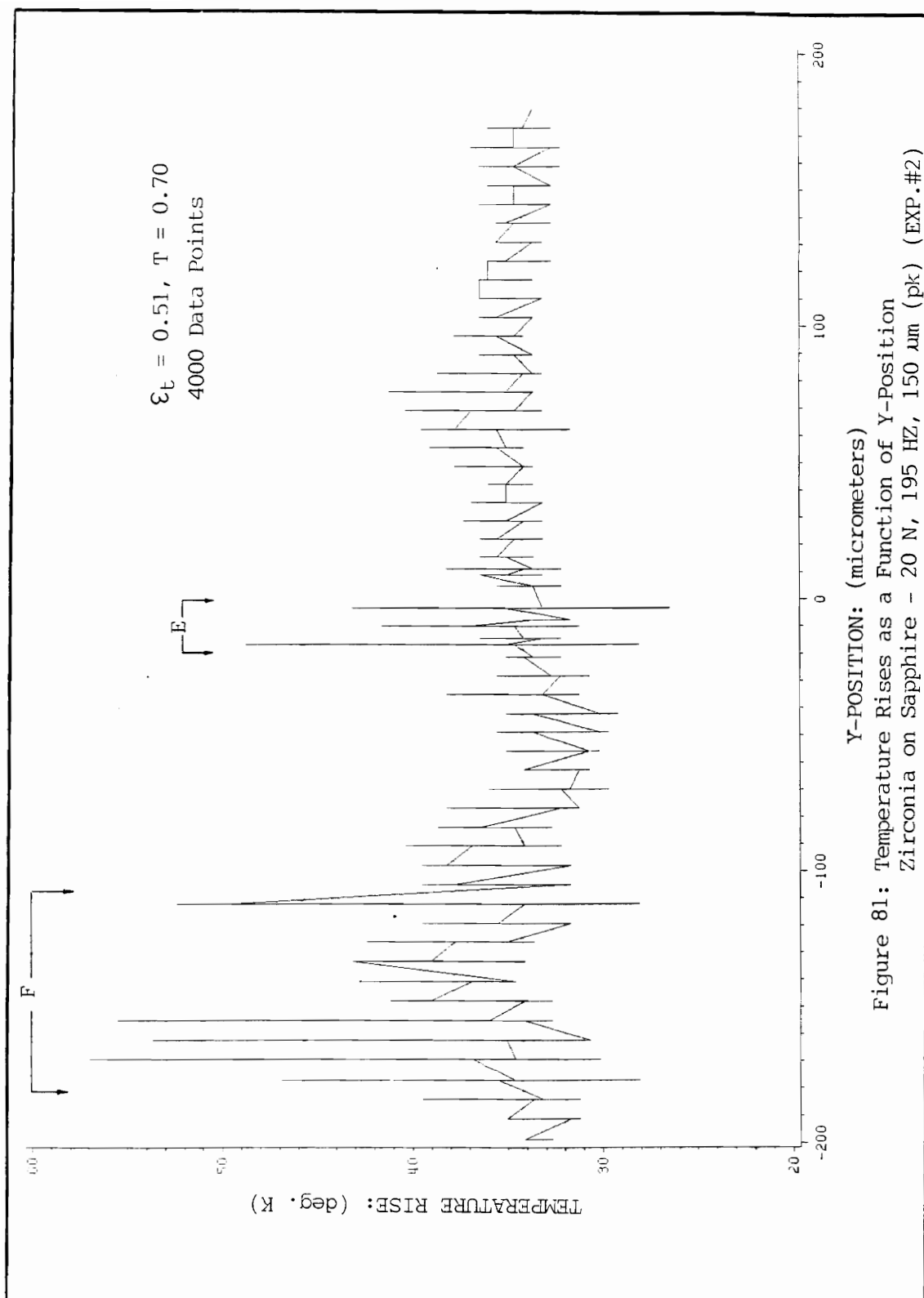
Figure 79: Comparison of Radiance and Y-Position
Zirconia on Sapphire - 20 N, 195 HZ, 150 μ m (pk)



Peak temperature regions occur at four separate intervals on the x-axis. The highest temperature region occurs between -100 and 100 μm . Although peaks are not present at 0 μm , there is a peak temperature region on either side of the 0 μm position. Temperature rises in these two regions, labelled A and B, are as high as 80 K. The next highest region is between -200 and -260 μm . It is labelled C, and temperature rises in this region are as high as 77 K. A fourth region is located between 170 and 200 μm , and has temperature rises as high as 58 K. It is labelled D.

Since multiple samples were taken at each position in Fig. 80, inferences can be made about the size and location of real contact areas. For instance, regions A and B suggest that a real contact area is present on either side of the 0 μm position. The width of each of these areas is between 30 and 40 μm . Region C has a width of 60 μm , and suggests that a real contact area is present approximately -240 μm away from the center. The fourth region, D, has a 30 μm width, and suggests the presence of a real contact area at 180 μm . Another facet of Fig. 80 is the increasing trend of the temperature rises toward the center. For instance, at -380 μm and 380 μm , the lowest temperature rises are present. Between -100 and 100 μm , the highest temperature rises are present. This increasing trend towards the center is present only in the x-direction. As demonstrated in the next paragraph, the y-direction scan does not contain this increasing trend.

Figure 79 shows output from the y-position LVDT and corresponding radiance trace. As described for the x-direction scan, the microscope's target spot is initially at the center of the contact region, (point A in Fig. 79). Then, it is moved completely out of the contact region to point B. After this, the target spot is moved back across the contact region to point C which lies outside the contact region. Finally, the target spot is brought back to the center at point D. As the target spot is brought across the center, the radiance increases, and two high radiance peaks are encountered. These peaks are designated by points E and F in Fig. 79. When compared to the y-position trace, these peaks correspond to constant positions of the target spot for finite time intervals. In other words, multiple radiance samples were obtained for certain y-positions. When radiance and y-position data are sampled simultaneously, the temperature rise as a function of y-position can be obtained. 4000 data points were sampled in the time interval "G" shown in Fig. 79. The resulting temperature vs. y-position plot is shown in Fig. 81.



Although there appears to be little correspondence between Fig. 81 and the radiance in time interval "G", one must consider that multiple samples are taken at each position. Therefore, peak E in Fig. 79 appears as three long vertical lines in Fig. 81 between -20 and $0\ \mu\text{m}$. In addition, peak F appears as a group of vertical lines between -110 and $-180\ \mu\text{m}$. As described for the x-position data, the data shown in Fig. 81 can also be used to make inferences about the location of real contact areas. For instance, the long vertical lines between -20 and $0\ \mu\text{m}$ suggest a real contact area near the center of the contact region, and the group of vertical lines between -110 and $-180\ \mu\text{m}$ suggests another real contact area away from the center.

Since Figs. 80 and 81 represent temperature rises as a function of position, it is useful to compare them with photographs of the contact region(s). Although these pictures were taken after the experiment, and the scanning was performed during the experiment, similarities between the two sets of results can be observed. Optical macrographs of the contact regions are shown in Figs. 82 and 83. Figure 82 is a macrograph of the zirconia surface at the end of the two-minute experiment, and Fig. 83 is a macrograph of the contact region on the sapphire disk. The orientation of the x-y coordinate axes is shown in each figure, and the location of the origin is at the center of each contact region. The y axes for the two figures are in opposite directions for the following reason: the picture of the sapphire disk's contact region represents the underside of the disk. This is the region that is actually in contact with the zirconia test specimen. Thus, to visualize the actual oscillating contact configuration, the sapphire disk's contact region in Fig. 83 should mentally be folded over on to the zirconia test specimen. In short, the interaction of the two surfaces should be considered when inferences about the real contact area are made. The whitish areas on the sapphire disk's contact region probably represent transferred zirconia material. When the disk is oscillating on the zirconia test specimen, this transferred material could be representative of real contact areas. Furthermore, the raised areas on the zirconia test specimen could also represent real contact areas. Most of these raised areas are present in the quadrant where x is positive and y is negative.

If the areas on the macrographs actually represent real contact areas during the experiment, the x and y scans should show higher temperatures in the vicinity of these areas.

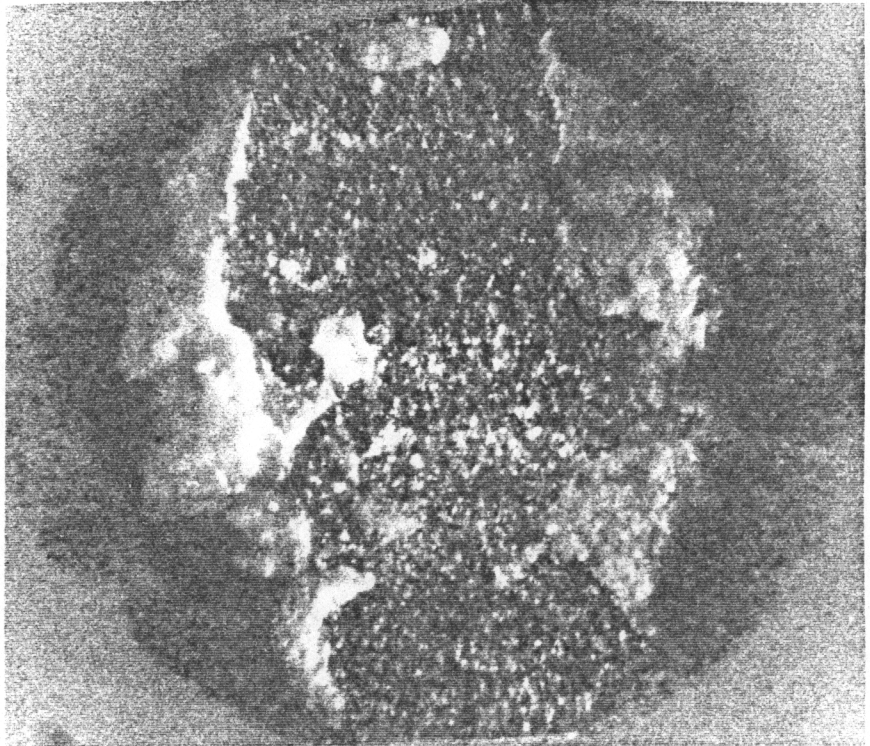
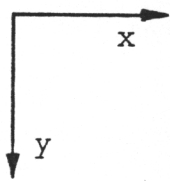


Figure 83: Optical Macrograph of the Contact Region on the Sapphire Disk
Zirconia on Sapphire - 20 N, 195 HZ, 150 μm (pk) (EXP.#2)

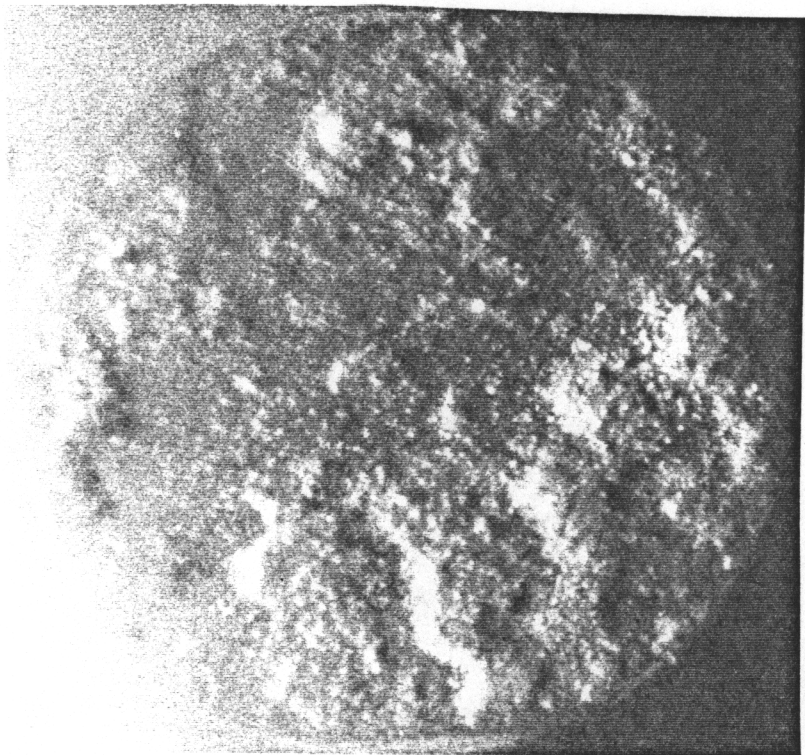
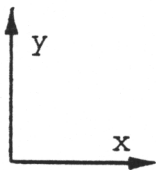


Figure 82: Optical Macrograph of a Zirconia Wear Scar
Zirconia on Sapphire - 20 N, 195 HZ, 150 μm (pk) (EXP.#2)

For example, Fig. 81 represents the scan in the y-direction. Between $y = -100$ and $y = -180 \mu\text{m}$ there are high temperature peaks that could correspond to real contact areas. These peaks are not present in the positive y-direction. In comparison, the zirconia wear scar has more raised areas in the negative y-direction than the positive y-direction.

When the scan in the x-direction is considered, there are four predominant high temperature intervals labelled as A, B, C, and D in Fig. 80. Interval C is present between $x = -200 \mu\text{m}$ and $x = -260 \mu\text{m}$; whereas interval D is present between $x = 170$ and $x = 200 \mu\text{m}$. This means that interval C is twice as wide as interval D. Furthermore, the peaks in interval C are higher than the peaks in interval D. In comparison to the macrographs, the interaction between the sapphire disk and zirconia test specimen must be considered. For instance, the negative x-direction contains the largest amount of transferred zirconia on the sapphire disk. If this transferred material is representative of a real contact area, then high peaks in temperature would be encountered during scanning in the negative x-direction. This is indeed the case as shown by interval C in Fig. 80.

The positive x-direction does not contain as much transferred material. However, there are some raised areas on the zirconia specimen in the positive x-direction. If these areas are acting as real contact areas, they could be the cause of interval D in Fig. 80.

At this point, it should be stated that intervals A and B in Fig. 80 do not correspond to any obvious surface characteristics shown on the macrographs. These intervals are present in the middle of the x-direction scan, and the macrographs do not depict the presence of any possible real contacts in this vicinity. However, by using an SEM of the zirconia wear scar, a possible justification for the presence of intervals A and B can be made. This SEM is shown in Fig. 84. The zirconia specimen is tilted in this figure, and the wear scar appears as a dished crater. There is obviously a greater amount of debris removed from the center of this wear scar. The cause of this dished characteristic could be higher temperatures at the center of the contact region. As shown in Fig. 80, this is indeed the case for the x-direction scan. The temperatures are higher at the middle of the contact region, and lower at the limits of the contact region. In addition, the temperature rises for intervals A and B are approximately 80 K. As stated previously, these intervals are present in the center of the contact region.



Figure 84: Scanning Electron Micrograph of a Zirconia Wear Scar
Zirconia on Sapphire - 20 N, 195 HZ, 150 μm (pk) (EXP.#2)

In summary, the macrographs shown in Figs. 82 and 83 support the presence of high temperature intervals C and D in the x-direction scan. Therefore, intervals C and D could represent the location of real contact areas during an experiment. However, Figs. 82 and 83 do not support the presence of intervals A and B. On the other hand, the SEM shown in Fig. 84 supports the presence of higher temperatures at the center of the contact region. This lends support to the inference that intervals A and B represent the location of real contact areas.

4.3 Results for Different Ceramic Materials

4.3.1 Radiance Traces and Temperature Rises

All the experiments discussed so far utilized a zirconia test specimen loaded against an oscillating sapphire disk. Since the sapphire disk cannot be interchanged with other materials, only the spherical test specimen can be interchanged. Therefore, in addition to zirconia, tungsten carbide, alumina, and sapphire were used as test specimens. Two experiments were performed for each material. A normal load of 40 N was used for one of the experiments, and a load of 20 N was used for the other. All eight of these experiments were performed at a frequency of 195.3 Hz and a relatively high amplitude. These amplitudes ranged from 117 μm to 156 μm (pk). Radiance traces for the eight experiments are shown in Fig. 85. Each trace has its own radiance scale, and all experiments lasted for 120 seconds. Scanning intervals for the x and y directions are identified on each trace. (The procedure used for these x and y scans is summarized in Fig. 38.) Also, the highest radiance peaks are identified by the letter "H" on each trace. All temperature rises presented in this section were calculated at these points.

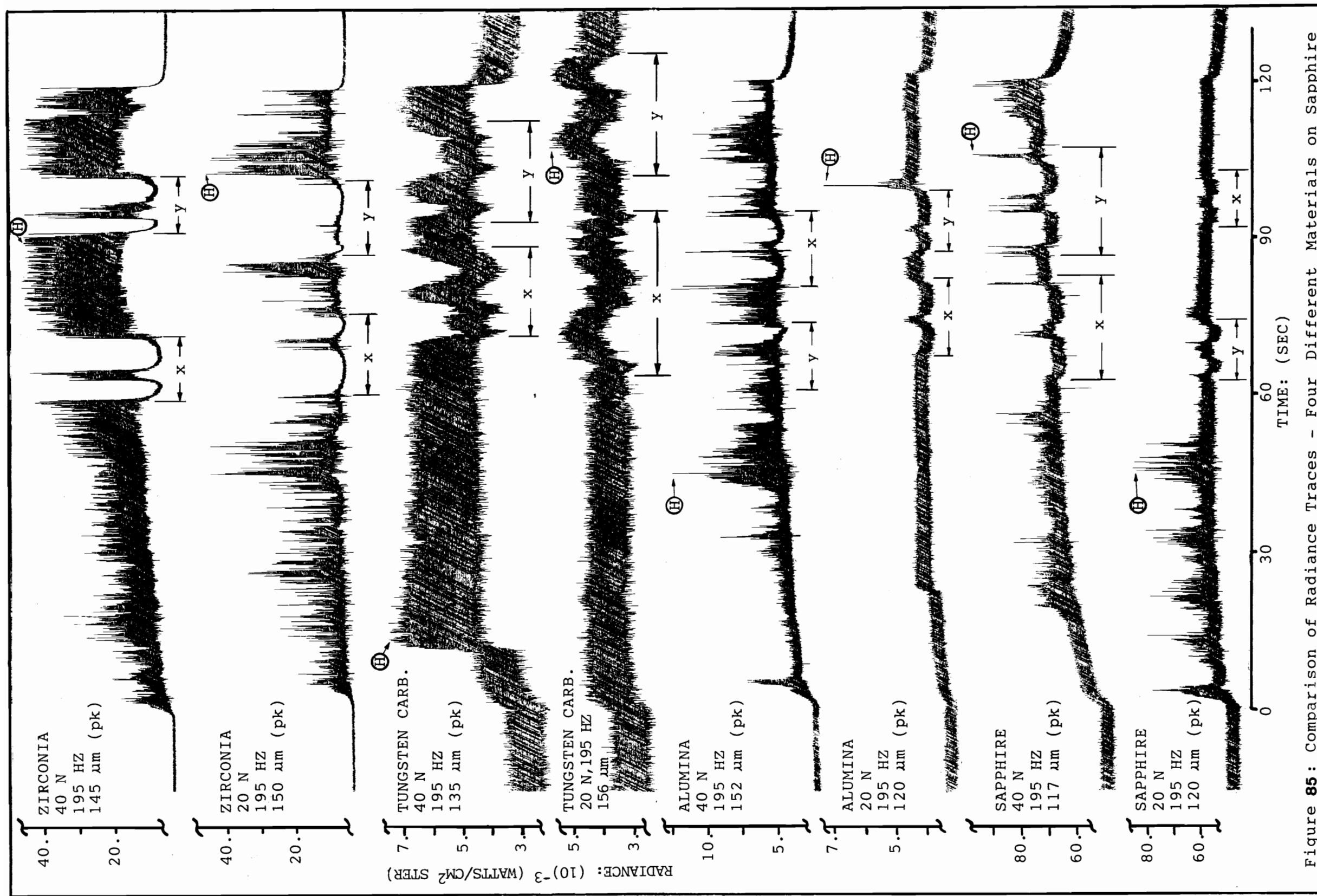


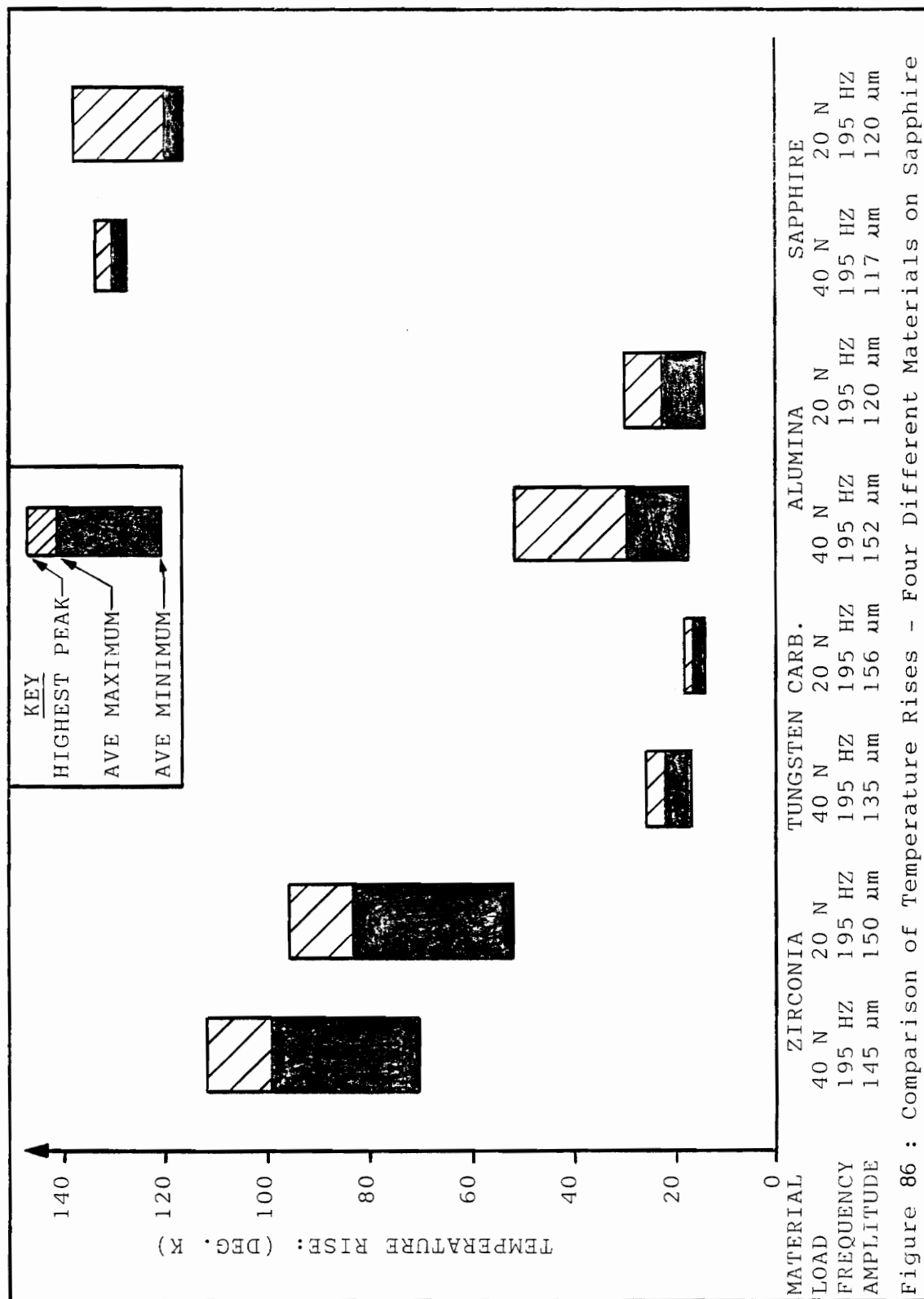
Figure 85: Comparison of Radiance Traces - Four Different Materials on Sapphire

4.3.1.a Zirconia-on-Sapphire Experiments

The radiance traces at the top of Fig. 85 are for the 40 N and 20 N zirconia experiments. These experiments were discussed in the previous section. In fact, they are labelled Exp. 1 and Exp. 2 in Figure 43. They are included in this section for comparison purposes. The first two bars in Figure 86 show the temperature rises measured for these experiments. Emissivity and transmittance values of 0.51 and 0.70 were used to calculate these temperatures. The average maximum and average minimum values are for 20 cycles. For the 40 N zirconia experiment, the average maximum temperature rise was determined to be 100 K and the average minimum was determined to be 71 K. For the 20 N zirconia experiment, the average maximum temperature rise was determined to be 83 K, and the average minimum 52 K. The absolute highest peak temperatures are also shown in Fig. 86. These values are 112 K for the 40 N zirconia experiment, and 96 K for the 20 N experiment.

4.3.1.b Tungsten Carbide-on-Sapphire Experiments

The next two experiments were performed using tungsten carbide as the test specimen. Although the traces for these experiments appear to have higher magnitudes than the zirconia experiments, this is not the case. The radiance scales shown for these tungsten carbide experiments are much smaller than the ones shown for the zirconia experiments. For instance, the radiance for the 40 N tungsten carbide experiment has peak levels of approximately $7(10)^{-3}$ watts/(cm² ster). This is significantly lower than the radiance for the 40 N zirconia experiment which has a peak level of approximately $40(10)^{-3}$ watts/(cm² ster). Prior to initiation of the tungsten carbide experiments, the microscope is used to detect an average reference radiance level of $3(10)^{-3}$ watts/(cm² ster). The peak-to-peak noise at this ambient level is approximately $1(10)^{-3}$ watts/(cm² ster). Since the radiance level only reaches a maximum of $7(10)^{-3}$ watts/(cm² ster), the signal-to-noise ratio is relatively small.



However, by using an appropriate amplification, a radiance increase above the ambient is detectable. Also, peak-to-peak variations in radiance of $2.5(10)^{-3}$ watts/(cm² ster) exceed the ambient peak-to-peak level during the 40 N experiment. At the end of the 40 N experiment, the radiance decreases rapidly to a level that is just above the ambient level. The 20 N tungsten carbide experiment actually lasts for about 140 seconds, and its radiance trace is not entirely contained within the boundaries of Fig. 85. However, at the end of this experiment, the radiance also decreases to near ambient levels.

Compared to the zirconia experiments, the experimental temperature rises determined for the tungsten carbide experiments are significantly smaller. For instance, average maximum temperature rises of 22 and 17 K were determined for the 40 N and 20 N tungsten carbide experiments. As shown in Fig. 86, these temperature rises are significantly smaller than the ones calculated for zirconia. Also, the peak-to-peak variation in temperature is less for tungsten carbide. As an example, the average variation of temperature is only 5 K for the 40 N tungsten carbide experiment. The temperature variation for the 40 N zirconia experiment is 29 K. Emissivity and transmittance values of 0.36 and 0.83 were used to calculate the temperature rises for tungsten carbide. As discussed in Section 4.1, both of these values were measured before the experiments. Since the wear and degradation of both the tungsten carbide and sapphire specimens is small, these values for emissivity and transmittance are not significantly changed during the experiment. Therefore, the temperature rises calculated for tungsten carbide are believed to be close approximations to the true values.

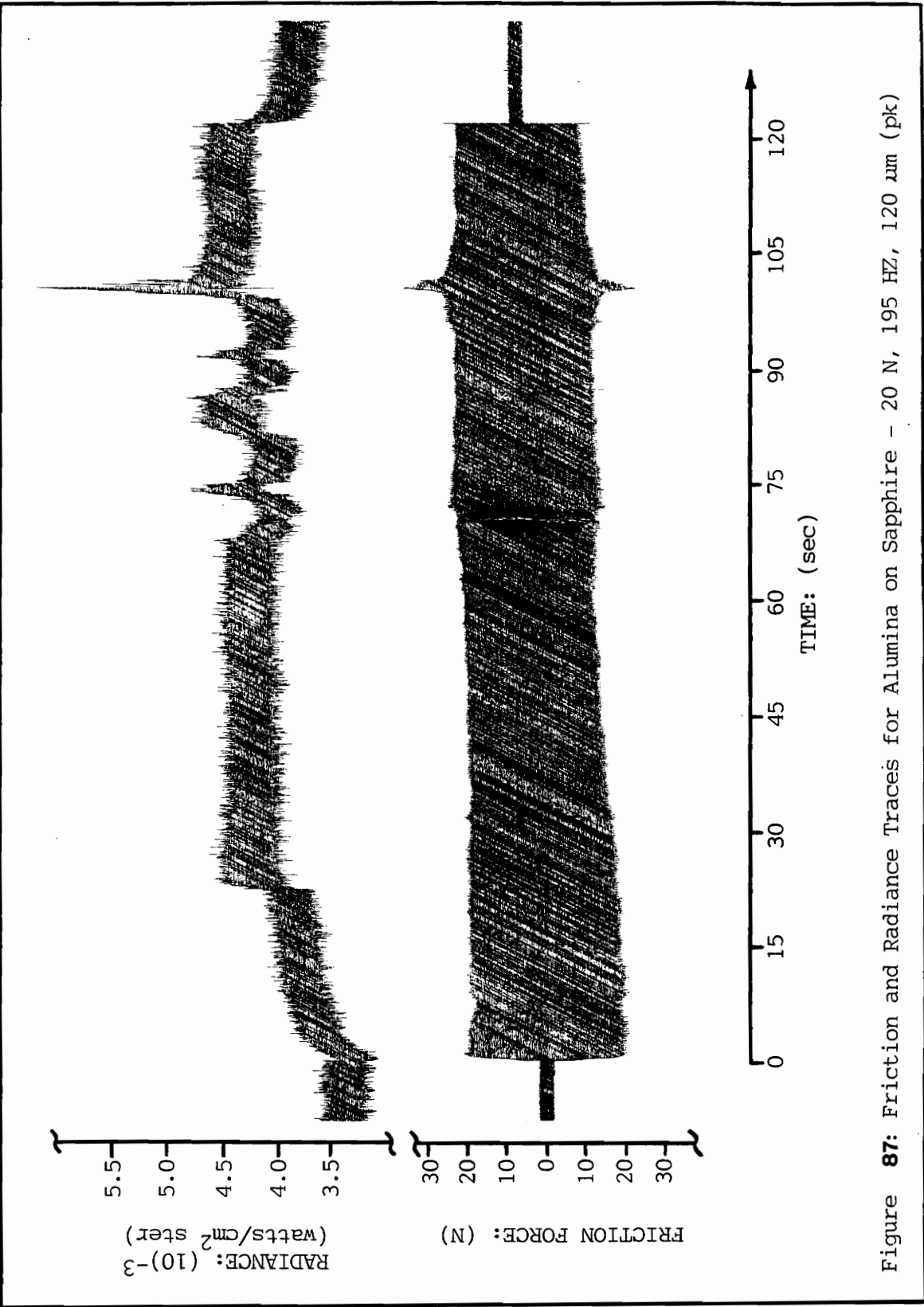
4.3.1.c Alumina-on-Sapphire Experiments

As shown in Fig. 85, the two alumina traces are located beneath the tungsten carbide traces. At the initiation of the 40 N alumina experiment, the radiance increases rapidly to a relatively high value. Then after approximately 5 seconds, the radiance drops to a base level that increases slightly throughout the experiment. At about 45 seconds from the start of the experiment, high radiance

peaks begin to appear on the increasing base level. This rapid fluctuation in radiance continues throughout the experiment. At 120 seconds, the motion of the disk is ceased, and the radiance drops to a level slightly above ambient. As shown by the radiance scale, the 40 N alumina experiment shows higher radiance levels than the tungsten carbide experiments. However, these radiance levels are less than those measured during the zirconia experiments. The highest radiance measured during the 40 N experiment occurs at 45 seconds. As shown in Fig. 86, the average maximum temperature rise at this point is 29 K, and the temperature rise for the highest peak is 52 K. Emissivity and transmittance values of 0.72 and 0.82 were used to make these calculations. As discussed in Section 4.1.3, both of these values were measured before the experiment.

