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NORTHROP AIRCRAFT, INC.



HAWTHORNE, CALIFORNIA

COMPARISON BETWEEN AIR TEMPERATURES AS MEASURED BY VARIOUS SHIELDED TEST THERMOCOUPLES AND A REFERENCE DOUBLE- SHIELDED ASPIRATED THERMOCOUPLE

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ABSTRACT

A comparison is made between air temperatures as measured by various single and multiple-sheath test thermocouples and by a reference double-shielded aspirated thermocouple. The test specimen and standard are centered, three inches apart, in the 78 in. x 15 in. floor of a 6 in. high test chamber the ceiling of which is adjusted for temperatures of 500°F, 700°F, and 900°F. Air enters the chamber at approximately 70°F, reaching temperatures in the range 80°F - 200°F at the center section, under turbulent flow conditions of from 0 to 48 lb - min⁻¹ - ft⁻². Specimens currently in use on aircraft installations are found to record air temperatures considerably in excess of those registered by the reference instrument. Furthermore, indications are that some sort of quality control should be exercised to assure production of instruments uniform in performance. Altogether, thirteen different instruments were tested. An aluminum double-shield specimen (3 in. long outer - 2 in. long inner-shield), having an outside shield diameter of 1 in., was finally evolved, and it recorded temperatures in much closer agreement with the reference thermocouple than any of the other instruments considered. The sources of error in this type of temperature measurement are also briefly discussed.

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NOMENCLATURE

- T - Total Temperature
- T_g - Effective Gas Temperature
- L - Length
- h - Film Coefficient
- k - Thermal Conductivity
- S - Surface Area
- A - Cross-Sectional Area
- ϵ - Emissivity
- σ - Stephan-Boltzmann Constant
- M - Mach Number
- γ - Ratio of Specific Heats, C_p/C_v
- r - Recovery Factor
- F_a, F'_a - Geometric Factors for Radiation

Subscripts

- c - conduction, convection (see context)
- i - indicated

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Subscripts (Cont'd)

w = wall

R = radiation

s = shield

o = static

r = recovery, radiation (see context)

p = probe

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STATEMENT OF PROBLEM

There is reason to believe that thermocouples currently in use on missile and aircraft installations, for measuring air temperatures (in the approximate range 70°F - 200°F) in the vicinity of radiant heat sources, are not optimum from the standpoint of accuracy, uniformity, complexity, and structural properties. Specifically, thermocouples presently used extensively on B-62 test stand programs and on F-89 engine bay cooling programs are suspected of being seriously in error and diverse in performance.

The objectives of the present test are twofold: (1) to compare the air temperatures measured by thermocouples now in use with temperatures measured by a reference "standard" taken to be measuring "true" air temperature; (2) to compare the readings of several varieties of thermocouples with readings obtained from the specimens above, and with the standard, in an effort to ascertain the optimum instrument.

The emphasis in the present investigation, then, is on comparison, in order to rank the specimens in order of increasing accuracy, where accuracy is defined as the difference between specimen reading and standard reading for a particular operating condition, or "fix". It was anticipated that the data gathered in compliance with

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the first-named objective above could be used for correcting the temperature readings of thermocouples presently in use; however, such a procedure should be used with reservation, and only when it is impractical to install more accurate thermocouples and repeat a given test.

Once an optimum instrument is chosen, the calibration of a few random samples of the specimen will give a measure of the quality control.

In conformity with the objectives, the following specimens were tested:

- (1) and (2): Two sample 1 in. long, single-shield, specimens (Figure 4B)
- (3): One 2 in. long, single-shield, specimen (Figure 4B)
- (4): One 2 in. long, double-shield, specimen (Figure 4C)
- (5): One 2 in. long, triple-shield, specimen (Figure 4D)
- (6): One Revere Corporation thermocouple - a 1-1/4 in. long triple shield specimen with encapsulated junction. (Reference Revere TK2702P Modification by NAI ETD #702369, pg. 2, item 12)
- (7): One bare thermocouple (Photo pg. 72)

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(8) and (9): Two sample "umbrella" - shield specimens (Figure 4A) currently in use on F-89 engine bay cooling programs.

The shield material is stainless-steel tubing; the elements are Iron-Constantan with silver-soldered junctions. Photographs of the specimens are shown on pg. 71 - 74.

As the test progressed, it became evident that some room was left for improvement; accordingly, the following additional specimens were designed and tested:

- (10): One sample 2 in. x 2 in. flat umbrella-shield specimen (Figure 4E)
- (11): Same as (10) but with insulation and aluminum foil over top of shield.
- (12): One sample 2 in. long inner-3 in. long outer-shield specimen (Figure 4G).
- (13): Same as (12) but with Venturi-shaped inner shield (Figure 4F)

The temperature-sensing element is the same as for the samples (1) through (9) above, but the shield material is aluminum. Photographs of the specimens tested are shown on pages 71 - 74.

The temperatures measured by these specimens were compared to that measured by a double-shielded aspirated thermocouple which was used as a standard. The test chamber used (Figure 5 and photos pg. 70) was dimensioned so as to simulate conditions extant in the engine bay, and several representative flow and hot wall conditions were considered.

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CONCLUSIONS

Strictly speaking, the performance of the various specimens is limited to the present experimental configuration, (Reference 10), but there is little reason to believe that the order of increasing accuracy discovered here would actually be reversed for a different test chamber geometry. Furthermore, while the inaccuracy is not the same function of flow and hot wall conditions for each specimen, the overall test results suggest the following ranking, in order of increasing accuracy (numbering refers to that assigned to specimens under "Statement of Problem", above):

(9) < (2) < (7) < (1) < (8) < (6) $\approx$ (3) $\approx$ (4) < (10) < (11) < (13) < (5) < (12)

The actual test results are shown in the graphs of Figures 2.

Two striking results are immediately apparent from the above arrangement: (a) The difference in the performance of samples of, presumably, the same specimen, e.g., thermocouples (1) and (2) and, particularly, (8) and (9); (b) The approximately equal performance of such geometrically dissimilar specimens as (3), (4), and (6).

As was suspected, the thermocouples now in use are reading much too high, and the data of Figure 2F, or

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Table 1 which shows the range of applicability (specimen-measured air temperature) should be used to "correct" the readings obtained in the past with these instruments.

The results (Figures 2H) from one of the newly designed instruments, specimen number (12), with the 3 in. long outer, 2 in. long inner, aluminum shields (Figure 4G) are very encouraging. This instrument functions every bit as well as the more cumbersome standard in the presence of a hot wall radiant source as high as 900°F when the air temperature is in the vicinity of 70° - 90°F, and the flow is in the vicinity of 48 lb - min⁻¹ ft⁻². For a somewhat lower flow, 19 lb - min⁻¹ - ft⁻², this instrument measured 10°F above the standard for a hot wall of 900°F and air temperature in the vicinity of 80° - 100°F. At still lower flows (9.6 lb - min⁻¹ - ft⁻²) the error is somewhat greater, the specimen reading 14°F above the standard for both a 700°F and a 900°F hot wall. For zero main air flow this instrument reads 85°F above the standard for a hot wall at 900°F, 49°F above the standard for a hot wall at 700°F, and 27°F above the standard for a 500°F hot wall. Even so, it will be noted that this double-shield specimen performs considerably better than any other specimen tested for all flow and hot wall conditions

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considered (Cf Figures 2D and H). It is interesting to note that whereas the slope (interpreted as the rate of change of "error" with hot wall temperature) of most of the curves increases with increasing hot wall temperature, in the case of both this double-shield and the triple-shield specimens it decreases with increasing hot wall temperature in the moderate to low flow ranges. The effect of flow orientation on this double-shield instrument is shown on Figures 3Q, R, S and T.

The consideration of an "umbrella" shield thermocouple, which a perfunctory thermodynamic analysis indicates to be subject to great error, is justified in the desire for a device that is insensitive to flow orientation. The umbrella-shield specimens are indeed less sensitive to the air flow vector, but the steeper slope of the curves, signifying greater intrinsic error, exaggerates any differences as shown on Figures 3. The flat umbrella-shield thermocouples (Figure 4E) were designed in an effort to overcome the effect of shield curvature, which modifies the air flow pattern over the junction as orientation is changed. An additional advantage of the flat shield is that it precludes the possibility of radiation being focused on the junction by the shield. The instrument designed, particularly

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the insulated-shield specimen, compares favorably (Figure 2F) with the better of the curved-umbrella-shield specimens (Spec. 8) now in use and has the added advantage of being less sensitive to flow orientation (Figures 3 M, N, O, and P) and of requiring less care in manufacture. However, the decreased flow-orientation sensitivity is not felt to be of sufficient significance to warrant this instrument's use (especially in view of its greater inherent inaccuracy) in deference to the completely shielded instrument.

Thermodynamic considerations indicate that the various specimens should read "truer" at high flows and such is indeed the case. Figure 1A, for example, indicates that it would be fairly safe to assume that above about $100 \text{ lb. min}^{-1} - \text{ft}^{-2}$, and a hot wall radiant source at 900°F , the deviations among the various specimens, as well as the deviations of each specimen from "true" air temperature, will not be significant. Figures 1 are included merely to indicate the nature of the dependence of temperature reading on flow and

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do not give a true picture of the inaccuracy. The points along a given ordinate represent different "fixes", e.g., at 12 lb - min⁻¹ ft² and a 900°F hot wall the reading of the curved-umbrella specimen is referred to the upper curve of the standard whereas the 2 in. single-shield specimen refers to the lower curve (Table 1). For the sake of clarity not all of the specimens are shown on these graphs.

Since the hot wall could not be maintained at a uniform temperature throughout, the temperatures near the center of the hot wall were adjusted to 500°, 700°, and 900°F for the various runs (Reference 10). Some typical temperature distributions are shown in Table 1.

A calibration test was run by simultaneously immersing all the specimens in a bath of Dow Corning #710 Fluid. At bath temperatures of 70°F, 150°F, and 212°F (as measured by a mercury-in-glass thermometer) all the specimens read within one or two degrees of one another, and no specimen gave a temperature differing by more than 3° from that indicated by the thermometer.

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CRITICAL CONDITIONS

The following "fixes" were used as being representative of conditions for which application of the thermocouple is contemplated:

48 lb-min⁻¹ ft⁻²; turbulent flow; hot wall 500°, 700°F, and 900°F (1)
 19 " " " " " " " " "
 9.6 " " " " " " " " "
 0 flow; hot wall 500°, 700°, and 900°F

The aspirated air flows for the standard (reference) thermocouple are as follows:

20 lb-hr⁻¹ for 900°F hot wall, zero flow
 18 " " 700°F " " " "
 16 " " 500°F " " " "
 14 " with flow, for all hot wall temperatures.

Under these conditions, the standard was taken to be measuring "true" air temperature.

Note (1) As mentioned under "conclusion" above, these temperatures refer to the center of the hot wall, immediately above the specimen and standard.

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ASSUMPTIONS

The paramount assumption in the present investigation is that the reference standard, which is a double-shield aspirated thermocouple (Figure 6) gives a true indication of the air temperature.

The idea of an aspirated thermocouple is an old one, dating back as early as 1887 in a model used by R. Assman (Reference 1); it soon became an established means of temperature measurement in Germany, and, at one time, imported models sold for \$300.00 in this country.

The instrument used in the present test is quite similar to Assman's early model and operates on the same principle (Reference 5). Thermocouples in the vicinity of radiant sources will be at a higher temperature than the surrounding air, provided that the air is at a lower temperature than the radiant source, due to the radiation incident on the thermocouple (1). In the converse case, where hot air is flowing through a cool duct, the thermocouple will register a lower temperature than that of the air since it loses heat, via radiation, to the cooler walls (References 2 and 3). By increasing the

Note (1) For all practical purposes, air may be considered transparent to this radiation; it therefore becomes heated by convection from the hot wall.

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velocity of the air over the junction, the Nusselt modulus, and hence the rate of convective heat transfer, is increased so that the temperature of the junction approaches the air temperature. Each increment in air velocity will result in a decrement in the temperature registered by the thermocouple until a point is reached at which further increase in flow leads to no change in temperature. This point, then, may be taken as the definition of "true" air temperature.

It should be noted, however, that if the temperature registered by the thermocouple is plotted versus the aspirated air flow a curve resembling one branch of hyperbola is obtained. In other words, the point at which a further increase in air flow leads to no further decrease in measured temperature may not be the lowest temperature the instrument could measure. Thus, whereas 2 lb-hr^{-1} increments may be quite satisfactory near the "knee" of the curve, as the asymptote is approached a further decrease of 2 or 3 degrees might be obtained after three or four additional 2 lb-hr^{-1} increments.

The reason for belaboring the above point is that the "good" specimen was so good it exceeded the accuracy of the standard, (under the present experimental conditions) reading 3°F lower at one fix ($48 \text{ lb-min}^{-1} - \text{ft}^{-2}$; 900°F hot wall.) This does not militate against

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the utility of the present investigation whose primary objective was the choice of an optimum instrument from among a group of specimens whose performances were compared. For this reason, the curves (Figure 2H) are not extended below the abscissa. In other words, having chosen a standard, it would be incompatible with the thermodynamics of the present situation (radiant source and cooler air) to draw a graph indicating that a certain number of degrees are to be added to the reading of the specimen, for as noted above, it is possible for the aspirated thermocouple to read slightly above the true air temperature because of the asymptotic nature of its temperature vs air flow curve.

