NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-655

Heat Transfer Model for Predicting Squib Ignition Times

V. Sernas

(NASA-CR-136834) HEAT TRANSFER MODEL FOR PREDICTING SQUIB IGNITION TIMES (Jet Propulsion Lab.) CSCL 20M N74-17640 Unclas G3/33 30000

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

January 15, 1974

N74-17640

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-655

Heat Transfer Model for Predicting Squib Ignition Times

V. Sernas

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

January 15, 1974

32

Prepared Under Contract No. NAS 7-100
National Aeronautics and Space Administration

PREFACE

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.

Preceding page blank

CONTENTS

Preceding page blank

ABSTRACT

This memorandum describes a squib ignition model based on transient heat conduction from the hot bridgewire to the pyrotechnic. No Arrhenius-type chemical reaction is included. Instead, a thermal contact resistance is postulated to exist between the hot bridgewire and the pyrotechnic. Ignition is assumed to occur when a 2.5-μm layer of pyrotechnic next to the bridgewire reaches a characteristic ignition temperature for that pyrotechnic.

This model was applied to the JPL squib, which uses a 50-μm (0.002-in.) diameter Tophet A bridgewire to ignite a boron, potassium perchlorate mix. A computer program was utilized that solves the transient heat condition problem with the boundary conditions stipulated by the model. The thermal contact conductance at the interface was determined by trial and error so that the experimentally determined ignition time for one firing condition would be properly predicted by the model. This matching test was a 3.5-A constant current firing at 21°C for which the thermal contact conductance value was found to be 31,200 W/m^2 - K (5,500 BTU/h-ft^2-°F). With this value of the thermal contact conductance, ignition times for other test conditions were predicted and compared with experimental data. The agreement was quite good for tests run between -129°C and +93.3°C at current levels of 3.5 and 5 A. The resultant radial temperature profiles within the bridgewire – pyrotechnic system are presented for a few test conditions. Axial heat conduction along the bridgewire is shown to be negligible.

I. INTRODUCTION

The phenomenon of pyrotechnic ignition has been modeled with various degrees of success by many investigators (Refs. 1 to 6). Some of these models were computer simulations (Refs. 4 and 6), while others were partially analytical models. This study is based on a computer model that differs from the previous studies in the way the heat transfer between the bridgewire and the pyrotechnic is handled. A finite thermal contact conductance is assumed to exist at this interface in the same way that it has been shown (Ref. 7) to exist at other solid-to-solid interfaces. It has been the objective of this study to reexamine the ignition process as it applies to JPL squibs and to formulate a heat transfer model of the bridgewire – pyrotechnic system. This model had to predict the time to ignition for low current level squib firings at ambient temperatures from 144.3 K to 366.5 K (-200°F to +200°F).

II. THE BRIDGEWIRE – PYROTECHNIC SYSTEM

Since the pyrotechnic ignition occurs next to the bridgewire, one needs to look at only that portion of the total squib that is in contact with the bridgewire and that can receive heat from the bridgewire. During the very short period of time that the firing current passes through the bridgewire, heat is generated within the bridgewire. Some of this heat is conducted into the Inconel pins (see Fig. 1), some into the alumina header, but most of the heat leaving the bridgewire is conducted to the pyrotechnic. It will be shown that only a small portion of the total heat generated within the bridgewire is conducted out, and that the majority of the generated heat goes into heating up the bridgewire. If axial conduction of heat to the pins is neglected within the bridgewire, the bridgewire should be at the same temperature along its length. (It will be shown in Subsection V-C that axial conduction is indeed negligible.) Thus we should be concerned only with a unit length of bridgewire surrounded with a concentric shell of pyrotechnic and alumina as shown in Fig. 2. The outer radius of the pyrotechnic mass should be the distance to which heat diffuses during the time that the bridgewire is heated. For ignition times of less than 2 ms and a pyrotechnic diffusivity of 0.518×10^{-6} m^2/s (0.02 ft^2/h) this distance amounts to about 5 bridgewire radii (Ref. 8, p. 337).

In the alumina header the heat penetration distance is difficult to estimate because a round bridgewire can make, at best, only a line contact with the alumina. Since the thermal diffusivity of the alumina is very large, the actual amount of alumina that has to be included within the system may be considerable.

The presence of the alumina makes the heat flow from the bridgewire two-dimensional. In other words, the quantity of heat flowing out of the top of the bridgewire is not the same as that flowing out of the bottom. There is evidence that the bridgewire lifts off the alumina while being welded to the pins. When the loose pyrotechnic powder is dropped in over the bridgewire, it is possible that a portion of the bridgewire is totally surrounded with pyrotechnic and that the bridgewire would make no contact with the alumina header. When the bridgewire is lifted off the alumina by a distance ℓ or greater, the bridgewire – pyrotechnic system becomes the one shown in Fig. 3. It is this system that will be considered in the remainder of this report. The heat flow in this system is one dimensional. The heat generated in the bridgewire flows radially out into the pyrotechnic and continues to flow radially through the pyrotechnic.

III. THE COMPUTER MODEL

The temperature distributions in the bridgewire – pyrotechnic system shown in Fig. 3 were simulated on the Univac 1108 computer using a library transient heat conduction program called HEAT. The system was broken up into twenty nodes, each representing a concentric shell of mass. Figure 4 shows a typical pie-shaped section of the bridgewire – pyrotechnic system and how it was divided into nodes. The bridgewire was broken up into two nodes of equal mass, and the pyrotechnic was broken up into seventeen nodes of varying mass. Nodes 12 through 19 that are not shown in Fig. 4 were made of shells 1.016×10^{-3}-cm (4×10^{-4}-in.) thick. The twentieth node was a heat sink kept at the ambient temperature. As shown in Fig. 4, node 3 is the pyrotechnic node that is in contact with the bridgewire. It is this node that becomes the hottest and reaches ignition temperature first. The thickness of node 3 was chosen as 2.5 μm (10^{-4} in.).

It is assumed that there is one characteristic ignition temperature for a particular pyrotechnic mix. Furthermore, it is assumed that once a 2.5-μm- (1×10^{-4}-in.-) thick layer of the pyrotechnic reaches this ignition temperature, a self-sustaining exothermic reaction will commence in the pyrotechnic (i. e., the pyrotechnic will ignite).

Each node of the computer program must be supplied with a heat capacity. A thermal conductance between adjacent nodes must also be specified. The thermal capacity of a node is its mass times its specific heat. The thermal conductance between two nodes is defined as $kA/\Delta r$ where k is the thermal conductivity of the solid making up the two nodes, A is the average cross-sectional area normal to a line joining the two nodes, and Δr is the distance between the two nodes. Thus it is necessary to know the following thermal properties both for the bridgewire and the pyrotechnic:

(1) Density.

(2) Specific heat and its variation with temperature.

(3) Thermal conductivity and its variation with temperature.

In addition, the thermal contact conductance, h, at the bridgewire – pyrotechnic interface must be known in order that the conductance between node 2 and node 3 in Fig. 4 can be specified. The thermal conductance between nodes 2 and 3 is defined as hA_c where A_c is the area of contact between the bridgewire and the pyrotechnic. If the thermal contact conductance were infinite, nodes 2 and 3 would be at the same temperature, but when h is finite (as it always is for two solids in contact with each other) there is a discontinuity in temperature across the interface.

IV. THERMAL PROPERTY ESTIMATES

As it has been mentioned above, a total of eight thermal properties or parameters are required to make this simplified, one-dimensional model work. Of these eight, only four are reasonably well known for the JPL squib at room temperature. These are:

(1) Density of Tophet A = 8.4 g/cm^3.

(2) Specific heat of Tophet A = 0.447 J/g-K at 293.15 K (0.107 cal/gm-°C at 20°C).

(3) Thermal conductivity of Tophet A = 0.134 W/cm-°C.

(4) Density of B-$KClO_4$-Viton pyrotechnic = 1.95 g/cm^3.

However, no specific information is available on the variation of these properties with temperature.

The remaining four properties are (1) specific heat of pyrotechnic, (2) thermal conductivity of pyrotechnic, (3) ignition temperature of pyrotechnic, and (4) thermal contact conductance.

The specific heat of the pyrotechnic was estimated from the specific heat of each component as a percentage of the total weight. The value arrived at was 0.84 J/g-K (0.2 cal/gm-°C). The accuracy of this estimate is suspect. Furthermore, any phase changes that may be present in the Viton binder at temperatures below the ignition temperature could change the effective specific heat of the pyrotechnic at elevated temperatures.

The thermal conductivity of the pyrotechnic has never been measured. It was estimated from "no-fire" Bruceton tests to be 0.882 W/m-K (0.51 BTU/h-ft-°F). This estimate was based on the experimental fact that a current of 1.7 A will fire a squib 50% of the time. The other 50% of the time the current can flow through the squib indefinitely. This means that, on the average, the heat generated by 1.7 A in the bridgewire raises the pyrotechnic next to the bridgewire to its ignition temperature. It is important to note that a thermal contact conductance value is not necessary for this steady-state heat transfer problem (Ref. 9, p. 190). This estimate can be grossly in error because the amount of heat drawn away by the alumina header at long times is unknown. In other words, the boundary of the system shown in Fig. 3 would increase with time and include the alumina header that, in turn, would affect the temperature distribution in the pyrotechnic and the bridgewire by an amount that cannot be calculated accurately at this time.

The characteristic ignition temperature for the B-$KClO_4$-Viton pyrotechnic was estimated to be about 672.03 K (750°F). This estimate was based on the fact that small tablets of the pyrotechnic ignited within 10 s after being dropped into a Woods-metal bath kept at 699.81 K (800°F).