Since there was some degradation of the alumina specimen and transfer of material to the sapphire disk, the temperature rises calculated for alumina might not be representative of the true surface temperatures. If the emissivity increases with an increasing roughness of the alumina specimen, the calculated temperature rises shown in Fig. 86 could be greater than the true surface temperatures. On the other hand, an increase in material transfer to the sapphire disk would cause a decrease in the transmittance of the disk. For this case, the temperature rises shown in Fig. 86 would be lower than the true surface temperatures. Furthermore, the increasing emissivity and decreasing transmittance effects could be canceling each other out, and the calculated temperature rises shown in Fig. 86 for alumina would be correct.

As shown in Fig. 86, the maximum temperature rise for the 20 N alumina experiment is 23 K. This is lower than the average maximum temperature rise calculated for the 40 N alumina experiment. The point in the radiance trace at which this 23 K temperature was calculated is designated by the letter H in Fig. 85. This high peak in the 20 N alumina experiment occurs just after the y-scan. It is actually a sudden increase in radiance that lasts for a very short period of time. The reason for this sudden increase in radiance is shown in Fig. 87. This figure shows the radiance and friction traces for the 20 N alumina experiment. At approximately 103 seconds, both the radiance and friction levels increase. The reason for this dual increase is unknown although a sudden change in the real contact area could be a factor.



4.3.1.d Sapphire-on-Sapphire Experiments

As shown in Fig. 86, the highest temperature rises measured were for the sapphire-on-sapphire experiments. For the 40 N experiment, the average maximum temperature rise was determined to be 131 K. For the 20 N sapphire experiment, the average maximum temperature rise was determined to be 120 K. Emissivity and transmittance values of 0.064 and 0.83 were used to make these calculations. The determination of these parameters is described in Sections 4.1.4 and 4.1.5. As discussed for the alumina-on-sapphire experiments, the emissivity and transmittance values can change during an experiment. Since there is significant degradation and/or transfer of material during the sapphire-on-sapphire experiments, one expects changes in emissivity and transmittance to occur. Since both surfaces become more opaque during the experiment, these changes could be significant. However, as stated for the alumina-on-sapphire experiments, the effects could be cancelling each other. In summary, the temperature rises calculated for the sapphire-on-sapphire experiments should be considered as estimates of the true surface temperature rises. The recommendations section of this thesis contains additional information on this subject.

Radiance traces for the two sapphire experiments are shown at the bottom of Fig. 85. The 40 N sapphire experiment shows the highest radiance levels with values exceeding $80(10)^{-3}$ watts/(cm² ster). The base level of radiance increases significantly during this experiment. Also, high peaks in radiance are superimposed on this base level for almost the entire experiment. At the initiation of the 20 N sapphire experiment, the radiance increases rapidly and then decreases to a relatively constant base level. Peaks are superimposed on this base level for approximately 50 seconds and then they disappear. The reason for this disappearance of radiance peaks can be explained by Fig. 88. This figure shows radiance and friction traces for the 20 N sapphire experiment. At approximately 50 seconds, the friction decreases to a lower level. This decrease in friction corresponds with the decrease in radiance peaks. The cause of the decrease in friction cannot be explained. However, an increase in wear debris between the surfaces could be a factor. This debris could be acting like miniature ball bearings resulting in a decrease in friction. Changes in the real area of contact could also be causing this dual decrease in friction and radiance.

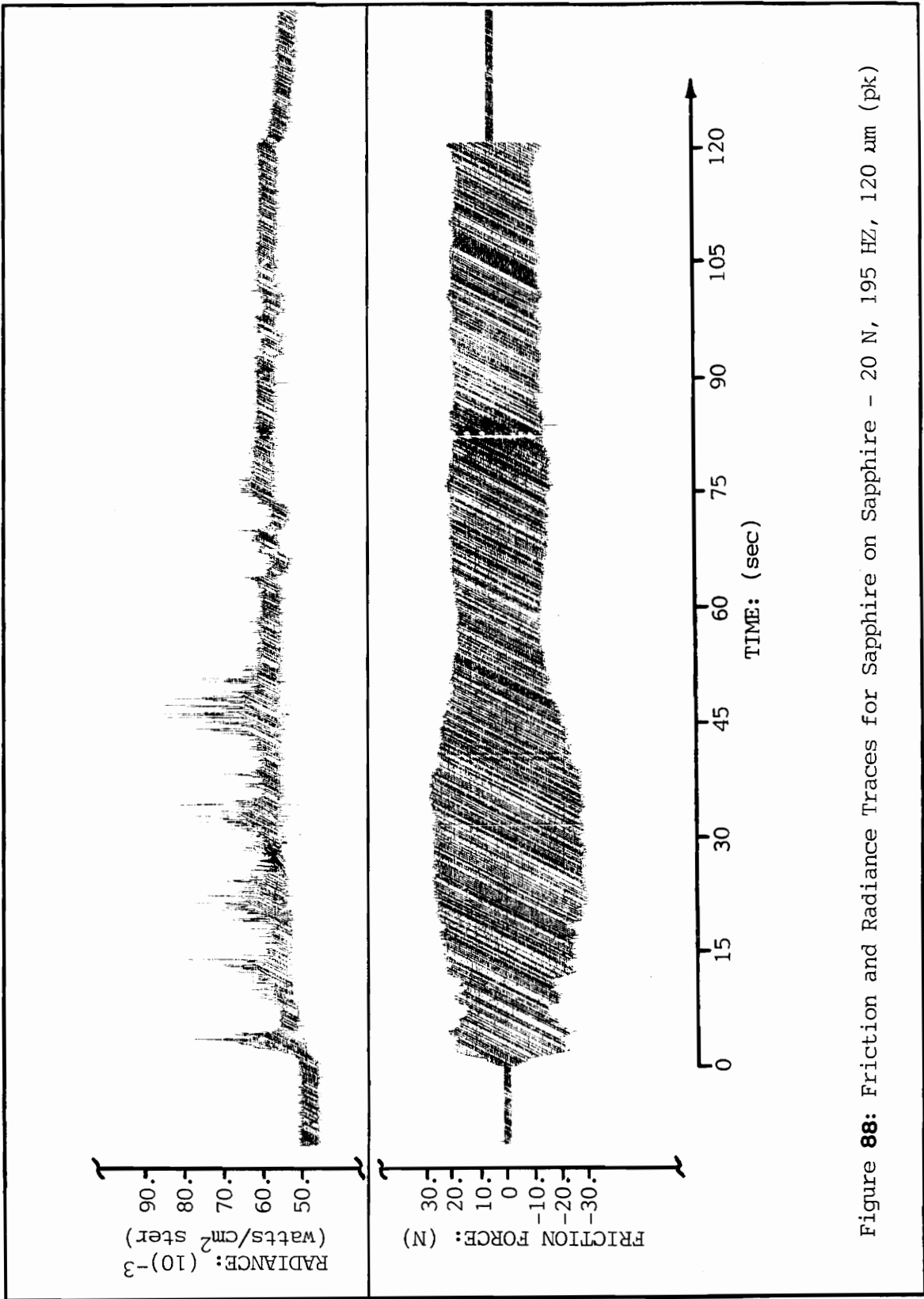


Figure 88: Friction and Radiance Traces for Sapphire on Sapphire - 20 N, 195 Hz, 120 μ m (pk)

4.3.2 Heat Generation Rates and Temperature Rises

Since the normal load, velocity, and friction coefficient are all measured quantities, heat generation rates can be calculated as shown below:

$$\dot{Q}_{\max} = \mu W v_{\max} \quad (36)$$

$$\dot{Q}_{\text{ave}} = \mu W v_{\text{ave}}; \text{ where, } v_{\text{ave}} = \frac{2}{\pi} v_{\max} \quad (37)$$

$\dot{Q}$ = rate of frictional heat generation in watts

μ = coefficient of friction

W = normal load in newtons

v = velocity in meters/second

These heat generation rates are shown in Fig. 89 for the eight experiments. The only variables present are load and material. The 40 N zirconia experiment produces the highest rate of heat generation with maximum and average values of 7.1 and 4.5 watts, respectively. For the 20 N zirconia experiment, the heat generation rates drop to 3.5 and 2.3 watts. This decrease in heat generation with a decrease in load is not unexpected. Since the friction coefficient and velocity are relatively constant between the two experiments, a lower load should result in a lower rate of heat generation. In fact, if the normal load is cut in half, the heat generation rates should be cut in half. This is indeed the case for the two zirconia experiments in Fig. 89. Furthermore, a decrease in heat generation with a decrease in normal load occurs for all the materials shown in Fig. 89.

Tungsten carbide produces the lowest rate of heat generation. For instance, the 40 N tungsten carbide experiment produces maximum and average values of 1.6 and 1.0 watts.

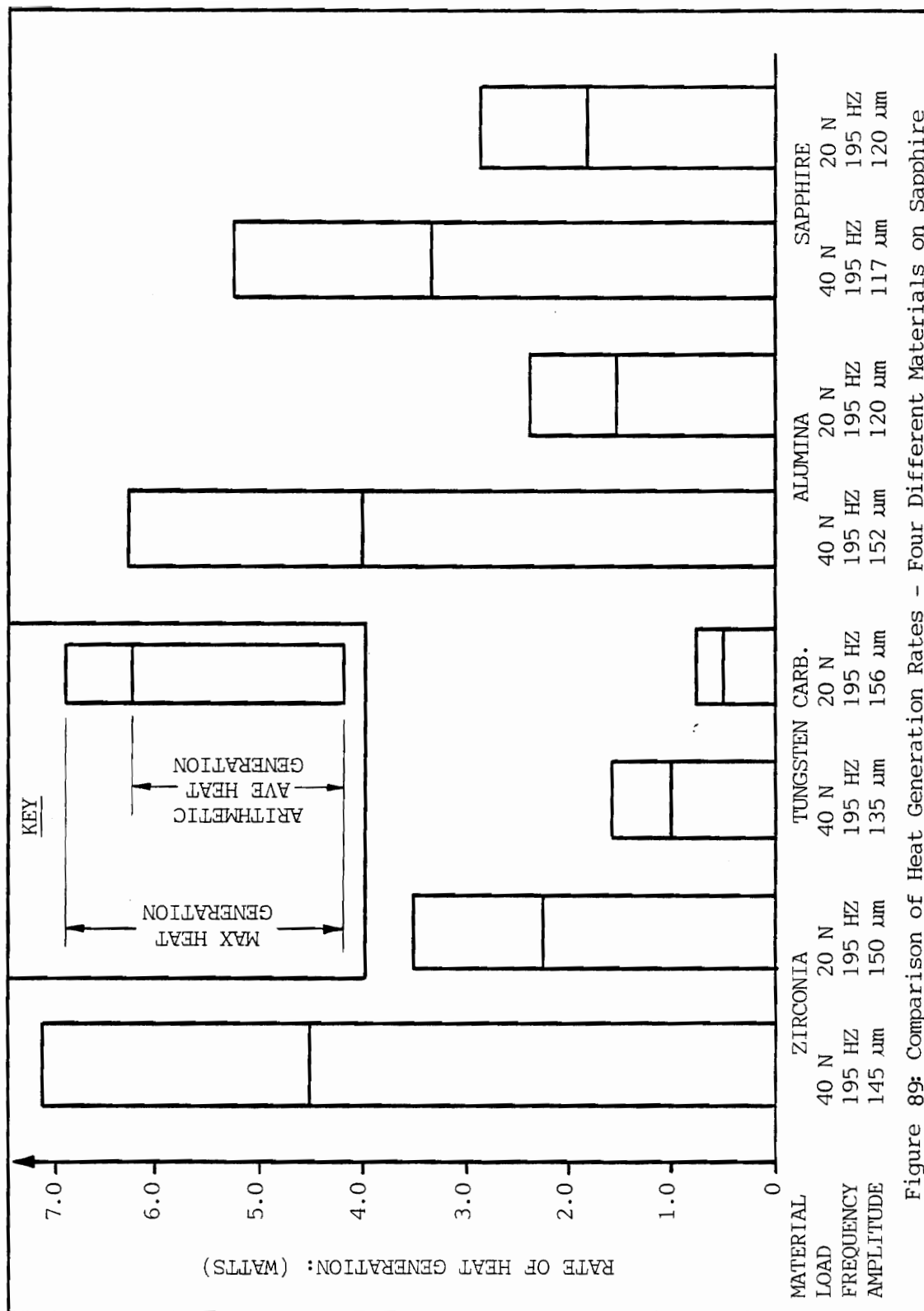


Figure 89: Comparison of Heat Generation Rates - Four Different Materials on Sapphire

The 20 N experiment produces corresponding values of 0.8 and 0.5 watts. As shown in Fig. 86, the tungsten carbide experiments also produce the lowest temperature rises. Average maximum rises of 22 K and 17 K were calculated for the two experiments. The relatively low heat generation rates and temperature rises for tungsten carbide are not unexpected. Tungsten carbide has a thermal diffusivity of $3.34(10)^{-5} \text{ m}^2/\text{s}$. This is almost **forty** times the thermal diffusivity of zirconia which is $8.73(10)^{-7} \text{ m}^2/\text{s}$. Tungsten carbide's thermal diffusivity is also higher than the respective values for sapphire and alumina, $2.50(10)^{-5}$ and $2.93(10)^{-6} \text{ m}^2/\text{s}$. The comparisons discussed above for thermal diffusivity are also true for thermal **conductivity**. Tungsten carbide has a relatively high thermal conductivity compared to zirconia, alumina, and sapphire, see Table 1. As a result, the heat generation rates (and temperature rises) for the zirconia, sapphire, and alumina experiments are higher than the values measured for the tungsten carbide experiments.

As shown in Fig. 89, the frictional heat generation rates for alumina and sapphire are nearly identical. At a 20 N load, the maximum rate of heat generation for sapphire-on-sapphire is 1.8 watts. This is only slightly higher than the maximum rate of heat generation for the 20 N alumina experiment, 1.5 watts. This similarity of heat generation rates is also true for the 40 N experiments. Since the heat generation rates are similar for alumina and sapphire, one might expect the temperature rises to be similar. However, this is not the case. As shown in Fig. 86, the temperature rises for the sapphire experiments are greater than the rises for the alumina experiments. In fact, the difference between the two experiments is more than 80 K. This difference could be due to variations in the size, location, and distribution of real contact areas between the alumina-on-sapphire and sapphire-on-sapphire experiments.

To gain a better understanding of the relationship between temperature rise and heat generation, Fig. 90 is presented. This figure shows temperature rise plotted as a function of heat generation. The KEY in this figure shows what each letter represents. Sapphire-on-sapphire obviously produces the highest temperature rise, but the rate of heat generation for this pair is less than the rate of heat generation for zirconia-on-sapphire. Note, zirconia-on-sapphire produces temperature rises that are less than those produced for sapphire-on-sapphire. This inconsistency can possibly be explained by the emissivity assumption used for the sapphire-on-sapphire experiments.

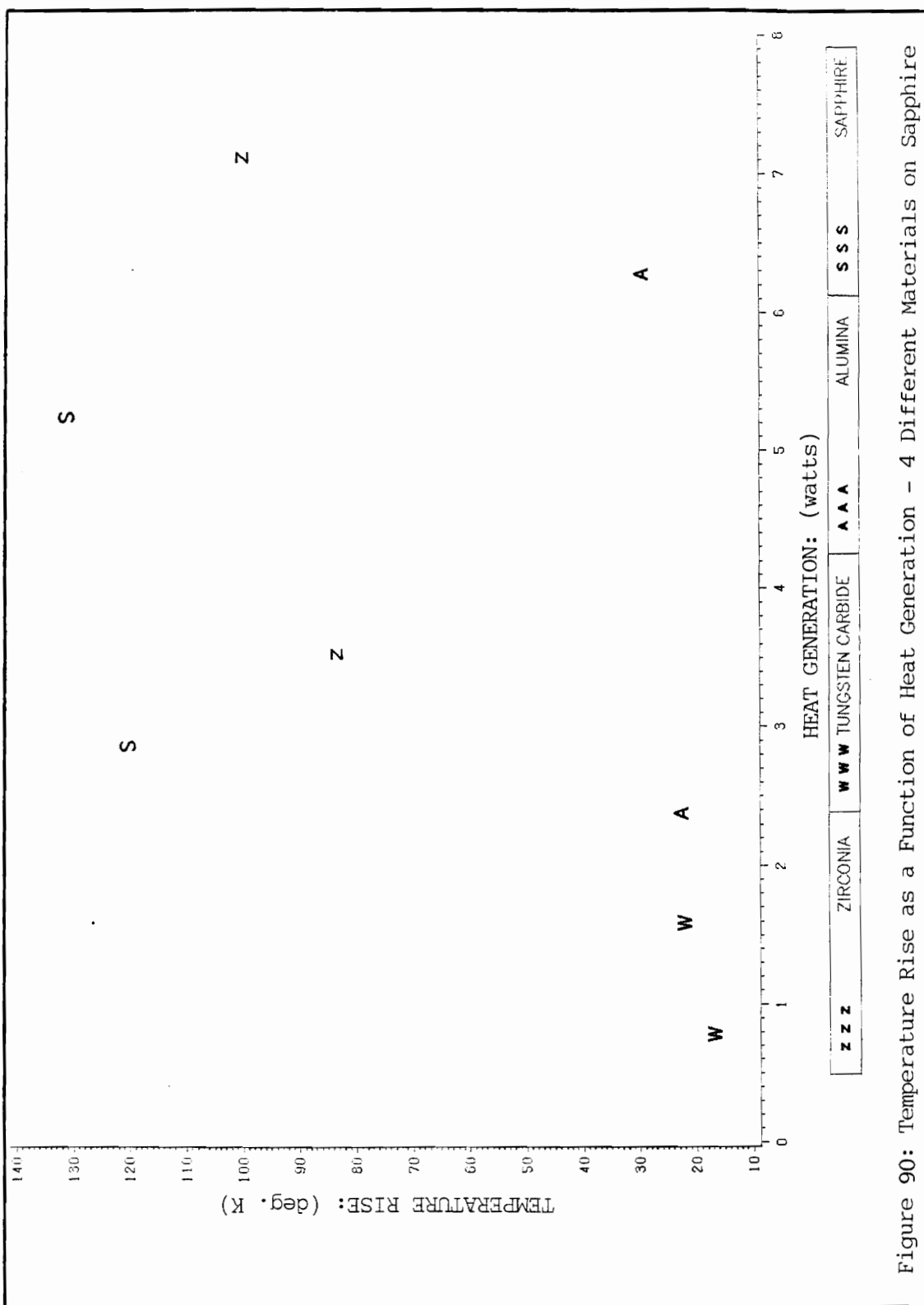


Figure 90: Temperature Rise as a Function of Heat Generation - 4 Different Materials on Sapphire

Since the emissivity probably increases during the sapphire-on-sapphire experiments, the temperature rises could be smaller. Another possible explanation lies with the small size of the microscope's target spot. This target spot size is significantly less than the size of the contact region. Because of this, calculated temperature rises are for a *very small region* within the total contact region. Therefore, the temperature rises calculated for sapphire-on-sapphire could represent an extreme upper limit to the variation in surface temperatures found in the entire contact region. On the other hand, the heat generation rates are the product of friction force and velocity. Thus, the values for heat generation account for the heat that is generated in the *entire* contact region. Furthermore, variations in the size, location, and distribution of real contact areas also play a factor. In fact, this is a more likely explanation for the difference between heat generation rates and temperature observed for the sapphire-on-sapphire experiments. In summary, a simple explanation for the high temperature rises and relatively low heat generation rates cannot be made for the sapphire-on-sapphire experiments.

4.3.3 Friction, Wear, and Temperature Rises

A comparison of friction coefficients for the eight experiments is shown in Fig. 91. As listed below, friction coefficients greater than 0.80 were measured for the zirconia, sapphire, and alumina experiments.

- The coefficients for zirconia-on-sapphire range from 0.96 to 1.0.
- The coefficients for sapphire-on-sapphire range from 0.88-0.97.
- The coefficients for alumina-on-sapphire range from 0.81-0.84.

These friction coefficients are significantly higher than the ones measured for tungsten carbide-on-sapphire.

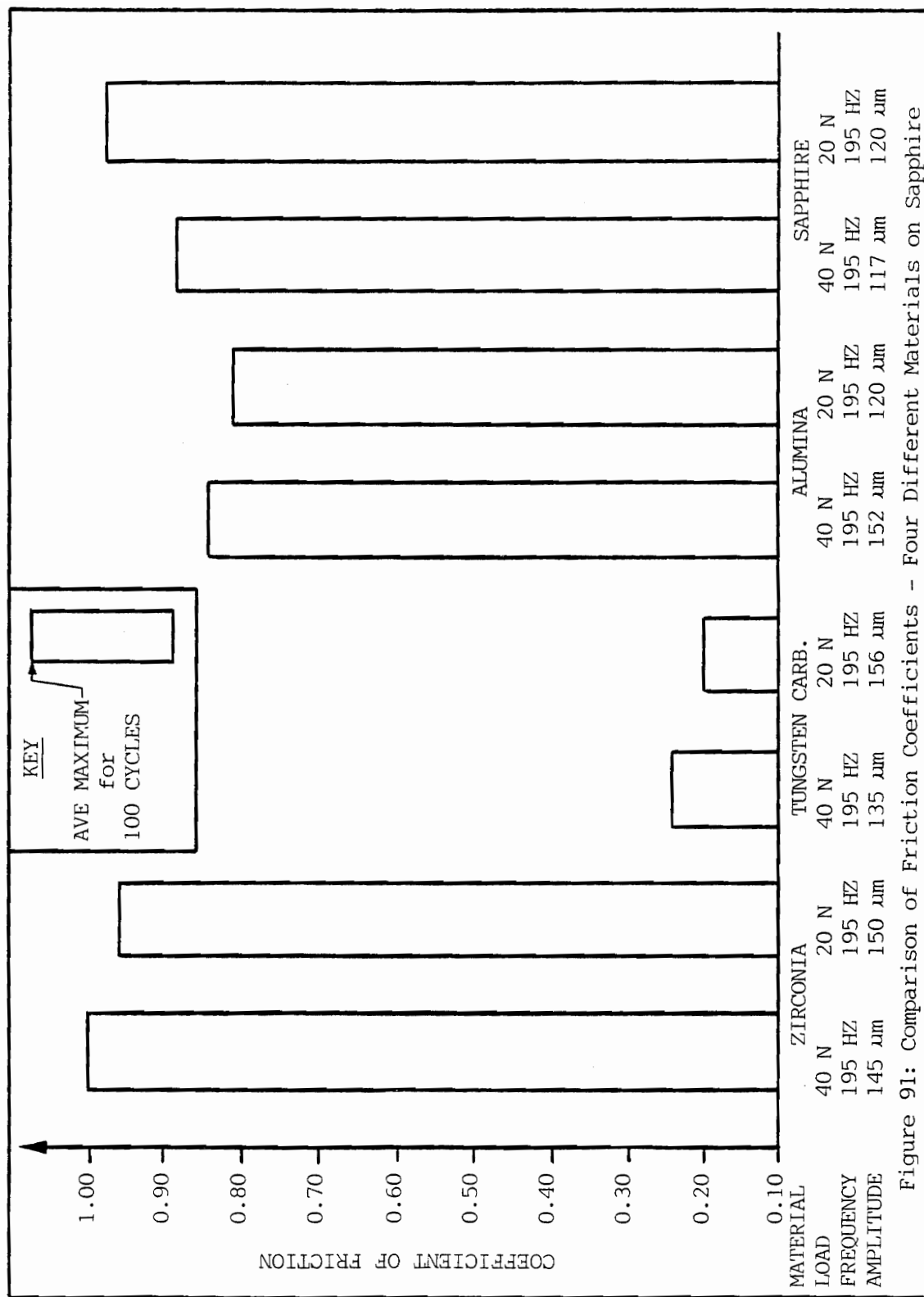


Figure 91: Comparison of Friction Coefficients - Four Different Materials on Sapphire

As shown in Fig. 91, the friction coefficients for tungsten carbide-on-sapphire range from 0.20-0.24. When compared to the other cases, the low friction coefficients for tungsten carbide-on-sapphire are not unexpected. Due to the fact that alumina, zirconia, and sapphire are all metal oxides, strong adhesive bonds are likely to occur when they are tribologically paired. The shearing of these strong adhesive bonds leads to high frictional forces at the interface. This is not the case when a carbide such as tungsten carbide is paired with an oxide such as sapphire. Strong adhesive bonds are not present and frictional forces are less.

Wear scar sizes for the eight test specimens are shown in Fig. 92. As defined in the KEY for this figure, major and minor diameters of the elliptical wear scars are shown. The largest wear scar diameters were measured for the two zirconia experiments. Major diameters of 953 and 950 μm were measured for these experiments. The smallest wear scar diameters were measured for the two tungsten carbide experiments. Major diameters of 155 and 107 μm were measured for these two experiments. Alumina-on-sapphire results show the greatest difference in wear between experiments performed using a 40 N load, and those performed using a 20 N load. The major wear scar diameter for the 40 N alumina experiment is 938 μm , and the major wear scar diameter for the 20 N experiment is 297 μm . The sapphire-on-sapphire experiments created major wear scar diameters of 900 and 709 μm on the sphere. Both the 40 N alumina and 40 N sapphire experiments resulted in wear scar diameters that are approximately equal to those measured for the zirconia experiments. If debris volumes are calculated, assuming a segment of the sphere has been removed, the similarity between these four experiments is more apparent. As shown in Fig. 93, the volume of debris removed for the four experiments is approximately $9(10)^5 (\mu\text{m})^3/\text{m}$. (Note, the units $(\mu\text{m})^3/\text{m}$ refer to volume of debris removed per total distance traveled by the disk.) As expected, tungsten carbide has the least amount of debris removed. In fact, the volume removed for tungsten carbide is approximately three orders of magnitude less than the volume removed for zirconia.

To compare wear with surface temperature, the volume of debris removed per sliding distance was plotted as a function of temperature rise. This plot is shown in Fig. 94. The four sapphire and zirconia experiments show that high temperature rises produce a great deal of wear. In addition,

the results for tungsten carbide show that low temperature rises produce a small amount of wear. The results for alumina are somewhere in between the two extremes.

For instance, results for the 40 N experiment show that a large amount of wear coincides with a relatively low temperature rise. In fact, as shown by the topmost "A" in Fig. 94, the temperature rise for the 40 N alumina experiment is close to the temperature rise for the 40 N tungsten carbide experiment. However, the wear for the 40 N alumina experiment is close to the wear measured for the zirconia and sapphire experiments. In summary, there is no concise relationship between wear and surface temperature. However, as discussed above, there are certain generalized relationships that can be observed in the data.

The sizes of the contact regions on the sapphire disks are shown in Fig. 95. These contact regions are formed by transferred material and/or wear of the disk itself. For the case of tungsten carbide-on-sapphire, the contact region appears to be highly polished compared to the rest of the disk. For the sapphire-on-sapphire case, the contact region is more opaque than the rest of the disk, and it is difficult to determine if this increase in opacity is due to wear or transfer from the sphere. To continue, the diameters of the contact regions on the disk are greater than the wear scar diameters on the spheres. However, the same general trends for the wear scar diameters are observed in the contact region data.

4.3.4 Scanning Electron Micrographs of the Test Specimen Surfaces

The purpose of this section is to present scanning electron micrographs (SEM's) of the worn surfaces of the test specimens. By observing these SEM's, predominant surface characteristics can be readily seen. For instance, raised areas on the surface can be distinguished from lower areas. These raised areas can be used to make inferences about the size and location of real contact areas during the experiment. Also, by tilting the specimen and observing the wear scar at an angle, inferences can be made about the three-dimensional nature of the entire wear scar. As an example,

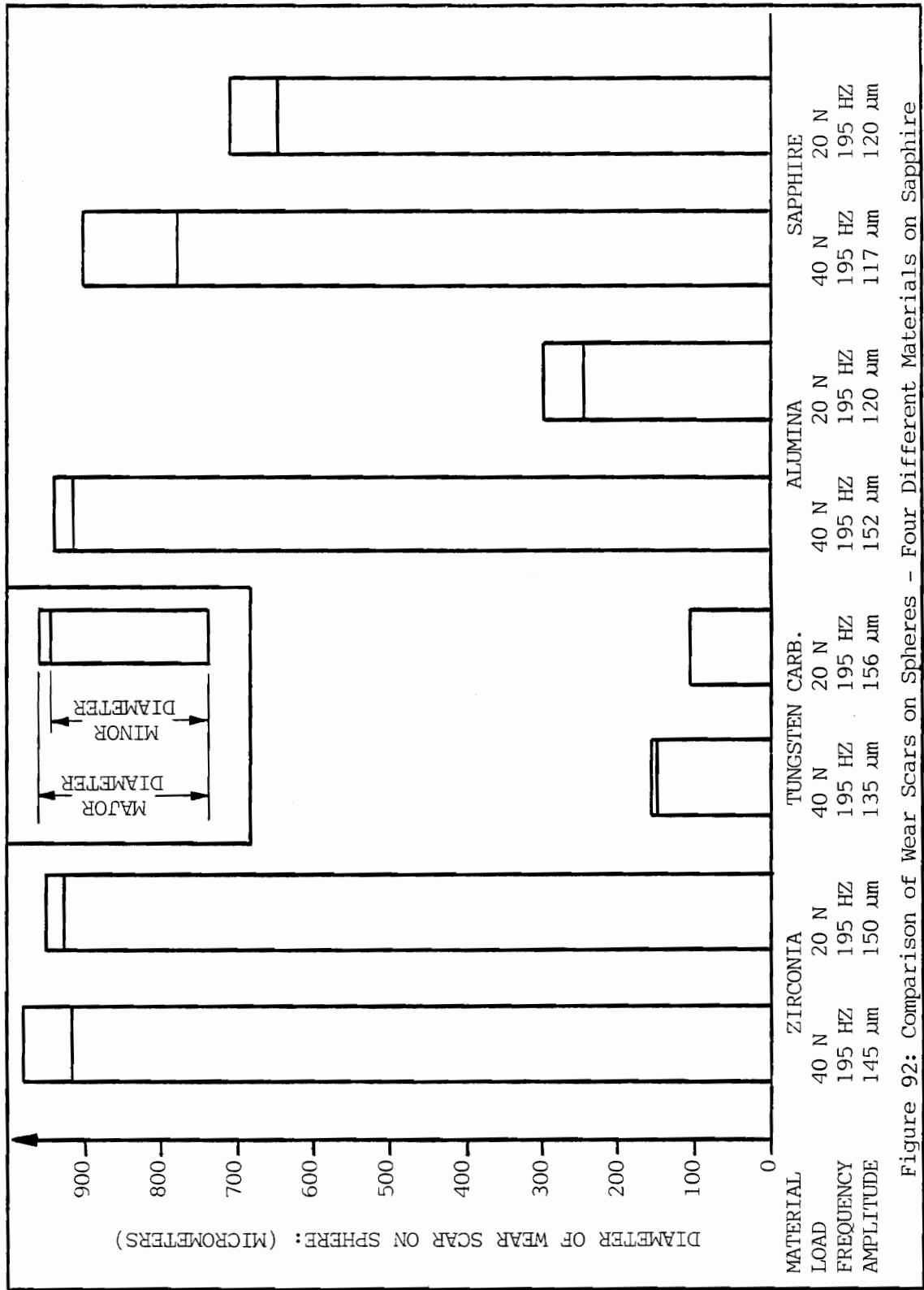


Figure 92: Comparison of Wear Scars on Spheres - Four Different Materials on Sapphire