An additional assumption, though it would seem from symmetry considerations to be a very reasonable one, is that the specimen and the aspirated thermocouple each measure the same thing, i.e., air at the same temperature and under roughly equal flow conditions. Furthermore, the specimen and standard are regarded as being in, essentially, the same environment from a radiation and over-all flow pattern standpoint.

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RECOMMENDATIONS

It is recommended that the use of all umbrella-shield thermocouples be discontinued. Temperatures formerly recorded by these instruments and used in current analyses should be corrected by interpolating between the two samples tested (Figure 2F), though the use of such a correction procedure is discouraged as noted in Reference (3).

Use of the 2 in. long inner, 3 in. long outer aluminum-shield specimen (Figure 4G) is recommended; these devices should be used for instrumentation requiring the measurement of air temperatures in the vicinity of radiant heat sources and air flows in the range covered by these tests.

Three or four random samples should be chosen from a group of these specimens in order to obtain a measure of the dispersion, or scatter, in their accuracy. It is essential that reasonable care be exercised to assure a uniform product as attested to by the wide discrepancies noted above between samples of the same specimen. Whether a correction, using graphs such as Figure 2H, is to be applied to the readings obtained with this instrument may be left to the discretion of the engineer in charge. It is believed, however, that the accuracy of this type of instrument is adequate for the tests and heat transfer analyses conducted on engine bays, although it may be desirable to apply a correction for flow orientation, using the curves of Figures 3Q, 3R, 3S and 3T.

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ANALYSIS

Reports dealing with the measurement of gas temperatures are legion (Reference 4). However, no previous work in the nature of the present study seems to have been undertaken.

As noted in all these reports, the exact measurement of air temperatures is hindered by the many inaccuracies inherent in this type of measurement. These errors, while they cannot be eliminated in their entirety, may, however, be rendered much less effective (References 6 and 7). Among the more influential factors contributing to the error of measurement the following may be singled out as deserving special consideration:

Conduction Error: If the thermocouple is attached to a surface at a lower (or higher) temperature than the air stream, heat will be conducted away from (or to) the junction along the thermocouple leads to (or from) the cooler (or hotter) surface with the result that the thermocouple junction will read too high (or too low). This effect can be reduced (a) by decreasing the wire diameter⁽¹⁾

Note (1): Other things being equal, a reduction from 8 Ga to 22 Ga in the leads of a bare thermocouple resulted in an increase in measured air temperature from 1850°F to 1950°F (the latter being closer to "true" air temperature) - Ref. 6, Fig. 7, p. 615.

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(b) by insulating the wire from the point of attachment, and (c) by exposing a section of the bare wire, leading away from the junction, to the air stream; the latter procedure helps to maintain the junction at air temperature by keeping the conduction path leading from the junction near air temperature. The conduction error may be evaluated from

$$(T_1 - T)_c = \frac{T_w - T}{\cosh (mL)} \quad (1)$$

where T = Total temperature (Theoretical value)

T_1 = Indicated total temperature ($T_1 > T$)

T_w = Wall temperature ($T_w > T_1 > T$)

L = Immersed length of probe.

and,

$$m = \sqrt{\frac{hS}{kA}} \quad (1a)$$

where h = Surface coefficient ("Film coefficient") of heat transfer.

k = Thermal conductivity of probe material.

S = Surface Area of probe.

A = Cross-sectional area of probe.

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From Equation (1) it follows that the conduction error is directly proportional to the difference between the temperature of the gas and the temperature of the wall in which the probe is mounted and inversely proportional to the length of the probe. Furthermore, it is seen that the error becomes smaller with increasing m (Equation 1a), i.e., when the surface coefficient of heat transfer is large, and when the thermal conductivity and cross-sectional area of the probe are small.

Radiation Error: Thermocouples, in the presence of radiant sources at a temperature above that of the surrounding air, receive heat directly from the radiating source (air being transparent to this radiation) and hence will be at a temperature above that of the air. Two means of combating this problem are: (a) Shielding the junction from the radiant source using one or more shields (b) Increasing the velocity of the air over the junction which has the effect of increasing the Reynolds' modulus which, at a given temperature (constant Prandtl modulus),

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increases the Nusselt modulus; thus more heat is convected away from the junction (or towards the junction if the latter happens to be below air temperature) with the result that it approximates the air temperature more closely. The thermometric error, $(T_i - T)_R$, due to radiative heat exchange between the sensing element and the surroundings, for a temperature probe with one radiation shield and a surface area of the sensing element small compared with the surface area of the shield, is given by

$$(T_i - T)_R = \frac{\sigma \epsilon}{h} \left[\left(\frac{T_s}{100} \right)^4 - \left(\frac{T_i}{100} \right)^4 \right] \quad (2)$$

where σ = Stephan-Boltzmann constant

ϵ = Emissivity of the temperature sensing element

h = Surface coefficient of heat transfer from the sensing element to the gas.

T , T_i , and T_s = The total temperature of the gas, the indicated temperature of the probe, and the temperature of the radiation shield, respectively.

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Equation (2) shows that, in order to reduce the radiation error, the emissivity of the sensing element should be low (this is one reason for silver-soldering the junction), that the surface coefficient of heat transfer should be large, and that the temperature difference between the element and the radiation shield should be small; this is sometimes accomplished by surrounding the inner shield with one or more outer shields. Interposing one shield between a radiating body and its surroundings will reduce the radiation by one-half, or to $1/(n + 1)$ of the value without shields, for approximately stagnant air (Reference 2) and to about $1/2^n$ with flowing air (Reference 3), where n is the number of shields.

Impact and Friction Error: These effects cause the thermocouple to read too high. Friction, in the boundary layer adjacent to the junction, will cause the boundary layer to assume a temperature somewhat higher than free stream and the compressibility effects will do likewise. The compressibility effects are accounted for

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in the expression

$$T/T_0 = 1 + \frac{(\gamma - 1)}{2} M^2 \quad (3)$$

where M = Mach number

γ = Ratio of specific heats, C_p/C_v

T = Total temperature

T_0 = Static temperature

The fact that the gas at the probe surface has a temperature greater than free stream temperature, T_0 , (and lower than T) is taken into account by defining a "recovery factor,"

$$r = (T_r - T_0)/(T - T_0), \quad (4)$$

where $T_0 < T_r < T$ and T_r is called the recovery temperature. As seen by Eq. (4), r is a measure of the fraction of the difference between T and T_0 by which the sensing element increases in temperature due to the conversion of kinetic energy into heat energy. At the low flows herein considered, this source of error may be neglected in comparison with the radiation and conduction errors.

In summary, the temperature assumed by the thermocouple is characteristic of a steady state in which the

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rate of heat transfer from the surroundings to the junction, via radiation, is equal to the rate of heat transfer from the junction to the surroundings via convection and conduction.

Assuming that the conduction error is made negligible by proper insulation, etc., then, in steady state,

$$Q_R = Q_C \quad (5)$$

i.e., the radiated heat in equals the convected heat out. Furthermore,

$$Q_C = h_c A_p (T_p - T_g), \text{ BTU/hr} \quad (6)$$

and

$$Q_R = \sigma \epsilon_p A_p F_a (\bar{T}_w^4 - T_p^4), \text{ BTU/hr} \quad (7)$$

It is more convenient to put the latter equation into a form similar to that for convective heat transfer; thus,

$$Q_R = h_r A_p (\bar{T}_w - T_p) \text{ BTU/hr} \quad (8)$$

For this case, the radiative heat transfer coefficient, h_r , can be computed, with only negligible error for

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most practical application, from

$$h_r = 4 \sigma \epsilon F_a' \left(\frac{T_w + T_p}{2} \right)^3 \quad (9)$$

The dependence of this coefficient on the cube of the average absolute temperature (instead of the 4th power) is merely a matter of convenience in calculation and may be used where a fairly constant temperature difference and a varying absolute temperature may be assumed (Ref. 3, p. 125).

Combining the above equations gives a measure of the error of the probe in terms of the temperature difference between the walls and the gas:

$$\text{Error, } T_p - T_g = \frac{h_r (T_w - T_g)}{h_r + h_c}$$

$$\% \text{ Error, } \frac{T_p - T_g}{T_w - T_g} = 100 \frac{h_r}{h_r + h_c} = \frac{100}{(1 + h_c/h_r)} \quad (10)$$

where A_p = Probe area, ft²
 F_a, F_a' = Geometric factors for radiation
 h_c = Convective heat transfer coefficient, BTU/hr-ft² °F
 h_r = Radiative heat transfer coefficient, BTU/hr-ft² °F

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- T_g = Effective gas temperature (= static temperature plus recovery factor times total minus static)
- T_w = Average wall temperature for radiation $^{\circ}F$ (a complex quantity consisting of a combination of shape factors and wall temperatures)
- ϵ = Total radiant emittance
- σ = Stephan - Boltzmann Constant

The above development is taken from Reference 3 with minor changes to fit the present situation.

Equation (10) clearly brings out the fact that, if the convective heat transfer coefficient is extremely large compared to the radiative heat transfer coefficient, the per cent error approaches zero, i.e., probe temperature equals gas temperature. On the other hand, if the radiation is extremely high, the error approaches 100%, i.e., probe temperature equals wall temperature.

Equation (10) also shows that as long as the radiation is not zero and there is a difference between gas and wall temperature, even if no other sources of error are present, the probe temperature can never equal the gas temperature.

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Turning to the results of the present test, the marked improvement in going from a 1 in. long single-shield specimen to a 2 in. long single-shield specimen (CF Figures 2A and B) is attributed to a change in "shape factor". Due to the shortness of the former shield, the thermocouple junction "sees" some of the radiating wall directly, out through the ends of the shield; the longer shield, on the latter specimen, "shades" the junction better.

Reasons that would account for the large discrepancy between the two samples of the 1 in. long single-shield specimen (Figure 4) are not readily apparent. Visual examination did disclose some differences between the two samples, but the major difference, that the junction of the better sample (specimen #1) was almost twice as large as that of the poorer sample, argues for a discrepancy the reverse of that actually observed. That is, specimen #2 (with the smaller junction) should have been the more accurate. Such an anomaly (and others) is not peculiar to the present investigation, however, as noted in Reference (3). What complicates matters further, in the case of the 2 samples above, is that the insulation was found to have worked its way out of the shield

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support⁽²⁾ of sample #1 (it is not known at which point of the investigation this occurred), and the fact that its stem (i.e., shield support) is 1.14 in. long as compared to sample #2 the stem of which is 1.01 in. long.

The fact that the 2 in. long double-shield specimen (Figure 4C) is not a material improvement over the 2 in. long single shield specimen (Cf Figures 2B and C) may well be due to the fact that the inner shield is not completely shaded from radiation. Geometric considerations, which demonstrate that a strip at each end of the inner shield sees the radiating wall directly, lend credence to this view.

As regards the two sample umbrella-shield specimens (Spec's 8 and 9; Cf Figure 4A), the only conspicuous difference between them is that the worse sample (Spec. #9) has a more sharply curved shield which, possibly, focused the radiation in the vicinity of the junction. Measurement disclosed that the stem (shield support) of the poorer sample (Spec. #9) is 1.50 in. long while that of the better sample (Spec. #8) is 1.58 in. long.

It was in an effort to exclude the possibility of focusing, as well as to inhibit the change in air flow pattern accompanying a change in specimen orientation,

Note (2): This seems to be a common complaint against the use of Sauereisen #7 paste. The other specimens contained a ceramic insulator in the stem bonded with Narmco metal bond #2021.

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that the flat umbrella-shield specimen (Figure 4E) was evolved.

At worst, a half-shield would seem to afford half as much protection against radiation. This is not so much due to the fact that the point of attachment, being heated by the radiant source, will be at a higher than air temperature (and thus radiate directly to the unprotected "bottom" of the instrument) as it is due to the fact that the "bottom" of the instrument will be unprotected from reflected radiation. The amount of radiation reflected from surfaces near the thermocouple is not so much dependent on the temperature of the surfaces as it is on their reflectivities or emissivities.

The relatively poor performance (Figure 2G) of the Revere instrument (Photo p. 74) was anticipated from its construction. Previous work (Reference 2) indicates that when the inter-shield spacing is reduced below a certain minimum value the several shields act as a unit, i.e., offer no more protection than a single shield. This would seem to follow from the fact that heat conduction along the intershield supporting struts will be greater the shorter they are (also the thicker they are, and the more numerous - factors that seem to have been overlooked in the construction of the present instrument).

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Furthermore, since both the viscosity and conductivity of air increase with temperature, some contribution to the increase in error with smaller spacing is probably made by the retarded convective heating in the annular passages and by heat conduction between the shields.

The Northrop triple-shield specimen (Figure 4D), though the shields were not polished (The Revere instrument had highly polished shields), performed considerably better (as shown by the data of Figure 2D.)

Since an investigation such as the present one could be continued almost indefinitely, assessing the effects of varying factor after factor, it was felt that a more profitable line of attack would consist in an outright attempt to design a good instrument based on theory tempered with the facts discovered above. Thus, an instrument was evolved which differs in several essential respects from any heretofore considered: shield material, size and geometry, and method of inter-shield support.

Of the four new specimens constructed (Figures 4E F & G and Photos pp.71,73) the best results were achieved with a 3 in. long outer, 2 in. long inner

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aluminum shield specimen (Figure 4G), the inner shield being attached to the outer with two slender threaded screws. This double-shield instrument performed considerably better than either of the triple-shield specimens considered, as illustrated by Figures 2H, G, and D.