The thermal contact conductance between the bridgewire and the pyrotechnic has never been measured experimentally. Because the pyrotechnic is placed on the bridgewire in a form of a fine powder and pressed down against it at 1.378×10^8 N/m^2 (20,000 psi), it was expected that the contact conductance would be much larger than those reported (Refs. 7 and 9) for metal-to-metal contact of machined surfaces. The proper value for h was determined by matching the computer predicted time for ignition with the experimentally measured time to bridgewire burnout (1.6 ms) for a current level of 3.5 A and a 294.3 K (70°F) ambient temperature. This means that an h was found by trial and error that made the computer program predict a temperature of 672.03 K (750°F) in node 3 after 1.6 ms of a constant 3.5-A input into the bridgewire. The only value for h that satisfies these conditions (when used with the above values for the thermal properties) was found to be 31,200 W/m^2-K (5,500 BTU/h-ft^2-°F). As it can be seen from Fig. 5, smaller values for h yield lower temperatures for node 3 at 1.6 ms, and, as a result, the computer predicted that the time to reach an ignition temperature of 672.03 K (750°F) would be larger than 1.6 ms.

V. RESULTS

With the eight thermal properties and parameters fixed at the values indicated in the previous Section, the computer program was run with different initial temperatures and higher current levels to test its ability to predict ignition times at those conditions. Table 1 shows a comparison between the computer predicted ignition time and the experimentally measured time to bridgewire burnout for MM'71 squib tests ranging from

144.25 K to 366.48 K (-200°F to +200°F) for both 3.5 and 5 A. The agreement in the current range is quite good. The program's performance at higher and lower currents will be discussed in Subsection V-D.

A. TEMPERATURE RESULTS

Figure 6 shows the temperature distribution within the bridgewire – pyrotechnic system at 0.4-ms time intervals for the 3.5-A, 294.3 K (70°F) ambient temperature condition. A number of important points about the system can be demonstrated with this figure. First, the discontinuity in temperature at the bridgewire – pyrotechnic interface is quite apparent. Second, there is very little temperature difference between the center of the bridgewire and the outside surface of the bridgewire. Finally, the heat does not diffuse past 1.016×10^{-2} cm (4×10^{-3} in.) within the pyrotechnic during the first 1.6 ms.

Figure 7 again demonstrates the dramatic temperature difference between the bridgewire and the hottest particles of the pyrotechnic. It also shows that the radial heat flux out of the bridgewire and into the pyrotechnic increases with time because it is directly proportional to the temperature difference between the bridgewire and node 3. The large magnitude of the heat flux (in the millions of W/m^2 ($BTU/h\text{-}ft^2$)) is due to the relatively large value of the thermal contact conductance.

Figures 8 and 9 show the temperature history within nodes 3 and 2 respectively when a 3.5-A current is added to a squib at 144.25 K, 294.3 K, and 366.48 K (-200°F, +70°F, and +200°F). It should be noted that the three curves on each figure are the same except for a temperature offset at time zero. This happens because the driving force for conduction heat transfer is a temperature difference. In other words, the temperature difference between the initial ambient temperature and the temperature at some time t is always the same for a given node regardless of the initial starting temperature.

Figure 10 shows the temperature (T) history of a bridgewire and the hottest pyrotechnic particles when a 3.5-A current is terminated after 1.0 ms. The heat in the hot bridgewire diffuses out into node 3 and raises the pyrotechnic's temperature above what it was when the pulse was terminated. The maximum temperature (T_{MAX}) in node 3 was reached 0.4 ms after the pulse was stopped. This type of behavior is consistent with the observed delayed firings that result when terminated pulses of low energy are used to fire squibs.

B. ENERGY RESULTS

Figures 11 and 12 show the total energy received by the bridgewire and the pyrotechnic as a function of time. The total electrical energy delivered to the bridgewire is I^2Rt, and the energy received by the pyrotechnic is the instantaneous heat flux out of the bridgewire (as shown in Fig. 7) integrated over time. It can be seen from Fig. 11 that at 294.3 K (70°F) ambient temperature (T_{AMB}) and 3.5-A input the total electrical input up to the ignition time is 26.4 mJ. About 30% of that energy, i.e., 8 mJ, will have been transferred into the pyrotechnic by the same time. These 8 mJ of energy diffused through the pyrotechnic to cause the temperature profile at 1.6 ms shown in Fig. 6. The energy curves of Figs. 11 and 12 are similar for the same reasons that the temperature curves of Figs. 8 and 9 are similar in Subsection V-A.

C. AXIAL TEMPERATURE DISTRIBUTION

One of the assumptions made in the one-dimensional heat conduction model shown in Fig. 4 is that axial heat conduction along the bridgewire is negligible. This assumption was tested by writing a more extensive program that incorporated all the same features as the previous one except that both radial and axial conduction was permitted in the bridgewire and pyrotechnic. A schematic of the new bridgewire – pyrotechnic system divided into 39 nodes is shown in Fig. 13. Since the axial temperature profile of the bridgewire is symmetric about its center, only one half of the bridgewire needed to be simulated. The library program HEAT permitted a maximum of forty nodes. Thus the nodes in the radial direction were made large to keep the total number of nodes below this allowable maximum. This coarser grid did not give as accurate a radial temperature distribution as the previous program.

The calculated axial temperature distribution in the bridgewire at 0.5-ms intervals for 3.5-A input is shown in Fig. 14. It can be seen that the temperature of the bridgewire drops sharply at both ends and that the central 90% of the wire is at the same temperature. Since there is no axial temperature gradient in the central 90% of the bridgewire, no axial heat conduction exists there, and thus the one-dimensional heat conduction assumption is valid over that portion of the bridgewire.

Axial conduction can become important in cases where the radial heat transfer coefficient (or thermal contact conductance) becomes very small. An example of this type is a bare Tophet A wire heated in still air. Figure 15 shows the axial temperature distribution for such a wire at 20-ms intervals. It is quite clear that the average bridgewire temperature is considerably smaller than the maximum bridgewire temperature, and that axial conduction is important over the whole wire.

D. PROGRAM DEFICIENCES

The bridgewire – pyrotechnic system of Fig. 3 has been shown to be an adequate system to predict squib initiation at 3.5- and 5-A current levels. For smaller currents, this one-dimensional system is inadequate because the heat diffusion from the bridgewire would be affected by the alumina header. The system shown in Fig. 2, or one like it, must be simulated on the computer to predict initiation in the vicinity of the "no-fire" current levels.

The computer program was also run at 15- and 20-A levels in an attempt to predict experimentally measured bridgewire burnout times at those current levels. The results were somewhat unrealistic at these high currents in that the computer program predicted the bridgewire would melt before the hottest pyrotechnic particles reaches 672.03 K (750°F). Two things can be done to obtain more reasonable computer results. First, an increase in h above the value of 31,200 W/m^2-K (5,500 BTU/h-ft^2-°F) used in the program would heat up the pyrotechnic faster and keep the bridgewire from becoming completely molten. Second, if the specific heat of Tophet A increases with temperature as much as it does for nickel and chromium (the two constituents of Tophet A), the bridgewire may be prevented from becoming molten. It is clear that the computer model should be extended to incorporate variable thermal properties for the system. The temperature variation of the specific heat of Tophet A must also be determined experimentally from room temperature up to the melting point.

VI. CONCLUSIONS

A transient heat conduction model for the prediction of squib initiation has been presented. The three main features of the model are:

(1) A thermal contact conductance between the bridgewire and the pyrotechnic is incorporated in the model.

(2) A single ignition temperature is assumed.

(3) The bridgewire and the pyrotechnic are treated together in a coupled system.

It has been shown that the model adequately predicts ignition at 3.5-A and 5-A levels for ambient temperatures between 144.25 K and 366.48 K (-200°F and +200°F). More accurate thermal properties for Tophet A and the pyrotechnic are required for accurate predictions at higher currents. At lower currents, the alumina header must be included in the system.

REFERENCES

1. Austing, J. L., et al., "A Heat Transfer Study of Hot Wire Ignition of a Metal-Metal Oxide Mixture," in Proceedings of the 5th Symposium on Electroexplosive Devices, Franklin Institute, Philadelphia, Pa., 1967.

2. Stresau, R. H., Peterson, R., and Chamberlain, D., "Electrical and Thermal Considerations in the Design of Electro-Explosive Devices," in Proceedings of the 5th Symposium on Electroexplosive Devices, Franklin Institute, Philadelphia, Pa., 1967.

3. Davenport, D. E., and Reynolds, H., "Quantitative Predictions of EED Firing Characteristics," in Proceedings of the 6th Symposium on Electroexplosive Devices, San Francisco, Calif., 1969.

4. Dansby, H. B., and Freeman, W. B., "Numerical Thermal Analysis of Electroexplosive Devices," in Proceedings of the 7th Symposium on Explosives and Pyrotechnics, Franklin Institute, Philadelphia, Pa., 1971.

5. Petrick, J. T., and Montgomery, R. L., "Recent Developments in Modeling the Hotwire Igniter," in Proceedings of the 7th Symposium on Explosives and Pyrotechnics, Franklin Institute, Philadelphia, Pa., 1971.

6. Osterkamp, A. M., and Peckham, H. D., "Pyrotechnic Deflagration Model," in Proceedings of the 7th Symposium on Explosives and Pyrotechnics, Franklin Institute, Philadelphia, Pa., 1971.

7. Fried, E., "A Joint Heat Transfer Data Critical Study and Design Guidelines," NASA-CR-119933. General Electric Valley Forge Space Center, Philadelphia, Pa., June 1971.