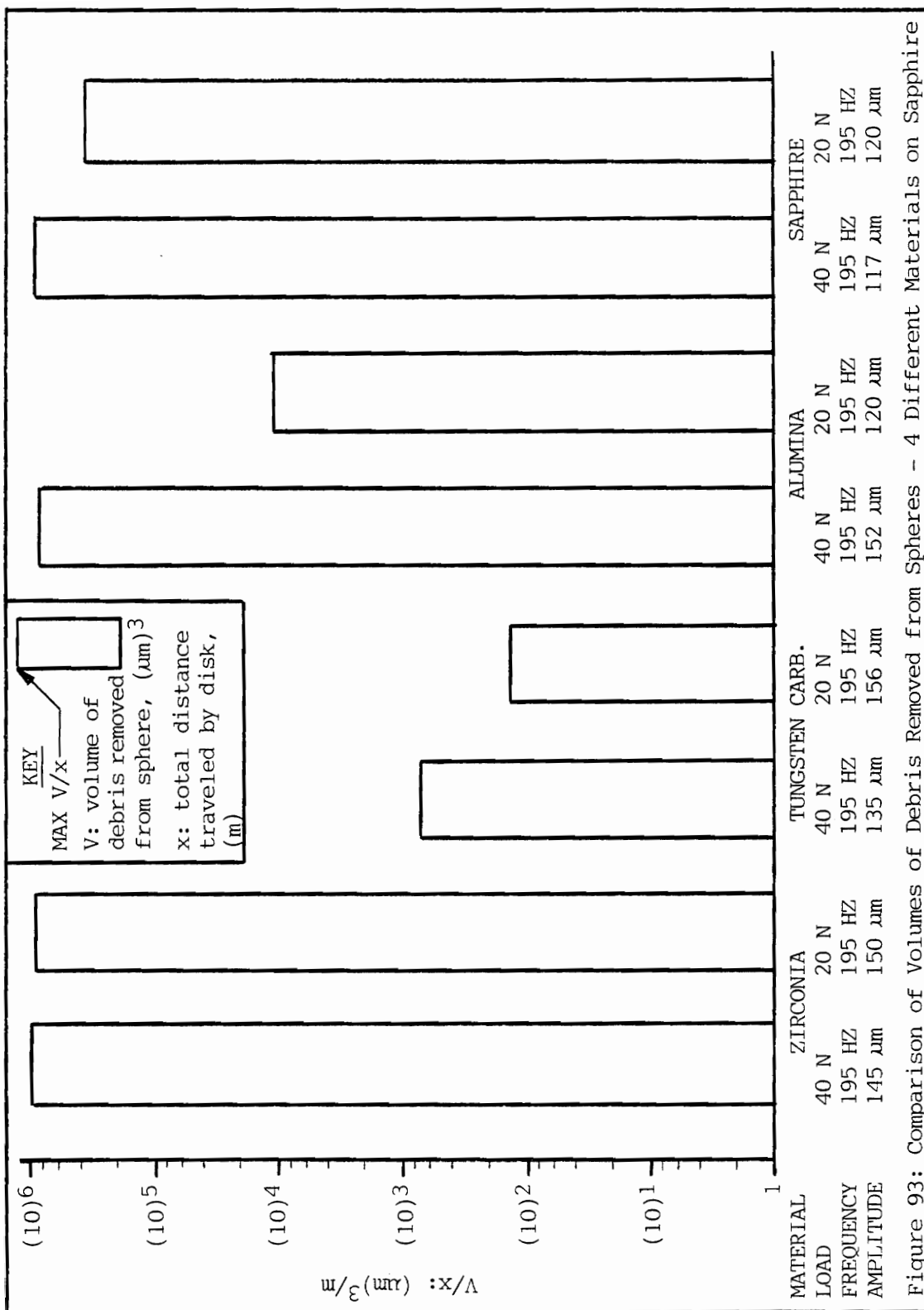


Figure 93: Comparison of Volumes of Debris Removed from Spheres - 4 Different Materials on Sapphire

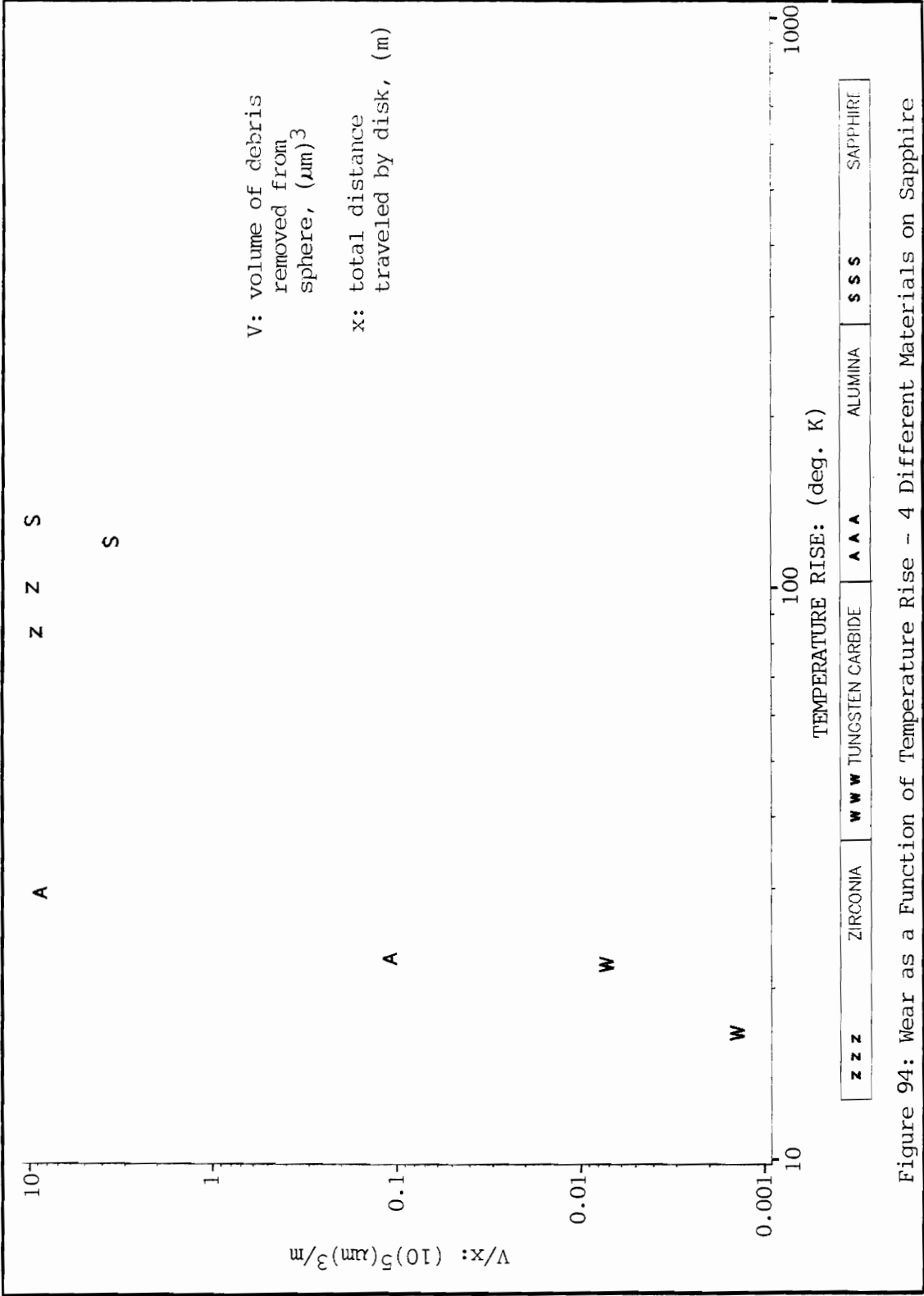
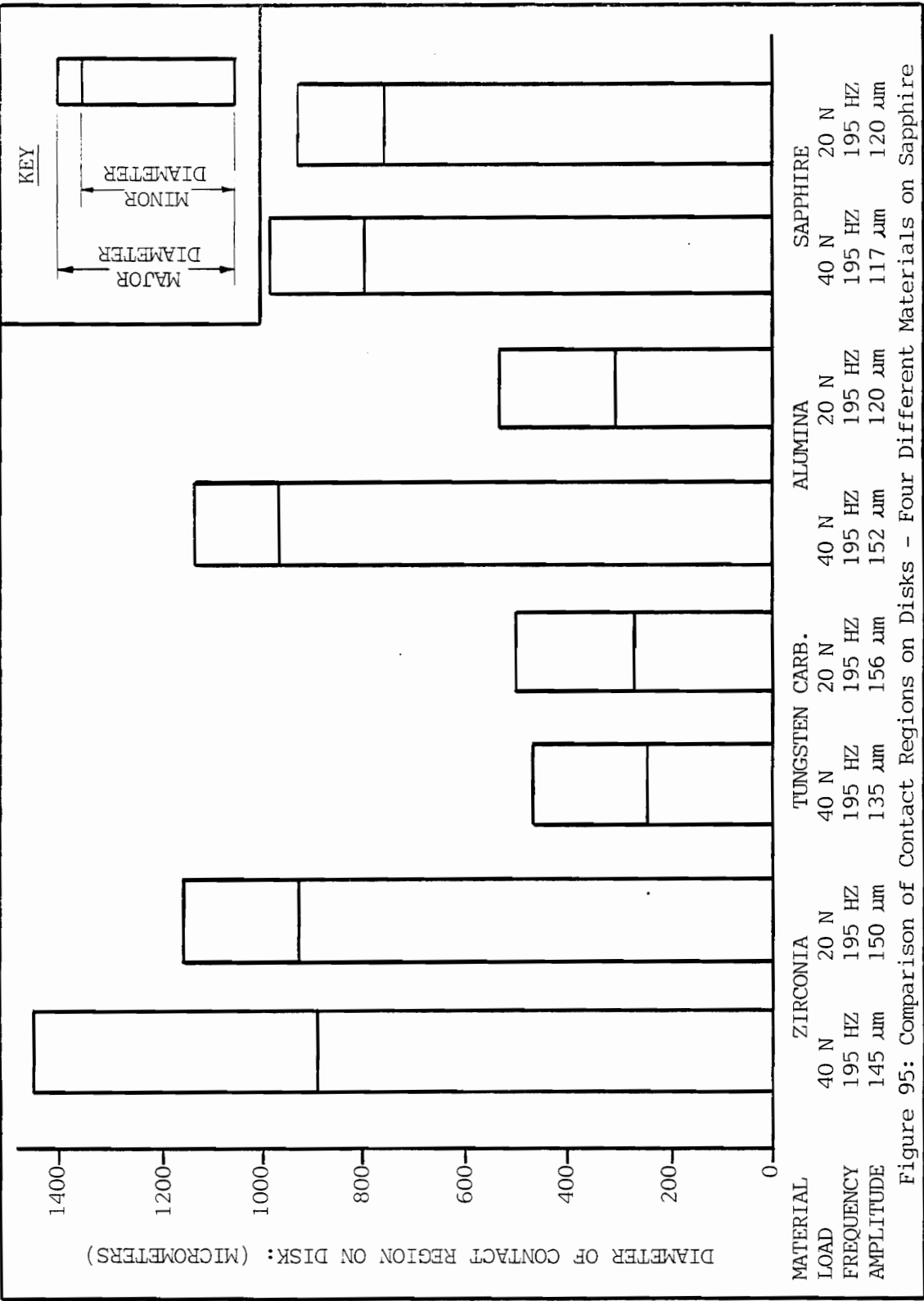


Figure 94: Wear as a Function of Temperature Rise - 4 Different Materials on Sapphire

some of the wear scars appear to be "dished" rather than planar in nature. The zirconia SEM's provide the best examples of a "dished" wear scar as was already demonstrated in Fig. 84.

Figures 96, 97, and 98 are SEM's of the wear scar of a zirconia test specimen. The normal load used was 40 N, and the sapphire disk was oscillated at a frequency of 195 Hz and amplitude of 145 μm (pk). The experiment was performed for two minutes. Note, this experiment corresponds to the first radiance trace shown in Fig. 43. Figure 96 shows an overhead picture of the wear scar at a low magnification of 80X. The sliding direction is denoted by the arrows in the picture. Raised regions in the wear scar appear to be perpendicular to the sliding direction. These raised areas are shaped like bands and are used in Section 4.4 to model real contact areas for comparison with theory. Also shown in Fig. 96 is a dark region approximately 350 μm from the center of the wear scar. Figure 97 represents a higher magnification of this dark region and shows that the zirconia material has possibly melted and flowed in a direction parallel to the motion of the sapphire disk. Note, high surface temperatures can lead to such melting as shown by Aronov and Ishigaki in references [80] and [81]. Aronov also shows how high surface temperatures can cause localized phase transformations and wear of zirconia surfaces. Based on these observations, one can infer that the dark region shown in Fig. 97 is caused by high surface temperatures generated during frictional heating of the surface.

When the zirconia wear scar is observed at an angle in Fig. 98, the dished nature of the wear scar is apparent. More material has been removed from the center of the scar than from other areas. From scanning experiments, higher surface temperatures are present in the center of the contact region than in other areas of the contact region. Therefore, the role of surface temperatures in wear and degradation of the zirconia specimen must be considered. Thouless and Braza [83,84] described how frictional heating of the surface of ceramic materials can cause the surface temperature to be much higher than the bulk temperature due to the low thermal conductivity of ceramics. This difference in temperature between the surface and bulk will produce large compressive stresses parallel to the surface. These compressive stresses lead to the formation of subsurface cracks that eventually propagate to the surface. As a result, wear particles defined as spalls are formed where high surface temperatures are present [83]. In short, one can infer that temperature-activated



spalling occurs at the center of the contact region shown in Fig. 98. Therefore, a large amount of wear occurs at the center of the contact region due to high surface temperatures.

Figures 99, 100, and 101 are SEM's of a tungsten carbide wear scar. The two-minute experiment that corresponds to this wear scar was performed under the following test conditions: normal load - 20 N, frequency - 195 Hz, and amplitude - 156 $\mu\text{m}(\text{pk})$. The radiance trace for this experiment is shown in Fig. 85. As shown in Fig. 99, the contact region can be described as clusters of small areas within a geometric circle. These clusters could be representative of the real contact areas during an experiment. When the wear scar is viewed at an angle in Fig. 100, the clusters appear as groups of asperities superimposed on a planar area. If this angle view is magnified to 3300X, the random size and location of these asperities becomes more apparent. This magnified view is shown in Fig. 101. As shown in this figure the height of the asperities is less than 3 μm , and the distribution can only be characterized as random. In summary, if an optically flat sapphire disk is pressed against this surface of asperities, one can easily imagine real contact areas forming by compression of these asperities. However, the true size and location of real contact areas during an experiment cannot be stated conclusively.

Figures 102, 103, and 104 are SEM's of the surface of the sapphire sphere after a two-minute sapphire-on-sapphire experiment. The radiance trace for this experiment is shown in Fig. 85, and the test conditions used are as follows: normal load - 40 N, frequency - 195 Hz, amplitude - 117 $\mu\text{m}(\text{pk})$. Figure 102 is an overhead view of the wear scar. In this figure, the dark areas within the scar are raised above the lighter areas. This is more obvious when the wear scar is viewed at an angle in Fig. 103. These figures also show a part of the contact region with markedly different characteristics. This region is located on the edge of the wear scar and is denoted by an asterisk in Figures 102 and 103. It is actually a large "gouge" in the surface of the test specimen, and is *not* a raised area. The reason why this gouge formed is not known. However, a large piece of material was obviously removed during the experiment. A close-up view of the edge of this gouge is shown in Fig. 104. A small piece of wear debris is shown in the center of this micrograph, and the wall of the gouge appears to be relatively smooth in certain areas. This smoothness could be the result of material cleavage at a defect in the lattice structure [83].

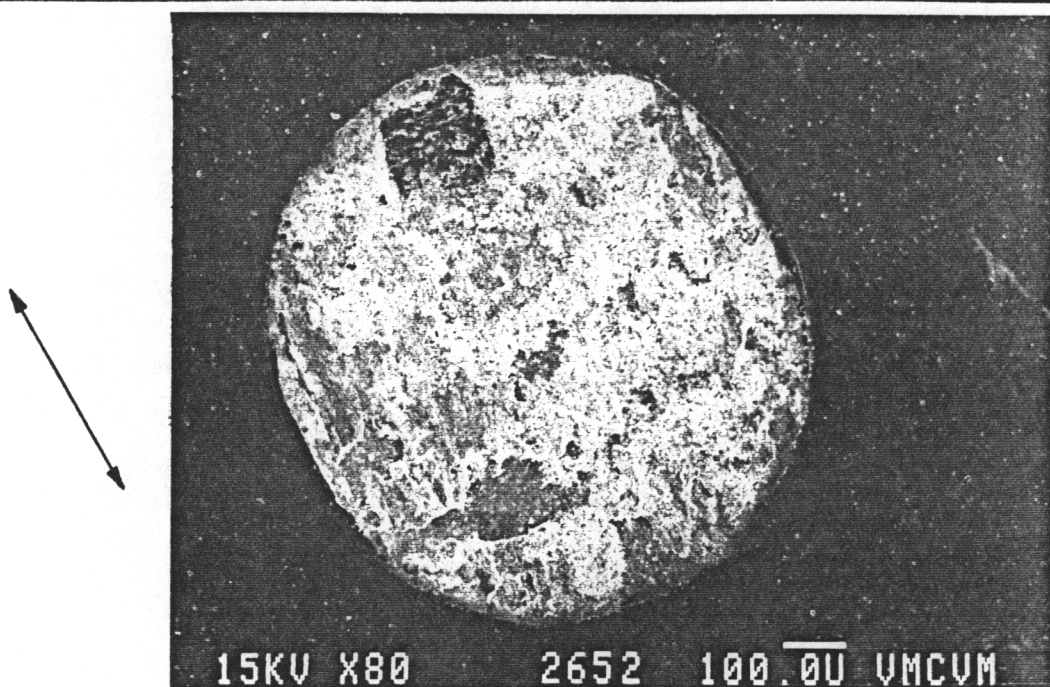


Figure 96 : Scanning Electron Micrograph of a Zirconia Wear Scar
Overhead View - Zirconia on Sapphire - 40 N, 195 HZ, 145 μm (pk)

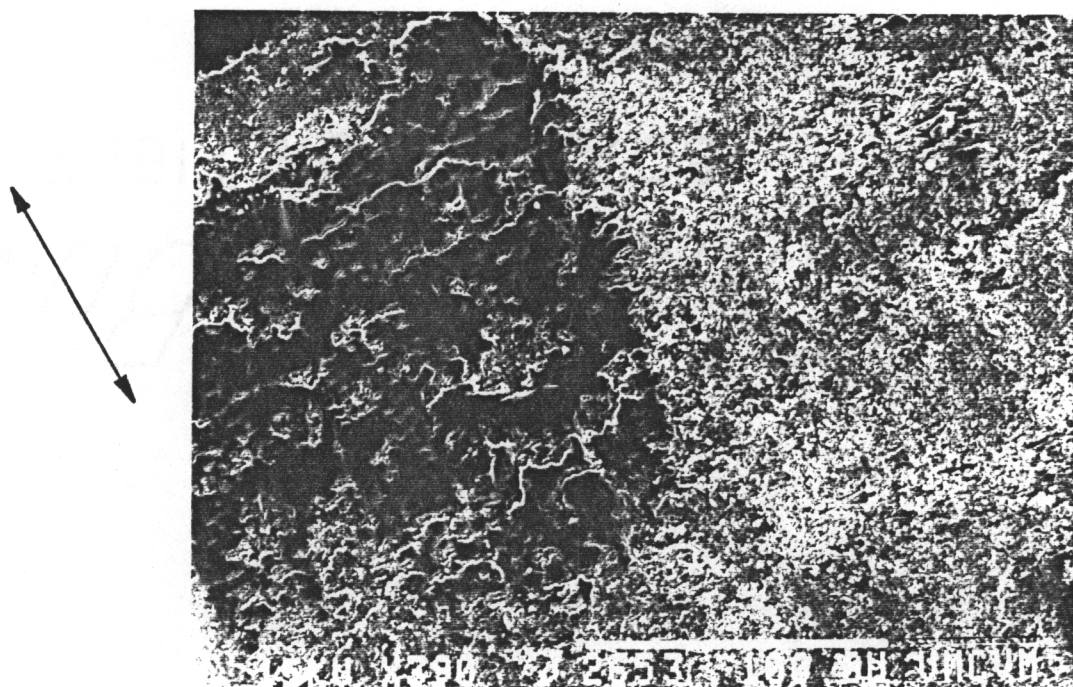


Figure 97 : Scanning Electron Micrograph of a Zirconia Wear Scar
Overhead View - Zirconia on Sapphire 40 N, 195 HZ, 145 μm (pk)

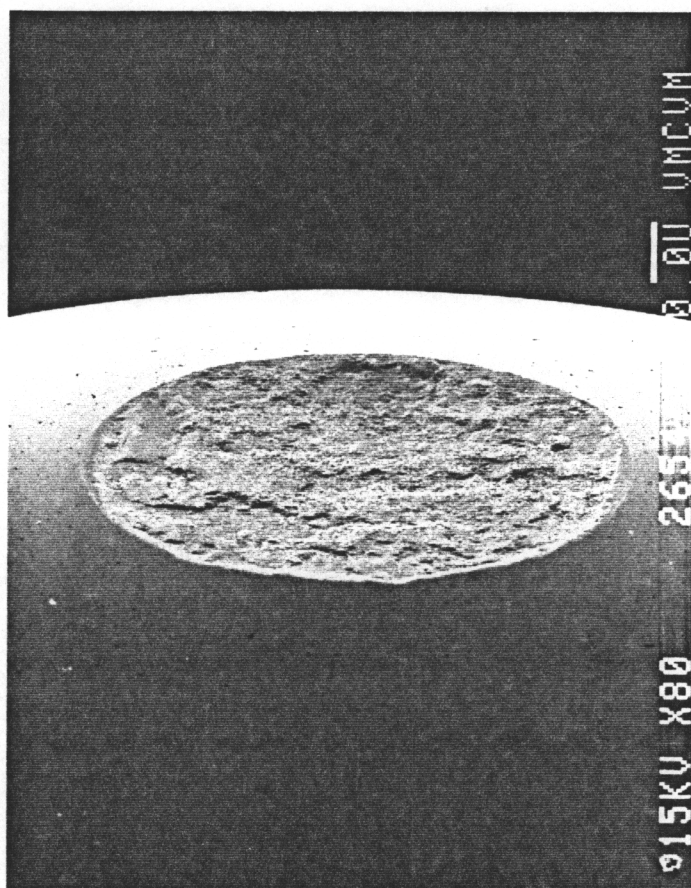


Figure 98 : Scanning Electron Micrograph of a Zirconia Wear Scar
Angle View - Zirconia on Sapphire - 40 N, 195 HZ, 145 μm (pk)

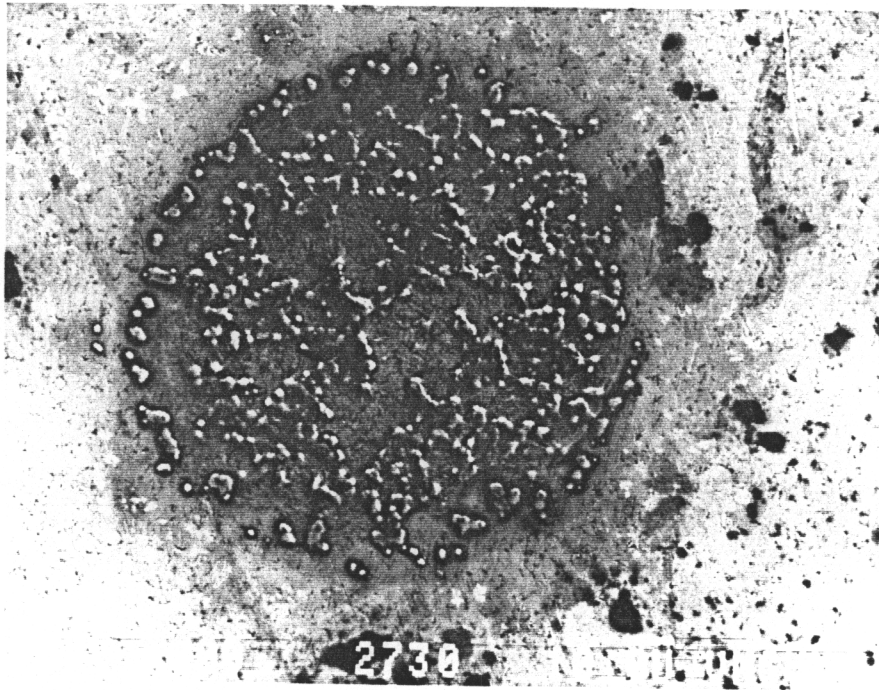


Figure 99: Scanning Electron Micrograph of a Tungsten Carbide Wear Scar
Overhead View - Tungsten Carbide on Sapphire - 20 N, 195 HZ, 156 μm

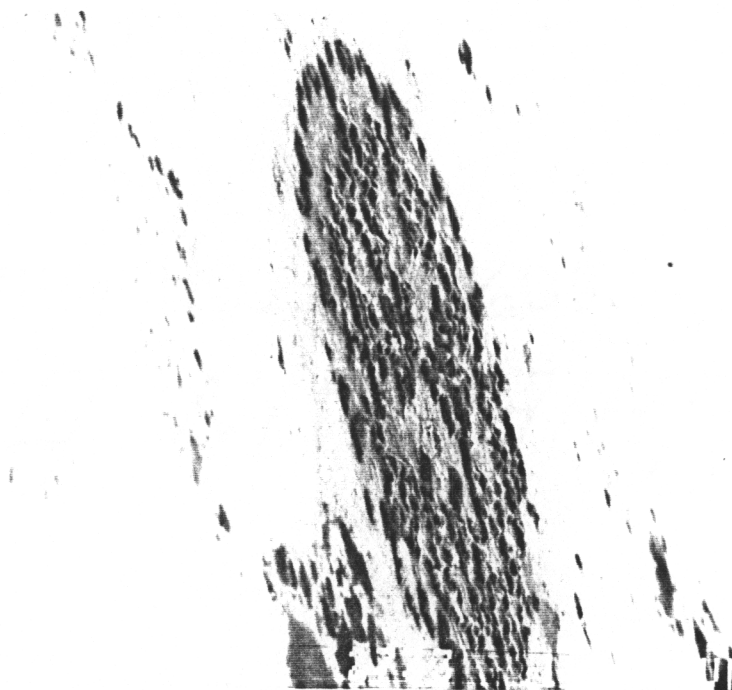


Figure100: Scanning Electron Micrograph of a Tungsten Carbide Wear Scar
Angle View - Tungsten Carbide on Sapphire - 20 N, 195 HZ, 156 μm (pk)

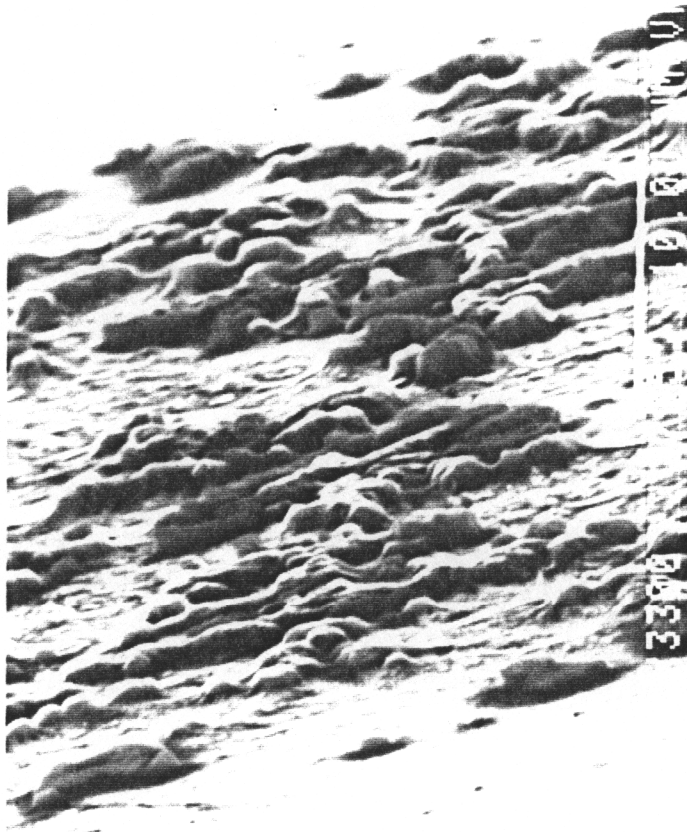


Figure101: Scanning Electron Micrograph of a Tungsten Carbide Wear Scar
Angle View - Tungsten Carbide on Sapphire - 20 N, 195 HZ, 156 μm (pk)

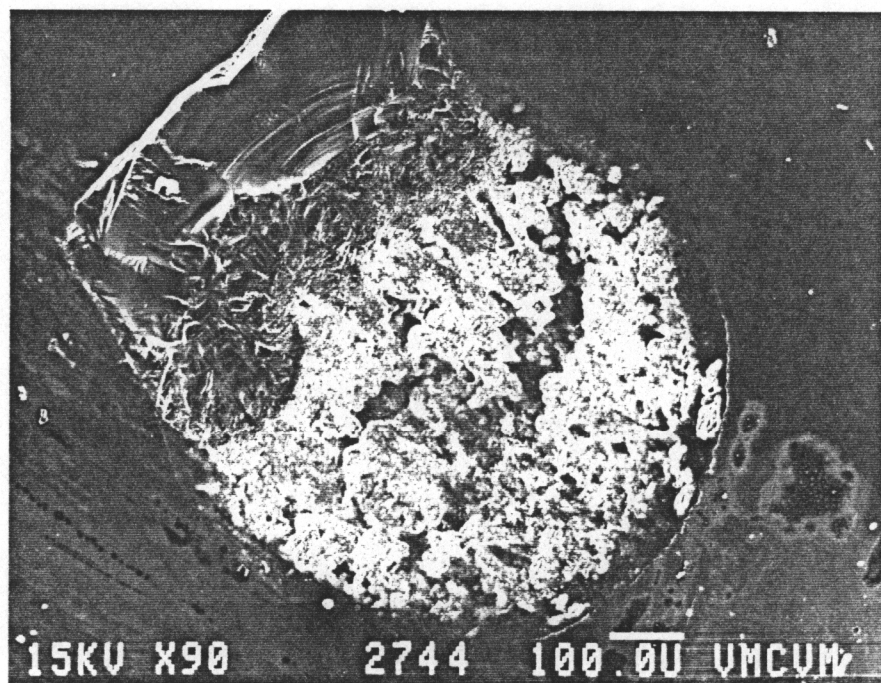


Figure 102: Scanning Electron Micrograph of a Sapphire Wear Scar
Overhead View - Sapphire on Sapphire 40 N, 195 HZ, 117 μm (pk)

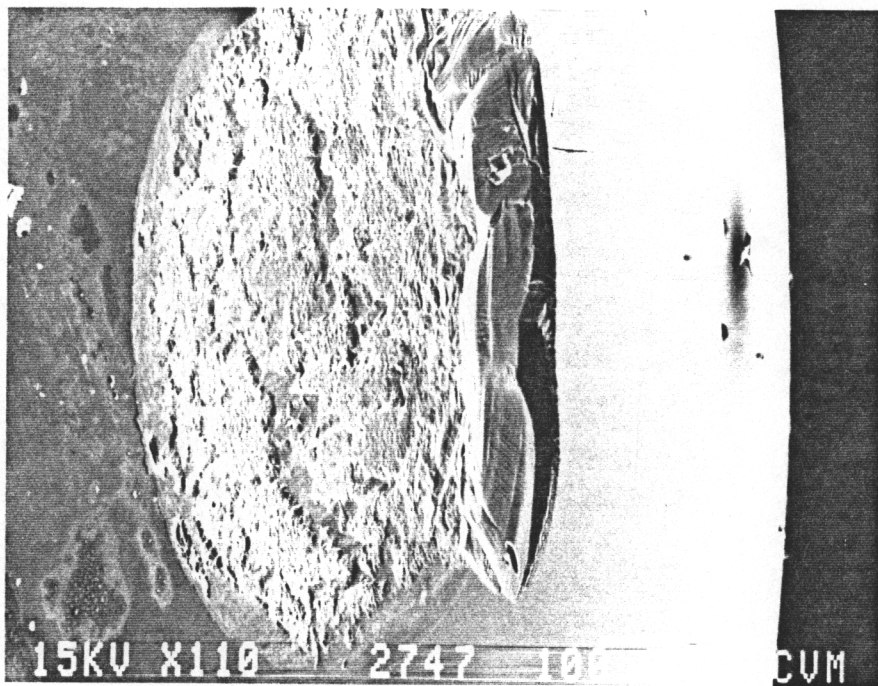


Figure 103: Scanning Electron Micrograph of a Sapphire Wear Scar
Angle View - Sapphire on Sapphire - 40 N, 195 HZ, 117 μm (pk)



Figure 104: Scanning Electron Micrograph of a Sapphire Wear Scar
Angle View - Sapphire on Sapphire - 40 N, 195 HZ, 117 μm (pk)

In other words, if the gouge was formed by removal of a large piece of material, the piece itself could have been formed by fracture at a defect in the crystalline lattice structure. Other wear modes such as chipping and spalling could also be the cause of this large removal of material, (see Table 2).