Aside from the fact that aluminum cannot be silver soldered nor welded readily, the use of screws as a shield support has the added advantage that the threads act as minute fins and reduce the amount of heat conducted from the outer to the inner shield. Limiting the supports to two screws further reduces the area available for heat transfer by conduction from outer to inner shield and should give sufficient rigidity for the use contemplated. The use of aluminum, instead of the usual stainless steel shields, is dictated by the fact that aluminum, even when oxidized, has an emissivity only about 25 per cent that of stainless steel. The nearly universal acceptance of stainless steel shields may be traced to the precedent established in a long line of high gas temperature studies (such as obtained in slag-bearing gases in pulverized-coal-fired, or oil fired furnaces) and is uncalled for in applications such as the present

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one where the air temperatures are not expected to go much beyond 200°F. Extending the outer shield beyond the inner will have the effect, noted previously, of keeping more of the inner shield "in the shade". A 1 in. long inner, 2 in. long outer shield specimen might perform as well (this would have to be ascertained experimentally), but it was not tried due to the marked improvement noted above in going from a 1 in. long single-shield to a 2 in. long single specimen.

As mentioned previously, strictly speaking, the results of the present test apply only in the present test rig. However, there is little reason to believe that the best instrument in the present experimental set-up will not also be the best instrument outside of it; though this instrument may not perform as well in a given installation, the performance of the other specimens, it is anticipated, will be still worse. At any rate, it is desirable to use the best instrument in the light of what is known and assume it will still be best in an unknown situation when evidence to the contrary is lacking.

Objections to the use of the umbrella-shield specimens have already been dealt with above. Their greater

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over-all inaccuracy is depicted in Figure 2J.

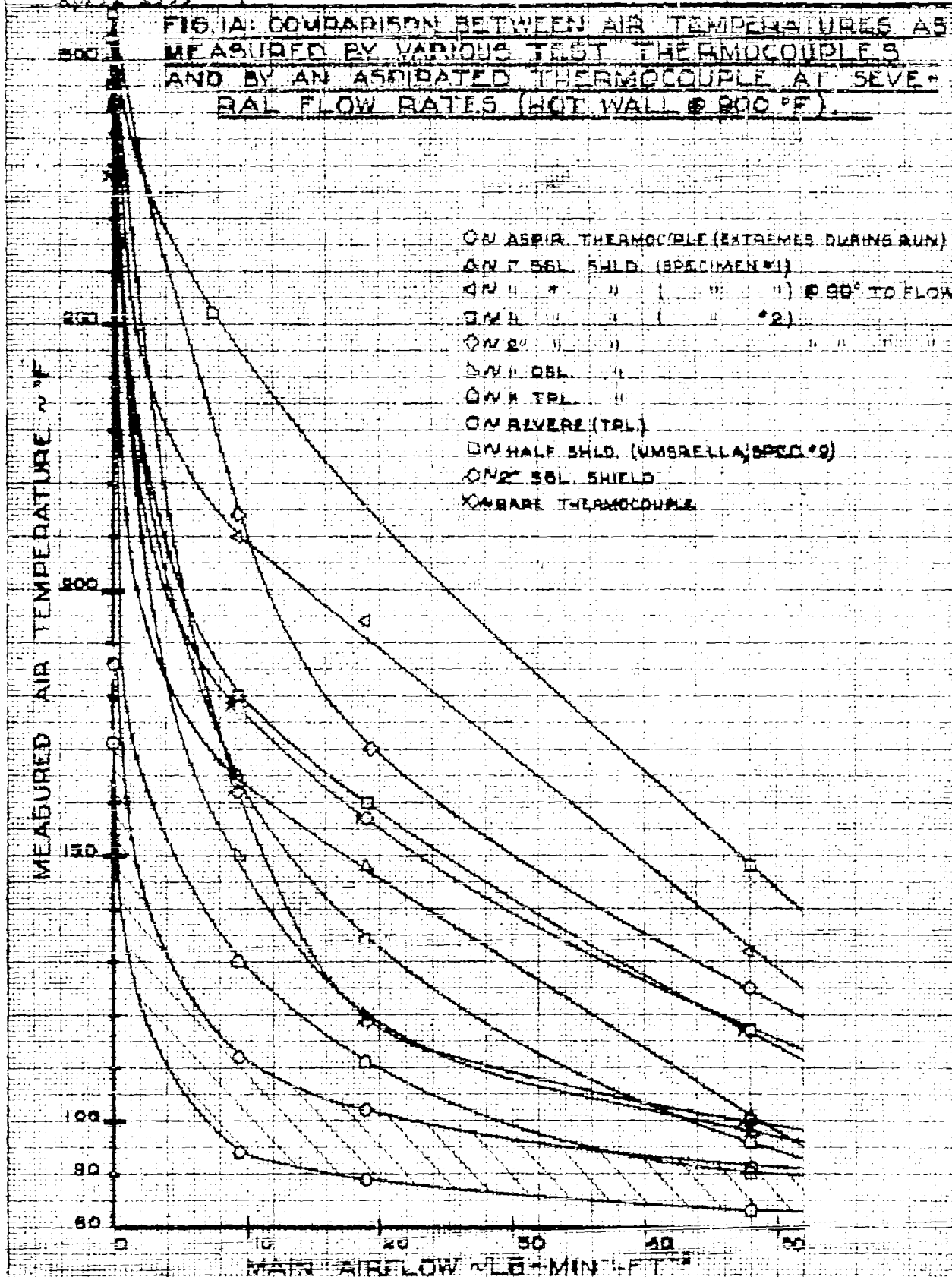
It was felt that constricting the inner shield near the thermocouple junction (Figure 4F) would have the desirable effect of promoting the convective heat transfer from the junction as a result of increased air velocity. Such an instrument (Figure 4F) was constructed to assess the amount of improvement, if any. Unfortunately this modification resulted in a less accurate instrument (Figure 2I). Three of the 5 strands on each thermocouple wire had been removed, the remaining 2 strands of each wire being formed into a junction, which should have resulted in a more accurate instrument, so that, evidently, constricting the inner shield has a more deleterious effect than brought out by the present data.

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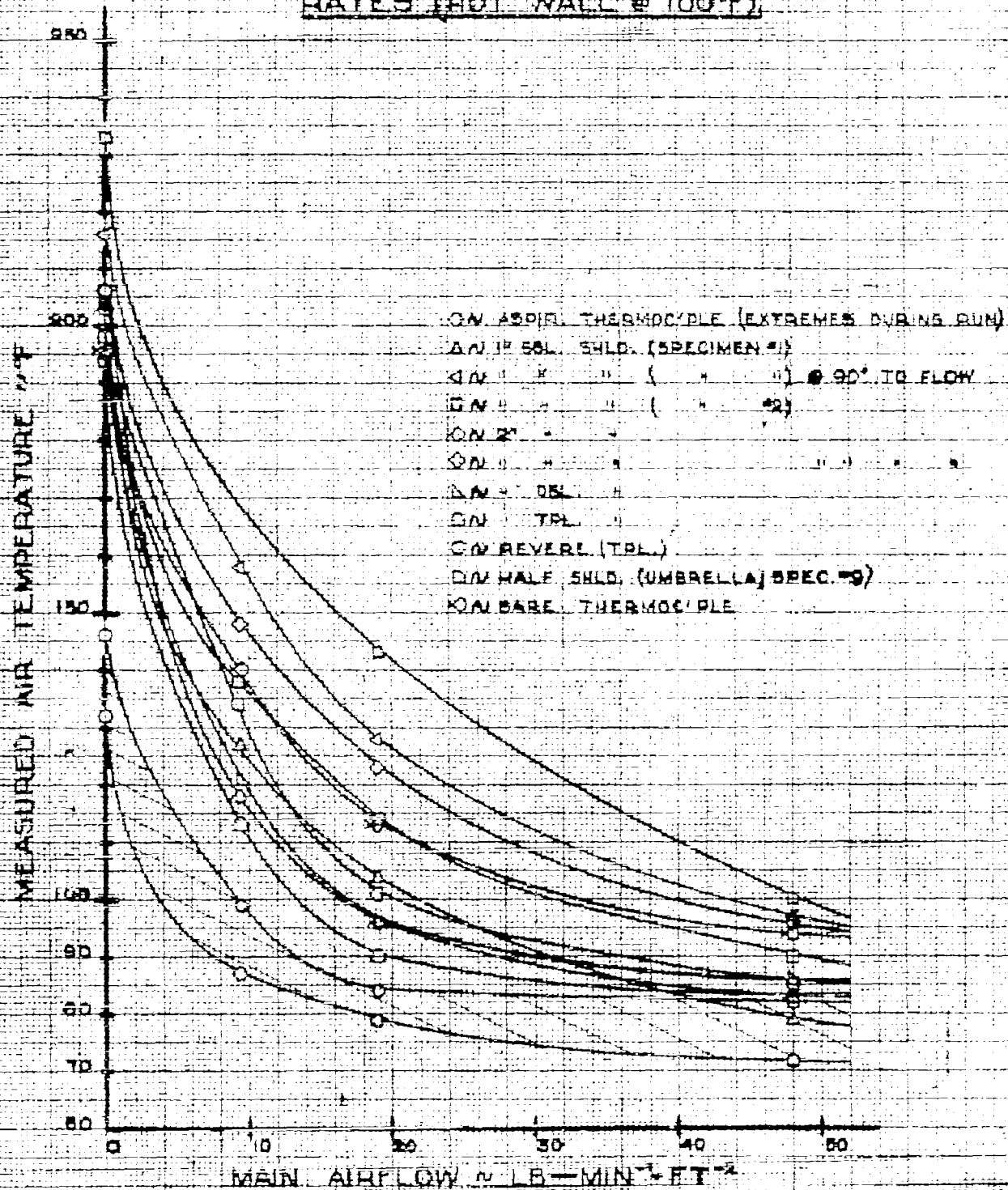
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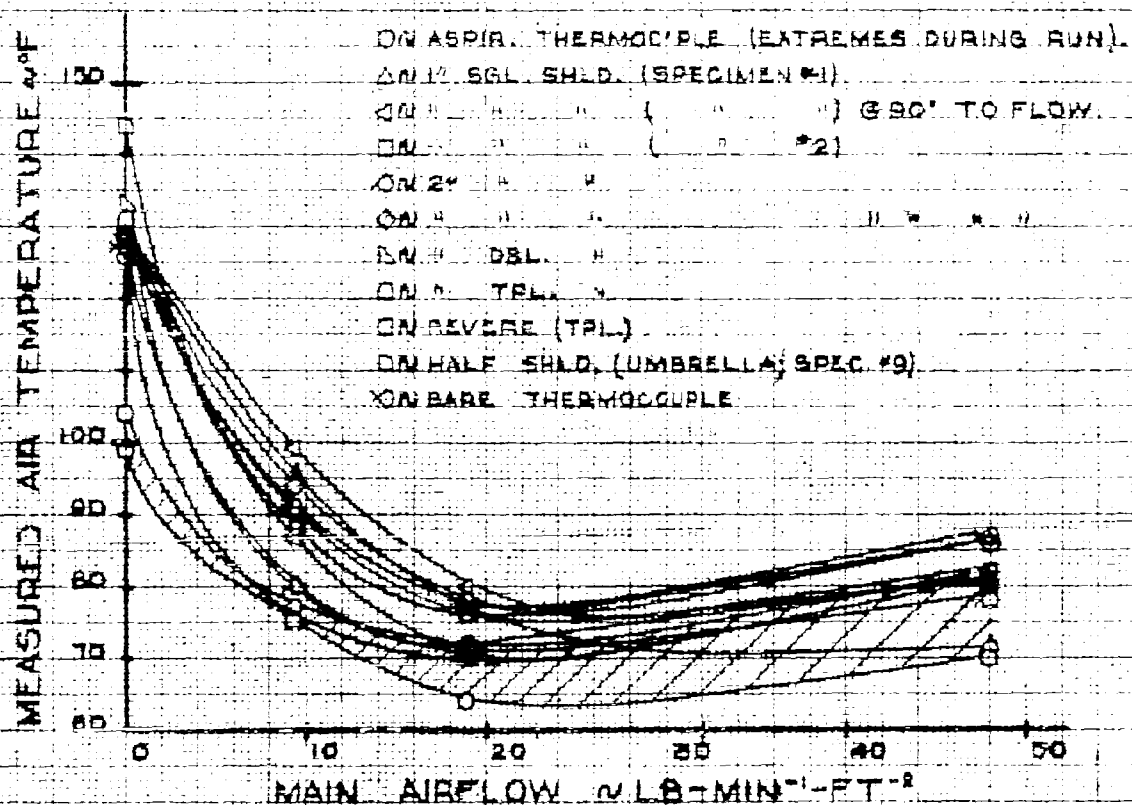
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FIG. 1B: COMPARISON BETWEEN AIR TEMPERATURES AS MEASURED BY VARIOUS TEST THERMOCOUPLES AND BY AN ASPIRATED THERMOCOUPLE AT SEVERAL FLOW RATES (HOT WALL @ 700°F).