8. Carslaw, H. S., and Jaeger, J. C., Conduction of Heat in Solids, 2nd Edition, Oxford University Press, Oxford, England, 1959.

9. Fletcher, L. S., "A Review of Thermal Control Materials for Metallic Junctions," AIAA Paper No. 72-284, presented at the AIAA 7th Thermophysics Conference, April 10 – 12, 1972, San Antonio, Texas, 1972.

Table 1. MM'71 firing data comparison

Amperes	Ambient temperature, K (°F)	No. of firings	Average time to burnout, ms	Range, ms	Model prediction of time to reach 672.03 K (750°F), ms
3.5	294.3 (70)	20	1.59	1.45 – 1.79	1.6
3.5	144.25 (-200)	10	2.02	1.8 – 2.2	2.27
3.5	366.48 (+200)	Bridgewire burnout data not available			1.31
5	294.3 (70)	3	0.84	0.80 – 0.88	0.82
5	144.25 (-200)	4	1.08	1.05 – 1.1	1.1
5	366.48 (+200)	4	0.58	0.51 – 0.71	0.70

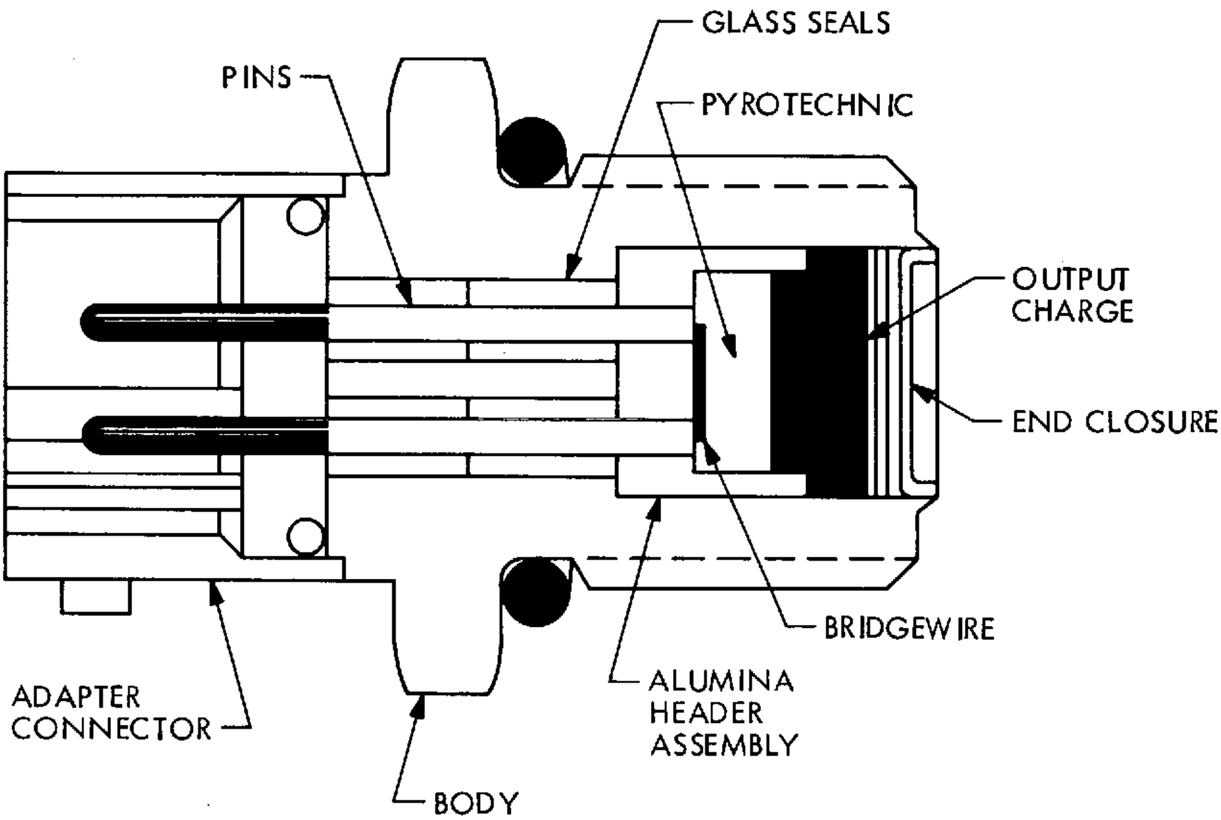

Fig. 1. Cutaway view of JPL squib

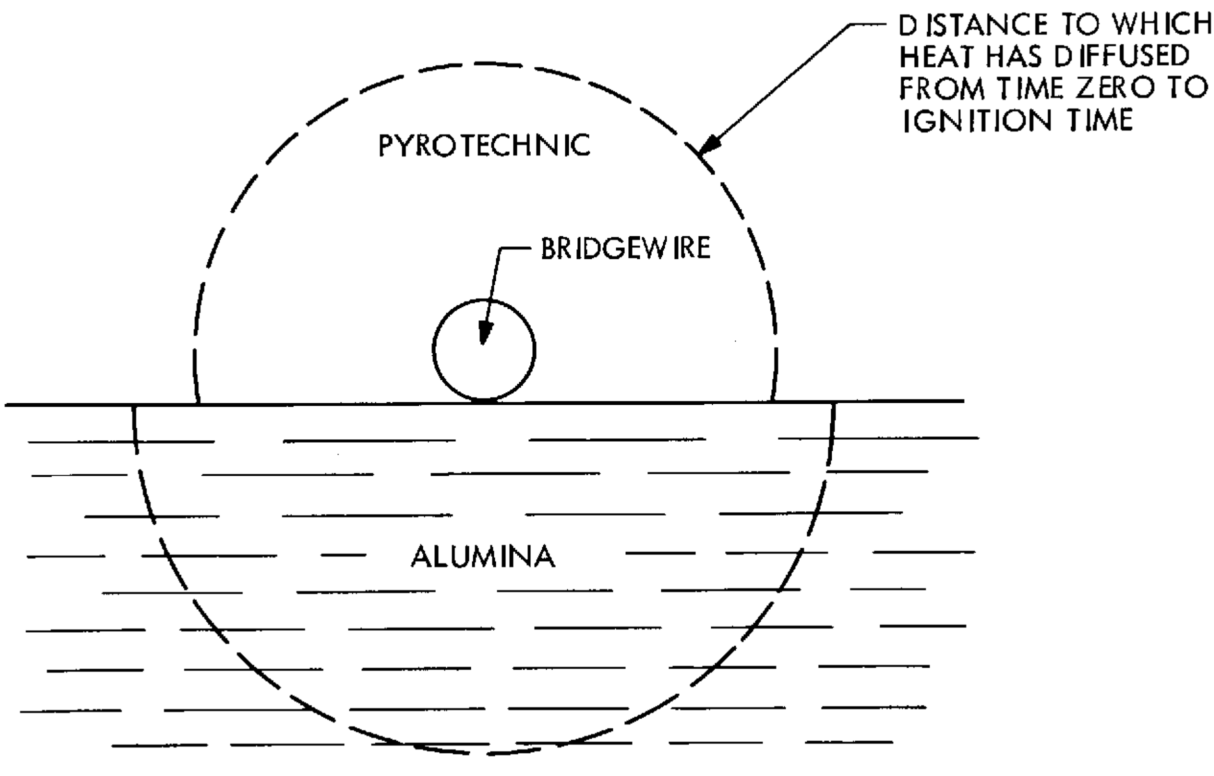

Fig. 2. The bridgewire — pyrotechnic — alumina system; axial heat conduction is neglected