Figures 105 and 106 are SEM's of the surface of alumina after a two-minute experiment. The radiance trace for this experiment is shown in Fig. 85, and the test conditions used are as follows: normal load - 20 N, frequency - 195 Hz, amplitude - 120 $\mu\text{m(pk)}$. Also, the friction force trace for this experiment is shown with the radiance trace in Fig. 87. As shown in this figure, a sudden increase in radiance corresponds with a sudden increase in friction force. This increase also corresponds with the formation of the "rectangular band" at the middle of the SEM shown in Fig. 105. This observation was made during the experiment by simply viewing the evolving contact region through the optical channel of the infrared microscope.

As shown in Figs. 105 and 106, the "rectangular band" is comprised of raised areas and depressions. These raised areas could be acting as real contact areas during the experiment. On either side of the rectangular band, the contact region is relatively smooth. These two regions could also be representative of real contact areas. Furthermore, the two regions on either side of the band are less porous than the rest of the alumina sphere. (Since the alumina sphere was formed by a sintering process, it tends to contain a large amount of pores.) The smooth areas of the test specimen could be the result of the wear mode defined in Table 2 as polishing. In this process, the surface of the ceramic material is smoothed by removal of material or by plastic deformation [83]. Since the formation of the rectangular band corresponds with an increase in radiance (and surface temperature), the large amount of wear in this region could correspond with thermally-activated wear mechanisms such as the spalling mechanism discussed previously.

In summary, the complex nature of the wear scars presented herein lend little insight to the size and location of real contact areas. In spite of this fact, the SEM's and optical macrographs of the high load (40 N) zirconia wear scar were used to estimate probable sizes and locations of real contact areas within the geometric contact region. These estimated real contact areas are used in the next section to theoretically calculate surface temperatures for comparison with experimentally measured values.

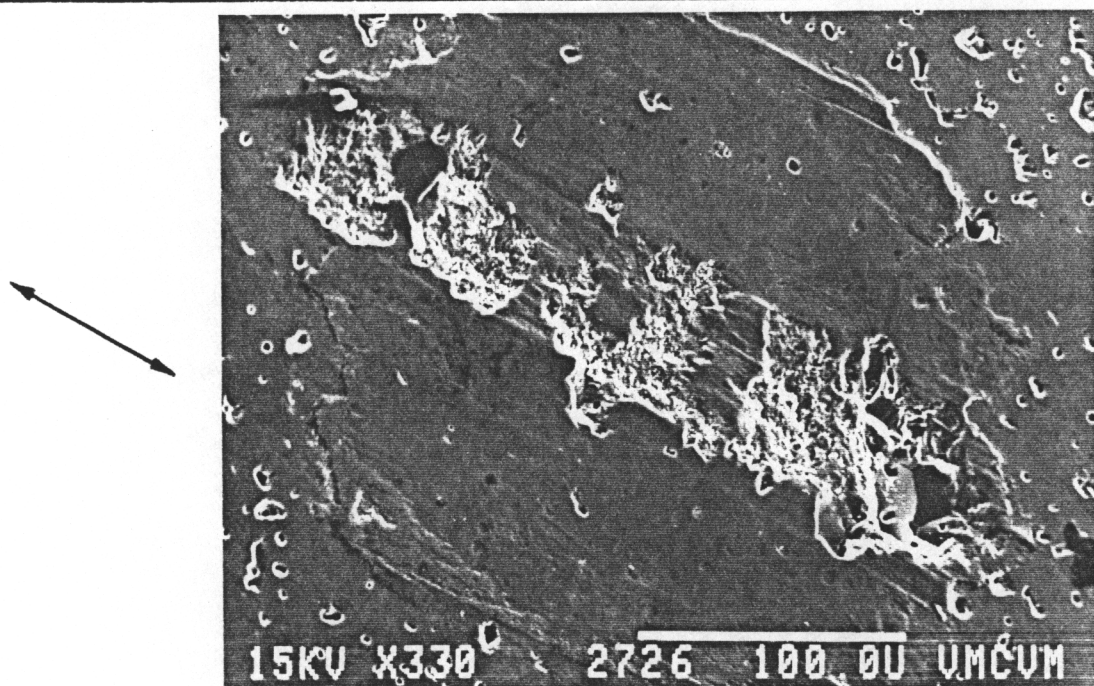


Figure 105: Scanning Electron Micrograph of an Alumina Wear Scar
Overhead View - Alumina on Sapphire - 20 N, 195 HZ, 120 μm (pk)

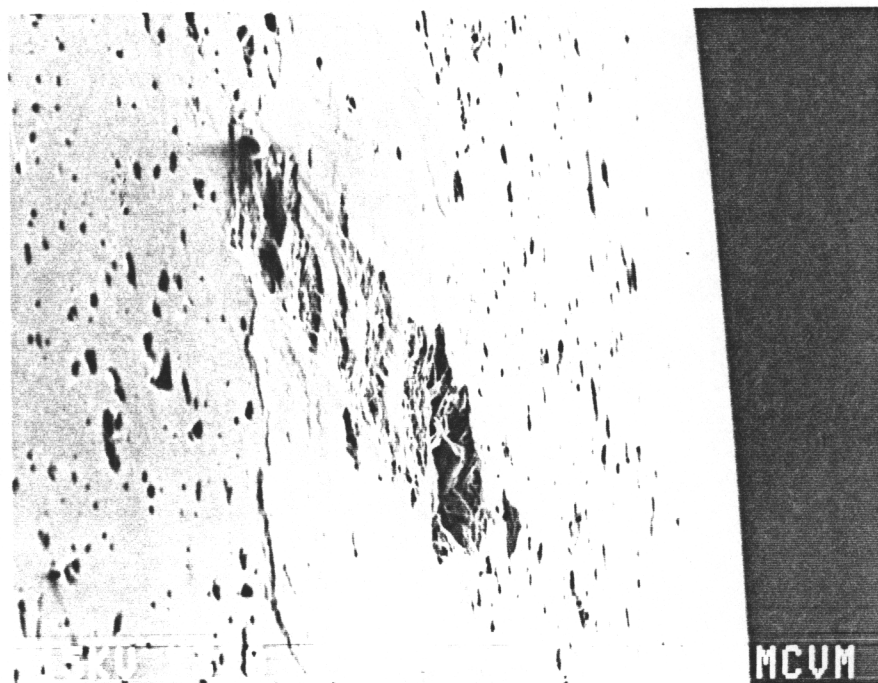


Figure 106: Scanning Electron Micrograph of an Alumina Wear Scar
Angle View - Alumina on Sapphire - 20 N, 195 HZ, 120 μm (pk)

Although inferences about the size and location of real contact areas are difficult to compile using the scanning electron micrographs, the influence of surface temperatures on the wear of ceramic materials can easily be observed. This correspondence between surface temperature and wear was also observed in Sections 4.2.3 and 4.3.3. For ceramic materials, high surface temperatures lead to high wear rates.

4.4 Comparison of Theory and Experiment [13,9]

To compare theory and experiment, the theoretical model developed in reference [9] was applied to a zirconia-on-sapphire experiment. The radiance for this experiment is shown in Fig. 107. A 40 N normal load was used, and the sapphire disk was oscillated at the following frequency and amplitude: 195 Hz and 145 μm (pk). The theoretical and experimental results are shown in Table 14.

As shown in Fig. 1, the theoretical surface temperatures for oscillating contact rise sharply during the initial period of time and asymptotically settle into a cyclic repetitive pattern referred to as a quasi steady-state. The experimental results displayed in Fig. 107 also rise in time and approach a quasi steady-state; but obviously the theoretical and experimental curves differ. We know that experimental measurements of surface temperature are often characterized by complex fluctuations and random occurrences. In addition, the theoretical predictions apply to a given fixed area (or areas) of contact while in fact the real area of contact is unknown and possibly changing with time.

The actual experiment with zirconia-on-sapphire lasted 120 seconds. During this time, the surface temperature as determined from IR measurements gradually increased to an average of somewhat more than 100 K--a temperature rise of 82 K--while the maximum surface temperature rise at 90 seconds was about 94 K. Note, the aforementioned temperature rises were calculated

using emissivity and transmittance values of 0.51 and 0.70. If values of 0.71 and 0.83 are used, the average and maximum surface temperature rises are 61 K and 71 K.

At the end of the experiment, the system was disassembled and both the ball and disk were examined using photomacrography and scanning electron microscopy. As shown in Fig. 108, the wear scar on the zirconia ball is macroscopically circular, but contains several irregular patches within the apparent contact region. Thus, one can consider this macroscopic or geometric wear area as a maximum (and improbable) area of contact. However, examination of Fig. 108 shows several regions (i.e., possibly 4-6 major areas) which appear to be separated, raised plateaus on the surface. These regions are approximately perpendicular to the direction of sliding. As a first approach, this subdivided contact region is approximated as five rectangles of equal size, thus producing a refined contact area assumption. These five rectangles are shown in Fig. 109. In addition, theoretical results using a single area based on plastic and elastic deformation are calculated.

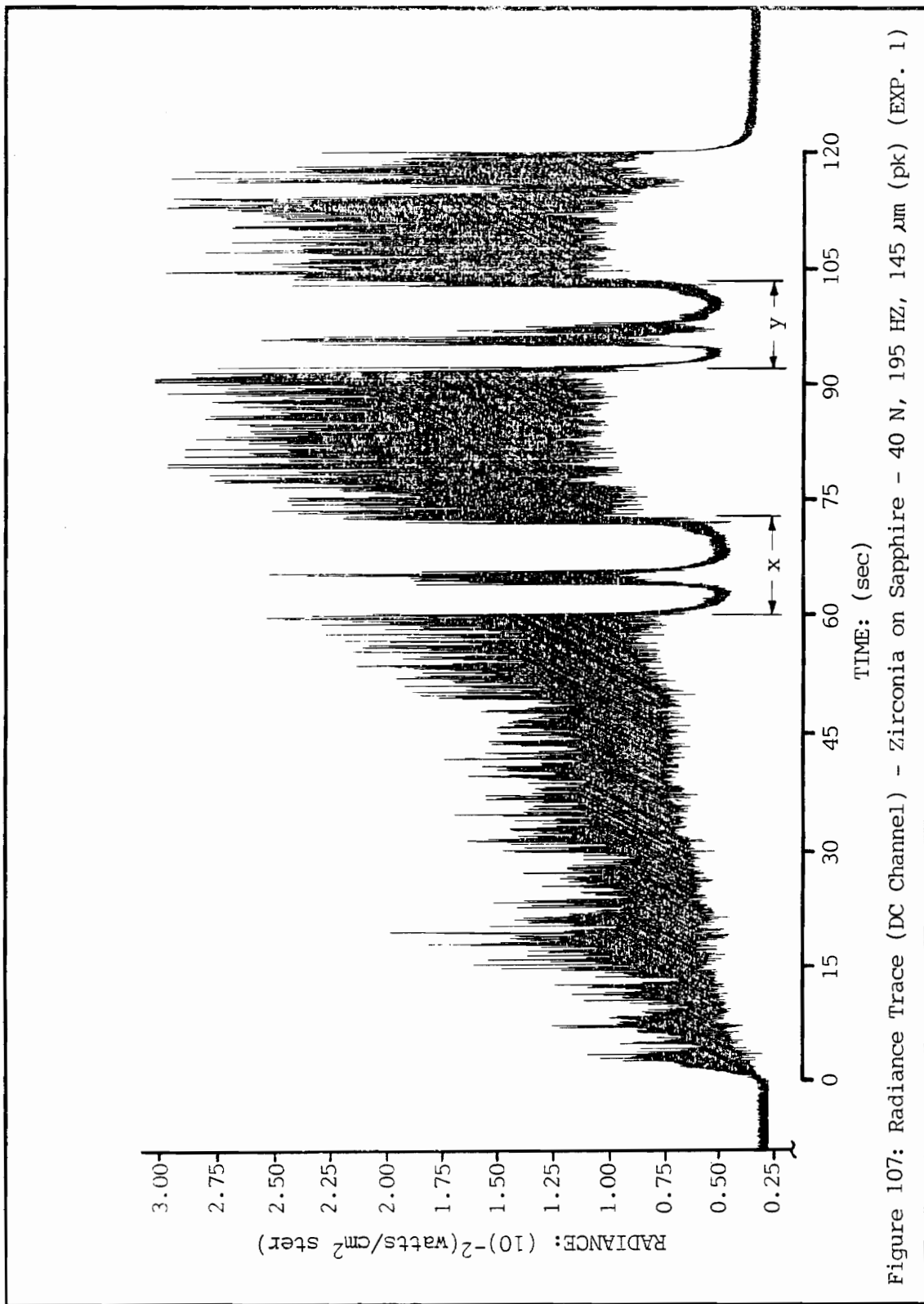
The long time or quasi steady-state theoretical predictions and the experimental measurements are summarized in Table 14. First of all, it can be seen that the use of a single area of contact produced by plastic deformation results in a theoretical prediction of over 800 K for an average surface temperature rise, while the corresponding experimental average values are 21-28 K (after 5 sec), and 61-82 K (after 90 sec). The use of a single area of contact governed by elastic deformation reduces the theoretical surface temperature rise to 280 K--still much greater than the experimental values.

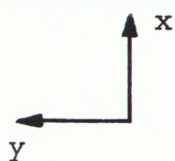
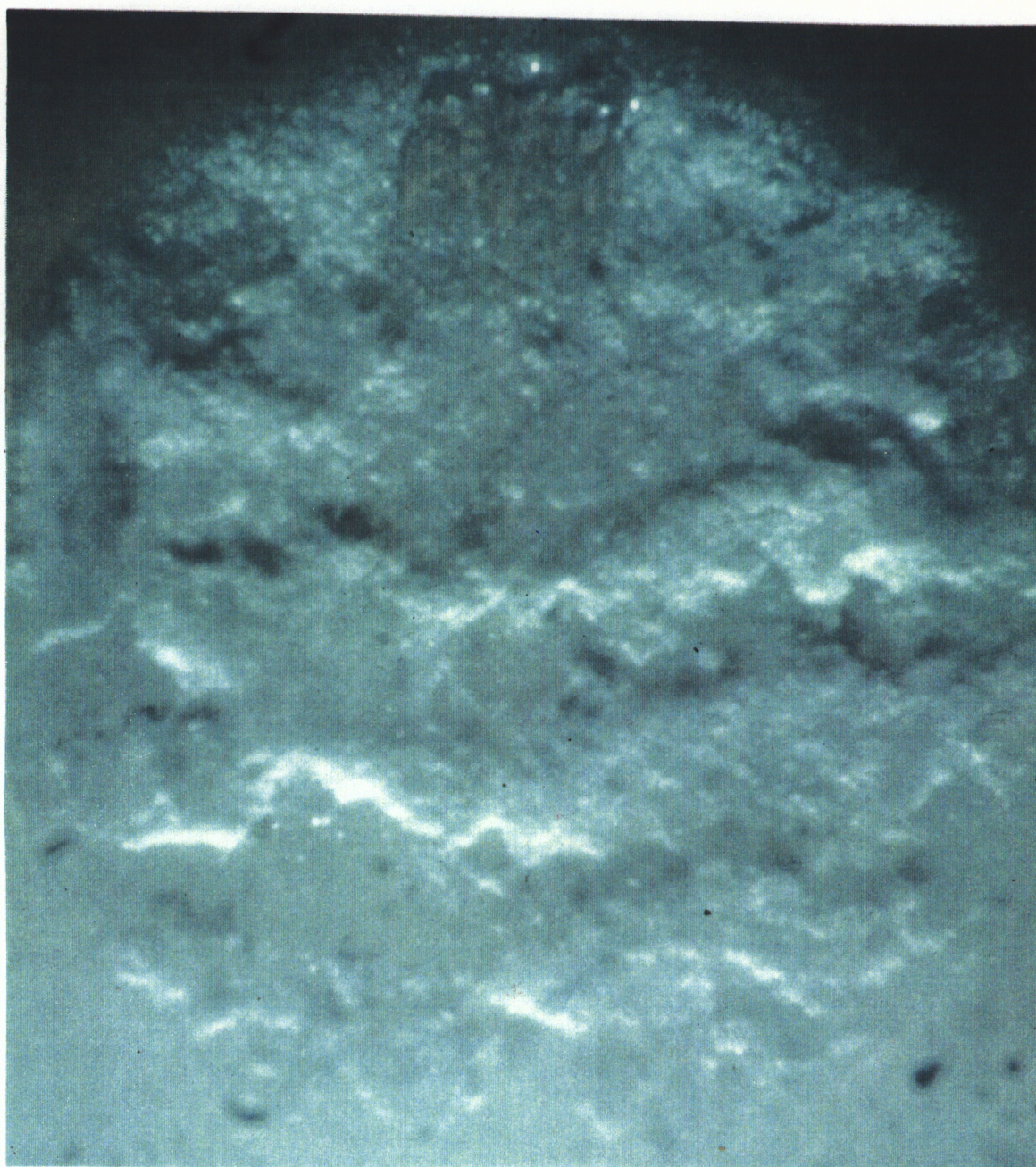
The assumption of the macroscopic area of contact results in a low theoretical prediction of average surface temperature rise (i.e., about 64 K). This compares well with the experimental value of 61 K. Recall that this experimental value was obtained assuming an emissivity and transmittance of 0.71 and 0.83. If values of 0.51 and 0.70 are used, the average experimental temperature rise is 82 K. This compares favorably with the theoretically determined average rise of 78 K that was calculated by using the divided contact area shown in Fig. 109. In addition, assuming the divided area, the theoretically determined maximum rise was 91 K, while the corresponding experimental value was 94 K. In summary, the experimental range is governed by the choice of emissivities and transmittances; while the theoretical range is governed by the choice of contact areas.

Table 14: Comparison of Theoretical and Experimental Results for a Zirconia-on-Sapphire Experiment

Input Parameters/Test Conditions after 5 sec: 40 N, 195 HZ, 136 μm (pk), Coef. of Fric = 0.86
Input Parameters/Test Conditions after 90 sec: 40 N, 195 HZ, 145 μm (pk), Coef. of Fric = 1.00

Area type	Total area (m ²)	THEORETICAL			EXPERIMENTAL				
		Vick and Foo, reference [9]		Archard, ref. [6]	Emissivity = 0.51 Transmittance = 0.70		Emissivity = 0.71 Transmittance = 0.83		Time (sec)
		ΔT_{ave} (K)	ΔT_{max} (K)	ΔT (K)	ΔT_{ave} (K)	Average ΔT_{max} (K)	ΔT_{ave} (K)	Average ΔT_{max} (K)	
Plastic Model	3.64(10) ⁻⁹	808	1190	598	28.1	33.1	21.4	25.6	5
Elastic Model	2.41(10) ⁻⁸	280	288	200					
Geometric Area	6.97(10) ⁻⁷	64.3	71.8	39.8	82.3	93.5	60.7	70.6	90
Divided Area 5-Contacts	3.16(10) ⁻⁷	77.7	90.7	64.9					





Major Diameter = 953 μm
Minor Diameter = 914 μm

Figure 108: Optical Macrograph of a Zirconia Wear Scar

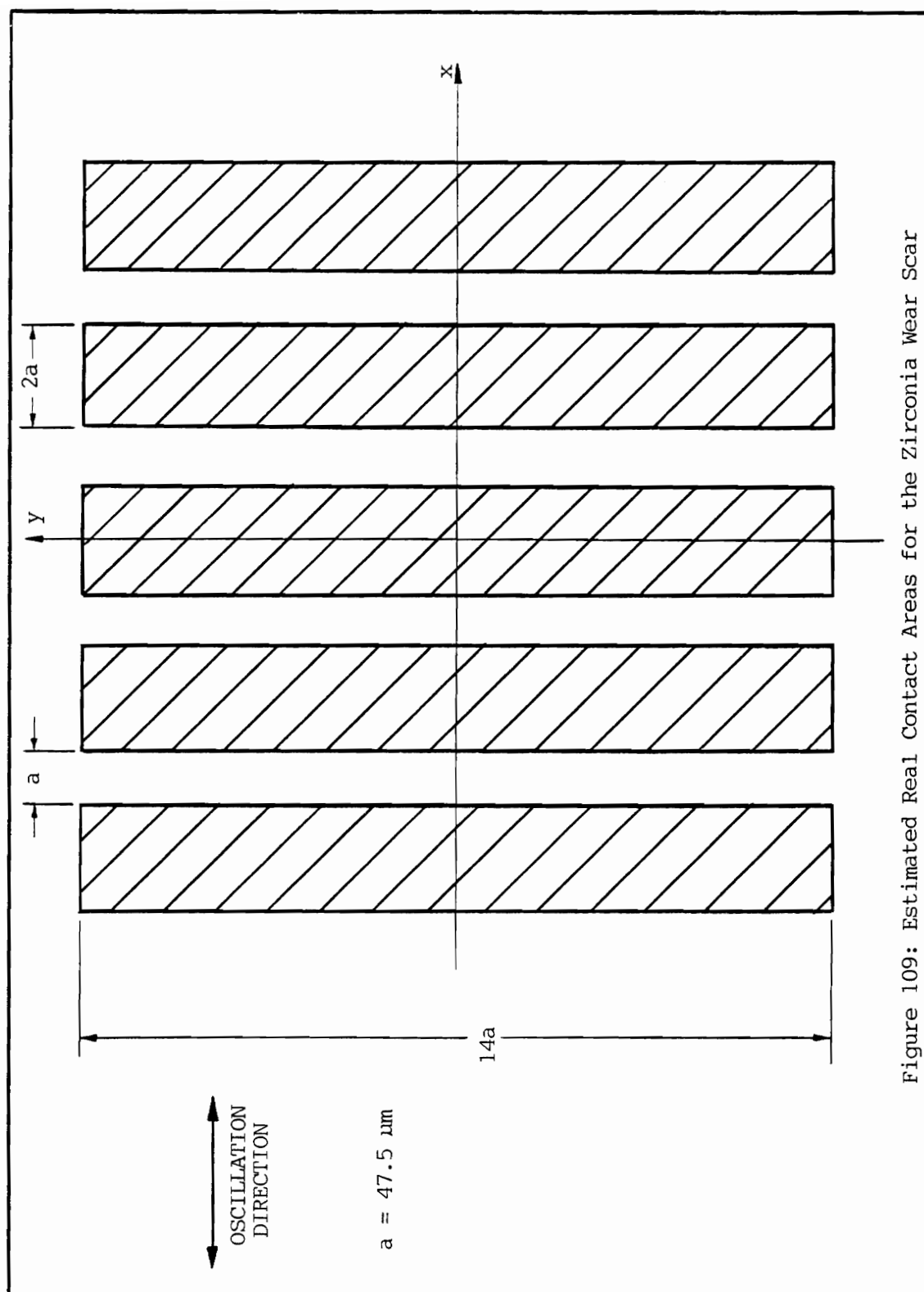


Figure 109: Estimated Real Contact Areas for the Zirconia Wear Scar

For this comparison, the experimental range of temperature rises falls within the theoretical range determined by assuming either a geometric or divided contact region. In short, the real area could be somewhere between the geometric and divided contact region.

It should be pointed out that this comparison was the first and only one made and not carefully selected or the "best" result of several. However, the reasonable assumption of a sub-divided contact region within the macroscopic wear area determined in this way produced remarkable agreement between theory and experiment.

5. CONCLUSIONS

1. An infrared microscope was successfully used to measure surface temperatures generated during oscillating/fretting contact.
2. Surface temperatures were measured for several ceramic-on-sapphire systems including zirconia-on-sapphire, alumina-on-sapphire, sapphire-on-sapphire, and tungsten carbide-on-sapphire.
3. Instantaneous fluctuations in surface temperatures over a single cycle have been measured and recorded.
4. An existing numerical technique for calculating surface temperatures from radiance data was modified [21]. This technique can now be used to expediently calculate instantaneous surface temperatures from radiance data.
5. A technique was developed for measuring instantaneous friction forces as a function of time. This technique incorporates the use of semiconductor strain gages mounted on an octagonal ring.

6. A numerical technique was developed for calculating instantaneous velocity data from the output of an accelerometer.
7. The predominant frequencies present in the temperature rise, friction, and acceleration signals were examined using Fourier transform techniques. The predominant frequency of the temperature signal proved to be twice the predominant frequency of the acceleration signal.
8. Phase differences between temperature rise, friction force, and velocity were measured using advanced signal processing techniques.
9. Instantaneous heat generation rates were effectively calculated by using instantaneous friction force and velocity data. Results proved that heat generation occurs at the same frequency as surface temperature.
10. Emissivities for the opaque ceramic test specimens were successfully measured. For the zirconia test specimen, the effect of wear on emissivity was not significant.
11. The high frequency, high amplitude zirconia-on-sapphire experiments performed using 20 N and 40 N loads, proved to have their own characteristic radiance traces. The radiance trace for the 20 N experiment had a constant base level with high peaks superimposed on the base. The radiance trace for the 40 N experiment had an increasing average radiance level with high peak-to-peak variations in radiance.
12. Normal load proved to be an important factor in surface temperature generation during fretting. Almost all the experiments performed using a normal load of 40 N had higher average surface temperatures than those performed at 20 N.
13. For the high amplitude zirconia-on-sapphire experiments, higher temperatures were generated at a 195 Hz oscillation frequency than at a 100 Hz frequency. For the low amplitude experiments, this trend was not observed.

14. Friction coefficients in the low frequency experiments were smaller than those at high frequencies.
15. For the zirconia-on-sapphire experiments, an increasing nonlinear trend was observed when temperature rise was plotted as a function of the frictional heat generation rate.
16. For zirconia-on-sapphire experiments, high temperature rises corresponded with large amounts of wear, while low temperature rises corresponded with small amounts of wear.
17. Sapphire-on-sapphire produced the highest temperature rise, 138 K, at a heat generation rate of 5.2 watts. Tungsten carbide-on-sapphire produced the lowest temperature rise, 18 K, at a heat generation rate of 0.8 watts.
18. Instantaneous temperature rises as high as 112 K were measured for zirconia-on-sapphire at a heat generation rate of 7.1 watts. Furthermore, variations in surface temperature as large as 50 K occurred in less than two thousandths of a second.
19. By using the infrared microscope in a scanning mode, surface temperatures were measured as a function of position in the contact region. By coupling the scanning results with scanning electron micrographs, inferences were made about the size, location, and distribution of real contact areas.
20. Experimental surface temperature measurements agreed well with theoretical predictions submitted by B. Vick and S. J. Foo [9,13]. As described below, the theoretical model used four contact area assumptions:
 - an elastic contact area.
 - a plastic contact area.

- a geometric contact area based on the diameter of the wear scar after an experiment.
- a subdivided contact area based on an optical macrograph of the test specimen's surface.

The experimental surface temperatures were determined using two emissivity and transmittance assumptions. These assumptions were based on measurements made before and after an experiment.

6. RECOMMENDATIONS

1. As a refinement to the present technique of emissivity measurement, a blackbody could be made in the test specimen by drilling a small hole at the surface of the material. This technique is described in references [92] and [93], and could provide a more exact blackbody reference source than the current source formed using black paint.
2. As discussed in Section 3, the infrared microscope has three modes of operation: DC, AC/DC, and AC. The DC and AC/DC modes of operation were used successfully in this research to measure surface temperatures. However, output from the AC mode of operation proved to be difficult to interpret. Since this mode has the highest frequency response of 20 kHz, future studies should examine ways to interpret data from the AC mode of operation.
3. Although the FM tape recorder was used effectively in this research to monitor seven different data sources, each of the channels has to be calibrated, and a 20 mv peak-to-peak noise band has to be counteracted using proper amplification levels. Furthermore, the usable voltage range of the tape recorder is only -1.4 to 1.4 volts. Because of these problems, alternatives to this data recording device should be examined.

4. To facilitate accurate comparisons with theoretical predictions, scanning techniques should continue to be utilized to determine the size, location, and distribution of real contact areas.
5. As discussed in Section 4.1.5, the emissivity of the sapphire **sphere** had to be calculated using transmittance values for the sapphire **disk**. A fundamental assumption for the use of this calculated emissivity value is the following: the surface reflectivity must be zero at the sapphire-sapphire interface. This is a viable assumption at the initiation of the experiment; however the surfaces become more opaque as they wear yielding a surface reflectivity that probably is not zero. Furthermore, since the sapphire ball is contained in a spherically-shaped holder, some of the energy generated at the sapphire-sapphire interface might be transmitted through the ball, reflected off the holder's interior, and retransmitted back through the interface towards the infrared microscope. Therefore, if sapphire-on-sapphire is used in future studies, a ray tracing analysis such as the ones shown in Figs. 19 and 20 should be performed, and the spherical interior of the specimen holder should be included in th analysis.
6. As an addition to the experimental system, an infrared camera might provide "real-time" information about the size, location, and distribution of real contact areas. Although this camera would probably not have the microscopic target spot sizes characteristic of the Barnes infrared microscope, it would provide a simultaneous record of all the "hot spots" that occur within the geometric contact region.
7. Throughout this research, amplifiers were used to increase the signal-to-noise ratio for the friction and radiance signals. Although these amplifiers functioned adequately throughout the research, they are 20 - 25 years old and are due to be replaced. Small, integrated operational amplifiers could provide an inexpensive, viable alternative.
8. Although the accelerometer proved to be an effective tool for measuring the velocity and amplitude of motion, it cannot be used to **directly** display amplitude as a function of time. A direct measurement of amplitude as a function of time is required to correctly set the shaker's

vibration amplitude between experiments. An existing LVDT was used to attempt measuring amplitude as a function of time. However, this device is over twenty years old, and produced a great deal of electronic noise that was greater than the actual amplitude signal! Therefore, a new LVDT should be purchased to allow for the direct measurement of amplitude as a function of time.

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Appendix A. Calibration of the Infrared Microscope

The infrared microscope is calibrated using a heated blackbody source and control unit shown in Fig. A1. The following procedure is used for this calibration.

1. The infrared microscope is turned-on and allowed to warm-up for approximately thirty minutes.
2. The settings on the microscope's control unit are positioned as follows:
 - emissivity dial at 1.0
 - ambient dial - OFF
 - HI impedance
 - LOX objective - (15X)
 - wide bandwidth
 - radiance scale - (X1)
3. Output from both the AC/DC and DC channels is monitored using digital multimeters.
4. The microscope is focused on the center of the blackbody source.

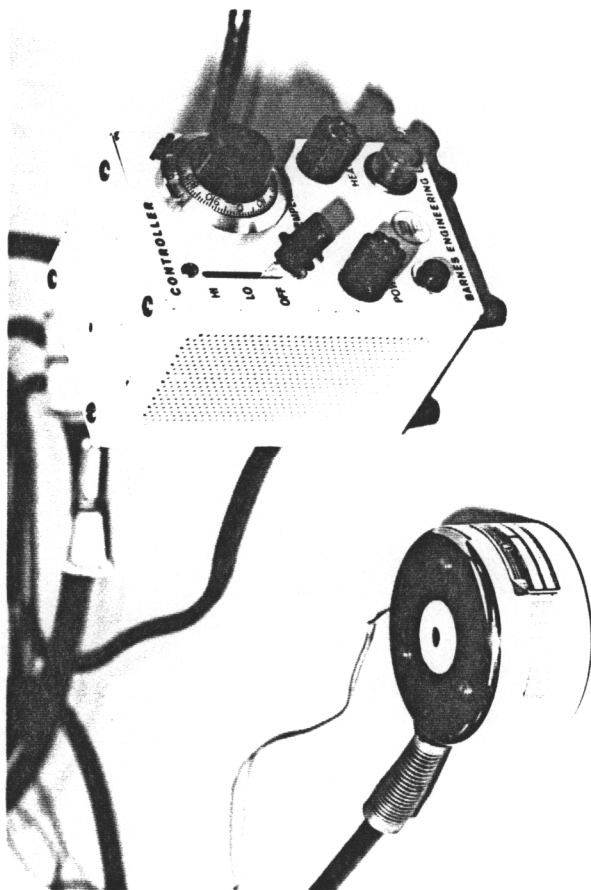


Figure A1: Blackbody Calibration Source and Control Unit

5. With the blackbody source at ambient temperature, the output from the microscope is zeroed as required using the zero-set knob on the control unit.
6. When the calibration source is heated to a different temperature, the microscope is positioned away from the source.
7. When the equilibrium temperature is reached (after approximately 10 minutes), the microscope is positioned over the blackbody source and voltage output from the AC/DC and DC channels is recorded.
8. Step's 6 and 7 are repeated for each of the desired temperature levels.