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FIG. 10: COMPARISON BETWEEN AIR TEMPERATURES AS MEASURED BY VARIOUS TEST THERMOCOUPLES AND BY AN ASPIRATED THERMOCOUPLE AT SEVERAL FLOW RATES (HOT WALL 2000°F)



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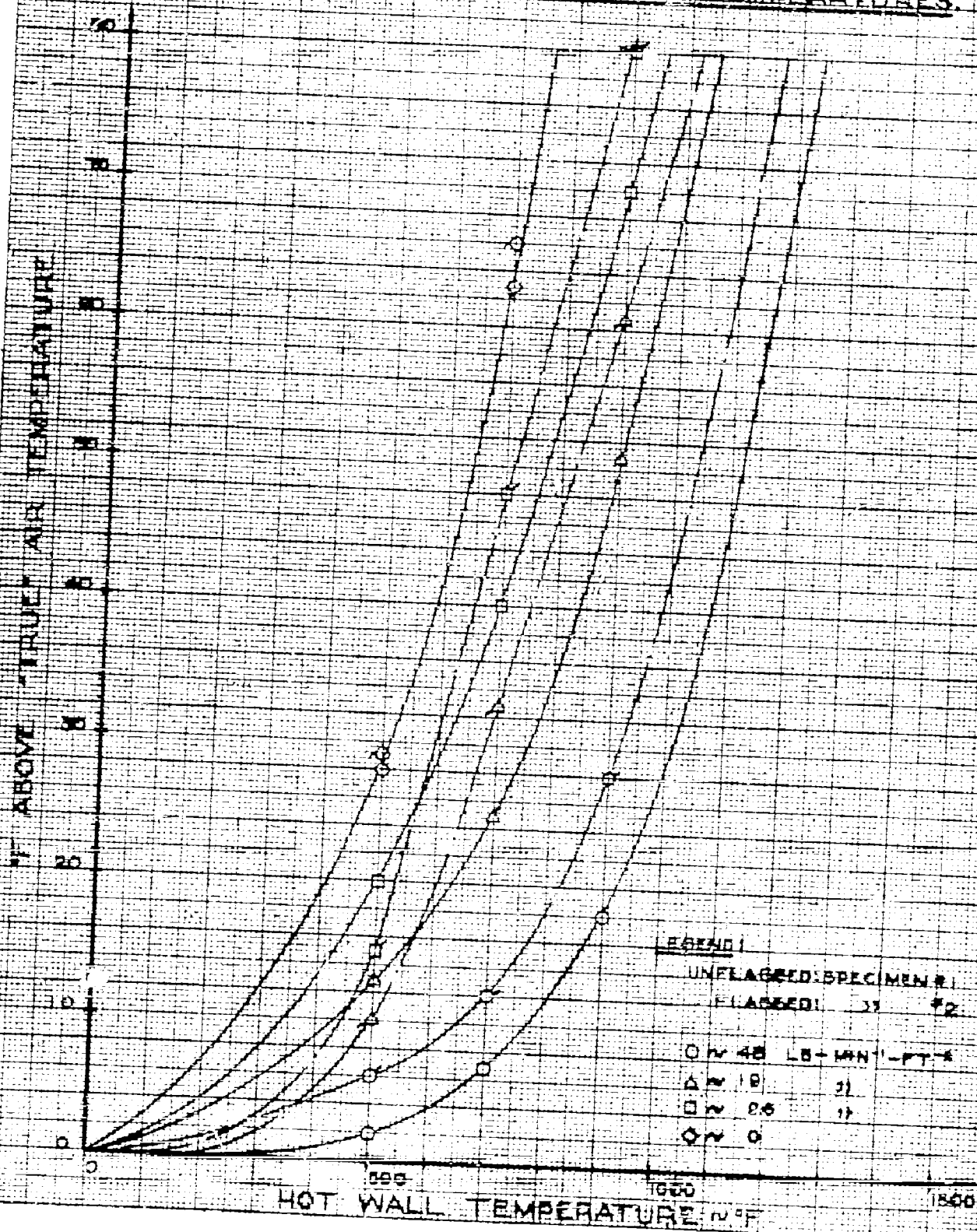
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FIG. 2A: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY LONG SOLID TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.



LEGEND:

UNFLAGGED SPECIMEN: 1

FLAGGED: 2, 3, 4, 5

ON 48 LB-MIN⁻¹-FT⁻²

Δ ~ 18 31

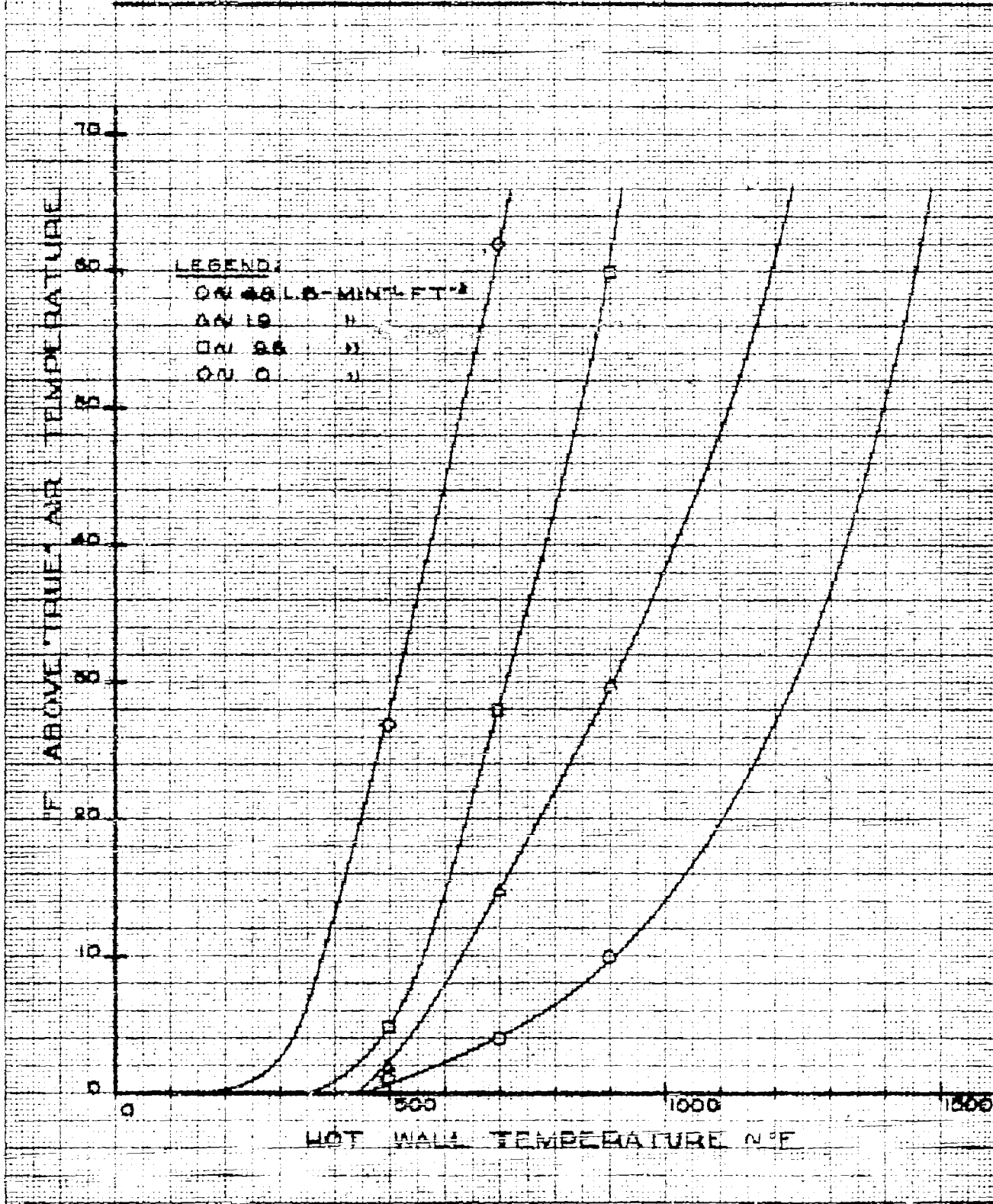
□ ~ 8.6 17

◇ ~ 0

HOT WALL TEMPERATURE, °F

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FIG. 25: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 2" LONG SSL SHLD. TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.