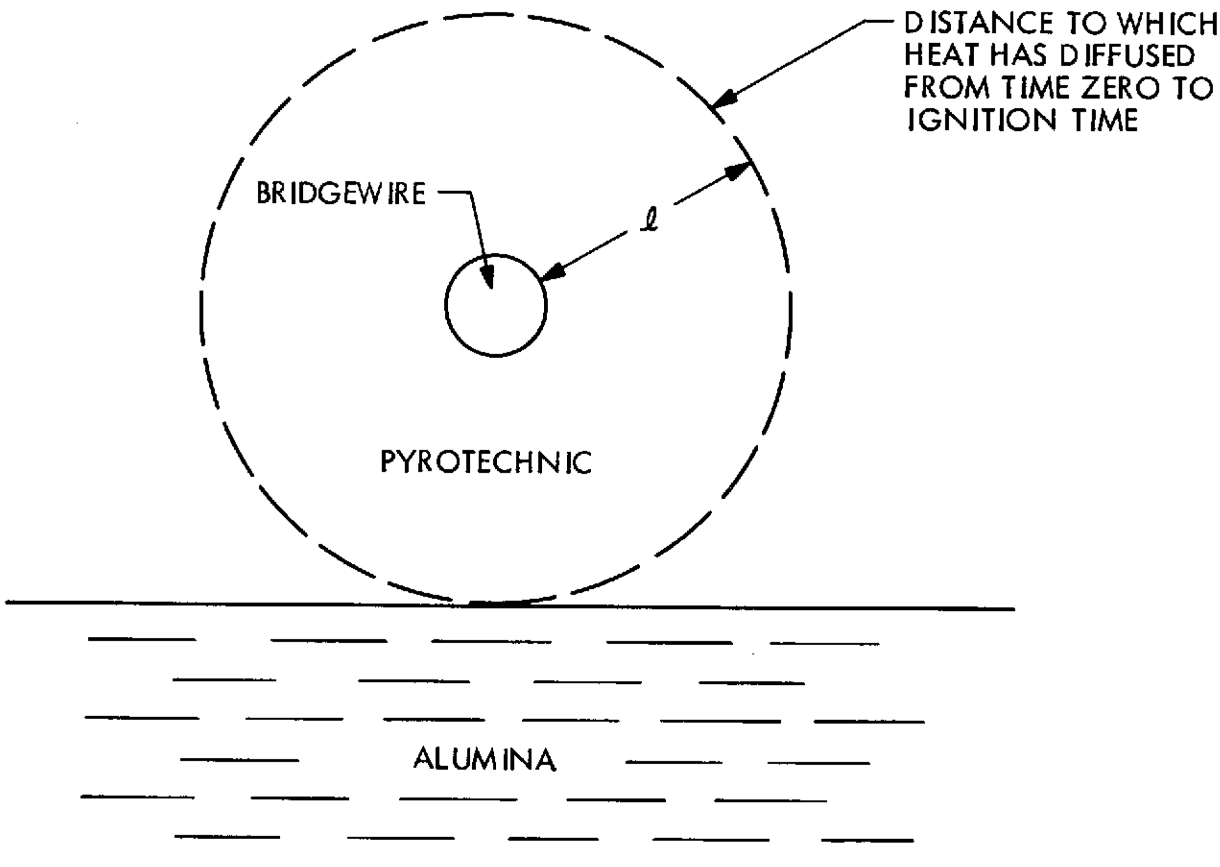

Fig. 3. The bridgewire – pyrotechnic system; axial heat conduction is neglected

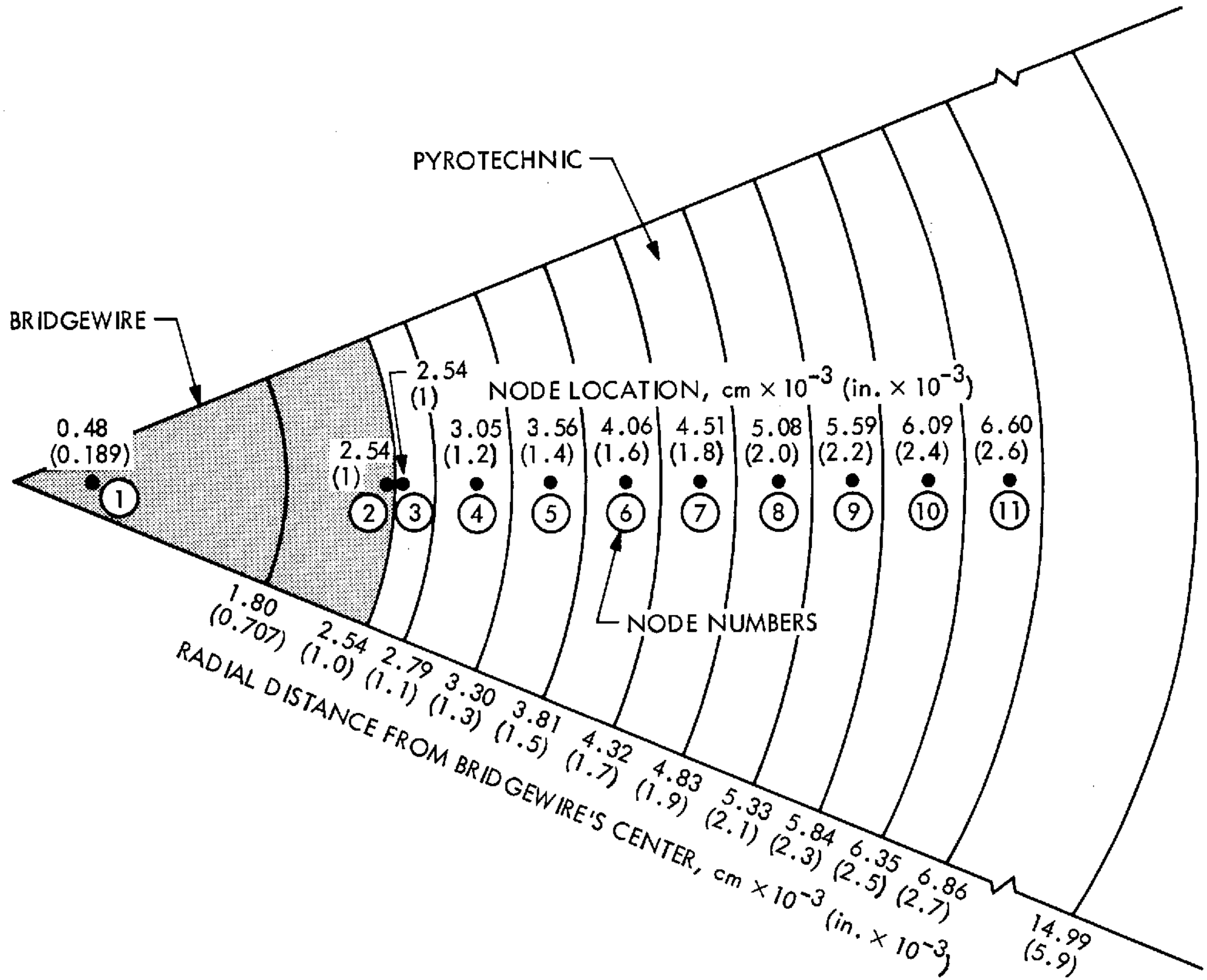

Fig. 4. The bridgewire – pyrotechnic system of Fig. 3 showing division into twenty nodes of variable mass