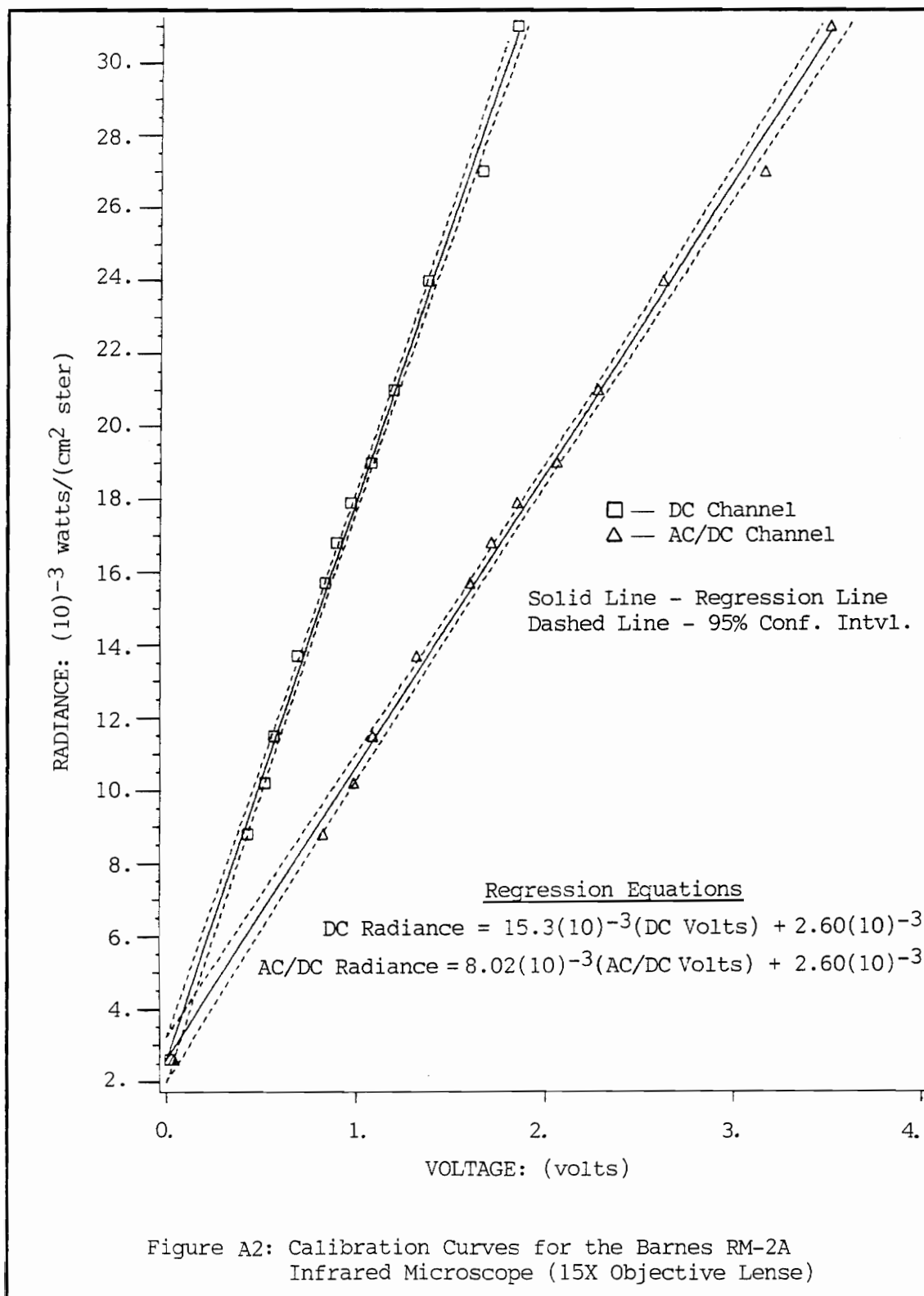
Calibration data recorded in accordance with the procedure above are shown in Tables A-1 and A-2. The resulting regression equations and standard deviations are shown below each of the two tables. Since the data in Table A-1 shows the lower standard deviation, the regression equations for this data are used to predict radiance from voltage output. Figure A2 shows the resulting calibration curves for the data in Table A-1. Ninety-five percent confidence intervals are represented in this figure as dashed lines.

Table A-1: Calibration of the Infrared Microscope AC/DC and DC Channels
(DATA SET NO. 1)

Temperature of Blackbody Deg. C	Radiance from Blackbody (10) ⁻² W/(cm ² sr)	Voltage Output from AC/DC Channel Volts	Voltage Output from DC Channel Volts
17.3	0.26	0.040	0.021
53.9	0.88	0.829	0.435
58.6	1.02	0.990	0.523
63.5	1.15	1.090	0.572
68.5	1.37	1.321	0.694
73.8	1.57	1.604	0.843
75.8	1.68	1.719	0.901
78.0	1.79	1.854	0.973
81.8	1.90	2.065	1.083
85.0	2.10	2.279	1.197
90.8	2.40	2.627	1.379
98.4	2.70	3.174	1.667
102.4	3.10	3.520	1.846
DC Radiance = $15.3(10)^{-3}(\text{DC Volts}) + 2.60(10)^{-3}$ Standard Deviation = $0.473(10)^{-3} \text{ W}/(\text{cm}^2 \text{ sr})$ 95% Confidence Interval = $\pm 0.59(10)^{-3} \text{ W}/(\text{cm}^2 \text{ sr})$ (max)			
AC/DC Radiance = $8.02(10)^{-3}(\text{AC/DC Volts}) + 2.60(10)^{-3}$ Standard Deviation = $0.466(10)^{-3} \text{ W}/(\text{cm}^2 \text{ sr})$ 95% Confidence Interval = $\pm 0.57(10)^{-3} \text{ W}/(\text{cm}^2 \text{ sr})$ (max)			

Table A-2: Calibration of the Infrared Microscope AC/DC and DC Channels
(DATA SET NO. 2)

Temperature of Blackbody Deg. C	Radiance from Blackbody (10) ⁻² W/(cm ² sr)	Voltage Output from AC/DC Channel Volts	Voltage Output from DC Channel Volts
57.5	0.98	0.811	0.420
70.4	1.40	1.364	0.764
87.9	2.17	2.460	1.294
93.0	2.44	2.980	1.567
106.1	3.28	3.600	1.894
112.7	3.77	4.223	2.221
119.1	4.30	4.865	2.558
119.5	4.35	5.510	2.900
125.7	4.93	6.140	3.230
133.3	5.71	6.755	3.550
DC Radiance = $14.8(10)^{-3}(\text{DC Volts}) + 3.11(10)^{-3}$ Standard Deviation = $1.779(10)^{-3} \text{ W}/(\text{cm}^2 \text{ sr})$ 95% Confidence Interval = $\pm 2.6(10)^{-3} \text{ W}/(\text{cm}^2 \text{ sr})$ (max)			
AC/DC Radiance = $7.75(10)^{-3}(\text{AC/DC Volts}) + 3.32(10)^{-3}$ Standard Deviation = $1.758(10)^{-3} \text{ W}/(\text{cm}^2 \text{ sr})$ 95% Confidence Interval = $\pm 2.5(10)^{-3} \text{ W}/(\text{cm}^2 \text{ sr})$ (max)			



Appendix B. Calibration of the Strain Ring

B.1 Calibration of the Tangential Channel

The tangential channel of the strain ring is used to measure frictional forces as described in Section 3.6. To calibrate this channel, the strain ring is incorporated into the test apparatus depicted in Fig. B1. As shown in this figure, known loads are imposed on the ring using a load arm and miniature cable pulley. Voltage output from the tangential channel is monitored on a multimeter when these loads are imposed. As a result, regression techniques can be used to obtain calibration equations.

Three data sets were obtained for the tangential channel as shown in Tables B-1 through B-3. Calibration equations, standard deviations, and 95% confidence intervals are shown below each table. The first two tables show data obtained at an ambient temperature of 72 F and the third table shows data obtained at an ambient temperature of 80 F. Different ambient temperatures were used because output from the strain gages changes significantly with room temperature. This is a common characteristic of semiconductor strain gages and is described in reference [90]. The calibration curves shown in Fig. B2 depict this effect of ambient temperature. For instance, at 80 F the slope of the regression line is 1.53 N/mv. At 72 F, the slope is 0.914 N/mv.

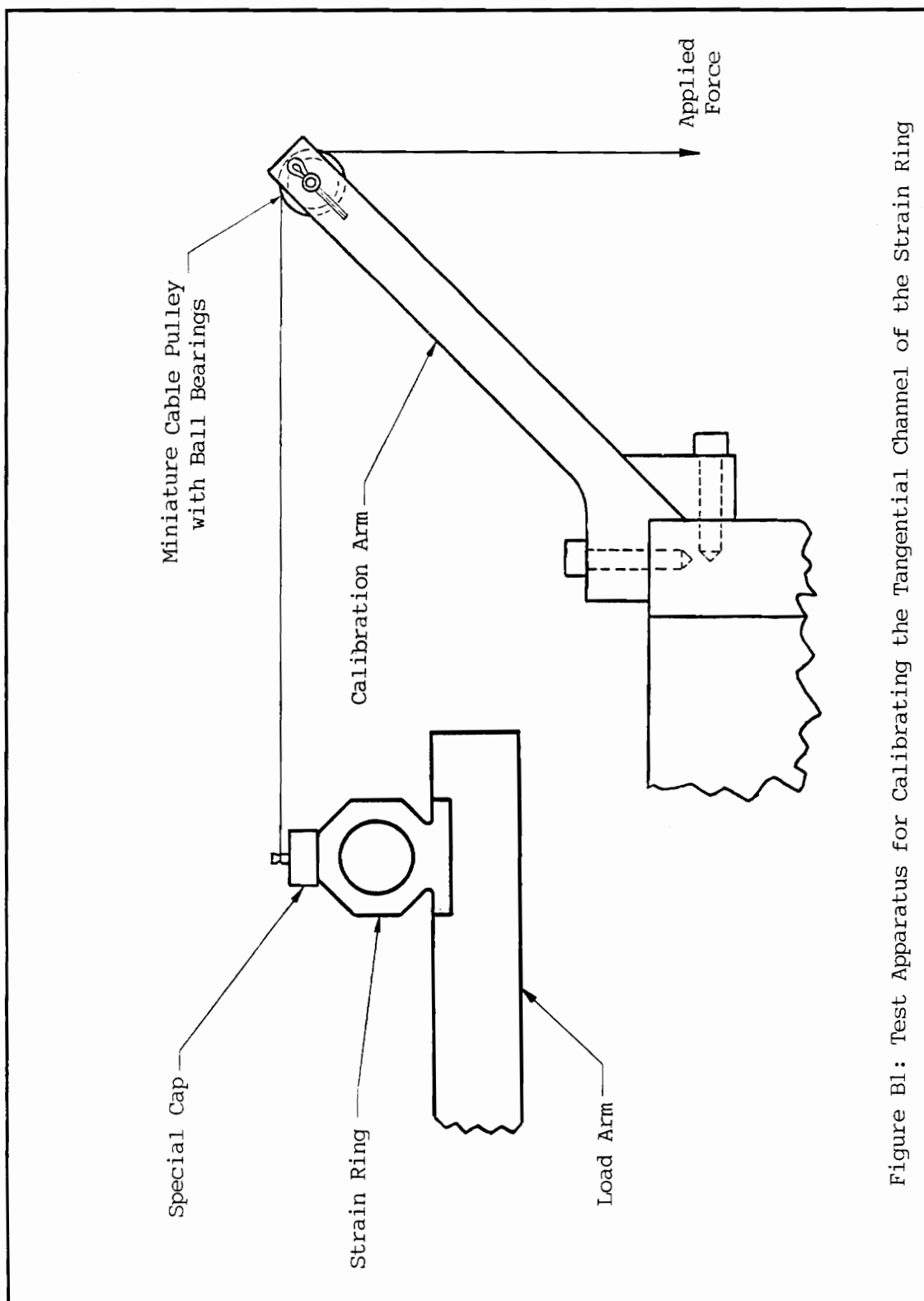


Figure B1: Test Apparatus for Calibrating the Tangential Channel of the Strain Ring

Table B-1: Calibration Data for the Tangential Channel of the Strain Ring (Data Set No. 1) Ambient Temperature = 71.5 F (22.0 C)	
TANGENTIAL FORCE (N)	TANGENTIAL CHANNEL (millivolts)
0.00	0.0
2.34	2.2
4.31	4.4
6.27	7.0
8.23	8.5
10.56	10.9
12.52	13.4
14.44	15.0
16.41	17.6
18.55	18.2
19.81	21.8
21.77	22.7
23.92	25.0
25.84	27.1
28.79	31.4
30.75	33.7
32.67	34.7
34.63	37.7
36.78	42.8
39.72	45.6
Tangential Force = 0.914(millivolts) Standard Deviation = 0.994 N 95% Confidence Interval = ± 0.77 N (max)	

Table B-2: Calibration Data for the Tangential Channel of the Strain Ring (Data Set No. 2) Ambient Temperature = 71.5 F (22.0 C)	
TANGENTIAL FORCE (N)	TANGENTIAL CHANNEL (millivolts)
0.00	0.0
2.34	2.6
4.31	4.5
6.27	6.9
8.23	8.3
10.56	11.3
12.52	14.3
14.44	14.8
16.41	17.3
18.55	19.2
19.81	21.3
21.77	22.8
23.92	24.7
25.84	29.6
28.79	30.6
30.75	32.2
32.67	35.5
34.63	36.7
36.78	39.2
39.72	45.2
Tangential Force = 0.927(millivolts) Standard Deviation = 0.810 N 95% Confidence Interval = ± 0.62 N (max)	

Table B-3: Calibration Data for the Tangential Channel of the Strain Ring (Data Set No. 3) Ambient Temperature = 79.7 F (26.5 C)	
TANGENTIAL FORCE (N)	TANGENTIAL CHANNEL (millivolts)
0.00	0.0
2.34	1.7
4.31	2.8
6.27	4.4
8.23	5.3
10.56	7.0
12.52	7.5
14.44	9.3
16.41	10.2
18.55	11.4
19.81	11.8
21.77	12.8
23.92	14.4
25.84	15.8
28.79	18.0
30.75	20.0
32.67	21.9
34.63	23.0
36.78	25.5
40.00	28.0
Tangential Force = 1.53(millivolts) Standard Deviation = 1.32 N 95% Confidence Interval = ± 1.0 N (max)	

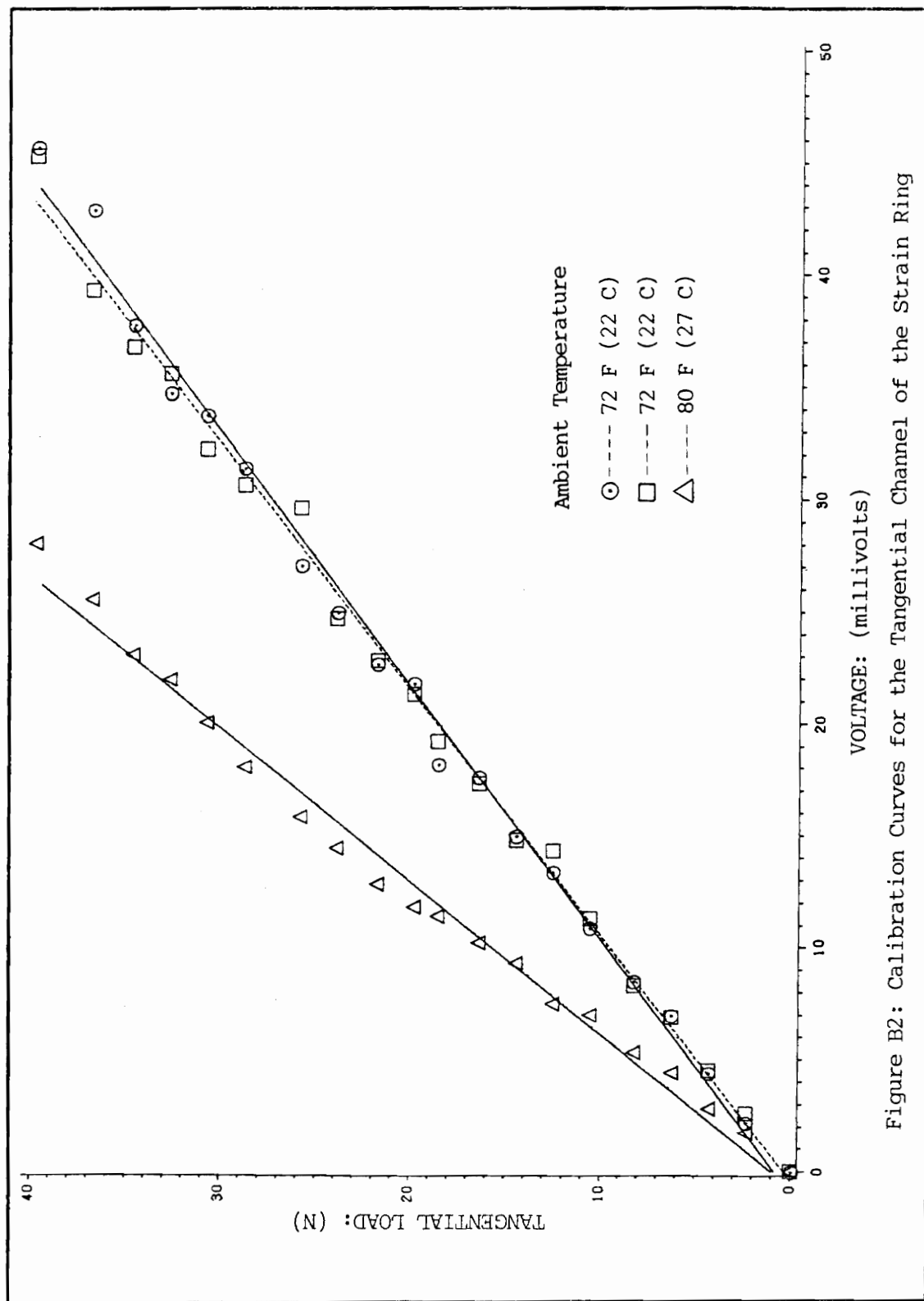


Figure B2: Calibration Curves for the Tangential Channel of the Strain Ring

The inverse of these slopes is 0.653 mv/N at 80 F and 1.10 mv/N at 72 F. Therefore, voltage output from the strain ring at 72 F is approximately 1.7 times higher than the voltage output at 80 F. Due to this fact, all experiments were performed at an ambient temperature of 72 F.

To ensure that the tangential channel of the strain ring is indeed producing accurate results, the calibration procedure was performed twice at 72 F. Therefore, two regression lines are shown in Fig. B2 for the 72 F test case. Since the slopes of these regression lines are nearly identical, one can conclude that the tangential channel of the strain ring is indeed producing accurate results. The standard deviations for the 72 F calibrations are 0.99 N and 0.81 N. Furthermore, 95% confidence intervals for the 72 F calibration equations are ± 0.33 N and ± 0.31 N. Because the data in Table B-2 has the lowest standard deviation and confidence interval, the calibration equation shown below this table was used to calculate friction forces.

B.2 Calibration of the Normal Channel

Although output from the normal channel of the strain ring is not particularly pertinent to this study, this channel was calibrated as described below. To calibrate the normal channel, the usual experimental test apparatus is set-up as shown in Figs. 4 and 5. Then, normal loads are imposed on the ring using the long load arm shown in these figures. Data obtained in this manner are shown in Table B-4 along with the resulting calibration equation, standard deviation, and 95% confidence interval.

B.3 Separation of the Normal and Tangential Channels

An important design characteristic of the strain ring is the separation of normal and tangential channels. In other words, when a tangential force is applied to the ring, the electrical output from

Table B-4: Calibration Data for the Normal Channel of the Strain Ring Ambient Temperature = 72.0 F (22.2 C)	
NORMAL LOAD (N)	NORMAL CHANNEL (millivolts)
0.00	0.0
2.34	0.9
4.31	1.7
6.27	2.7
8.23	3.4
10.56	4.3
12.52	5.7
14.44	6.1
16.41	7.5
18.55	8.1
19.81	8.9
21.77	9.4
23.92	10.9
25.84	11.5
28.79	12.5
30.75	13.3
32.67	13.9
34.63	14.4
36.78	16.0
40.00	18.0
Normal Load = 2.29(millivolts) Standard Deviation = 0.682 N 95% Confidence Interval = ± 0.58 N (max)	

the normal channel should be zero. The converse relationship should also be true. When a normal force is applied to the ring, electrical output from the tangential channel should be zero. Since separation of channels is an **ideal** characteristic of strain rings, it is important to know the **real** effect of one channel on the other. This important aspect of the strain ring is discussed in detail in Section 3.6.

Appendix C. X-Y Table Calibration

As shown in Fig. C1, the infrared microscope is mounted on an x-y table to facilitate measuring radiance and surface temperature as a function of position. The position of the microscope can be obtained using vernier-type micrometers, or linear variable differential transformers (LVDT's) mounted on the table. There are two LVDT's mounted on the table: one for measuring the x-position, and one for measuring the y-position. The coordinate axes are defined in Fig. 37. To calibrate the LVDT's, the vernier micrometers are used to measure the position of the microscope and the resulting voltage output from the LVDT's is monitored using a multimeter. This data is shown in Tables C-1 and C-2. Calibration equations are also listed in these tables for each direction.

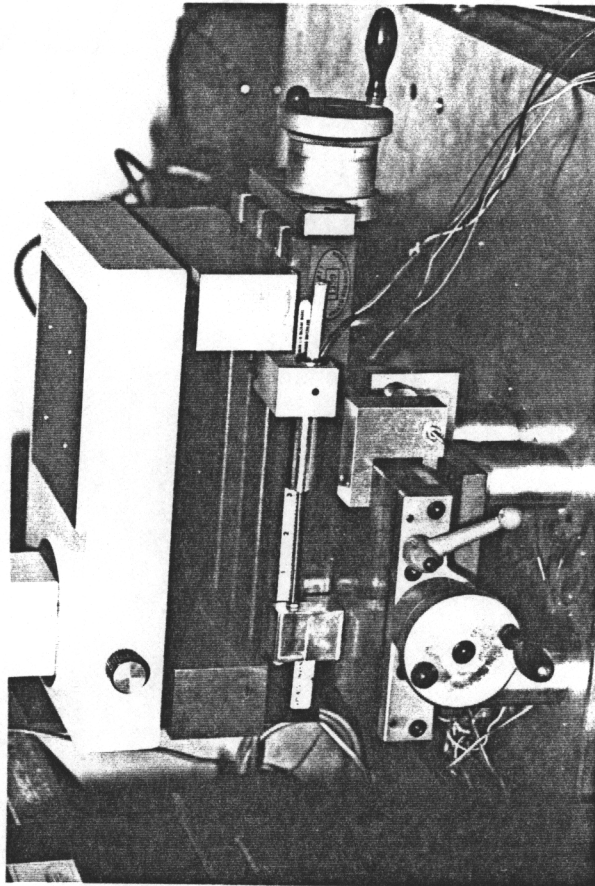


Figure C1: The X-Y Table

Table C-1: Calibration Data for the X-Position LVDT			
Voltage Input to LVDT = 20.0 volts			
X-POSITION (POSITIVE) (micrometers)	LVDT OUTPUT (millivolts)	X-POSITION (NEGATIVE) (micrometers)	LVDT OUTPUT (millivolts)
0.0	0.1	0.0	0.0
25.4	31.3	- 25.4	- 29.5
50.8	58.7	- 50.8	- 61.9
76.2	89.1	- 76.2	- 89.9
101.6	118.8	-101.6	-121.7
127.0	149.3	-127.0	-154.5
152.4	182.7	-152.4	-187.6
177.8	216.5	-177.8	-216.6
203.2	243.9	-203.2	-248.7
228.6	274.9	-228.6	-280.5
254.0	310.9	-254.0	-313.3
279.4	336.6	-179.4	-347.1
304.8	369.1	-304.8	-374.0
330.2	406.0	-330.2	-408.9
355.6	431.5	-355.6	-445.1
381.0	463.9	-381.0	-471.8
406.4	495.9	-406.4	-501.2
431.8	524.7	-431.8	-533.1
457.2	555.2	-457.2	-564.1
482.6	591.3	-482.6	-600.3
508.0	621.7	-508.0	-626.9
533.4	655.2	-533.4	-660.9
558.8	682.1	-558.8	-690.5
584.2	713.7	-584.2	-724.3
609.6	744.9	-609.6	-753.1
635.0	779.3	-635.0	-788.8
$X_p = 0.814(\text{millivolts}) + 3.13$ $(X_p = \text{positive x-position in micrometers})$ $\text{Standard Deviation} = 1.92 \text{ } \mu\text{m}$ $95\% \text{ Confidence Interval} = \pm 1.9 \text{ } \mu\text{m (max)}$			
$X_N = 0.804(\text{millivolts}) + 2.09$ $(X_N = \text{negative x-position in micrometers})$ $\text{Standard Deviation} = 1.64 \text{ } \mu\text{m}$ $95\% \text{ Confidence Interval} = \pm 1.6 \text{ } \mu\text{m (max)}$			

Table C-2: Calibration Data for the Y-Position LVDT

Voltage Input to LVDT = 20.0 volts

Y-POSITION (POSITIVE) (micrometers)	LVDT OUTPUT (millivolts)	Y-POSITION (NEGATIVE) (micrometers)	LVDT OUTPUT (millivolts)
0.0	0.0	0.0	0.0
25.4	32.5	- 25.4	- 32.2
50.8	66.6	- 50.8	- 67.2
76.2	103.9	- 76.2	-105.5
101.6	142.0	-101.6	-142.7
127.0	178.4	-127.0	-176.9
152.4	218.2	-152.4	-212.8
177.8	254.4	-177.8	-247.9
203.2	288.8	-203.2	-289.2
228.6	329.7	-228.6	-320.5
254.0	366.6	-254.0	-356.3
279.4	402.2	-279.4	-391.0
304.8	438.0	-304.8	-428.0
330.2	475.6	-330.2	-464.1
355.6	516.0	-355.6	-498.4
381.0	550.4	-381.0	-535.0
406.4	589.1	-406.4	-571.4
431.8	631.5	-431.8	-609.0
457.2	661.9	-457.2	-646.0
482.6	702.2	-482.6	-685.9
508.0	738.0	-508.0	-715.4
533.4	773.0	-533.4	-754.0
558.8	810.5	-558.8	-790.1
584.2	847.9	-584.2	-824.2
609.6	884.6	-609.6	-859.6
635.0	922.1	-635.0	-896.5

$$Y_P = 0.684(\text{millivolts}) + 3.70$$

(Y_P = positive y-position in micrometers)

Standard Deviation = 1.46 μm

95% Confidence Interval = $\pm 1.1 \mu\text{m}$ (max)

$$Y_N = 0.706(\text{millivolts}) + 1.99$$

(Y_N = negative y-position in micrometers)

Standard Deviation = 1.34 μm

95% Confidence Interval = $\pm 1.1 \mu\text{m}$ (max)

Appendix D. Fourier Transform Techniques

D.1 The Fast Fourier Transform (FFT)

The purpose of this appendix is to describe Fourier transform techniques used to analyze data in the frequency domain. A summary of digital integration methods is also presented.

A finite range Fourier transform of a real-valued or complex-valued record $x(t)$ is defined by the complex-valued quantity shown below [95]:

$$X(f,T) = \int_0^T x(t)e^{-j(2\pi f)t} dt \quad (D.1)$$

where,

$X(f,T)$ = fast Fourier transform of the data record $x(t)$

j = the square root of negative one

f = frequency in Hz

T = length of data record in seconds

By using Euler's relationship, Eq. D.1 can be written in terms of periodic functions. Euler's equation is shown below:

$$e^{-j\omega t} = \cos(\omega t) - j\sin(\omega t) \quad (D.2)$$

Substituting Eq. D.2 into Eq. D.1 yields the following:

$$X(f,T) = \int_0^T x(t)[\cos(\omega t) - j\sin(\omega t)]dt \quad (D.3)$$

where,

$$\omega = \text{radial frequency (rads/sec)} = 2\pi f$$

Equation D.3 shows that $X(f,T)$ actually expresses the periodic components of the real-time data record $x(t)$.

If $x(t)$ is sampled at N equally spaced points a distance Δt apart, then the sampling times $t_n = n\Delta t$ can be utilized in the following expression:

$$x_n = x(t_n) = x(n\Delta t); \quad n = 0, 1, 2, 3, \dots, N-1 \quad (D.4)$$

This relationship can be used to write the discrete version of Eq. (D.1) shown below:

$$X(f,T) = \Delta t \sum_{n=0}^{N-1} x_n e^{-j(2\pi f)n\Delta t} \quad (D.5)$$

$X(f,T)$ is calculated by selecting discrete frequency values in accordance with the following equation:

$$f_k = \frac{k}{N\Delta t}; \quad k = 0, 1, 2, 3, \dots, N-1 \quad (D.6)$$

At these frequencies, the Fourier transform can be written as follows:

$$X(f_k) = \Delta t \sum_{n=0}^{N-1} x_n \exp \left[-j \frac{2\pi kn}{N} \right]; \quad k = 0, 1, 2, 3, \dots, N-1 \quad (D.7)$$

The results using this discrete Fourier transform are unique only out to $k = N/2$ since the Nyquist frequency occurs at this point [95]. Therefore, if $N = 2048$ data points are sampled, only the first 1024 data points will yield unique, pertinent information.

To calculate $X(f_k)$, Eq. D.7 has been incorporated into a FORTRAN subroutine in accordance with the algorithm specified in reference [95]. This subroutine is shown in Section D.5 and can be used to obtain the real and imaginary components of $X(f_k)$ as shown below:

$$X(f_k) = R(f_k) + jI(f_k) \quad (D.8)$$

where,

$R(f_k)$ = real component

$I(f_k)$ = imaginary component

By using this subroutine, data sampled as a function of time can be transformed into the frequency domain for further analysis.

D.2 The Autospectral Density Function

To determine the predominant frequencies contained within a signal, the fast Fourier transform of the data is obtained and the autospectral density is determined. This technique not only

describes the frequency content of a signal, but also describes the magnitude of the signal at each discrete frequency.

As derived in Section D.1, the fast Fourier transform, $X(f_k)$, of a real-time data record, $x(t)$, can be obtained using the subroutine shown in Section D.5. This function $X(f_k)$ has real and imaginary components as shown in Eq. D.8. Therefore, the magnitude of $X(f_k)$ can be obtained as shown below:

$$|X(f_k)| = \sqrt{R(f_k)^2 + I(f_k)^2} \quad (D.9)$$

When N samples of the signal $x(t)$ are taken at a time interval Δt , the resolution can be defined as shown below:

$$\text{Resolution (in Hz)} = \frac{1}{N\Delta t} = \frac{\text{samples/sec}}{\text{samples}} \quad (D.10)$$

(Note, $1/\Delta t$ is defined as the sampling rate in samples/second.)

The resolution of a sampling procedure expresses the smallest possible frequency that will be obtained when a Fourier transform of $x(t)$ is calculated. Furthermore, the resolution expresses the frequency interval Δf for the transformed data record, $X(f_k)$. This is analogous to a time interval Δt for a real-time data record, $x(t)$.