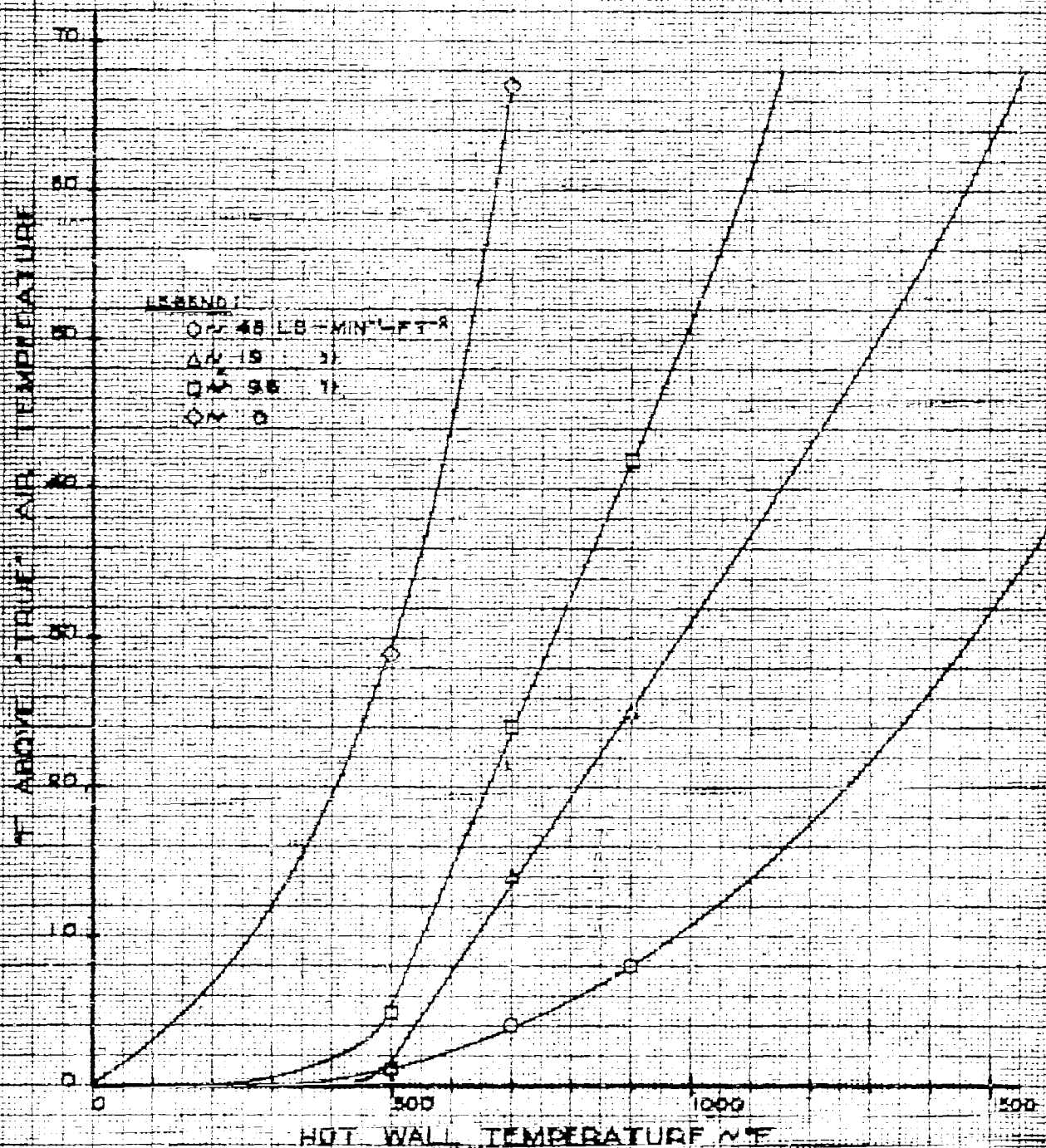


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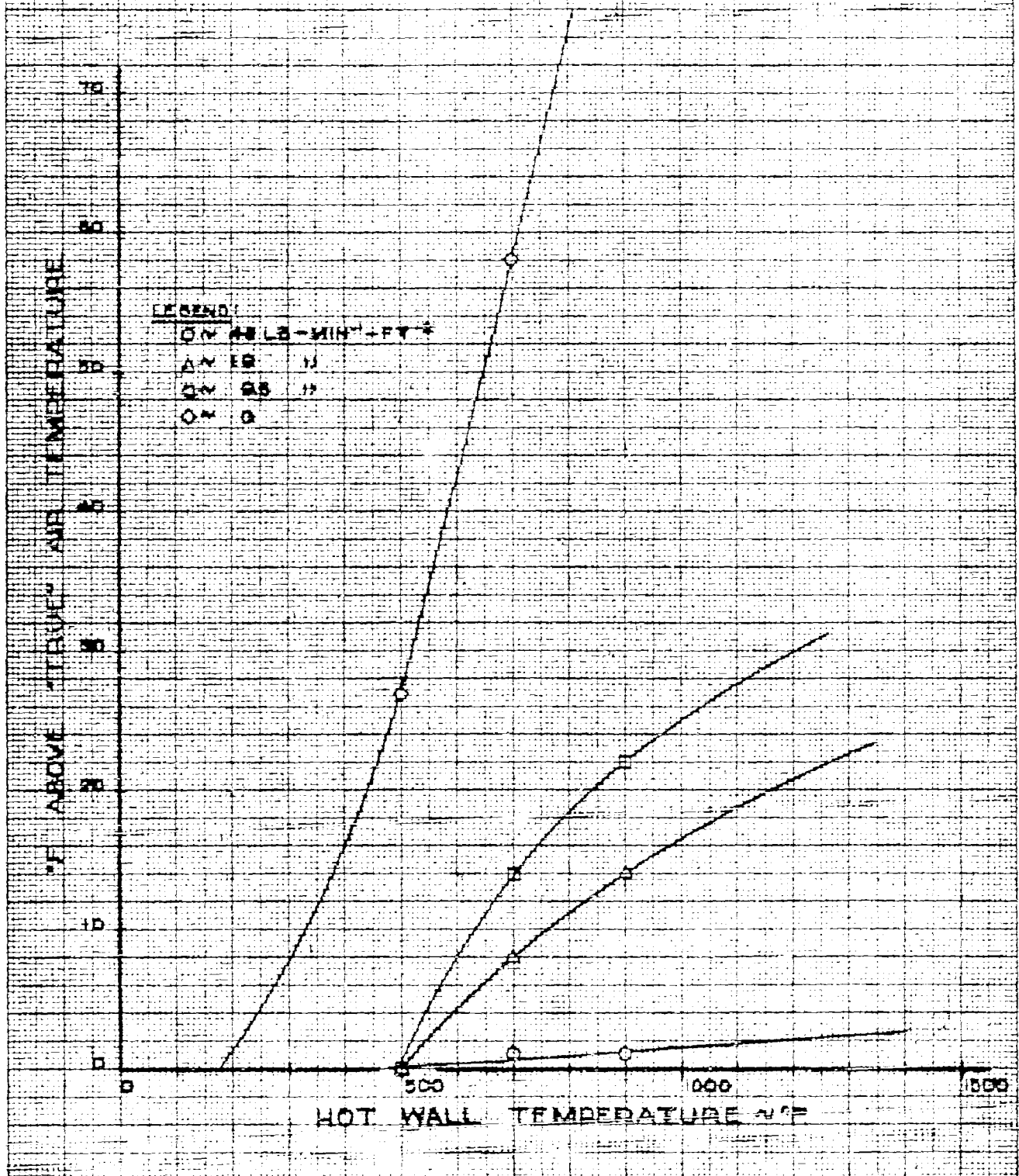
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FIG. 2C: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 2" LONG DBL SHLD TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.



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FIG. 20: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 2" LONG TPL SHLD. TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.



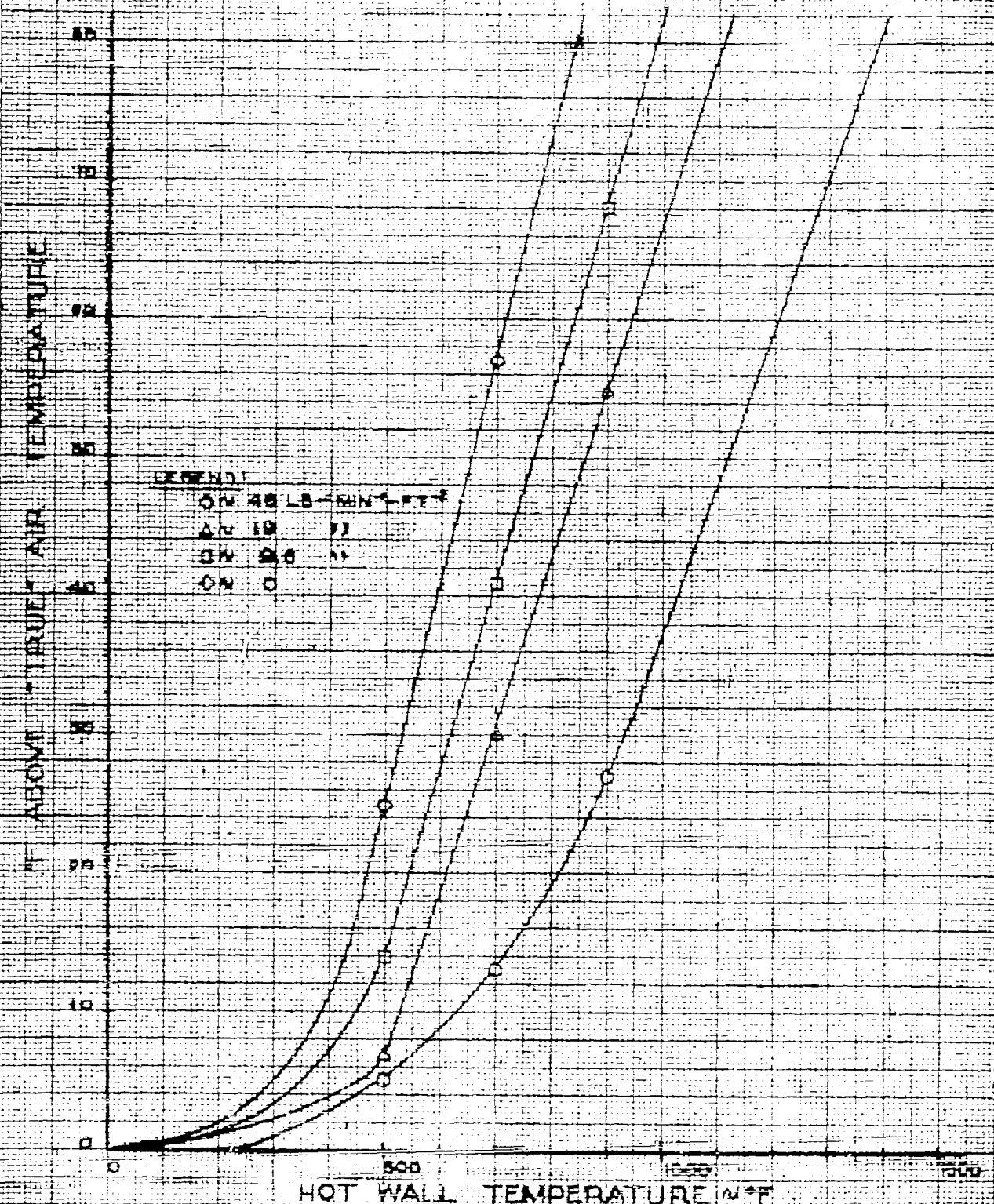
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FIGURE 1: $^{\circ}\text{F}$ ABOVE "TRUE" AIR TEMPERATURE INDICATED
BY BASE TEST THERMOCOUPLE FOR SEVERAL FLOWS
AND HOT WALL TEMPERATURES.



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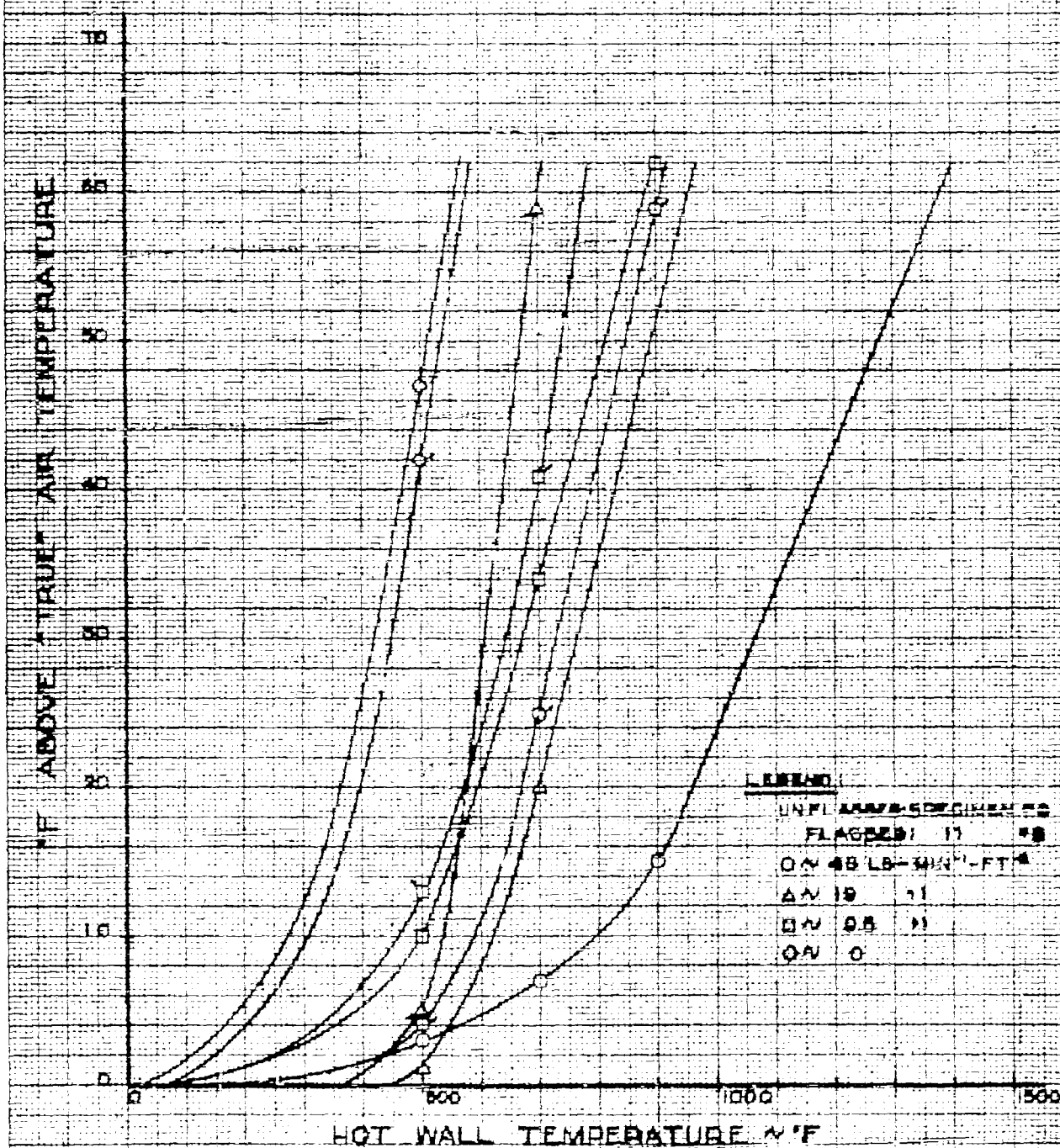
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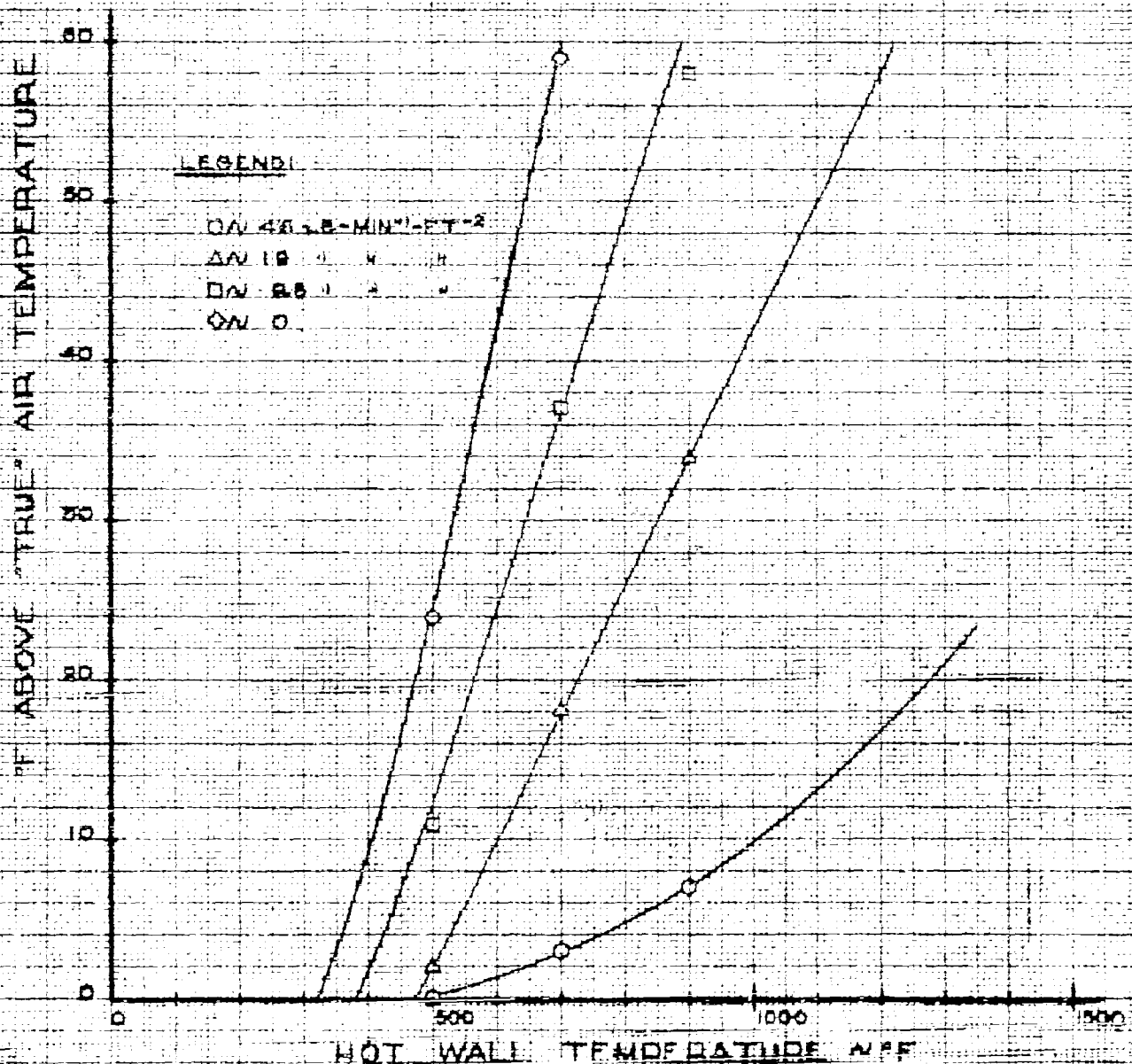
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FIG. 2F: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY
HALF-SHLD. TEST THERMOCOUPLE FOR SEVERAL
FLOWS AND HOT WALL TEMPERATURES.