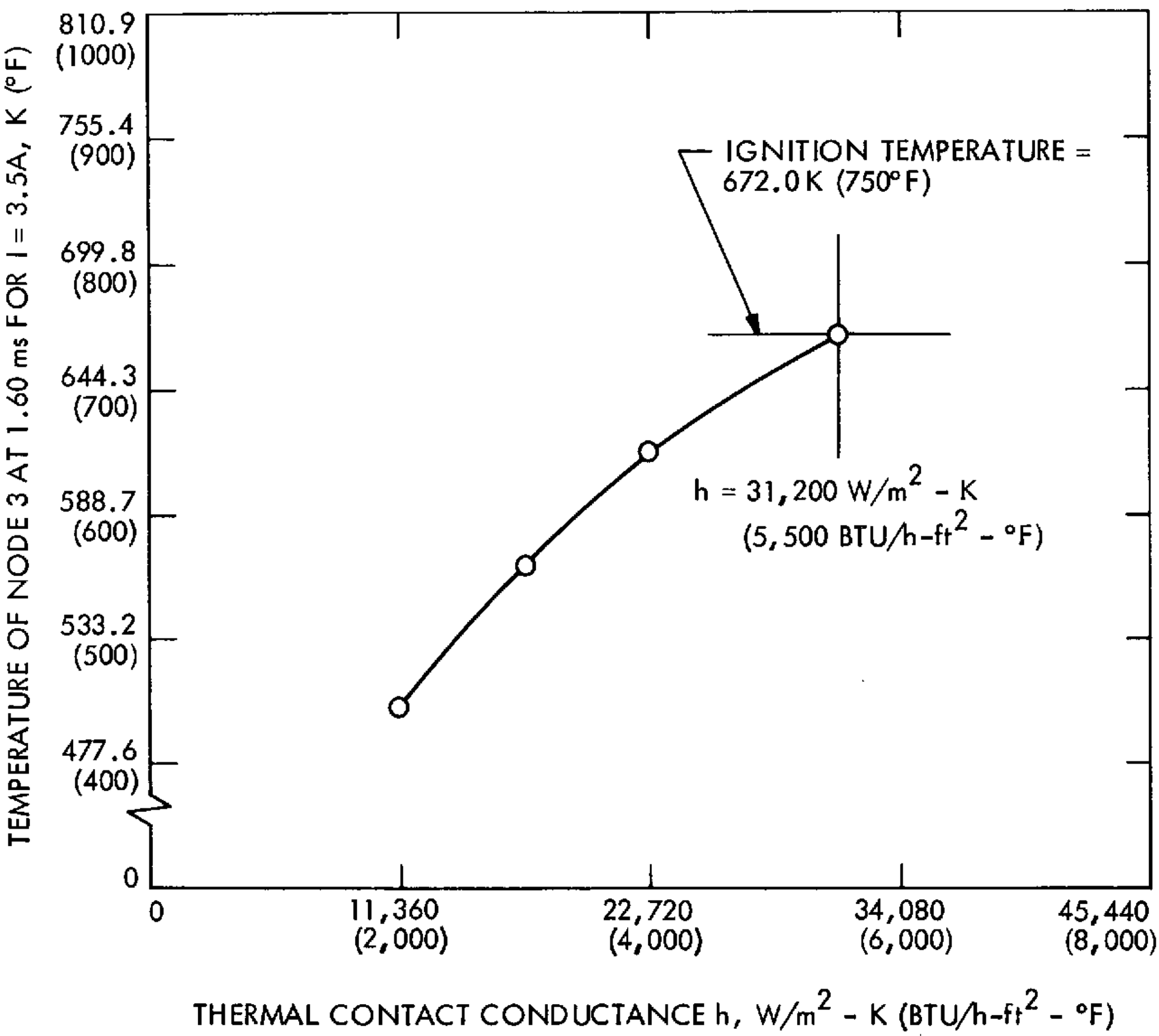

Fig. 5. Node 3 temperature at the bridgewire – pyrotechnic interface

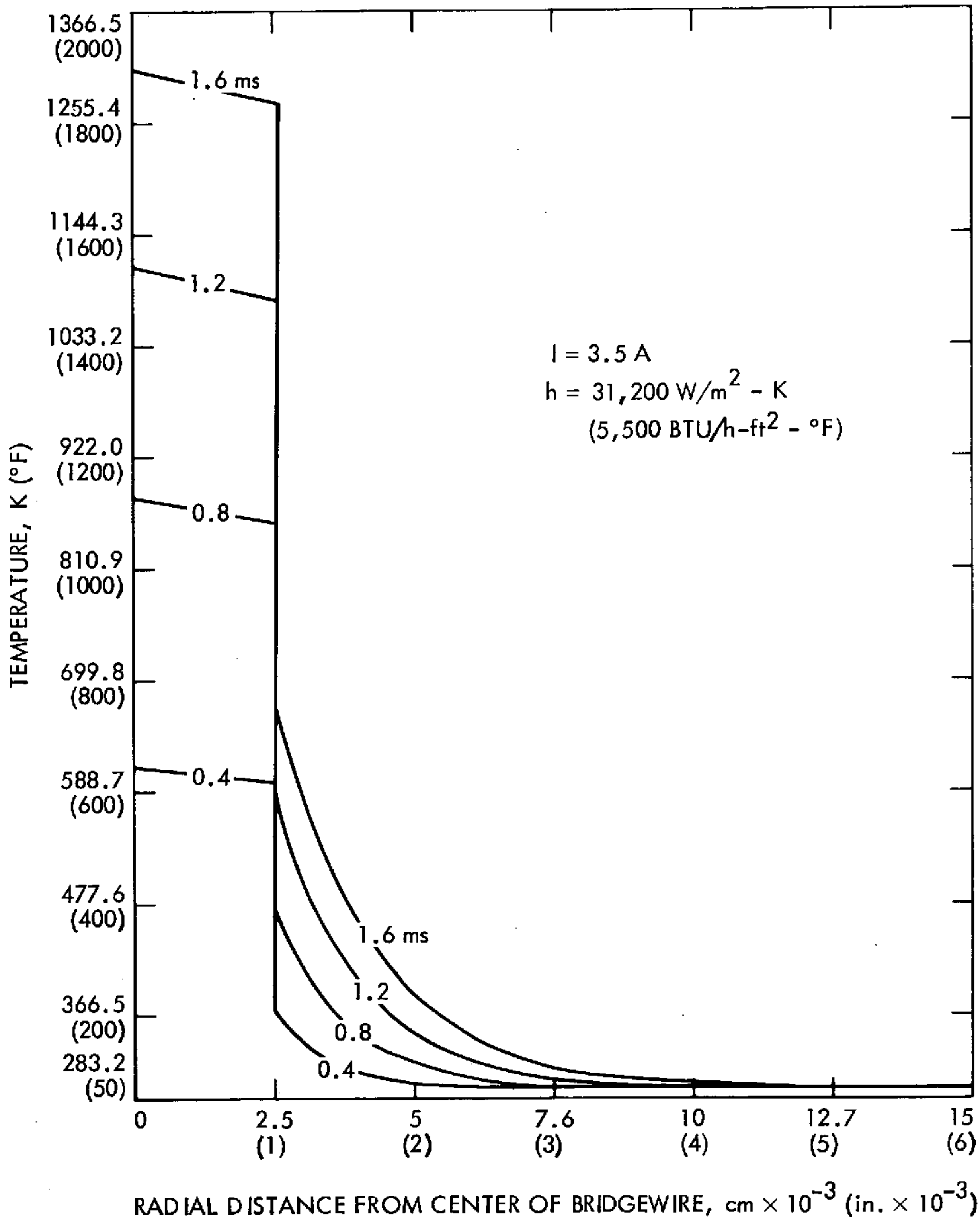

Fig. 6. Radial temperature distribution within the bridgewire — pyrotechnic system

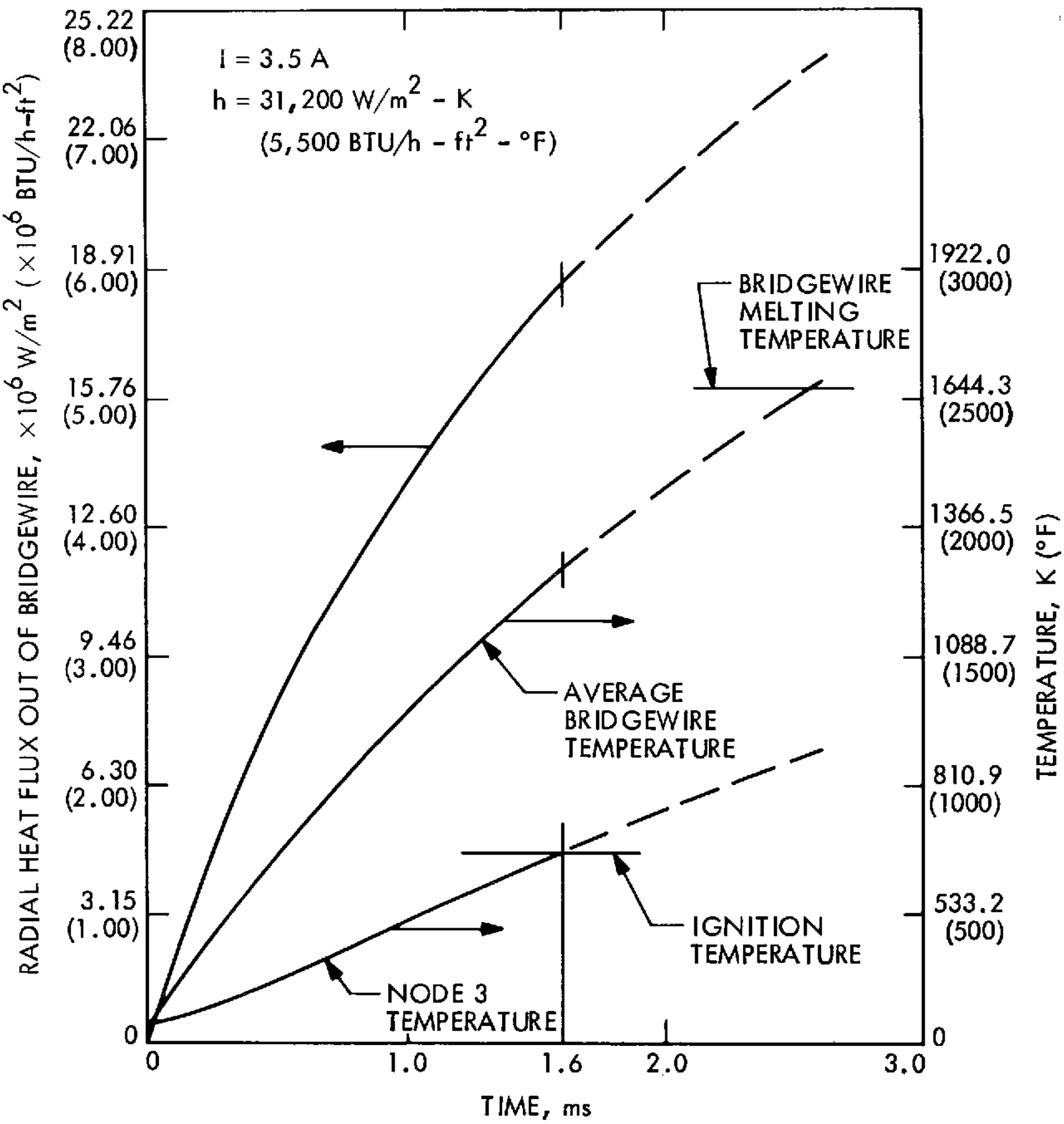

Fig. 7. Instantaneous radial heat flux and instantaneous temperature of bridgewire and node 3