To calculate an estimate of the autospectral density function, $G_{xx}(f_k)$ the square of the magnitude of $X(f_k)$ is calculated and divided by the resolution. This relationship is shown below:

$$\begin{aligned} \hat{G}_{xx}(f_k) &= \frac{[2|X(f_k)|]^2}{(\text{Resolution})} = \frac{[2|X(f_k)|]^2}{(1/N\Delta t)} \\ \hat{G}_{xx}(f_k) &= N\Delta t[2|X(f_k)|]^2 \end{aligned} \quad (D.11)$$

where,

$G_{xx}(f_k)$ = the autospectral density of a signal $x(t)$

A factor of two is present in the numerator because only half the original data set is used due to the Nyquist cut-off frequency [95]. Note that $\hat{G}_{xx}(f_k)$ is really an estimate of the true autospectral density, $G_{xx}(f_k)$, because the data used in the procedure above is discrete rather than continuous.

To facilitate understanding the autospectral density function, Fig. D1 is presented. This figure shows the autospectral density of a digitally created sinusoidal signal written below. This signal represents the acceleration of a sapphire disk at 226 m/s². The frequency of oscillation is 195.3 Hz.

$$a(t) = 226\sin(2\pi(195.3)t) \quad (D.12)$$

The magnitude of the autospectral density in Fig. D1 is in units of (m/s²)²/Hz. The single spike shown in this figure occurs at the oscillation frequency 195.3 Hz and has a magnitude of 2.613(10)⁴ (m/s²)²/Hz. To determine the peak magnitude of the input signal at 195.3 Hz, the autospectral density must be converted to m/s². This is done by simply multiplying 2.613(10)⁴ by the resolution in Hz and taking the square root:

$$\sqrt{2.613(10)^4 \frac{(\text{m/s}^2)^2}{\text{Hz}} \frac{(4000 \text{ samples/sec})}{(2048 \text{ samples})}} = 226 \text{ m/s}^2(\text{pk}) @ 195.3 \text{ Hz} \quad (D.13)$$

Therefore, the magnitude of the spike at 195.3 Hz corresponds to the peak acceleration of the input signal.

Although the example above is very simplistic, it illustrates how autospectral density functions are used to analyze signals. If more than one frequency was contained in the input signal, a multitude of spikes would occur at each discrete frequency contained within the signal. Also, the magnitude of these spikes would correspond to the magnitude of the signal at each discrete frequency.

Since Eq. D.12 represents an acceleration signal, Fig. D1 can also be used to illustrate how velocity and amplitude can be calculated using autospectral density functions. As shown in Eq. D.13, the magnitude of the autospectral density at 195.3 Hz corresponds to a peak acceleration of 226 m/s². Since the peak acceleration is actually $\omega^2 A$, the quantity 226 m/s² can be divided by ω to obtain the peak velocity $\omega A = 184 \text{ mm/sec}$.

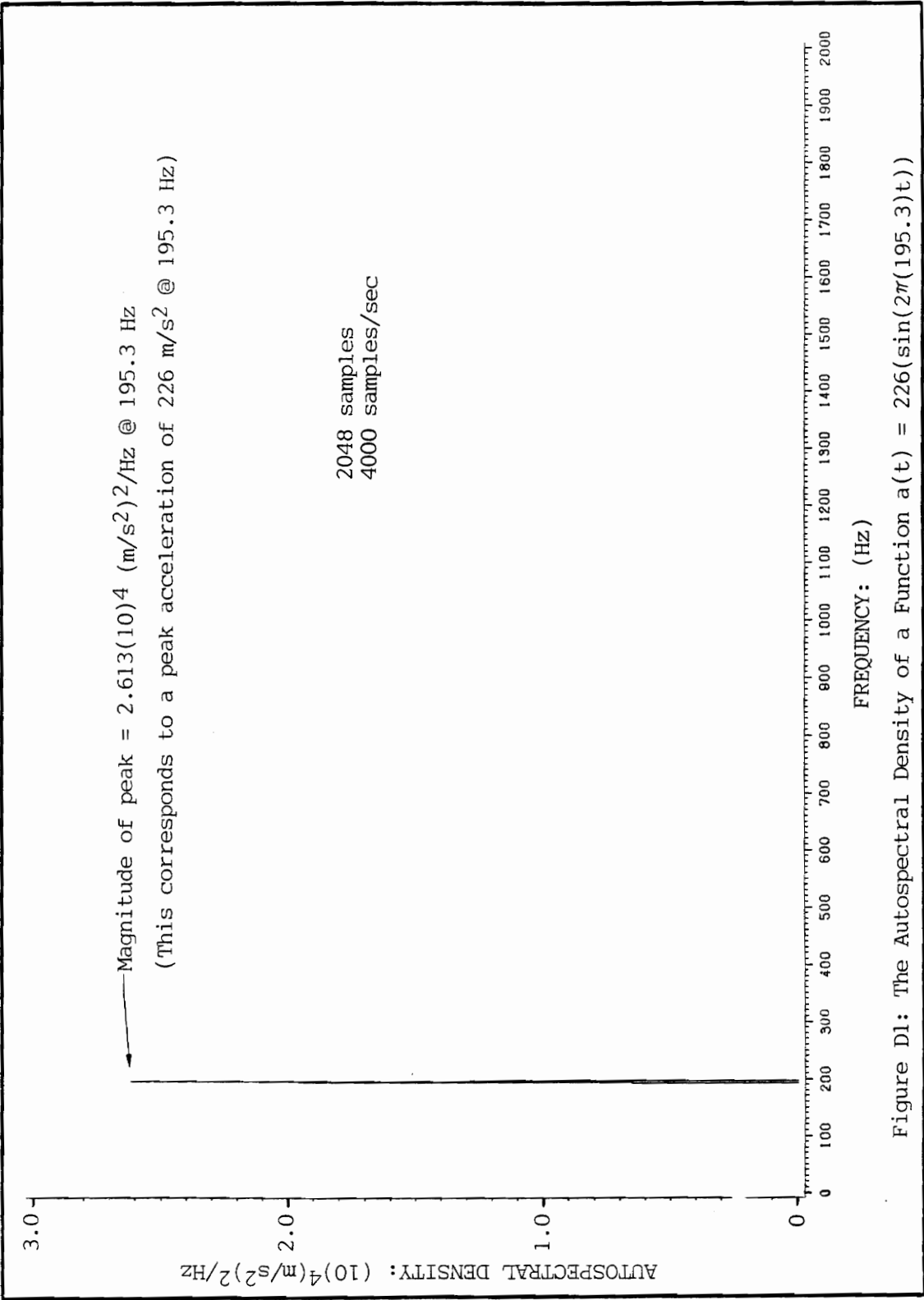


Figure D1: The Autospectral Density of a Function $a(t) = 226(\sin(2\pi(195.3)t))$

Furthermore, $\omega^2 A = 226 \text{ m/s}^2$ can be divided by ω^2 to obtain the peak amplitude $A = 150 \text{ }\mu\text{m}$. Therefore, by using the accelerometer to measure acceleration of the sapphire disk, the autospectral density of the resulting signal can be used to calculate the peak acceleration, velocity, and amplitude of oscillation at the predominant driving frequency $\omega = 2\pi f$.

D.3 The Cross-Spectral Density Function

When two signals such as friction force and acceleration are sampled, Fourier transform techniques can be used to determine if there are any frequencies common to **both** signals. The function used to obtain this information is called the cross-spectral density. It is obtained by calculating the fast Fourier transform of the two input signals in accordance with Eq. D.7. These transforms can be labelled $Z(f_k)$ and $Y(f_k)$ for two respective data records $z(t)$ and $y(t)$. Note that both of these data records must be sampled at the same rate and their total time periods, T , must be equal. The cross-spectral density, $G_{zy}(f_k)$, can be calculated from the transforms of the two signals as shown below [95]:

$$\hat{G}_{zy}(f_k) = \frac{|2Z(f_k)Y^*(f_k)|}{(\text{Resolution})} = \frac{4|Z(f_k)Y^*(f_k)|}{(1/N\Delta t)}$$

$$\hat{G}_{zy} = 4N\Delta t|Z(f_k)Y^*(f_k)| \quad (D.14)$$

where,

$G_{zy}(f_k)$ = cross-spectral density

$Z(f_k) = R_z(f_k) + jI_z(f_k)$ in accordance with Eq. D.7

$Y(f_k) = R_y(f_k) + jI_y(f_k)$ in accordance with Eq. D.7

$Y^*(f_k)$ = complex conjugate of $Y(f_k)$

Since $Z(f_k)$ and $Y^*(f_k)$ can be expressed in terms of their respective real and imaginary components, the quantity $|Z(f_k)Y^*(f_k)|$ can be written as shown below:

$$|ZY^*| = \sqrt{[R_z R_y + I_z I_y]^2 + [R_y R_z - R_z R_y]^2} \quad (D.15)$$

The two squared quantities under the square root sign in Eq. D.15 are called the coincident and quadrature spectral density functions. These functions are labelled $C_{zy}(f_k)$ and $Q_{zy}(f_k)$ as shown below:

$$C_{zy} = R_z R_y + I_z I_y \quad (D.16a)$$

$$Q_{zy} = R_z R_y - I_z I_y \quad (D.16b)$$

Therefore, Eq. D.15 can be written in terms of C_{zy} and Q_{zy} :

$$|ZY^*| = \sqrt{[C_{zy}(f_k)]^2 + [Q_{zy}(f_k)]^2} \quad (D.17)$$

The importance of the coincident and quadrature functions can be seen when the phase difference between the two signals $z(t)$ and $y(t)$ is calculated. This phase difference is actually a function of the discrete frequencies, f_k . It is obtained from C_{zy} and Q_{zy} as shown below:

$$\phi(f_k) = \tan^{-1} \left[\frac{Q_{zy}(f_k)}{C_{zy}(f_k)} \right] \quad (D.18)$$

If $\phi(f_k)$ is divided by each discrete radial frequency ω_k , the time delay $\tau(f_k)$ can be determined at each discrete frequency:

$$\tau(f_k) = \frac{\phi(f_k)}{2\pi f_k} \quad (D.19)$$

where, $\omega_k = 2\pi f_k$

Note that $\tau(f_k)$ only has meaning at frequencies where the cross-spectral density shows a spike. At these frequencies, the two input signals are said to be coherent and the time delay between the two signals can be found from $\tau(f_k)$.

To illustrate how the cross-spectral density function and corresponding time delays are obtained, the signals shown in Fig. D2 are presented. The two sinusoidal signals shown in this figure were digitally calculated using the equations shown below:

$$y(t) = 200\sin(\omega t + \pi/8) \quad (D.20a)$$

$$z(t) = 100\sin(\omega t) \quad (D.20b)$$

$$\text{where, } \omega = 2\pi(195.3 \text{ Hz})$$

The phase angle between $y(t)$ and $z(t)$ is $\pi/8$ radians. This means that $y(t)$ reaches a maximum 0.32 milliseconds before $z(t)$ reaches a maximum. This is indeed the case for the two signals shown in Fig. D2.

When the cross-spectral density of $y(t)$ and $z(t)$ is calculated Fig. D3 is obtained. This figure shows a single spike at 195.3 Hz. The magnitude of the spike is 10240 which corresponds to the multiplication of the amplitudes for the two signals. Therefore, the quantity $(100)(200) = 20000$ is obtained when the cross-spectral density 10240 is multiplied by the resolution:

$$(10240) \left[\frac{4000 \text{ samples/sec}}{2048 \text{ samples}} \right] = 20000$$

Since $y(t)$ and $z(t)$ are only coherent at 195.3 Hz, the time delay $\tau(f_k)$ only has meaning at this frequency. This time delay was calculated to be 0.32 milliseconds at 195.3 Hz as expected.

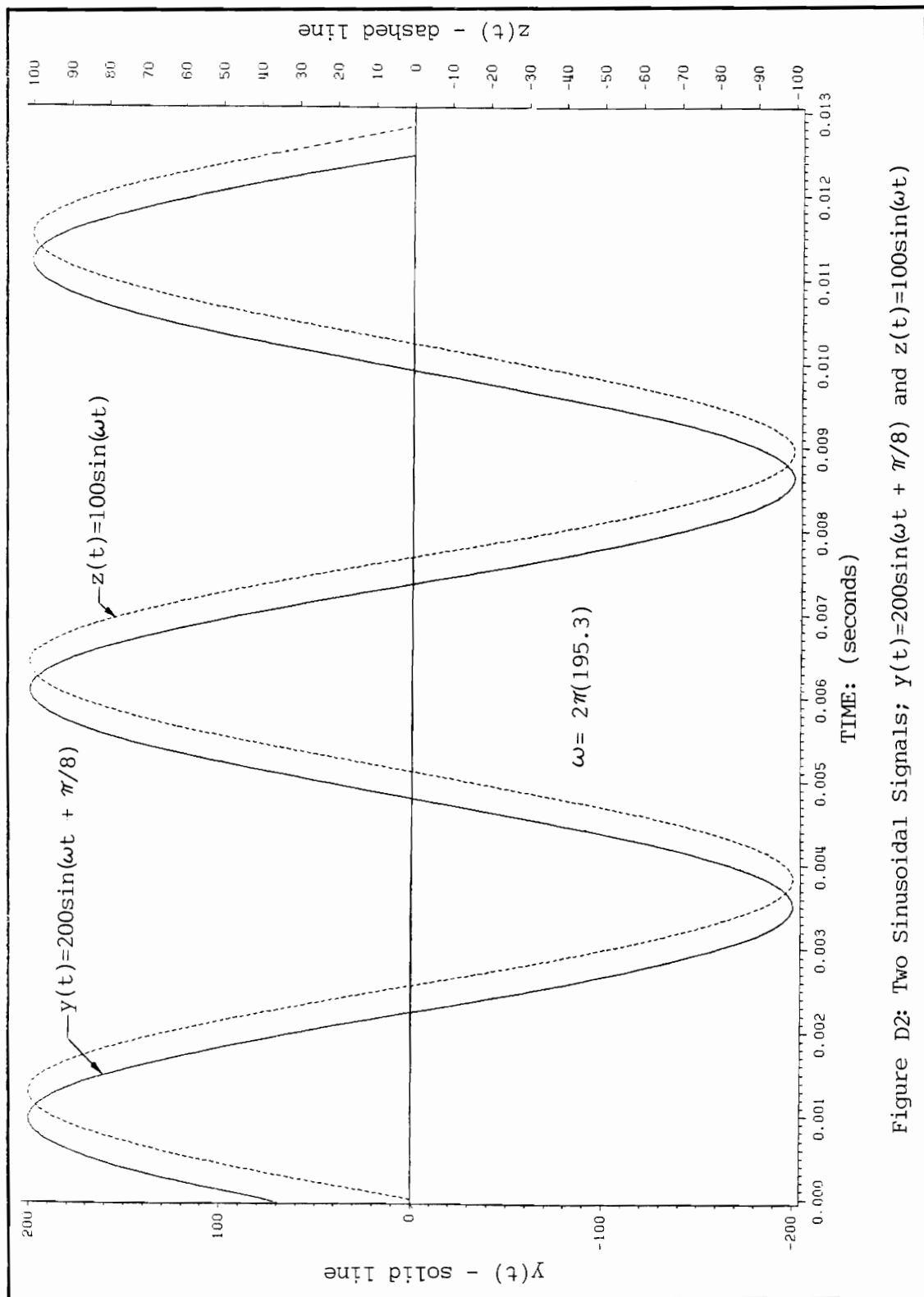


Figure D2: Two Sinusoidal Signals; $y(t)=200\sin(\omega t + \pi/8)$ and $z(t)=100\sin(\omega t)$

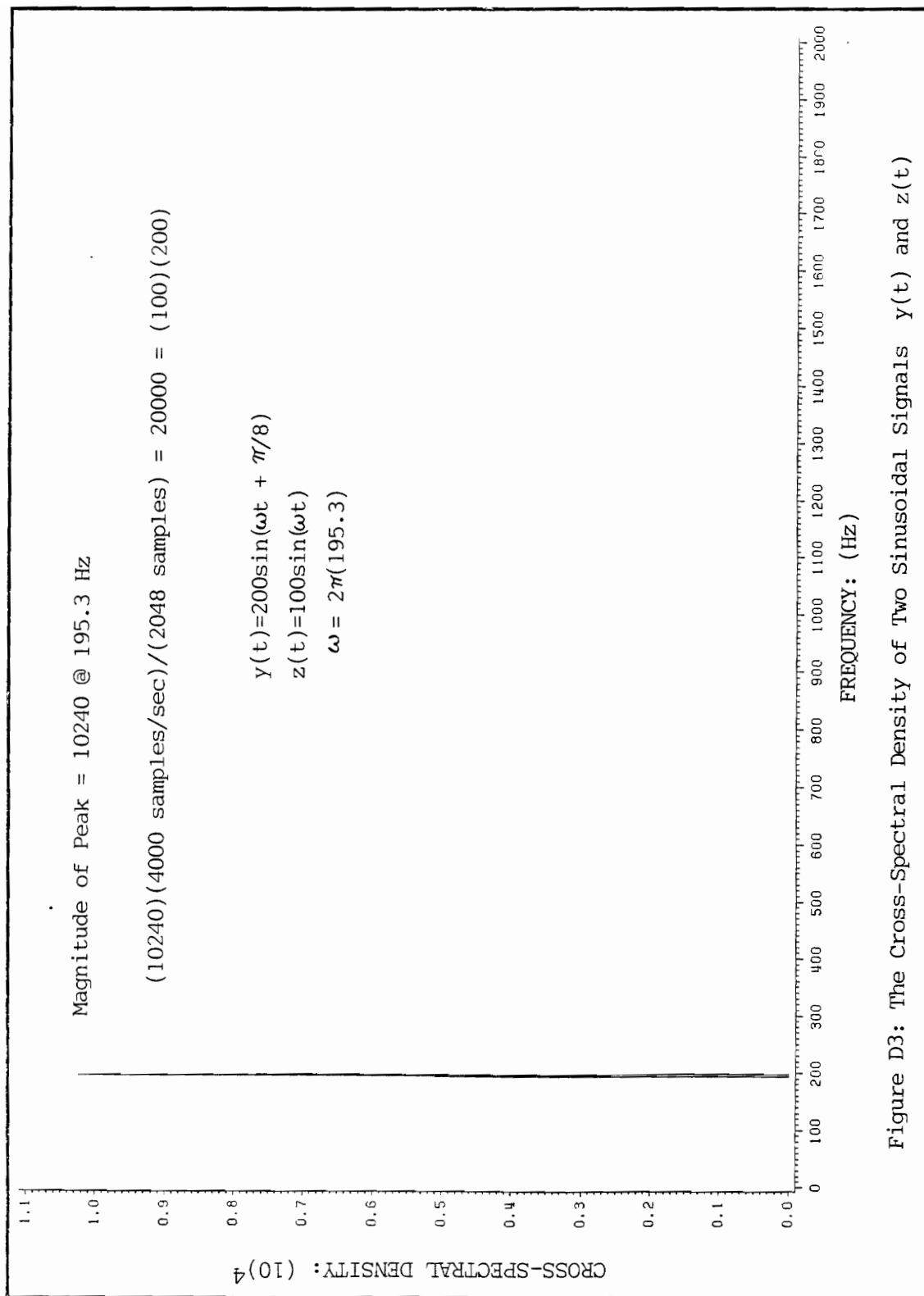


Figure D3: The Cross-Spectral Density of Two Sinusoidal Signals $y(t)$ and $z(t)$

D.4 Digital Integration

As discussed in Section 4.2.4.e, comparisons are made between surface temperature and velocity. Since velocity is not directly measured, digital integration techniques are used to calculate discrete velocity data from the acceleration data measured using the accelerometer. The basis for this digital integration technique is the Fourier transform. More specifically, the acceleration data is transformed into the frequency domain and simple procedures are then used to obtain velocity and amplitude as a function of frequency. Subsequently, an inverse Fourier transform is used to obtain discrete velocity and amplitude data as a function of time. These inverse transforms can be calculated using the subroutine in Section D.5.

The equations used to convert transformed acceleration data into velocity and amplitude data are shown below. Note that the radial frequency $\omega_k = 2\pi f_k$ is used in lieu of f_k to simplify the notation.

$$A(\omega_k) = 2(R_a(\omega_k) + jI_a(\omega_k)) \quad (D.21a)$$

$$V(\omega_k) = \frac{2}{\omega_k} (I_a(\omega_k) - jR_a(\omega_k)) \quad (D.21b)$$

$$D(\omega_k) = \frac{-2}{\omega_k^2} (R_a(\omega_k) + jI_a(\omega_k)) \quad (D.21c)$$

where,

$A(\omega_k)$ = Acceleration as a function of frequency

$V(\omega_k)$ = Velocity as a function of frequency

$D(\omega_k)$ = Amplitude as a function of frequency

The transformed acceleration data, $A(\omega_k)$, is simply twice the Fourier transform of the acceleration data record $a(t)$. $R_a(\omega_k)$ is the real component of the acceleration signal and $I_a(\omega_k)$ is the imaginary component. As discussed in Section D.1, a factor of two must be included with each of these terms to account for the fact that only half the data record is actually used. This factor of two also shows up in the equations for $V(\omega_k)$ and $D(\omega_k)$. Since the data is in the frequency domain, $V(\omega_k)$ is directly calculated from the real and imaginary components of $A(\omega_k)$. Each component is divided by ω_k to obtain the magnitude of velocity at each frequency, and the positions and signs of the components are arranged as shown in Eq. D.21b to account for the 90 degree phase difference between velocity and acceleration. Likewise, amplitude as a function of frequency, $D(\omega_k)$, is also calculated using $2R_a(\omega_k)$ and $2I_a(\omega_k)$. For this derivation, the acceleration components are divided by ω_k^2 and a negative sign is used to cause a 180 degree phase shift between amplitude and acceleration. Once $V(\omega_k)$ and $D(\omega_k)$ are obtained, the discrete data records $v(t)$ and $d(t)$ are obtained by using the inverse Fourier transform procedures incorporated into the subroutine shown in Section D.5.

To test this integration procedure, digitally created acceleration data was used to determine if velocity and amplitude are calculated correctly. The acceleration function is shown below along with the **expected** velocity and amplitude functions:

$$a(t) = -226 \text{ m/s}^2 \sin(2\pi(195.3)t) \quad (D.22a)$$

$$v(t) = 184 \text{ mm/s} \cos(2\pi(195.3)t) \quad (D.22b)$$

$$d(t) = 150 \mu\text{m} \sin(2\pi(195.3)t) \quad (D.22c)$$

Figure D4 shows acceleration superimposed on the velocity signal obtained using the digital integration procedure. Acceleration is the solid line and velocity is the dashed line. As expected, velocity is ninety degrees out-of-phase with respect to acceleration. Furthermore, the peak velocity is approximately 180 mm/sec which agrees with the expected peak velocity shown in Eq. 22b. Therefore, one can conclude that the digital integration technique correctly calculates velocity from acceleration.

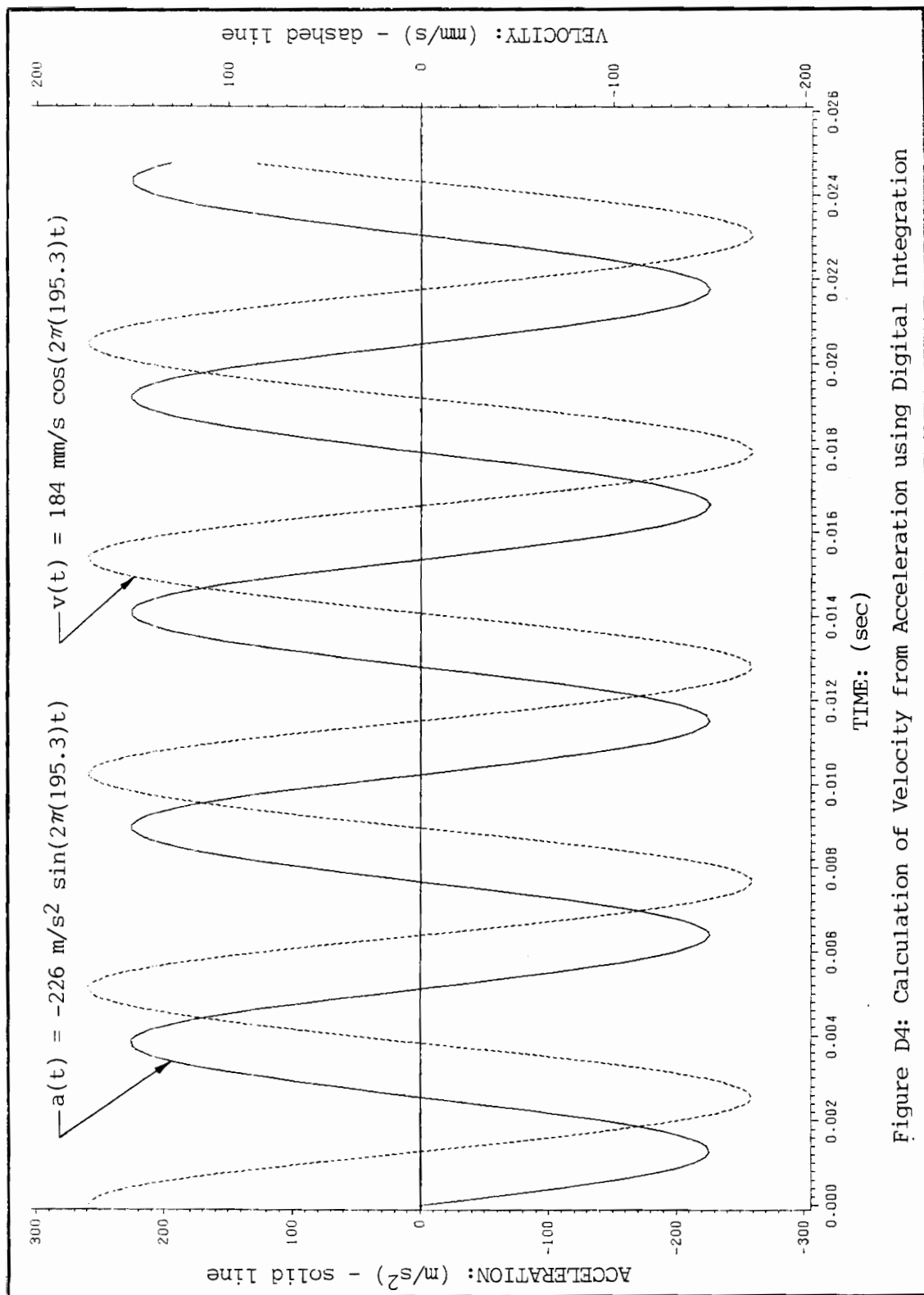


Figure D4: Calculation of Velocity from Acceleration using Digital Integration

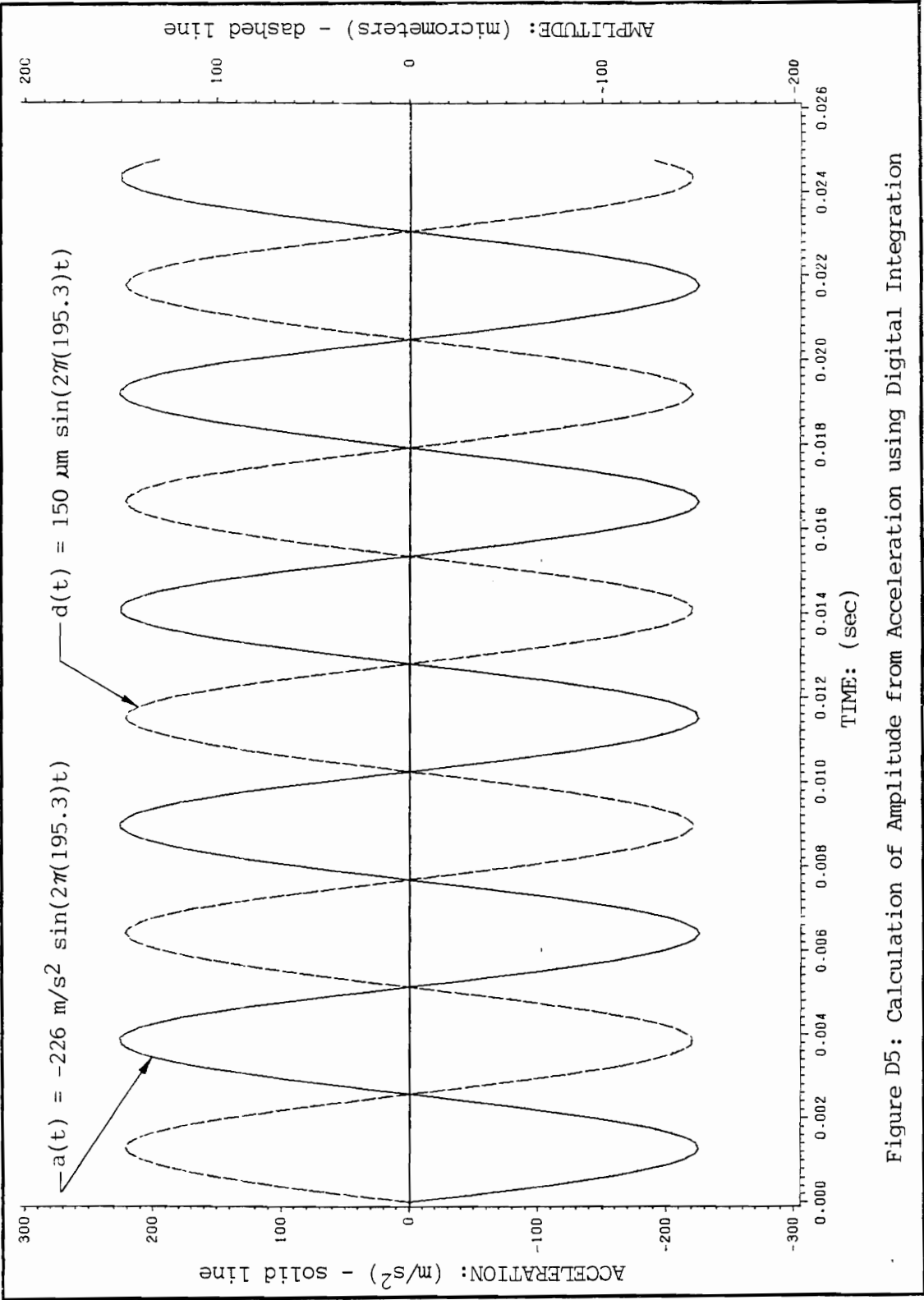


Figure D5: Calculation of Amplitude from Acceleration using Digital Integration

Figure D5 shows acceleration superimposed on amplitude. As expected, the two signals are 180 degrees out-of-phase. Also, the peak amplitude is approximately $150\text{ }\mu\text{m}$ in agreement with Eq. D.22c. As a result, the digital integration of acceleration to obtain amplitude is also adequate.

As a final note, it should be pointed out that the **pure**, digitally created signals shown in Figs. D4 and D5 are a lot simpler to operate on than the **real** signals obtained during an experiment. These real signals contain many frequencies and digital problems such as leakage and aliasing can lead to erroneous results [95]. In fact, the double integration of acceleration to obtain amplitude proved to be extremely difficult to perform accurately. However, the velocity data obtained by a single digital integration proved to be both accurate and useful as discussed in Section 4.2.4.e.