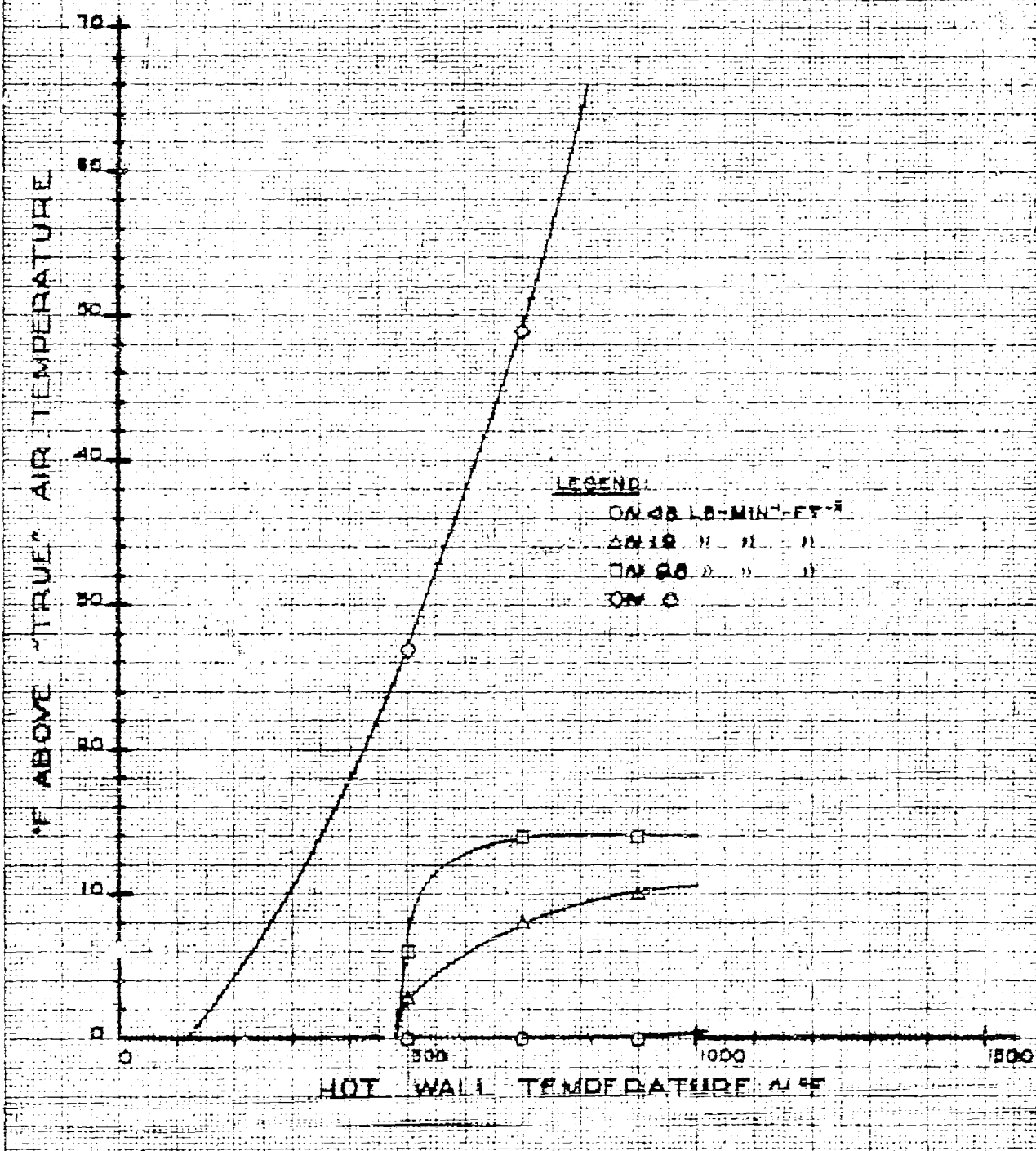
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FIG 20: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY REVERE (TPL SHLD) TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.



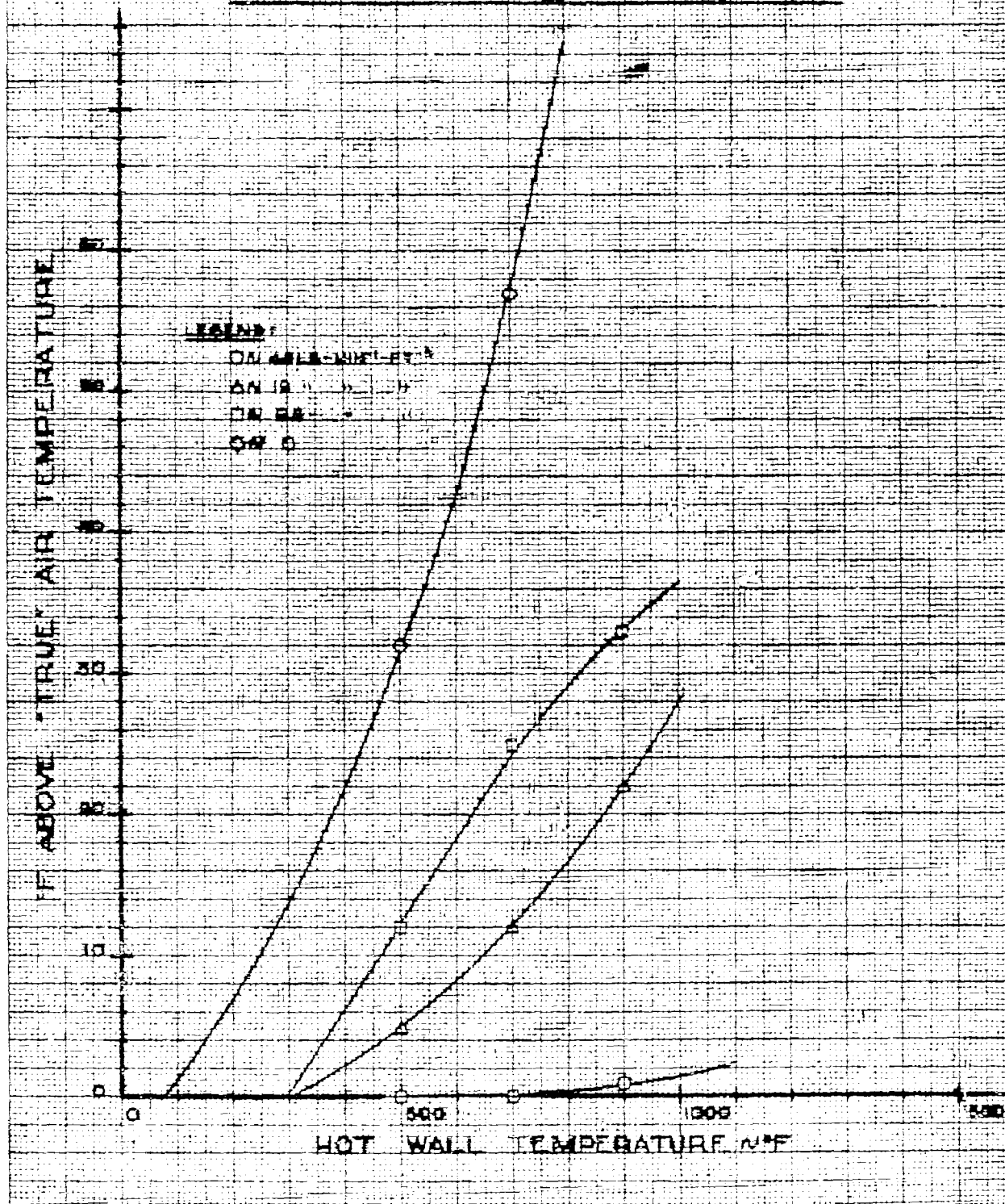
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FIGURE 1: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 3" OUTER - 2" INNER ALUMINUM DBL SHLD TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.



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FIG. 21 IF ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 3" OUTFLOW - 2" VENTURIMETER ALUMINUM DBL SHLD. TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.



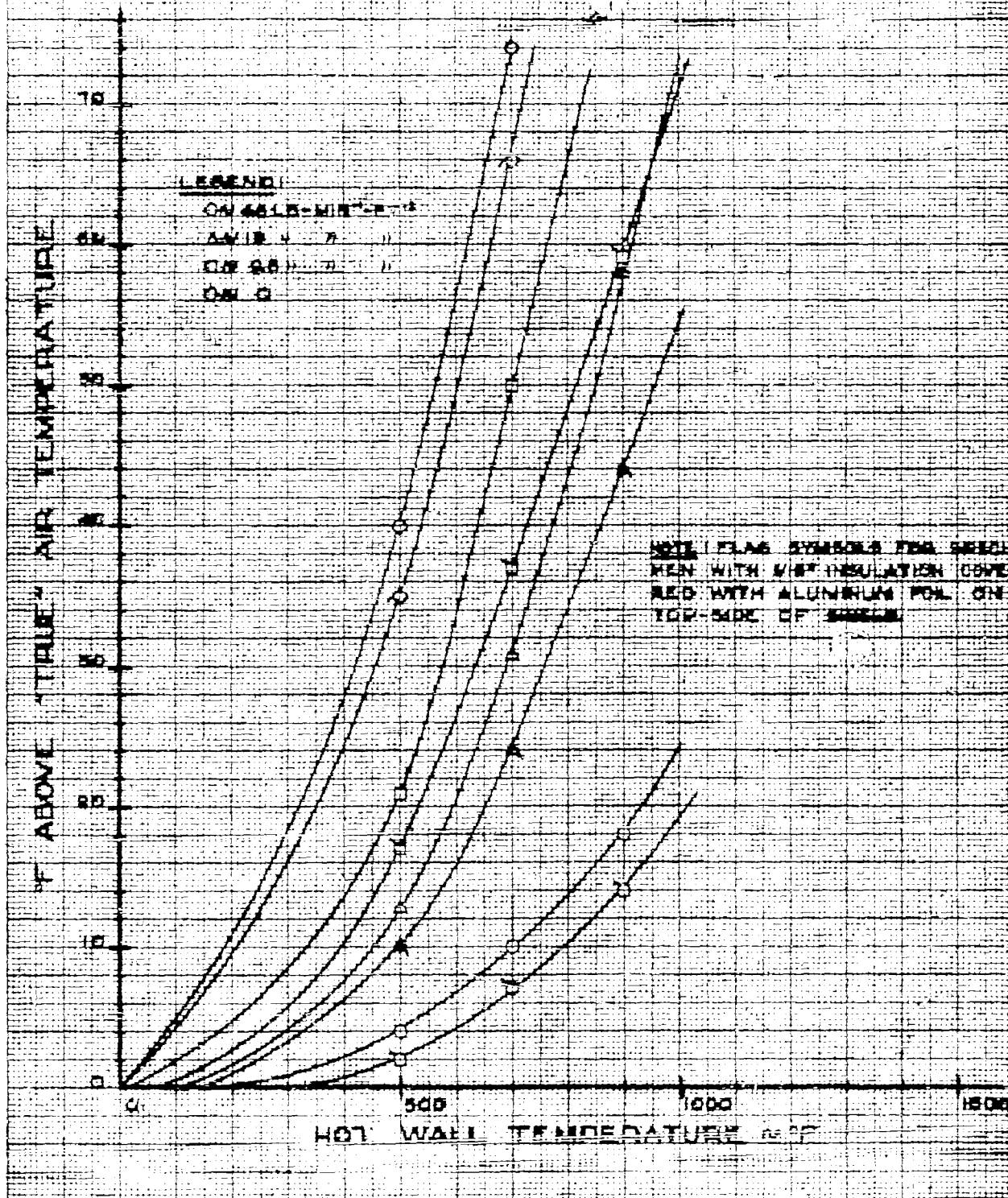
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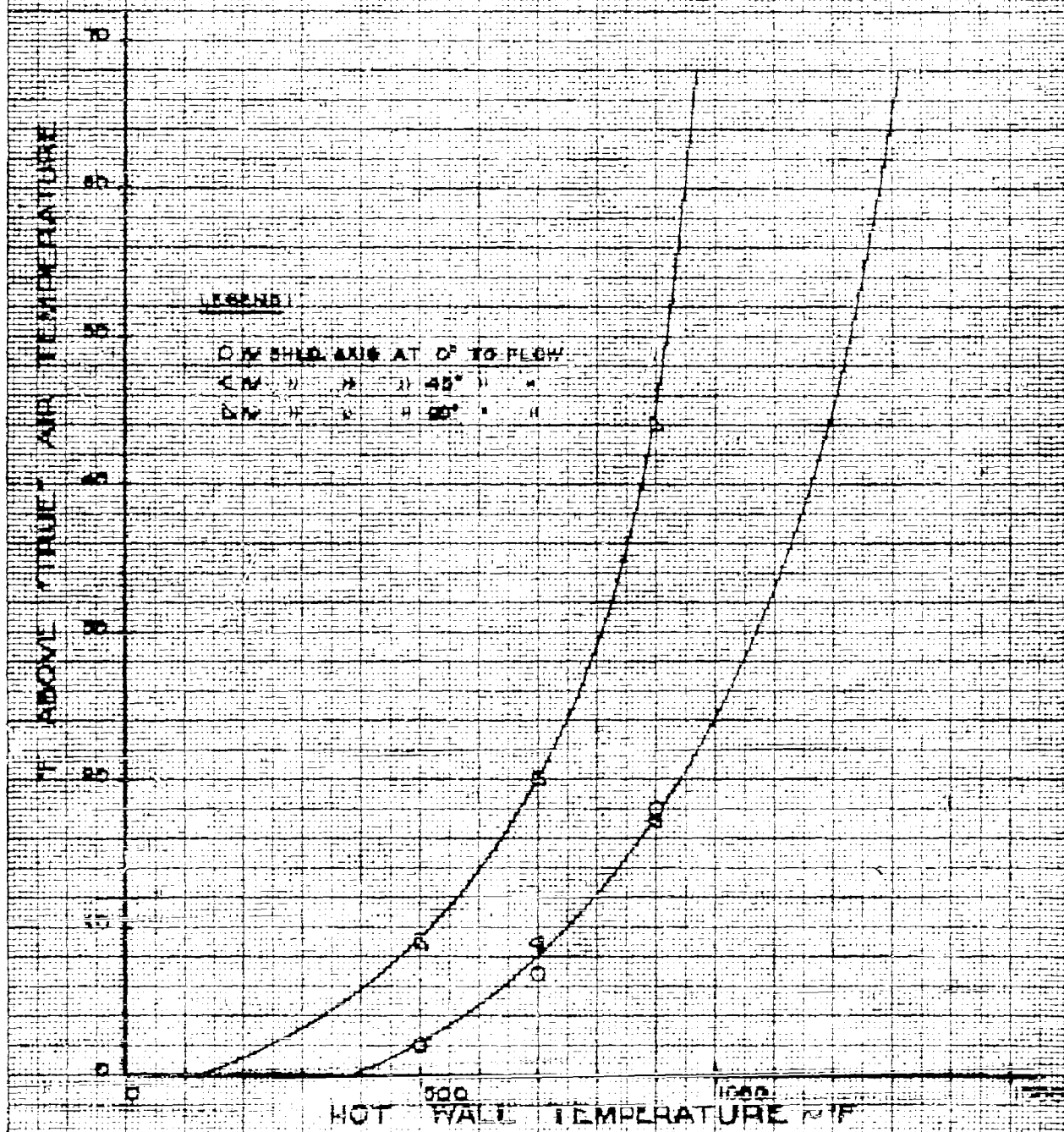
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FIG. 20: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 2"x2" UMBRELLA ALUMINUM TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES



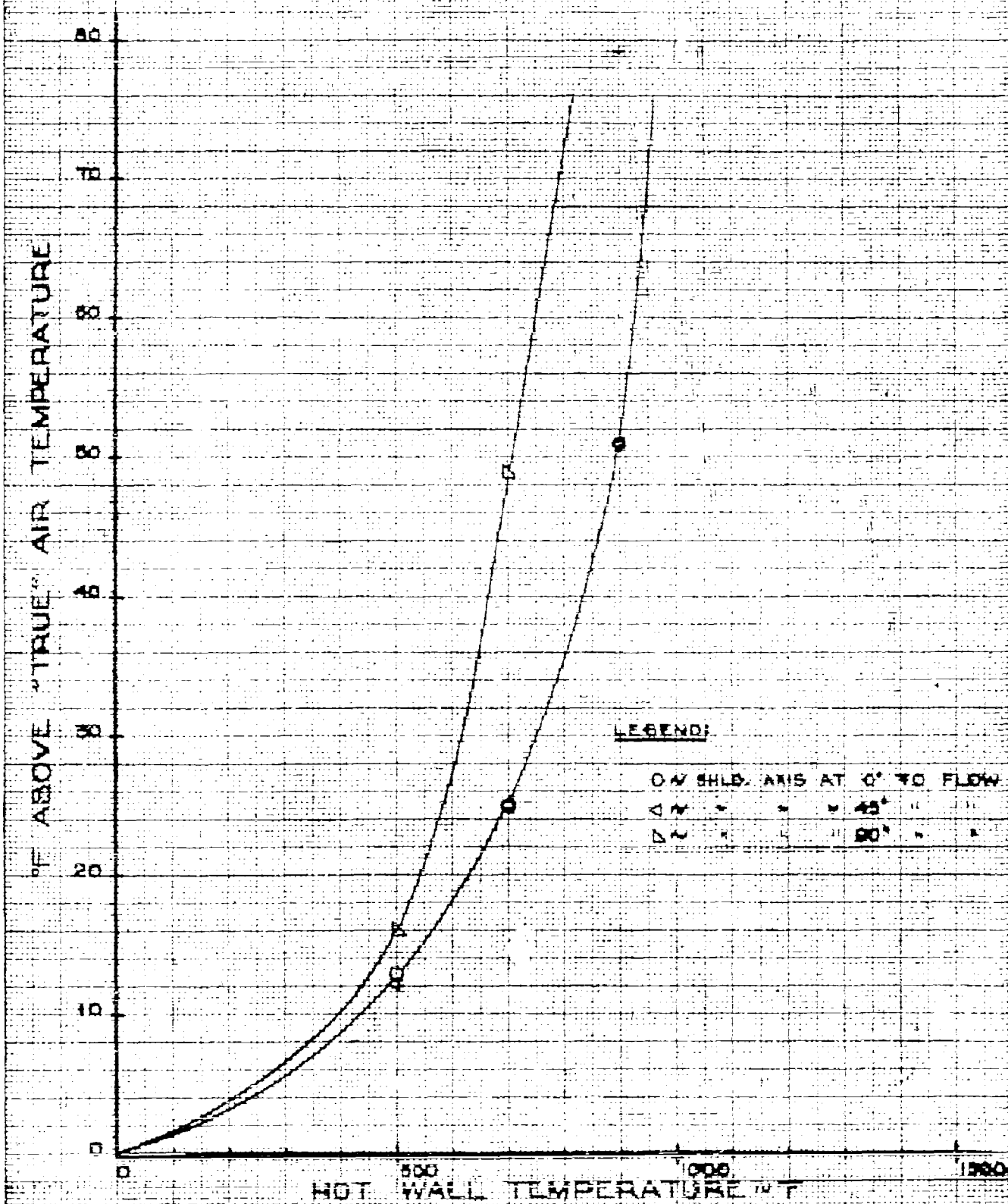
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FIG. 26: EFFECT OF ORIENTATION TO 40 LB-MIN-FT² FLOW ON TEST THERMOCOUPLE READING.
(1" 56L 54D - SPECIMEN #1)



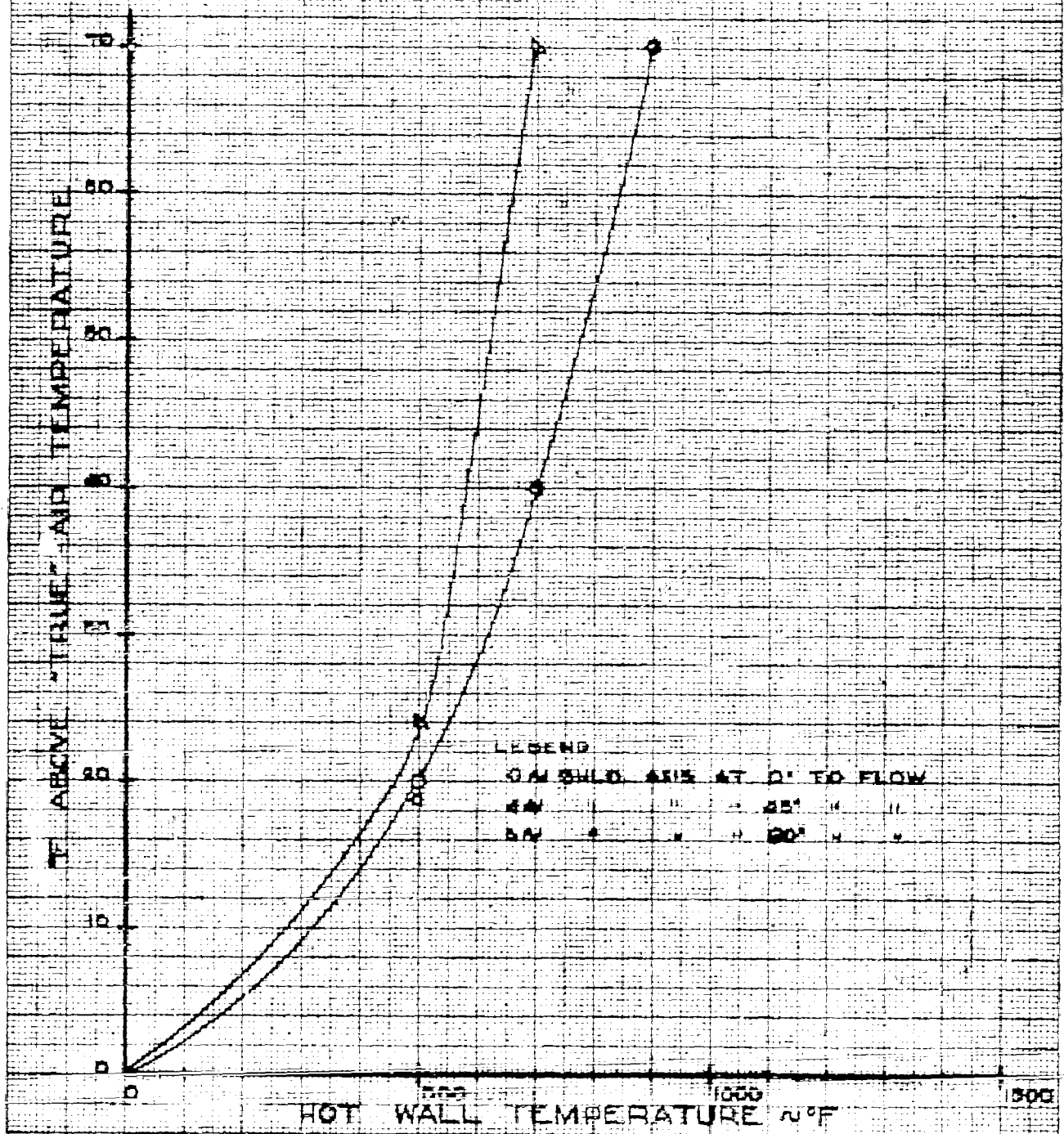
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FIG. 23: EFFECT OF ORIENTATION TO 10 LB-MIN-FT² FLOW ON TEST THERMOCOUPLE READING. (1" SOL. SHLD. - SPECIMEN *)



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FIGURE EFFECT OF ORIENTATION TO 65 LBS. MIN. AIR FLOW ON TEST THERMOCOUPLE READING (1" SGL SHLD SPECIMEN)