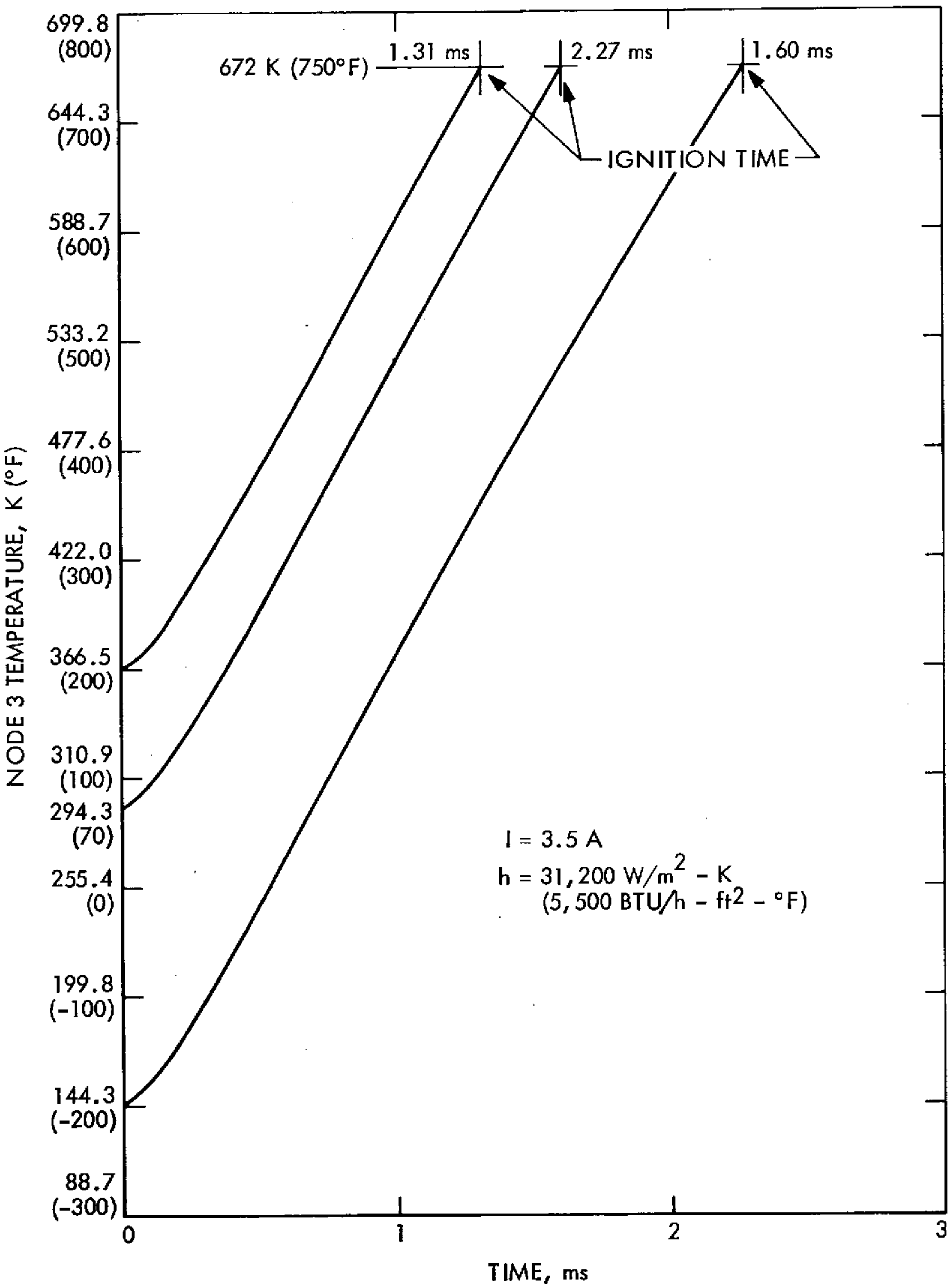

Fig. 8. Temperature history of node 3 for initial squib temperatures of 144. 25 K, 294. 3 K, and 366. 48 K

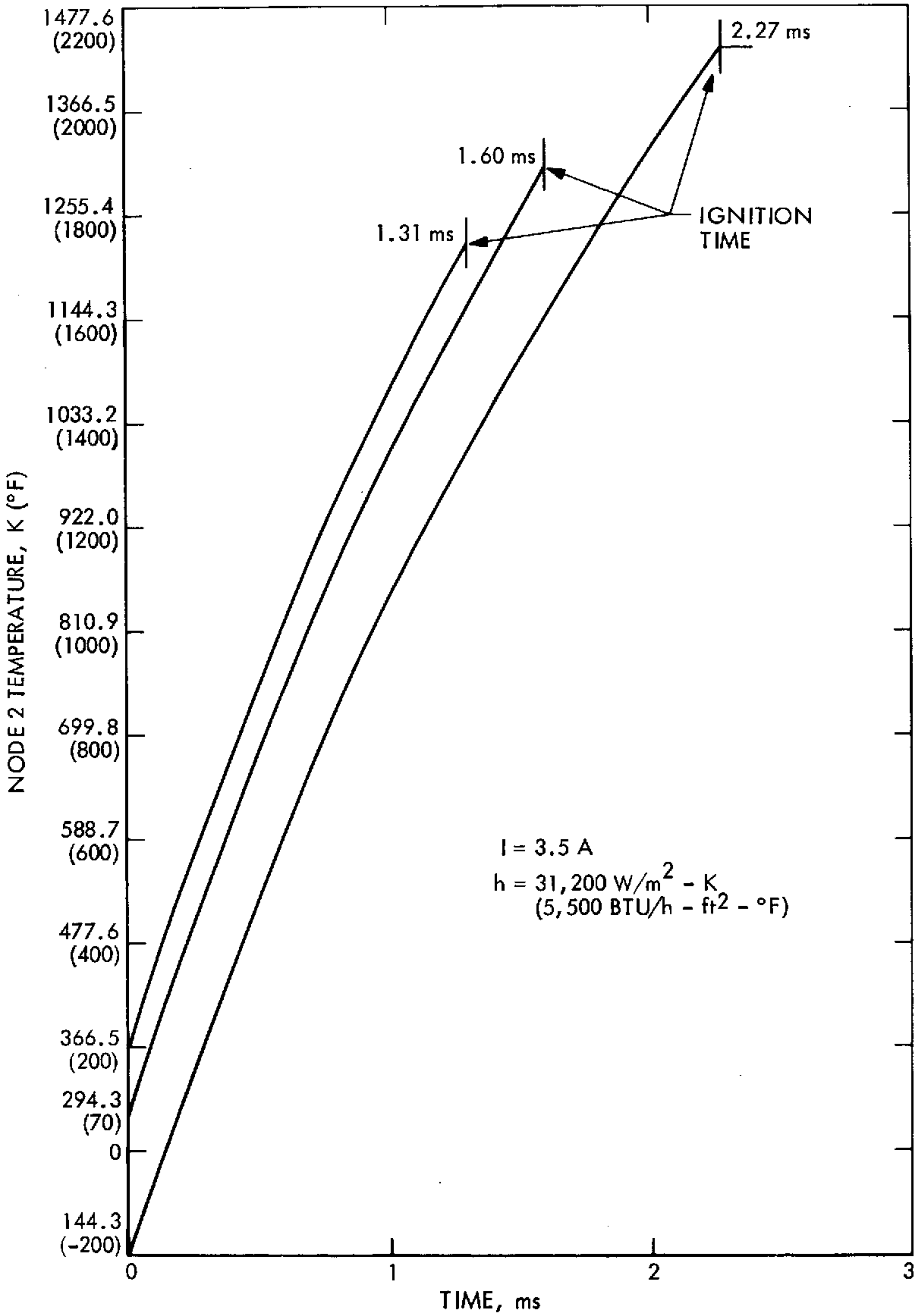

Fig. 9. Temperature history of node 2 for initial squib temperatures of 144. 25 K, 294. 3 K, and 366. 48 K

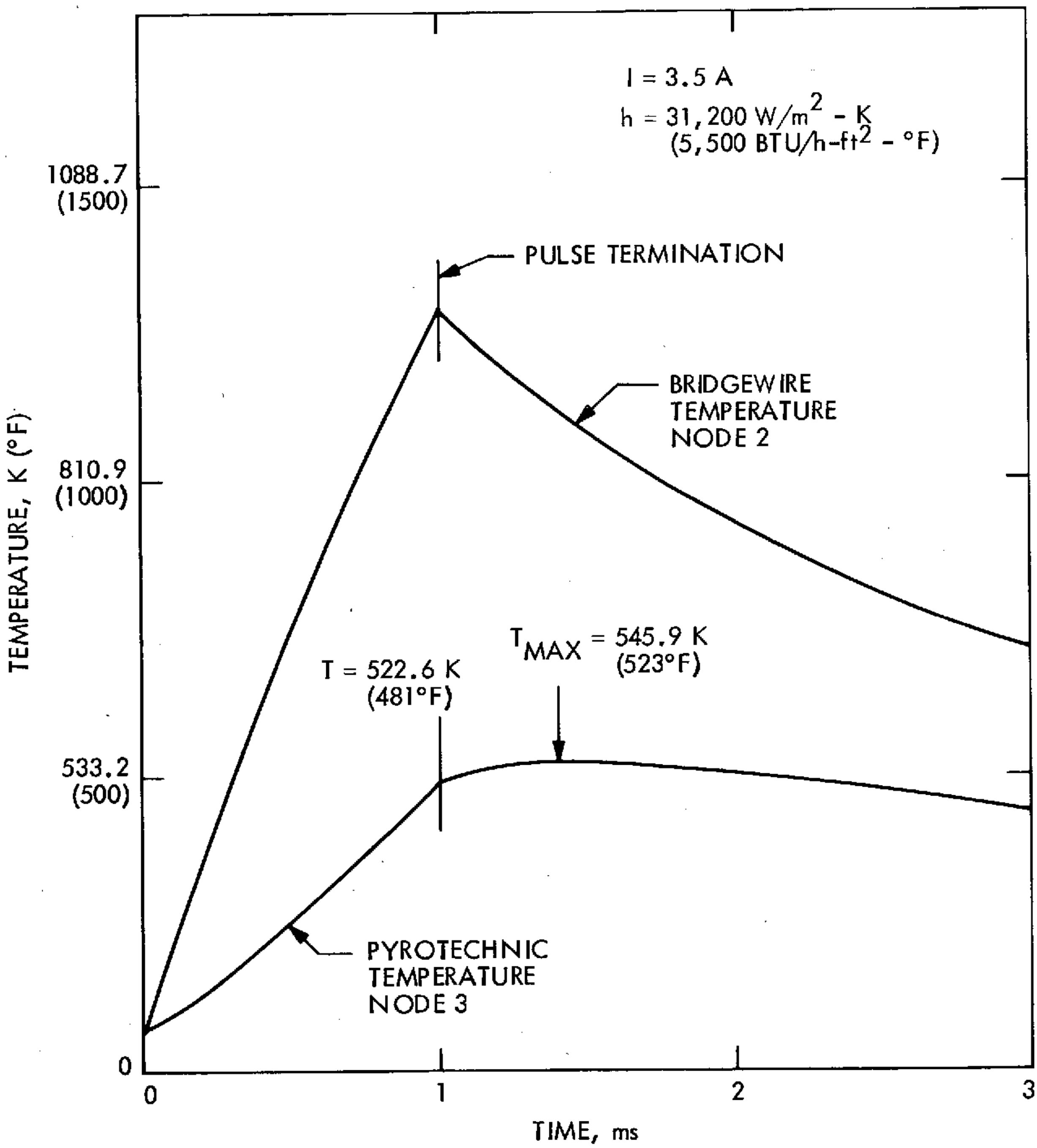

Fig. 10. Temperature history of nodes 2 and 3 during a constant current pulse of 3.5 A for 1 ms