D.5 Listing of the Subroutine: *FFT.FOR* [95]

```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE FFT(XR,XI,N,INV)
      IMPLICIT REAL*8 (A-H,O-Z)
C=====
C      SEE REFERENCE [95] FOR A DESCRIPTION OF THIS ALGORITHM
C==== Input ====
C      XR,XI : Real and Imag. Part of Data of DIM. N
C      N : Must be 2**M , Ex) N=...,256,512,1024,....
C      INV : =0 FFT, =1 Inverse FFT
C==== Output ====
C      XR,XI : Transformed Data
C==== For the transform of a real signal pass XI( )=0.
C==== Use Double Precision
C=====
      DIMENSION XR(1),XI(1),UR(15),UI(15)
      UR(1)=0.
      UI(1)=1.
      DO 110 I=2,15
        UR(I)=DSQRT((1.D0+UR(I-1))/2.D0)
        UI(I)=UI(I-1)/(2.D0*UR(I))
110  CONTINUE
120  IF(N.GT.0 .AND. N.LE.2**14) GO TO 130
      INV=-1
      RETURN
130  NO=1
      I1=0
140  NO=NO+NO
      I1=I1+1
      IF(NO.LT.N) GO TO 140
      I1=NO/2
      I3=1
      I0=I1
C-----

```

```

DO 260 I4=1,I1
C-----
DO 250 K=1,I1
WR=1.D0
WI=0.D0
KK=K-1
C-----
DO 230 I=1,I0
IF(KK.EQ.0) GO TO 240
MOD=KK-(KK/2)*2
IF(MOD.EQ.0) GO TO 230
J0=I0-I
WS=WR*UR(J0)-WI*UI(J0)
WI=WR*UI(J0)+WI*UR(J0)
WR=WS
230 KK=KK/2
C-----
240 IF(INV.EQ.0) WI=-WI
L=K
DO 250 J=1,I3
L1=L+I1
ZR=XR(L)+XR(L1)
ZI=XI(L)+XI(L1)
Z=WR*(XR(L)-XR(L1))-WI*(XI(L)-XI(L1))
XI(L1)=WR*(XI(L)-XI(L1))+WI*(XR(L)-XR(L1))
XR(L1)=Z
XR(L)=ZR
XI(L)=ZI
250 L=L1+I1
C-----
I0=I0-1
I3=I3+I3
260 I1=I1/2
C-----
UM=1.D0
IF(INV.EQ.0) UM=1.D0/NO
DO 310 J=1,NO
K=0
J1=J-1
DO 320 I=1,I1
K=2*K+J1-(J1/2)*2
320 J1=J1/2
K=K+1
IF(K.LT.J) GO TO 310
ZR=XR(J)
ZI=XI(J)
XR(J)=XR(K)*UM
XI(J)=XI(K)*UM
XR(K)=ZR*UM
XI(K)=ZI*UM
310 CONTINUE
C
RETURN
END

```

Appendix E. Calibration of the FM Tape Recorder

As discussed in Section 3.7 and reference [77], the FM tape recorder used in this research attenuates signals supplied as input to the device. This means that the output signal from the tape recorder is not the same as the input signal. Table E-1 illustrates this aspect of the tape recorder for each of the seven channels. For instance, the first column in this table shows input voltages that are recorded on the FM tape recorder. When these signals are "played-back", each of the seven channels attenuates the signal. As an example, an input voltage of 0.100 volts recorded on channel no. 1 is only 0.073 volts when the tape is played-back.

To account for this attenuation of input signals, regression techniques were used to develop calibration equations for the FM tape recorder. These equations are shown in Table E-2 for each of the seven channels. By using these equations, signals recorded on the FM tape can be corrected for the attenuation factors discussed previously. These equations are incorporated into a simple computer program that allows the user to correct signals that are sampled from the tape recorder using the IBM PC's data acquisition board.

As shown in Table E-2, the calibration equations are extremely accurate with standard deviations between 0.6 and 4 millivolts depending on the channel. Therefore, they can be confidently used to enhance the capabilities of the FM tape recorder and overall data acquisition system.

Table E-1: Calibration Data for the FM Tape Recorder							
INPUT VOLTAGE (volts)	OUTPUT VOLTAGE FROM THE SEVEN CHANNELS OF THE FM TAPE RECORDER (ME#653)						
	Ch. No. 1	Ch. No. 2	Ch. No. 3	Ch. No. 4	Ch. No. 5	Ch. No. 6	Ch. No. 7
.100	.073	.073	.060	.058	.117	.104	.103
.200	.163	.158	.109	.111	.202	.197	.196
.300	.250	.240	.157	.164	.282	.285	.286
.400	.333	.320	.205	.215	.366	.373	.375
.500	.419	.398	.250	.264	.451	.458	.462
.600	.505	.480	.297	.313	.539	.544	.550
.700	.591	.563	.344	.364	.622	.629	.634
.800	.680	.646	.391	.416	.710	.719	.725
.900	.772	.733	.441	.470	.802	.810	.819
1.000	.867	.823	.492	.526	.898	.907	.916
1.100	.969	.918	.548	.585	.999	1.008	1.019
1.200	1.078	1.022	.606	.649	1.109	1.118	1.130
1.300	1.195	1.133	.670	.719	1.227	1.236	1.250
1.400	1.327	1.259	.742	.798	1.362	1.371	1.386

Table E-2: Calibration Equations for the FM Tape Recorder		
CHANNEL	REGRESSION EQUATION	Stand. Dev.
#1	$V_1 = 0.0153 + 1.12(V_O) + 0.160(V_O)^2 - 0.164(V_O)^3$	0.0016
#2	$V_2 = 0.0106 + 1.18(V_O) + 0.188(V_O)^2 - 0.199(V_O)^3$	0.0016
#3	$V_3 = -0.0207 + 1.94(V_O) + 0.851(V_O)^2 - 1.20(V_O)^3$	0.0019
#4	$V_4 = -0.0090 + 1.81(V_O) + 0.720(V_O)^2 - 0.975(V_O)^3$	0.0022
#5	$V_5 = -0.0153 + 1.06(V_O) + 0.271(V_O)^2 - 0.210(V_O)^3$	0.0049
#6	$V_6 = -0.0091 + 1.02(V_O) + 0.286(V_O)^2 - 0.208(V_O)^3$	0.0020
#7	$V_7 = -0.0108 + 1.04(V_O) + 0.243(V_O)^2 - 0.186(V_O)^3$	0.0022
(V _O - output voltage from each channel of the FM tape recorder)		

Appendix F. Listing of the Program:

INFRATEMP.FOR

MAIN PROGRAM

```
PROGRAM INFRATEMP
  (VERSION 5) B. L. Weick
!
! This program calculates surface temperatures from radiance
! data when the following information is supplied as input:
!
!   - an array of voltages from the AC/DC or DC channels of the
!     infrared microscope
!   - an emissivity value for the test specimen
!   - the transmittance of the sapphire disk
!   - the reference level voltage output from the microscope
!     obtained before an experiment
!   - the ambient temperature of the microscope
!
! This program is based on a FORTRAN program originally written by
! C. A. Rogers [21]. Modifications have been made to this original
! program to allow for expedient calculation of instantaneous
! temperature rises from instantaneous radiance data.
!
! The theoretical basis for this program can be found in
! section 3, along with the actual procedure used to calculate
! surface temperatures from radiance data.
!
!   DOUBLE PRECISION EMISS,TNAUC,TNAUK,RESP1(4000),AMBR,SURF,IR,
!   SFRES,EXTER,TRANS,REFLS1,REFLS2,REFLA1,REFLA2,REFLA3,N1,N2,CAL,
!   $TIME(5000),RAWVOLT(5000),ZTIME,ZDCVOLT(5000),ZDCAVE,DCVOLT(5000),
!   $ZEROCALC,RESP2(4000),TEMPSK,EXPRAD(5000),THYRAD,FPRIMOFT,FOFT,
!   $TEMPRISE(5000),AVERAD,AVERISE,MAXRAD,MAXRISE
!
```

```

        INTEGER NDC,NZ,J,K,L,M,I
!
        CHARACTER DCFIL*15,ZFILE*15,VRTFILE*15,TNRFILE*15,TNTFILE*15,
        SANS*1,CHAN*1
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
C Interactive statements for entering the required input data
!
        PRINT *, 'Enter the emissivity of the specimen:'
        READ *, EMISS
!
        PRINT *, 'Enter the AMBIENT TEMPERATURE of the microscope'
        PRINT *, 'in degrees C:'
        READ *, TNAUC
!
        PRINT *, 'Enter the EXTERNAL TRANSMITTANCE of the sapphire disk.'
        PRINT *, '{ 0.8296 is the external transmittance of an unused'
        PRINT *, '0.040 inch (1.02 mm) thick sapphire disk }.'
        READ *, EXTER
!
        PRINT *, 'Enter name of INPUT file containing voltage output'
        PRINT *, 'from the AC/DC or DC channel of the infrared microscope:'
        PRINT *, '(THE OPTICAL OBJECTIVE OF THE MICROSCOPE MUST BE 15X)'
        READ (*, '(A15)') DCFIL
        OPEN(2, FILE=DCFIL, STATUS='OLD')
        PRINT *, 'Enter length of ', DCFIL
        READ *, NDC
!
        PRINT *, 'Enter name of INPUT file containing the ZERO reference'
        PRINT *, 'level voltage output from the microscope:'
        READ (*, '(A15)') ZFILE
        OPEN(4, FILE=ZFILE, STATUS='OLD')
        PRINT *, 'Enter length of ', ZFILE
        READ *, NZ
!
        PRINT *, 'Enter name of OUTPUT file that will contain the '
        PRINT *, 'following: DC VOLTAGE OUTPUT, DC RADIANCE, and the '
        PRINT *, 'TEMPERATURE RISES in deg. K that correspond to these '
        PRINT *, 'levels.'
        READ (*, '(A15)') VRTFILE
        OPEN(8, FILE=VRTFILE, STATUS='NEW')
!
        PRINT *, 'Enter name of OUTPUT file that will contain the '
        PRINT *, 'following: TIME and DC RADIANCE.'
        READ (*, '(A15)') TNRFILE
        OPEN(10, FILE=TNRFILE, STATUS='NEW')
!
        PRINT *, 'Enter name of OUTPUT file that will contain the '
        PRINT *, 'following: TIME and TEMPERATURE RISE in deg. K.'
        READ (*, '(A15)') TNTFILE
        OPEN(12, FILE=TNTFILE, STATUS='NEW')
!
2      PRINT *, 'Is the data from the AC/DC or DC channel? (enter A or D)'
        READ (*, '(A1)') CHAN
!
C Calibration constants for the AC/DC and DC channels:
!
        IF (CHAN .EQ. 'A') THEN
            CAL=8.017D-3
        ELSE IF (CHAN .EQ. 'D') THEN
            CAL=1.528D-2
        ELSE
            GOTO 2
        END IF
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
C Determine the ambient background radiance in accordance with Eq. (23):
!
        TNAUK=TNAUC+273.
        CALL SPECRESP(1.8,5.5,0.001,RESP1)

```

```

      CALL PLANK(1.8,5.5,0.001,RESP1,TNAUK,AMBR)
!
C Set the surface reflectivity to zero if the spherical test specimen
C is sapphire:
!
5  PRINT *, 'IS THE SPHERICAL TEST SPECIMEN SAPPHIRE? (Y/N)'
   READ (*, '(A1)') ANS
   IF (ANS.EQ.'Y') THEN
      SURF=0.0
   ELSE IF (ANS.EQ.'N') THEN
      SURF=1.0-EMISS
   ELSE
      GOTO 5
   END IF
!
C Calculate the parameters  $n_1$ , and  $n_2$  as defined by
C Eqs. 15 and 17.
!
   IR=1.65
   FRES=(IR-1.0)**2/((IR+1.0)**2)
   TRANS=EXTER*((1+FRES)/(1-FRES))
   REFLS1=(1-FRES)*TRANS
   REFLS2=(1-FRES)*SURF*FRES*(TRANS**3)
   REFLA1=FRES
   REFLA2=(1-FRES)**2*SURF*(TRANS**2)
   REFLA3=(1-FRES)**2*(SURF**2)*FRES*(TRANS**4)
   N1=REFLS1+REFLS2
   N2=REFLA1+REFLA2+REFLA3
!
C Read in voltage output from either the DC or AC/DC channels of the
C infrared microscope
!
   DO 20 K=1,NDC
      READ(2,*) TIME(K),RAWVOLT(K)
!
C Read in reference level voltage output from either the DC or AC/DC
C channels of the infrared microscope
!
   DO 30 L=1,NZ
      READ(4,*) ZTIME,ZDCVOLT(L)
!
C Rewrite the voltage output measured during the experiment with
C respect to the reference voltage output measured before the experiment
!
      CALL AVERAGE(ZDCVOLT,NZ,ZDCAVE)
      CALL REWRITREL(RAWVOLT,DCVOLT,ZDCAVE,NDC)
!
C Calculate a reference voltage level based on the ambient radiance
C calculated using ambient temperature measurements
!
      ZEROALC=AMBR*((EMISS*N1)+N2-1.0)*(1./CAL)
!
C Write the following parameters to an output file:
C objective of the microscope,  $N_0$ ,  $\epsilon$ ,
C  $r_s$ ,  $\rho_t$ ,  $\tau$ ,  $n_1$ ,  $n_2$ 
!
      WRITE(8,90)
      WRITE(8,100) OBJ,AMBR,EMISS,FRES,SURF,TRANS,N1,N2
      WRITE(8,110)
!
C Set-up a function RESP2 that is defined as the spectral response of
C the infrared microscope in the 1.8 to 5.5  $\mu\text{m}$  wavelength interval
!
      CALL SPECRESP(1.8,5.5,0.020,RESP2)
!
C Calculate the radiance being emitted at the interface in accordance
C with Eq. 7, and write the data to an output file
!
      DO 40 M=1,NDC
         TEMPSK=600.
         EXPRAD(M)=( (DCVOLT(M)*CAL)+AMBR-(N2*AMBR) )/(EMISS*N1)

```

```

        WRITE(10,125)TIME(M),EXPRAD(M)
!
C Use Newton's method to calculate surface temperatures from radiance
C data in accordance with Eq. 22. The derivative of Plank's
C distribution function, and the function itself, are incorporated into
C two separate subroutines: DERIVPLANK and PLANK. Convergence is
C obtained when the difference between the experimental and theoretical
C radiance is less than 0.00001. The calculated temperature rises are
C subsequently written to an output file.
!
        DO 50 I=1,100
            CALL PLANK(1.8,5.5,0.020,RESP2,TEMPSK,THYRAD)
            CALL DERIVPLANK(1.8,5.5,0.020,RESP2,TEMPSK,FPRIMOFT)
            FOFT=EXPRAD(M)-THYRAD
!
            IF (ABS(FOFT).GE.0.00001) THEN
                TEMPSK=TEMPSK-FOFT/FPRIMOFT
            ELSE
                TEMPRISE(M)=TEMPSK-TNAUK
                WRITE(12,125) TIME(M),TEMPRISE(M)
                WRITE(8,120) DCVOLT(M),EXPRAD(M),TEMPRISE(M)
                GOTO 40
            END IF
!
50      CONTINUE
!
40      CONTINUE
!
C Determine the average and absolute maximum radiance and temperature
C rise, and write them to an output file
!
        CALL AVERAGE(EXPRAD,NDC,AVERAD)
        CALL AVERAGE(TEMPRISE,NDC,AVERISE)
        CALL BIGGEST(NDC,EXPRAD,MAXRAD)
        CALL BIGGEST(NDC,TEMPRISE,MAXRISE)
!
        WRITE(8,105) ZEROCALC,ZDCAVE,AMBR,TNAUC,AVERAD,AVERISE,MAXRAD,
$          MAXRISE
!
        STOP
90      FORMAT(2X,'OBJ',2X,'AMB RAD',4X,' EMISS ',' FRESN ',' RHOS ',
$ ' TRANS ',, ATTN1 ',, ATTN2 ',,
$ 2X,' ',X,' ',2X,6(' ',,))
100     FORMAT(2X,F3.0,X,G10.5,X,6(F7.3),///)
105     FORMAT (//,2X,G16.5,' = the calculated reference voltage level',/,
$ 2X,G16.5,' = the experimentally determined reference voltage
$ level',/,
$ 2X,G16.5,' = the ambient radiance in watts/(cm**2*ster)',/,
$ 2X,G16.5,' = the ambient temperature in degrees C',/,
$ 2X,G16.5,' = the average radiance in watts/(cm**2*ster)',/,
$ 2X,G16.5,' = the average temperature rise in degrees K',/,
$ 2X,G16.5,' = the maximum radiance in watts/(cm**2*ster)',/,
$ 2X,G16.5,' = the maximum temperature rise in degrees K',/)
110     FORMAT(2X,' DC VOLTS ',, RADIANCE ',, TEMP RISE K ',/)
120     FORMAT(2X,G10.4,X,G10.4,X,G10.4)
125     FORMAT(2X,F20.8,X,G15.5)
        END

```

SUBROUTINE SPECRESP

```

        SUBROUTINE SPECRESP(A,B,DLMDA,TAU)
        DOUBLE PRECISION A,B,DLMDA,DIV,WAV,TAU(4000)
        INTEGER L
!
C This subroutine calculates the ratio of the spectral response of the
C infrared microscope to the peak spectral response of the microscope,
C (See Eq. 20)

```

```

!
!
DIV=(B-A)/DLMDA
WAV=A-DLMDA
!
DO 200 L=1,DIV
WAV=WAV+DLMDA
IF(WAV.GE.1.6.AND.WAV.LT.2.0) TAU(L)=.75*WAV-1.2
IF(WAV.GE.2.0.AND.WAV.LT.2.2) TAU(L)=-.10*WAV+.50
IF(WAV.GE.2.2.AND.WAV.LT.2.4) TAU(L)=.0375*WAV+.1975
IF(WAV.GE.2.4.AND.WAV.LT.2.6) TAU(L)=.1125*WAV+.0175
IF(WAV.GE.2.6.AND.WAV.LT.2.8) TAU(L)=.20*WAV-.21
IF(WAV.GE.2.8.AND.WAV.LT.3.0) TAU(L)=.25*WAV-.35
IF(WAV.GE.3.0.AND.WAV.LT.3.2) TAU(L)=.30*WAV-.50
IF(WAV.GE.3.2.AND.WAV.LT.3.4) TAU(L)=.425*WAV-.90
IF(WAV.GE.3.4.AND.WAV.LT.4.2) TAU(L)=.375*WAV-.73
IF(WAV.GE.4.2.AND.WAV.LT.4.8) TAU(L)=.225*WAV-.10
IF(WAV.GE.4.8.AND.WAV.LT.5.0) TAU(L)=.10*WAV+.50
IF(WAV.GE.5.0.AND.WAV.LT.5.2) TAU(L)=-.60*WAV+4.
IF(WAV.GE.5.2.AND.WAV.LT.5.4) TAU(L)=-1.30*WAV+7.64
IF(WAV.GE.5.4.AND.WAV.LT.5.6) TAU(L)=-2.35*WAV+13.31
IF(WAV.GE.5.6.AND.WAV.LT.5.8) TAU(L)=-.45*WAV+2.67
IF(WAV.GE.5.8.AND.WAV.LT.6.0) TAU(L)=-.25*WAV+1.51
200 IF(WAV.GE.6.0.AND.WAV.LT.6.2) TAU(L)=-.05*WAV+.31
RETURN
END

```

SUBROUTINE PLANK

```

SUBROUTINE PLANK(A,B,DLMDA,TAU,TSK,EFFRAD)
DOUBLE PRECISION A,B,DLMDA,TAU(4000),TSK,EFFRAD,DIV,WAV,C2PLAMT,
$INT(4000),EFRAD
INTEGER I,K
!
C This subroutine calculates Plank's distribution function in accordance
C with Eq. 21
!
DIV=(B-A)/DLMDA
WAV=A-DLMDA
!
DO 300 I=1,DIV
WAV=WAV+DLMDA
C2PLAMT=14388./(WAV*TSK)
IF (C2PLAMT.GT.86.DO) THEN
INT(I)=0.0DO
ELSE
INT(I)=((11909./WAV**5)*(1./(DEXP(C2PLAMT)-1.)))*TAU(I)
END IF
300 CONTINUE
!
EFRAD=0.0
DO 310 K=3,DIV,2
310 EFRAD=EFRAD+(DLMDA/3.0)*(INT(K-1)+4.0*INT(K)+INT(K+1))
!
EFFRAD=EFRAD*13.50
!
RETURN
END

```

SUBROUTINE DERIVPLANK

```

SUBROUTINE DERIVPLANK(A,B,DLMDA,TAU,TSK,DERIVF)
DOUBLE PRECISION A,B,DLMDA,TAU(4000),TSK,DERIVF,DIV,WAV,C2PLAMT,
$SKERN(4000),DERIF

```

```

      INTEGER I,K
!
C This subroutine calculates the derivative of Plank's distribution
C function, (See Eq. 21).
!
      DIV=(B-A)/DLMDA
      WAV=A-DLMDA
!
      DO 400 I=1,DIV
        WAV=WAV+DLMDA
        C2PLAMT=14388./(WAV*TSK)
        IF (C2PLAMT.GT.86.DO) THEN
          KERN(I)=0.0
        ELSE
          KERN(I)=( TAU(I)*14388.*11909.*DEXP(C2PLAMT) )/
$          ( WAV**6*TSK**2*( ( DEXP(C2PLAMT)-1. )**2 ) )
        END IF
400    CONTINUE
!
      DERIF=0.0
      DO 410 K=3,DIV,2
410    DERIF=DERIF+(DLMDA/3.0)*(KERN(K-1)+4.0*KERN(K)+KERN(K+1))
!
      DERIVF=-13.50*DERIF
!
      RETURN
      END

```

SUBROUTINE REWRITREL

```

      SUBROUTINE REWRITREL(INPU,OUTPU,ZEDAVE,N)
      DOUBLE PRECISION INPU(5000),OUTPU(5000),ZEDAVE
      INTEGER I,N
!
C This subroutine rewrites the voltage output measured during the
C experiment with respect to the reference voltage output measured
C before the experiment
!
      DO 600 M=1,N
        OUTPU(M)=INPU(M)-ZEDAVE
600    CONTINUE
      RETURN
      END

```

SUBROUTINE BIGGEST

```

      SUBROUTINE BIGGEST(N,PARAM,MAX)
      DOUBLE PRECISION PARAM(5000),MAX
      INTEGER Q,N
!
C This subroutine finds the largest number in an array
!
      MAX=0.0
      DO 700 Q=1,N
        IF (ABS(PARAM(Q)).GT.MAX) THEN
          MAX=ABS(PARAM(Q))
        END IF
700    CONTINUE
      RETURN
      END

```

SUBROUTINE AVERAGE

```
      SUBROUTINE AVERAGE(INPUT,N,AVE)
      DOUBLE PRECISION INPUT(5000),SUM,AVE
      INTEGER I,N
!
! C This subroutine finds the average of an array of numbers
!
      SUM=0
      DO 500 I=1,N,1
        SUM=SUM+INPUT(I)
500 CONTINUE
      AVE=SUM/DFLOAT(N)
      RETURN
      END
```

Appendix G. Listing of the Program:

BWSCOPE3.FOR

MAIN PROGRAM

```
SLARGE
C
C This interactive program is based on an original program written by
C S. Jayaram and F. Caldwell [77]. It can be used with a Data
C Translation no. 2805 data acquisition board to sample up to eight
C channels of data.
C
C Requirements for this program are a PC with color graphics,
C a system disk with PCLAB drivers installed, a math co-
C processor if linked with a co-processor library, and a DATA
C TRANSLATION 2805 configured with differential, bipolar
C inputs.
C
C PCLAB subroutines -- FORTRAN definition include file
C Not all are used in this program, added are particular
C variables for this program
SDEBUG
  INTEGER*2 STATUS,STARTC,ENDCHA,GAIN,TIMING,SAMPLE
  INTEGER*2 XINIT,XTERM,XSB,XST,XSCD,ANALOG(20000),DATPTS
  INTEGER*2 XDLY,XSTB,XWD,XSC,XGC,XCEV,XREV,XGF,CHANLS
  INTEGER*2 XAV,XAOT,XSA,XAS,XBAD,XCAD,XTAD,XWAD,XSAD
  INTEGER*2 XDV,XDOT,XSD,XDS,XBDD,XCDD,XTDD,XWDD,XSDD
  INTEGER*2 XEFO,XEFI,XODV,XODOT,XIDV,XIDOT,XIXR,XIXW
  INTEGER*2 XSECW,XGDE,XRD,XFDL,XESC,XDSC,PLOTS,PLTPNT
  INTEGER*4 CLOCKD
  EXTERNAL XINIT,XTERM,XSAD,XSDD,XWD,XSC,XCEV,XESC,XDSC
  REAL X(10000),Y(10000),FRQRES,PFS,MFS,NOC,RESOL
  CHARACTER*9 FNAME
  CHARACTER*1 ANS,FLAG
C
```



```

DATA IFIRST/0/
DATA XMN,XXM,YMN,XXY/4*0./
C
C
C end of PCLAB subroutines definition
C
MFS=-10.0
PFS=10.0
NOC=4096.0
C
10 STATUS = 0
WRITE (*,20)
20 FORMAT(1X,'NUMBER OF DATA POINTS PER CHANNEL? ( < 8000 PTS.)')
READ (*,*)DATPTS
WRITE (*,30)
30 FORMAT(1X,'FREQUENCY RESPONSE (KHZ)? ( < 8KHZ )')
READ (*,*)FRQRES
CLOCKD=INT(1./((FRQRES*1.E3*2.50E-6)))
WRITE (*,50)
50 FORMAT(1X,'START CHANNEL?')
READ (*,*)STARTC
WRITE (*,60)
60 FORMAT(1X,'END CHANNEL?')
READ (*,*)ENDCHA
WRITE (*,*) 'AFTER GAIN IS ENTERED, ACQUISITION WILL BEGIN;'
WRITE (*,*) 'THE TRIGGER AND CLOCK ARE BOTH INTERNAL.'
WRITE (*,70)
70 FORMAT(1X,'ENTER GAIN? (1,10,100) ')
READ (*,*)GAIN
TIMING=0
C
CHANLS = (ENDCHA+1)-STARTC
SAMPLE = CHANLS*DATPTS
RESOL = FRQRES/CHANLS
C The following 'STATUS =' statements are functions that effect specified
C operations on the interface card and if 'STATUS' is not zero an error
C has occurred and the number delivered specifies the particular error
C that can be used in error handling routines.
STATUS = XDSC
C Disable PC's time of day clock so it won't interrupt.
STATUS = XRD
C Reset 2801-A card.
STATUS = XINIT
C Initialize card.
STATUS = XSCD(CLOCKD)
C Set clock divider with number of ticks between samples.
STATUS = XSA(TIMING, STARTC, ENDCHA, GAIN)
C Set respective parameters on card.
80 STATUS = XDSC
C Disable PC's time of day clock so it won't interrupt.
C Get number of samples beginning with analog(1)
STATUS = XBAD(SAMPLE, ANALOG(1))
C
STATUS=XWAD(ANALOG(SAMPLE))
C
STATUS=XTERM
C
STATUS=XESC()
C
C Initialize time sum to zero.
TIMSUM = 0
C Initialize first plot point to one.
PLTPNT = 1
C Do a plot for each specified channel.
DO 95 PLOTS=1,CHANLS
C Fill a plot array with respective channels samples.
DO 90 I=PLOTS,SAMPLE,CHANLS
C Put accumulated time in x plot array.
X(PLTPNT+1)=TIMSUM
C Increment time element.
TIMSUM=TIMSUM+(FLOAT(CLOCKD)*.00000250*FLOAT(CHANLS))
C Scale analog from binary offset to volts and put in y plot array.

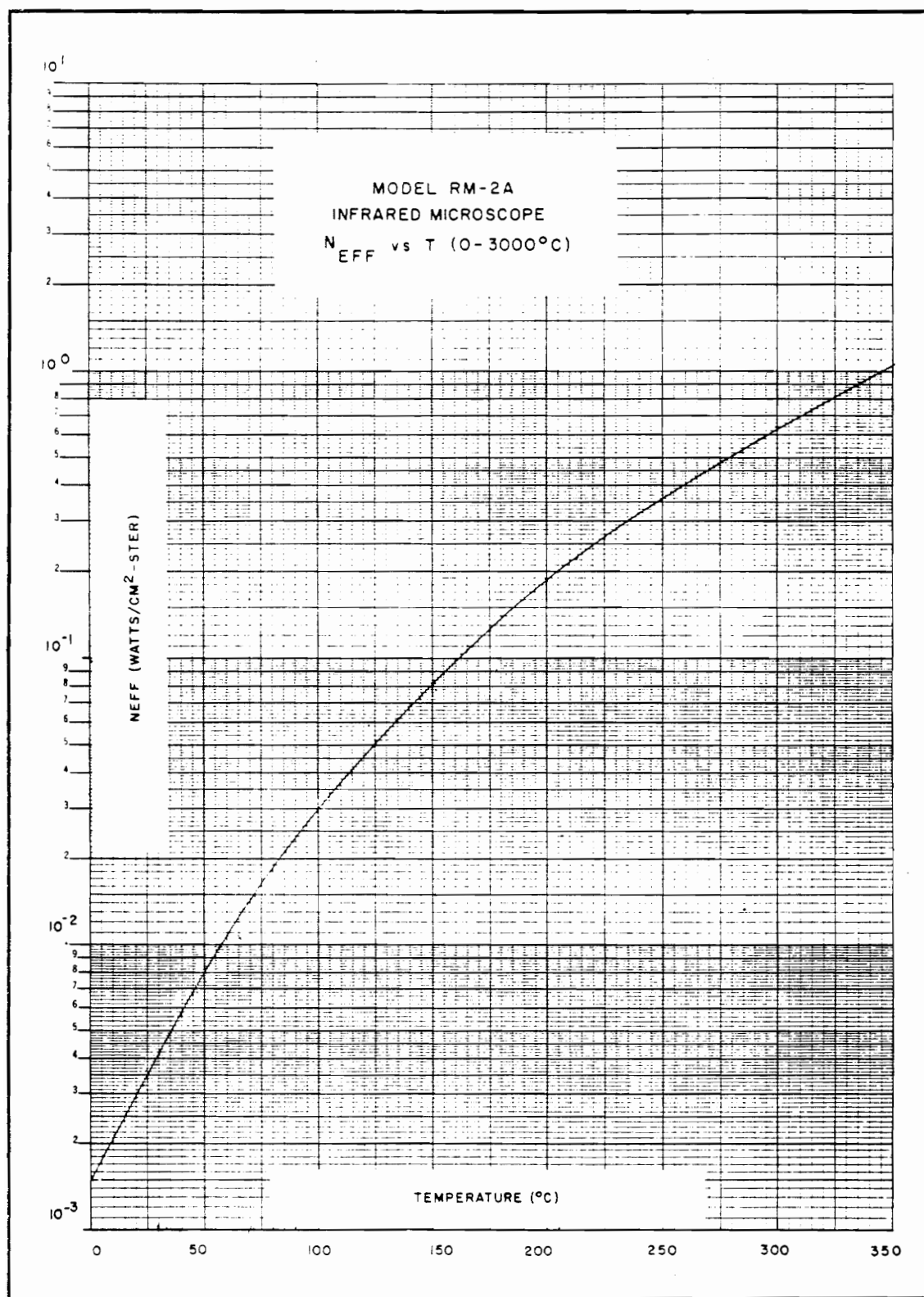
```

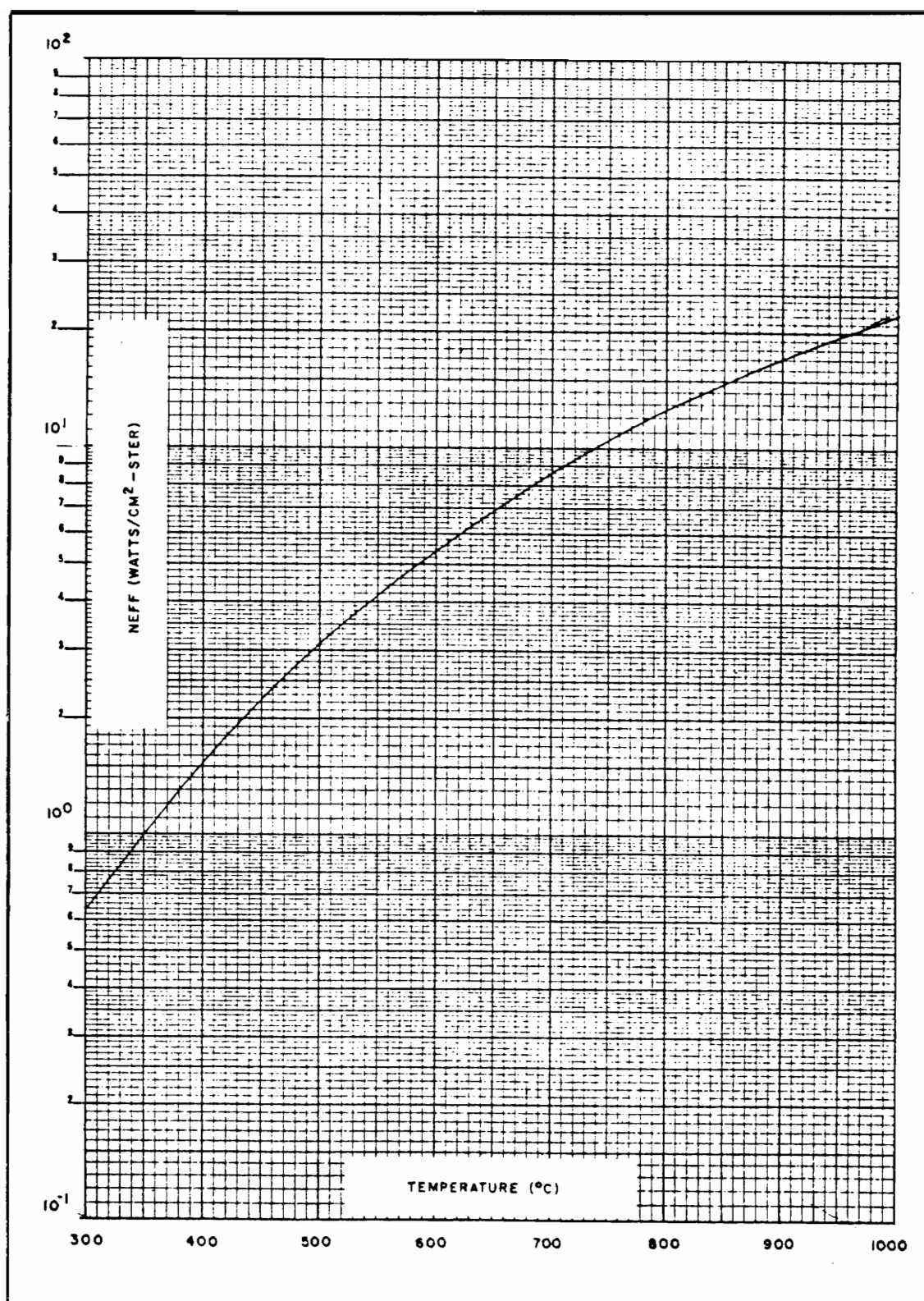
```

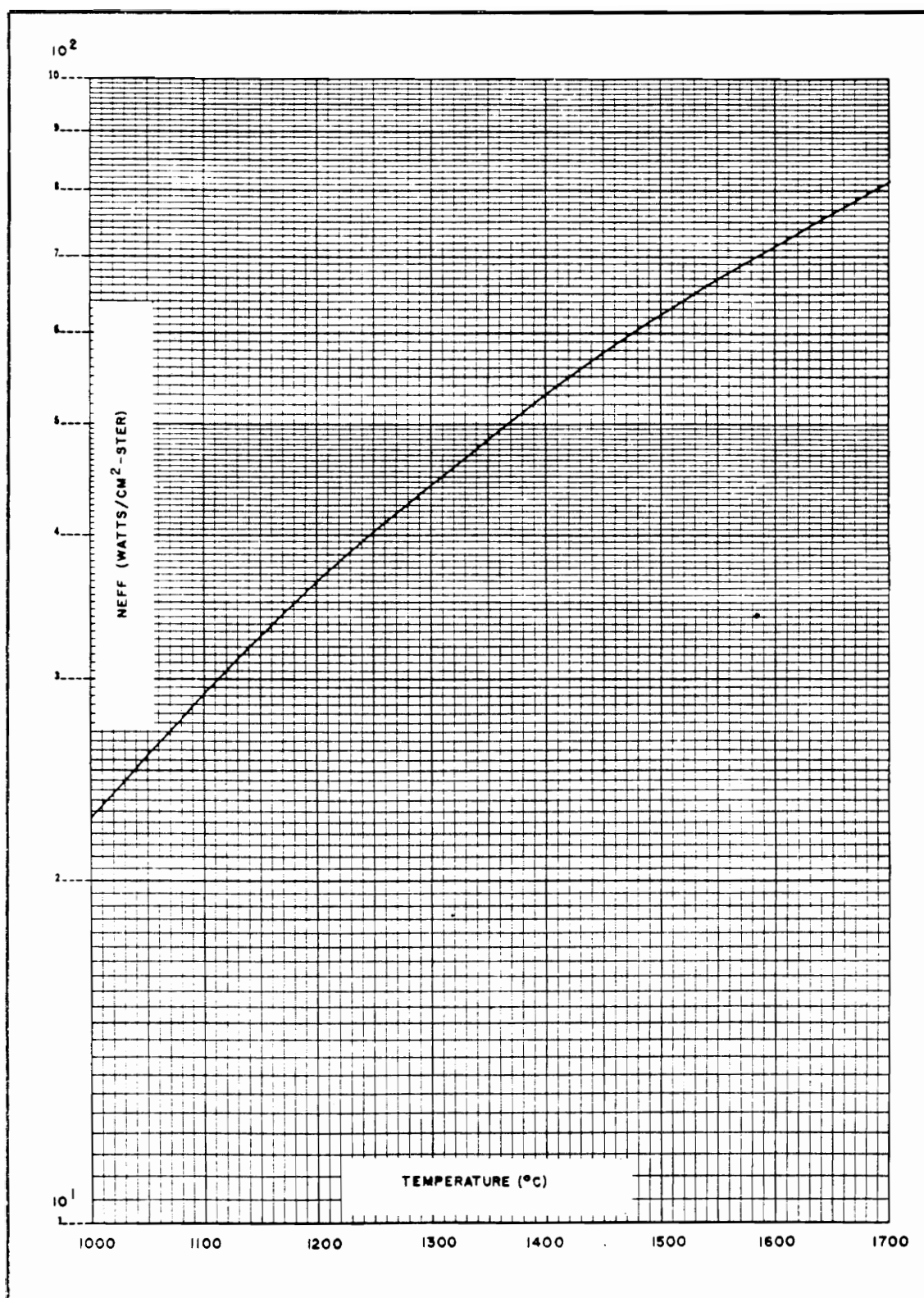
      Y(PLTPNT+1)=( ( FLOAT(ANALOG(1)) * (PFS-MFS)/NOC ) + MFS )
C   Increment plot array elements.
90   PLTPNT=PLTPNT+1
C   Set number of plot array elements.
      X(1)=FLOAT(DATPTS)
C   Set number of plot array elements.
      Y(1)=FLOAT(DATPTS)
C   Plot the array.
      CALL INITT(3)
      CALL BINITT
      CALL CHECK(X,Y)
      CALL DSPLAY(X,Y)
      CALL TINPUT (IOP)
C
      WRITE(*,91) GAIN,DATPTS,RESOL
91   FORMAT(12X,'GAIN = ',13,3X,'DATA PTS = ',15,3X,'FREQ RES =',F9.2)
      READ(*,'(A)') FLAG
C
92   WRITE(*,*) 'DO YOU WANT TO SAVE THE ARRAY FOR THIS PLOT? (Y/N)'
      READ(*,'(A)') ANS
      IF (ANS.EQ.'Y') THEN
        WRITE(*,*) 'GIVE THE NAME OF THE FILE ( <9 CHARACTERS) '
        READ(*,'(A)') FNAME
        OPEN (9,FILE=FNAME,STATUS='NEW',FORM='FORMATTED')
        DO 94 J=2,DATPTS
          WRITE (9,*) X(J),Y(J)
94   CONTINUE
        CLOSE(9)
        ELSE
          IF (ANS.NE.'N') GOTO 92
        END IF
C
      PLTPNT = 1
C   Re-initialize plot array elements.
95   TIMSUM = 0
C   Re-initialize accumulated time sum.
97   WRITE(*,100)
100  FORMAT(1X,'DO AGAIN,CHANGE PARAMETERS,QUIT (1,2,3)?')
      READ (*,*)RQUEST
C   Input requested desires.
      IF (RQUEST.EQ.1) GOTO 80
      IF (RQUEST.EQ.2) GOTO 10
      IF (RQUEST.EQ.3) GOTO 110
      GOTO 97
110  CALL FINITT(0,0)
      END

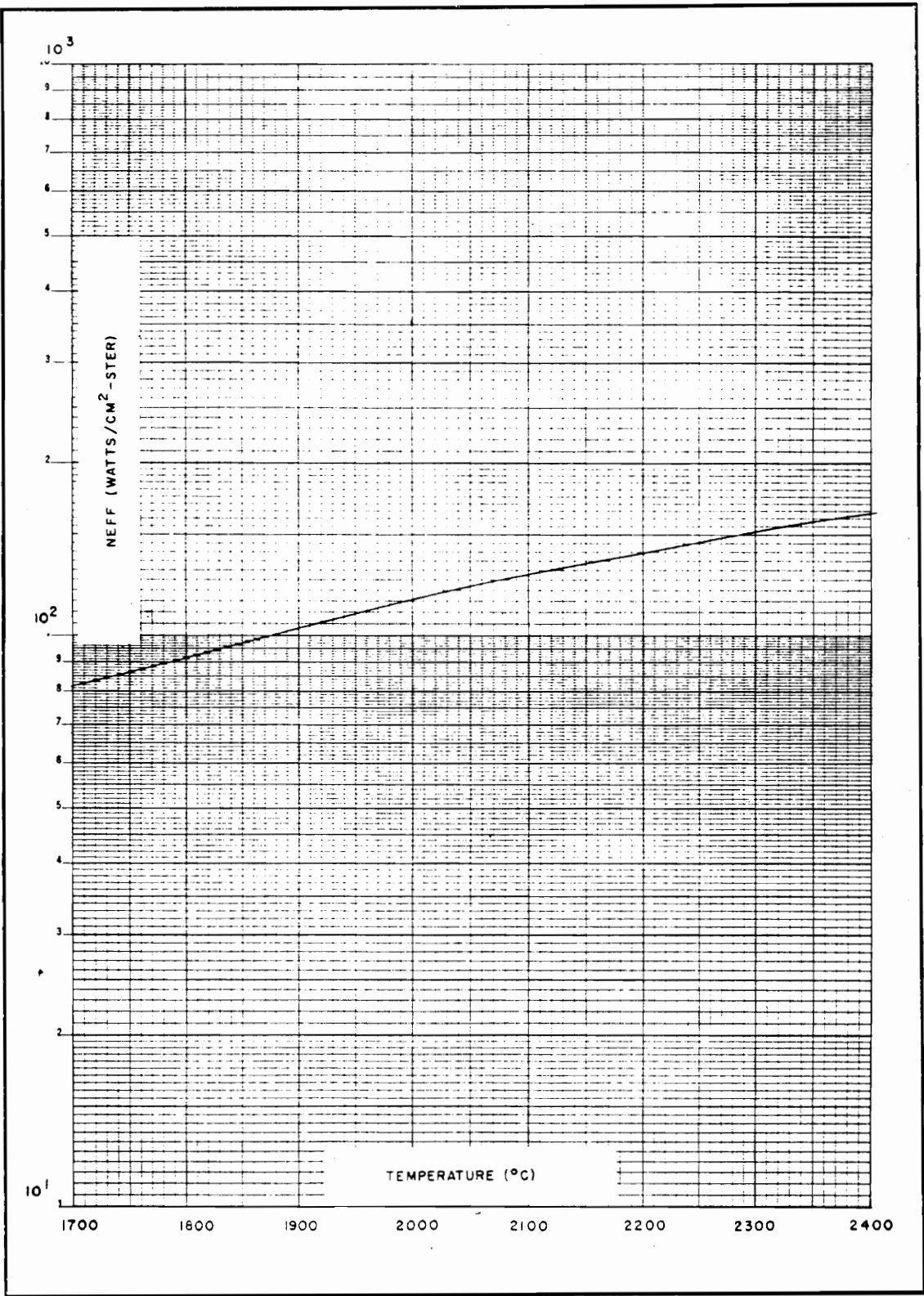
```

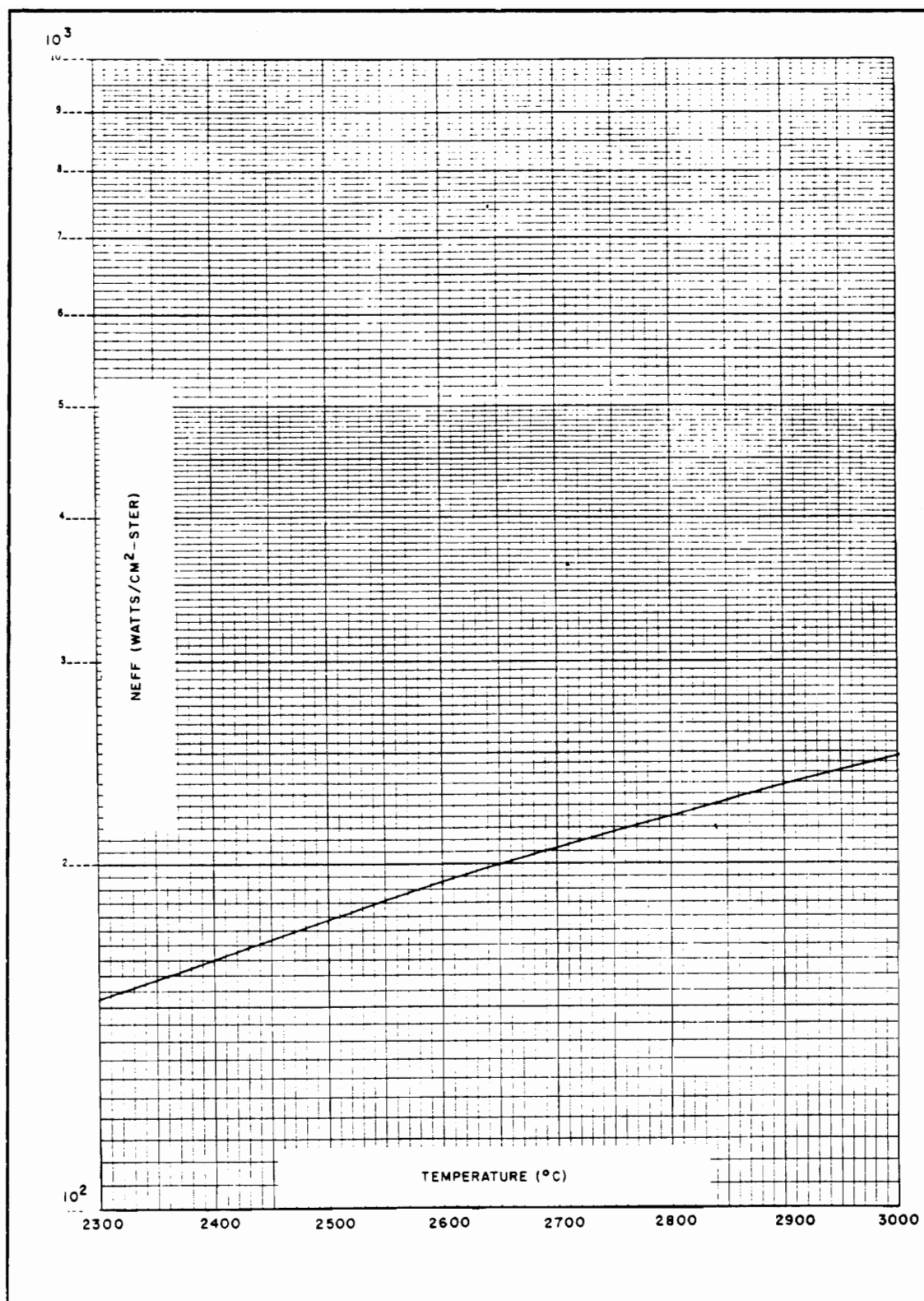
Appendix H. Radiance Curves for the Infrared Microscope [88]











Appendix I. Procedure for Determining a Disk's Transmittance

The transmittance of the sapphire disk is measured using the infrared microscope and blackbody calibration source in accordance with the following procedure:

1. The infrared microscope is turned-on and allowed to warm-up for thirty minutes.
2. The blackbody calibration source is set to a specified temperature. At least ten minutes is allowed for the blackbody source to reach an equilibrium temperature.
3. The microscope is focused on the center of the blackbody.
4. Radiance from the blackbody source is measured using the microscope.
5. The sapphire disk is placed on the calibration source's insulated body and radiance transmitted from the blackbody through the disk is measured.
6. The sapphire disk and infrared microscope are moved away from the blackbody source to prevent them from heating up.

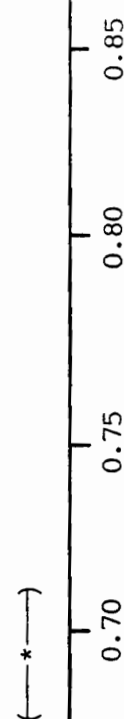
7. The blackbody source is set to different temperature levels and steps 4 through 6 are repeated.
8. Transmittance, T, at each temperature level is calculated as shown below:

$$T = \frac{\text{Radiance from the Blackbody Transmitted through the Sapphire Disk}}{\text{Radiance from the Blackbody}}$$

Transmittance data obtained using this procedure is shown in Tables I-1 and I-2.

Table I-1: Transmittance Data for a Sapphire Disk [§]					
TEMPERATURE OF BLACKBODY (DEG. C)	Transmittance Measurements for Different Positions of the Microscope's Target Spot (points A-D are for the contact region of the disk as shown in Fig. 40)				
	CLEAR AREA	POINT A	POINT B	POINT C	POINT D
60	.818	.768	.764	.735	.638
65	.828	.764	.763	.736	.697
70	.824	.749	.752	.724	.695
75	.833	.769	.763	.726	.725
80	.826	.754	.751	.714	.707
85	.831	.767	.754	.718	.701
90	.835	.763	.754	.719	.692
100	.835	.765	.757	.736	.699
105	.837	.766	.759	.733	.708
110	.829	.771	.752	.720	.672
§-(see Table I-2 for a statistical summary of these measurements)					

Table I-2: Summary of Transmittance Results for the Sapphire Disk (see Table I-1 for the complete data set) (Temperature Range: 60 - 110 C)			
Position of Microscope's Target Spot	Average Transmittance ± 95% Confidence Interval	Standard Deviation	Individual 95% Confidence Intervals
Clear Area	0.830 ± .005	0.0058	(*)
Point A	0.764 ± .005	0.0069	(*)
Point B	0.757 ± .004	0.0051	(*)
Point C	0.726 ± .006	0.0083	(*)
Point D	0.693 ± .017	0.0237	(*)



Appendix J. Emissivity Data

Table J-1:Emissivity Data for an <u>Unused</u> Zirconia Specimen			
EMISSIONITY (ϵ_p = 0.95)§	EMISSIONITY (ϵ_p = 0.90)	TEMPERATURE OF SPECIMEN (DEG. C)	
.700	.663	35.7	
.708	.671	40.3	
.722	.684	48.1	
.713	.675	52.0	
.713	.675	56.2	
.724	.686	59.7	
.715	.677	61.3	
.714	.676	63.6	
.705	.668	63.9	
.717	.680	68.2	
.698	.661	70.1	
.719	.681	72.2	
.719	.681	73.7	
.719	.681	74.4	
.716	.679	75.7	
§(ϵ_p - emissivity assumption for the black spot)			
<u>Assumed Emissivity of Black Spot</u>	<u>Number of Measurements</u>	<u>Ave. Emissivity ± 95% Confidence Interval</u>	<u>Standard Deviation</u>
0.95	15	0.71 ± .004	0.0078
0.90	15	0.68 ± .004	0.0074

Table J-2: Emissivity Data for a Worn Zirconia Specimen [§]						
TEMPERATURE OF SPECIMEN (DEG. C)	Emissivity Measurements for Different Positions of the Microscope's Target Spot (points A-E are for the worn region of the specimen as shown in Fig. 39) (assumed emissivity of black spot is 0.90)					
	UNWORN AREA	POINT A	POINT B	POINT C	POINT D	POINT E
42.6	.470	.511	.492	.507	.551	.470
48.6	.490	.525	.508	.529	.567	.504
52.4	.494	.528	.505	.523	.560	.505
55.1	.503	.533	.513	.528	.559	.513
58.9	.505	.531	.514	.529	.566	.509
61.4	.518	.548	.528	.544	.580	.520
63.4	.522	.546	.543	.559	.585	.524
64.5	.533	.566	.554	.573	.587	.538
70.2	.565	.614				
70.5	.561	.608				
70.9	.546	.597				
70.9	.556	.604				
71.1	.554	.600				
71.2	.555	.602				
71.5	.556	.604				
§-(see Table J-3 for a statistical summary of these measurements)						

Table J-3: Summary of Emissivity Results for a Worn Zirconia Specimen (see Table J-2 for the complete data set) (Temperature Range: 43 - 65 C)			
Position of Microscope's Target Spot	Ave. Emissivity ± 95% Confidence Interval §	Standard Deviation	Individual 95% Confidence Intervals
Unworn Area	0.50 ± .02	0.020	(-----*-----)
Point A	0.54 ± .02	0.017	(-----*-----)
Point B	0.52 ± .02	0.021	(-----*-----)
Point C	0.54 ± .02	0.021	(-----*-----)
Point D	0.57 ± .02	0.013	(-----*-----)
Point E	0.51 ± .02	0.020	(-----*-----)
§ --- assumed emissivity of black spot is 0.90			0.500 0.525 0.550 0.575

Table J-4: Emissivity Data for Tungsten Carbide (Data Set No. 1)			TEMPERATURE OF SPECIMEN (DEG. C)
EMISSIONITY ($\epsilon_p = 0.95$)§	EMISSIONITY ($\epsilon_p = 0.90$)		
.423	.400	53.5	
.421	.399	62.4	
.360	.341	73.1	
.354	.335	76.8	
.391	.370	77.5	
.437	.414	93.5	
.439	.416	102.5	
.432	.410	109.6	
.438	.415	114.8	
.429	.407	117.8	
.430	.407	120.3	
§-(ϵ_p - emissivity assumption for the black spot)			
<u>Assumed Emissionity of Black Spot</u>	<u>Number of Measurements</u>	<u>Ave. Emissionity ± 95% Confidence Interval</u>	<u>Standard Deviation</u>
0.95	11	0.41 ± .02	0.031
0.90	11	0.39 ± .02	0.029

Table J-5: Emissivity Data for Tungsten Carbide (Data Set No. 2)			TEMPERATURE OF SPECIMEN (DEG. C)
EMISSIONITY ($\epsilon_p = 0.95$) [§]	EMISSIONITY ($\epsilon_p = 0.90$)		
.346	.328	42.7	
.343	.325	45.6	
.370	.350	49.0	
.360	.341	52.5	
.460	.436	57.2	
.419	.397	62.0	
.484	.458	62.7	
.480	.454	64.3	
.365	.346	65.4	
.348	.329	66.0	
.377	.358	66.5	
.356	.337	70.6	
.399	.378	73.0	
.457	.433	74.8	
.345	.326	76.1	
.337	.319	79.0	
.332	.314	79.8	
.319	.302	79.8	
.339	.321	79.8	
.327	.310	80.4	
§-(ϵ_p - emissivity assumption for the black spot)			
<u>Assumed Emissivity of Black Spot</u>	<u>Number of Measurements</u>	<u>Ave. Emissivity ± 95% Confidence Interval</u>	<u>Standard Deviation</u>
0.95	20	0.38 ± .03	0.053
0.90	20	0.36 ± .03	0.050

Table J-6: Emissivity Data for Alumina

Table J-6: Emissivity Data for Alumina			
EMISSIONITY ($\epsilon_p = 0.95$) [§]	EMISSIONITY ($\epsilon_p = 0.90$)	TEMPERATURE OF SPECIMEN (DEG. C)	
.744	.705	40.3	
.853	.808	43.6	
.852	.807	46.7	
.739	.700	48.2	
.721	.683	50.4	
.721	.683	52.2	
.717	.680	54.1	
.719	.681	55.9	
.703	.666	58.9	
.751	.712	85.1	
.716	.678	91.0	
.709	.672	93.7	
.711	.674	103.5	
.725	.687	112.7	
.717	.679	125.4	
.723	.685	135.4	
.755	.715	140.3	
.780	.739	143.9	
.780	.739	146.3	
.806	.764	147.3	
.833	.789	148.0	
.868	.822	148.7	
§-(ϵ_p - emissivity assumption for the black spot)			
<u>Assumed Emissivity of Black Spot</u>	<u>Number of Measurements</u>	<u>Ave. Emissivity ± 95% Confidence Interval</u>	<u>Standard Deviation</u>
0.95	22	0.76 ± .02	0.053
0.90	22	0.72 ± .02	0.050

Appendix K. Data used for the Bar Charts in Section 4.

Table K-1: Data used for the Bar Charts in Section 4.8														
EXP [§] DES.	ε _t	TRANS	T _{ABS} (K)	T _{MAX} (K)	T _{AVE} (K)	T _{MIN} (K)	f	D _{BMAJ} (μm)	D _{BMIN} (μm)	V (μm) ³	x (m)	V/x (μm) ³ /m	Q̇ _{MAX} (W)	Q̇ _{AVE} (W)
Z1	.51 .71	.693 .830	111.9 87.4	99.7 76.6	86.4 64.8	70.6 50.8	1.0	953.	914.	1.28(10) ⁷	13.57	9.43(10) ⁵	7.12	4.53
Z1P	.51 .71	.693 .830	86.1 64.7	75.9 55.4	65.5 46.1	46.9 29.7	-	-	-	-	-	-	-	-
Z2	.51 .71	.693 .830	96.0 70.5	83.3 62.1	69.0 49.4	51.9 34.2	.96	950.	925.	1.27(10) ⁷	14.04	9.05(10) ⁵	3.53	2.25
Z2P	.51 .71	.693 .830	100.3 77.0	80.9 59.8	66.4 46.9	48.7 31.3	-	-	-	-	-	-	-	-
Z3	.51 .71	.693 .830	105.5 81.8	82.6 61.4	61.2 42.5	30.1 15.0	.54	749.	724.	4.89(10) ⁶	6.67	7.33(10) ⁵	1.91	1.21
Z4	.51 .71	.693 .830	83.8 62.5	54.6 36.5	34.2 18.6	20.9 6.9	.85	660.	622.	2.94(10) ⁶	6.24	4.71(10) ⁵	1.38	.88
Z5	.51 .71	.693 .830	87.7 66.0	73.6 53.4	58.5 40.0	41.6 25.0	.94	521.	483.	1.14(10) ⁶	4.96	2.30(10) ⁵	2.44	1.55
Z6	.51 .71	.693 .830	94.8 72.2	83.0 61.7	69.5 49.7	48.4 31.0	.95	584.	584.	1.80(10) ⁶	6.74	2.67(10) ⁵	1.70	1.08
Z7	.51 .71	.693 .830	11.5 3.9	8.8 3.7	7.5 3.6	6.2 3.5	.73	216.	152.	3.37(10) ⁴	1.73	1.95(10) ⁴	.651	.415
Z8	.51 .71	.693 .830	88.3 66.5	77.0 56.4	46.8 29.7	25.4 10.9	.80	508.	483.	1.03(10) ⁶	2.64	3.90(10) ⁵	.547	.348
W1	.36	.830	25.9	22.0	19.5	16.9	.24	155.	150.	8.93(10) ³	12.60	7.09(10) ²	1.59	1.01
W2	.36	.830	18.3	16.7	15.5	14.4	.20	107.	105.	2.03(10) ³	14.60	1.39(10) ²	.783	.499
A1	.72	.830	51.5	29.3	22.8	17.3	.84	938.	913.	1.21(10) ⁷	14.20	8.52(10) ⁵	6.28	4.00
A2	.72	.830	30.0	22.5	18.5	14.4	.81	297.	242.	1.20(10) ⁵	11.2	1.07(10) ⁴	2.38	1.52
S1	.064	.830	134.1	130.5	129.1	127.9	.88	900.	778.	1.02(10) ⁷	11.0	9.27(10) ⁵	5.24	3.33
S2	.064	.830	138.0	119.9	118.1	116.6	.97	709.	645.	3.92(10) ⁶	11.2	3.50(10) ⁵	2.86	1.82

§-(Table K-2 is the key for the experiment designations shown in this table.
Table K-3 defines the nomenclature used in this table.)

§-(Table K-2 is the key for the experiment designations shown in this table.
Table K-3 defines the nomenclature used in this table.)

Table K-2: Key for Experiment Designations shown in Table K-1
(unless otherwise noted, all experiments were performed for two minutes)
(sapphire was used as the countersurface for all experiments)

EXP DES.	LOAD (N)	FREQUENCY (Hz)	PEAK AMPLITUDE (μm)	COMMENTS
Z1	40	195	145	preliminary 1 min. exp.
Z1P	40	200	150	
Z2	20	195	150	preliminary 1 min. exp.
Z2P	20	200	150	
Z3	40	100	139	
Z4	20	100	130	
Z5	40	195	53	
Z6	20	195	72	
Z7	40	100	36	
Z8	20	100	55	
W1	40	195	135	
W2	20	195	156	
A1	40	195	152	
A2	20	195	120	
S1	40	195	117	
S2	20	195	120	
Z - zirconia, W - tungsten carbide, A - alumina, S - sapphire				

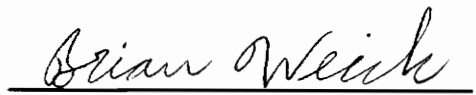
Table K-3: Nomenclature for Table K-1

EXP DES.	- experiment designation number - see Table K-2 for a description of each experiment
ϵ_t	- emissivity of the test specimen - Two values are shown for each of the zirconia-on-sapphire experiments as discussed in Section 4.1.1. These values represent the extrema of emissivities measured for zirconia.
TRANS	- transmittance measurements for the sapphire disk - Two values are shown for each of the zirconia-on-sapphire experiments as discussed in Section 4.1.4. These values represent the extrema of transmittances measured for the sapphire disk.
T_{ABS}	- absolute maximum temperature rise in degrees kelvin corresponding to the "hot" spots shown in Figs. 43 and 85
T_{MAX}	- average maximum temperature rise in degrees kelvin [§]
T_{AVE}	- average temperature rise in degrees kelvin [§]
T_{MIN}	- average minimum temperature rise in degrees kelvin [§]
f	- coefficient of friction - average value for 100 cycles
D_{BMAJ}	- major wear scar diameter on ball, (μm)
D_{BMIN}	- minor wear scar diameter on ball, (μm)
D_{DMAJ}	- major diameter of contact region on disk, (μm)
D_{DMIN}	- minor diameter of contact region on disk, (μm)
V	- volume of debris removed from the ball, (μm) ³
x	- total distance traveled by disk, (m)
V/x	- volume of debris removed per distance traveled, (μm) ³ /m
$\dot{Q}_{MAX}$	- maximum rate of heat generation = (friction coefficient)X (normal load)X(maximum velocity), units - (watts)
$\dot{Q}_{MIN}$	- average rate of heat generation = (friction coefficient)X (normal load)X(average velocity), units - (watts)

§ - Average values were calculated for 400 data points sampled at a rate of 8 kHz. These data points were sampled at the "hot" spots shown in Figs. 43 and 85.

Vita

The author was born on June 1, 1964 in Schenectady, N.Y. to Dr. Charles F. Weick and Mrs. Janet M. Weick. He received his Bachelor of Science degree in Mechanical Engineering from Union College in June 1986. After graduation, the author was employed by the Electric Boat Division of General Dynamics as a Project Design Engineer. In August 1988, the author began his graduate studies at Virginia Polytechnic Institute and State University with the expectation of receiving a Master of Science degree in Mechanical Engineering. The author is currently a member of Tau Beta Pi, Sigma Xi, and the American Society of Mechanical Engineers.

A handwritten signature in cursive script that reads "Brian Weick". The signature is written in dark ink and is positioned above a horizontal line.

Brian L. Weick