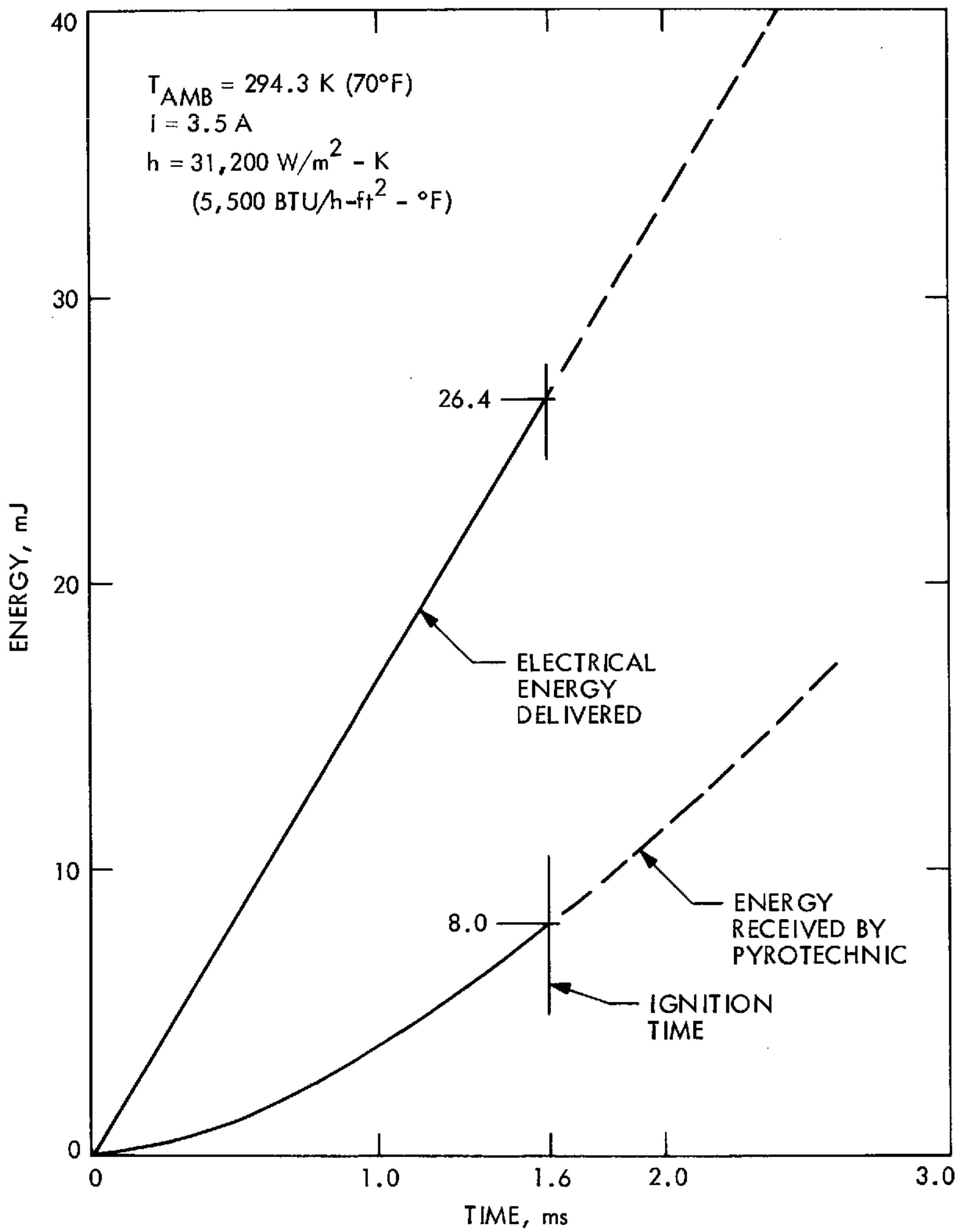

Fig. 11. Energy delivered to the bridgewire and pyrotechnic: T_{AMB} = 294.3 K

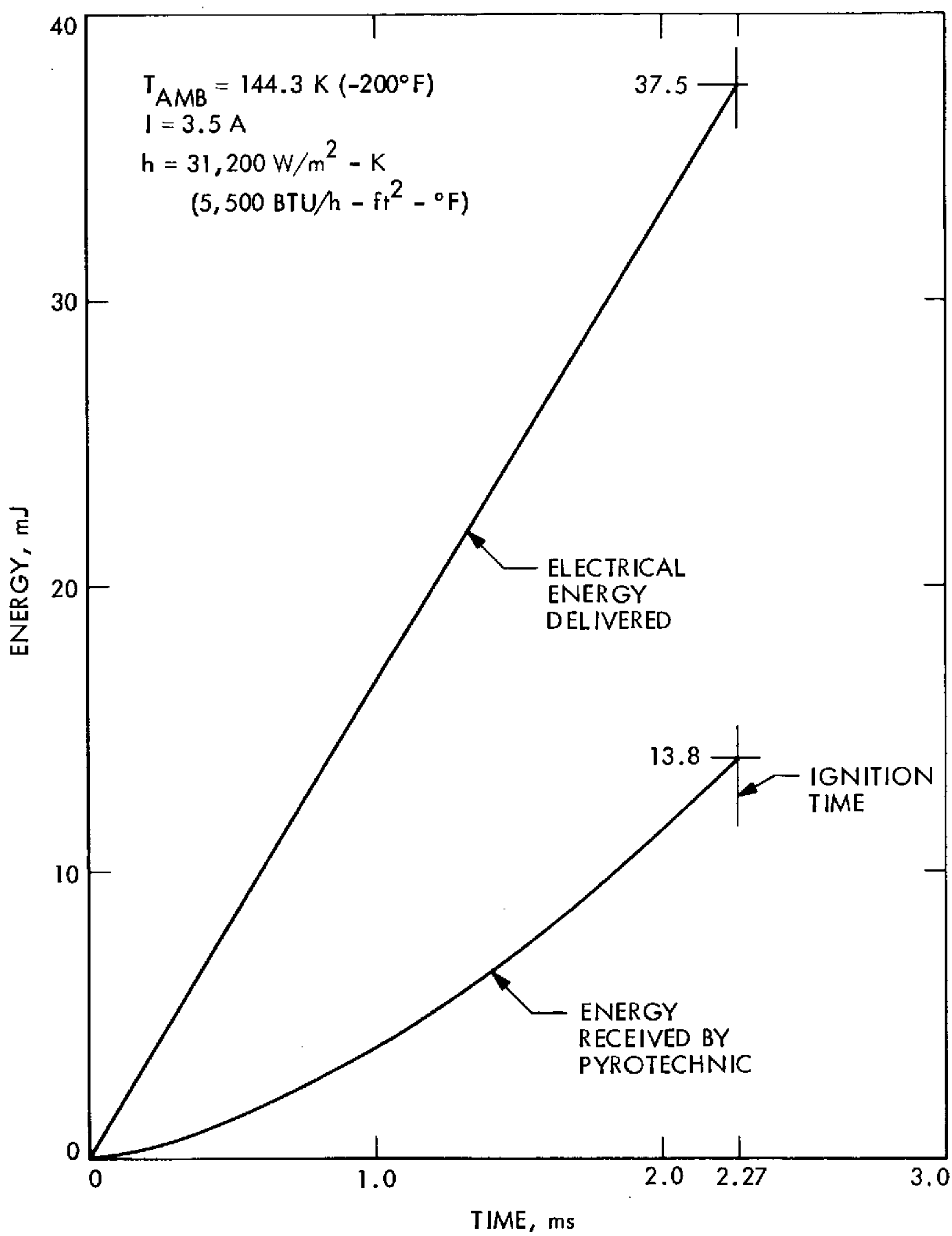

Fig. 12. Energy delivered to the bridgewire and pyrotechnic: T_{AMB} = 144.25 K

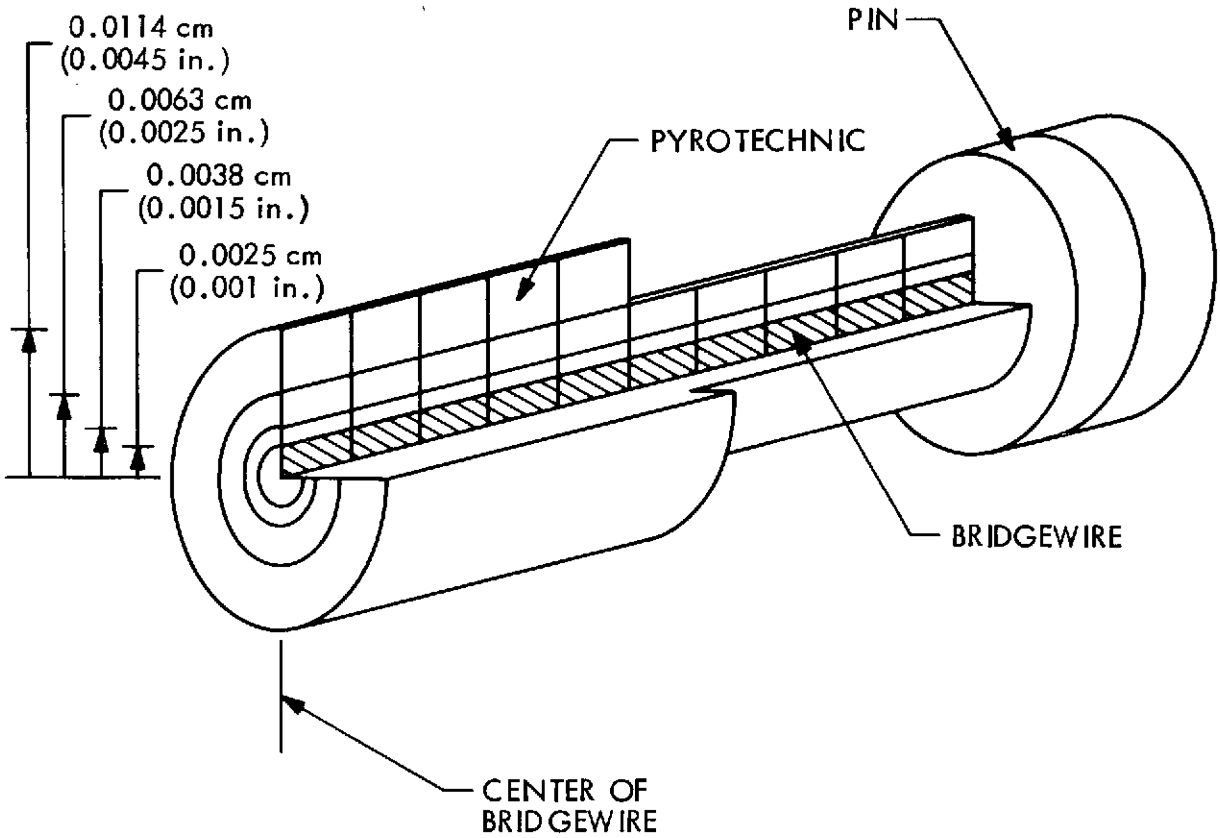

Fig. 13. Division of the two-dimensional bridgewire – pyrotechnic system into nodes; the bridgewire is divided axially into 10 nodes, the pyrotechnic into 25 nodes, and the pin into 2 nodes

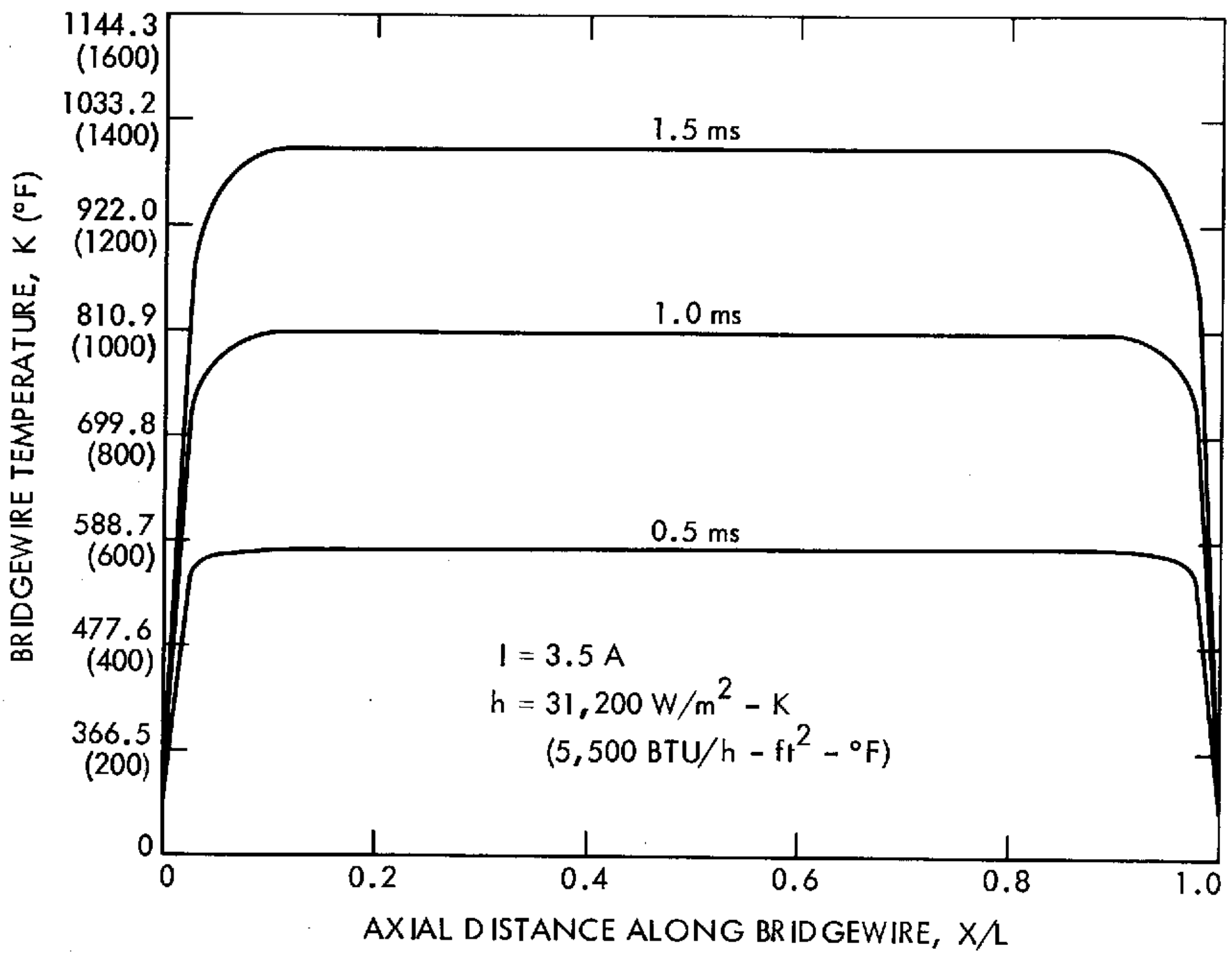

Fig. 14. Axial bridgewire temperature distribution; the bridgewire is embedded in the pyrotechnic

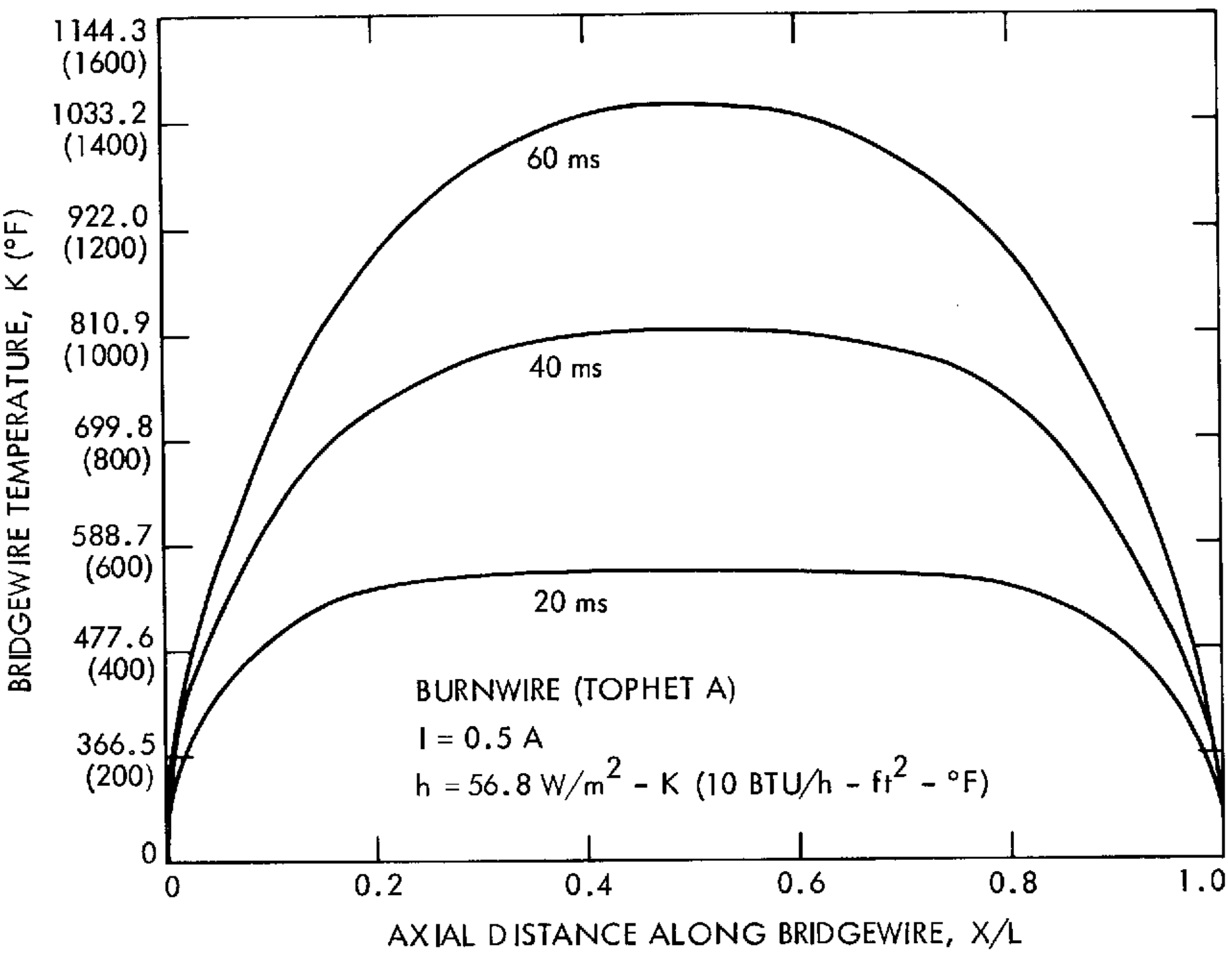

Fig. 15. Axial temperature distribution within the bare bridgewire (burnwire)

NASA–JPL–Coml., L. A. Calif.