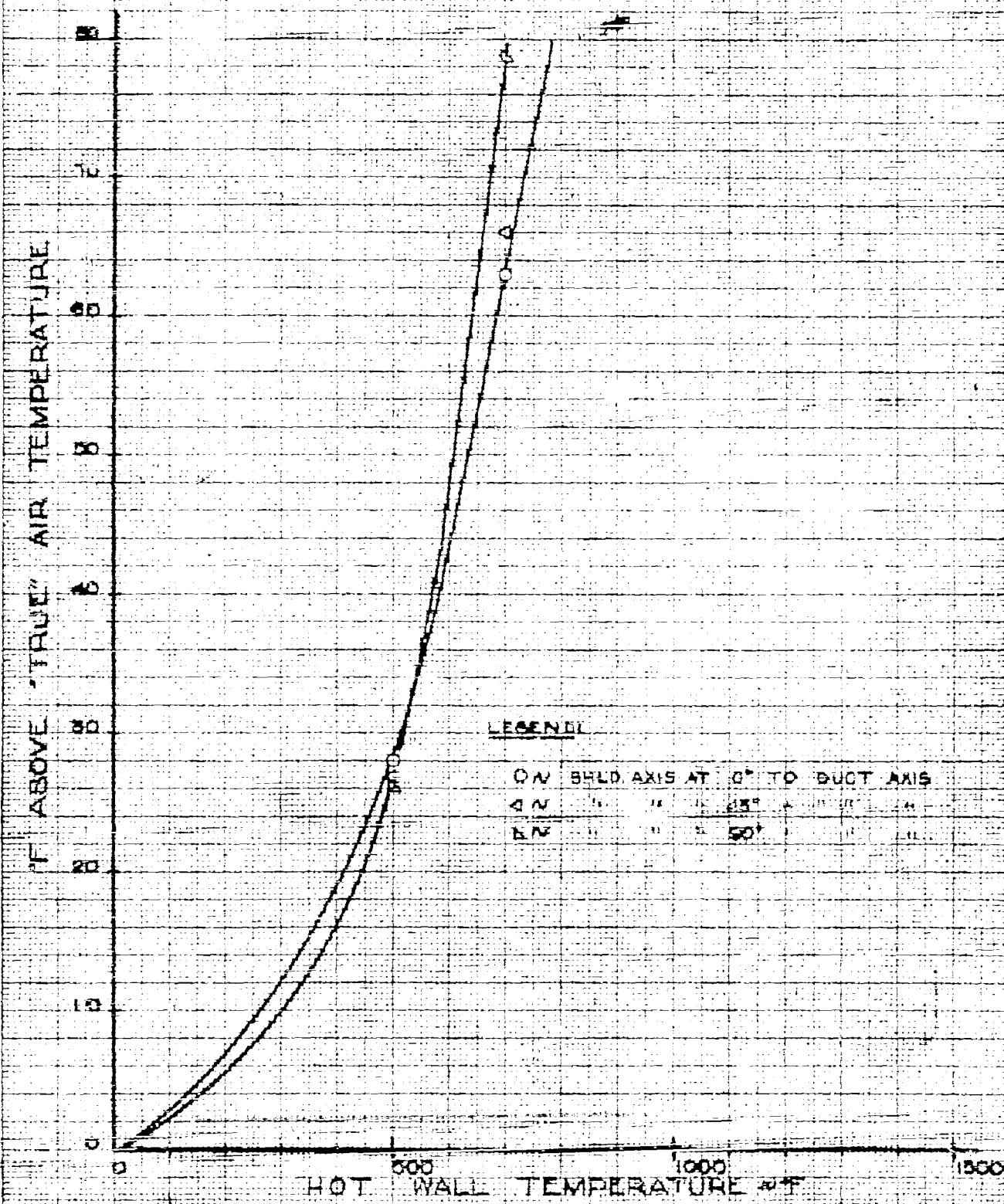


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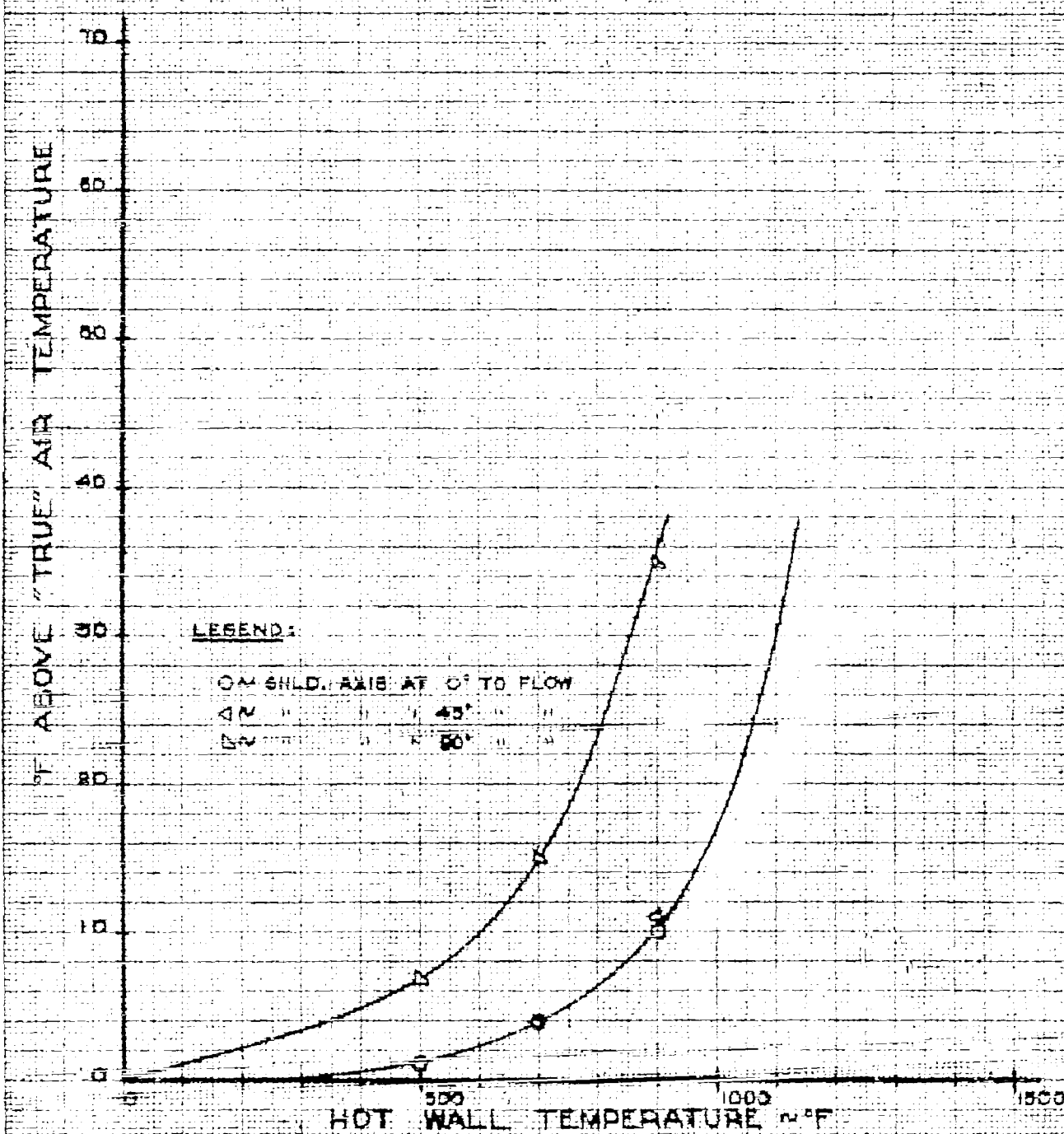
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FIG. 30: EFFECT OF ORIENTATION ON TEST THERMO-
COUPLE READING AT ZERO FLOW.
(1" SOL. SHLD. - SPECIMEN*)



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FIG. 35: EFFECT OF ORIENTATION TO 40 LB-MIN-FT² FLOW ON TEST THERMOCOUPLE READINGS (2" 36L SHLD.)



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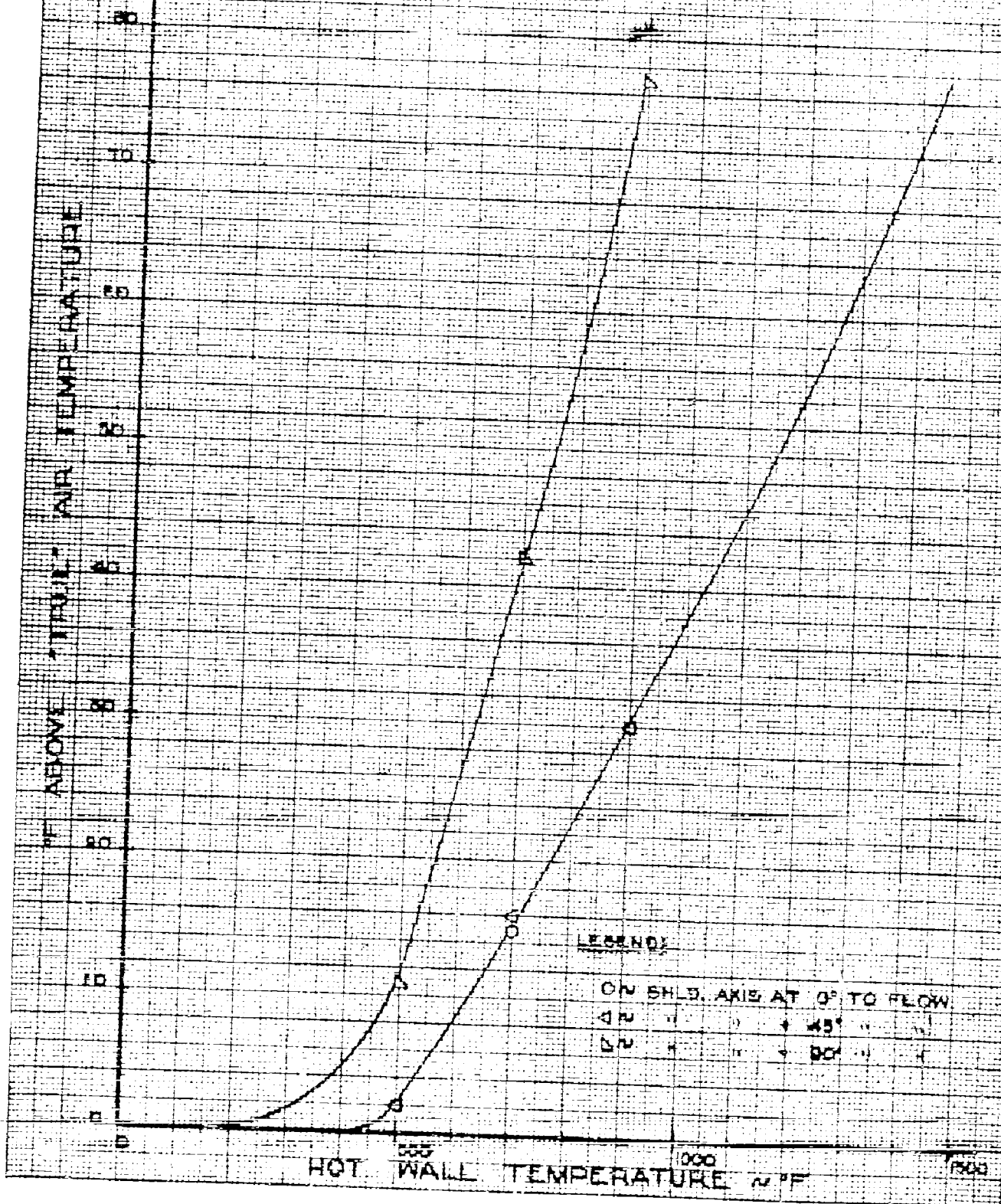
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FIG. 3E1 EFFECT OF ORIENTATION TO 1915-MIN-FT²
FLOW ON TEST THERMOCOUPLE READING
(2" SOL SHLD)



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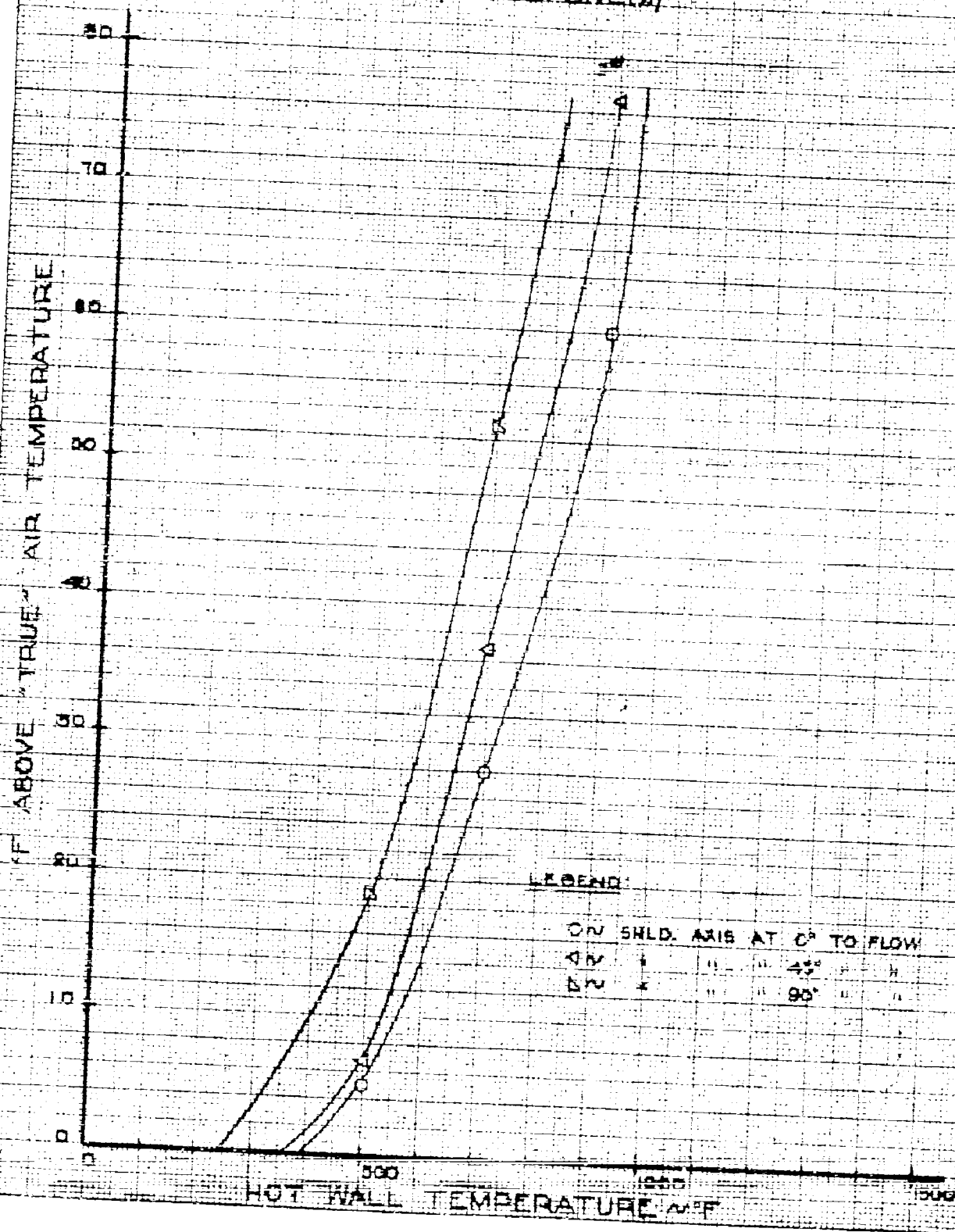
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FIG. 56: EFFECT OF ORIENTATION TO 9.6 LB-MIN-FT.²
FLOW ON TEST THERMOCOUPLE READING,
(2" 96L SHLD.)



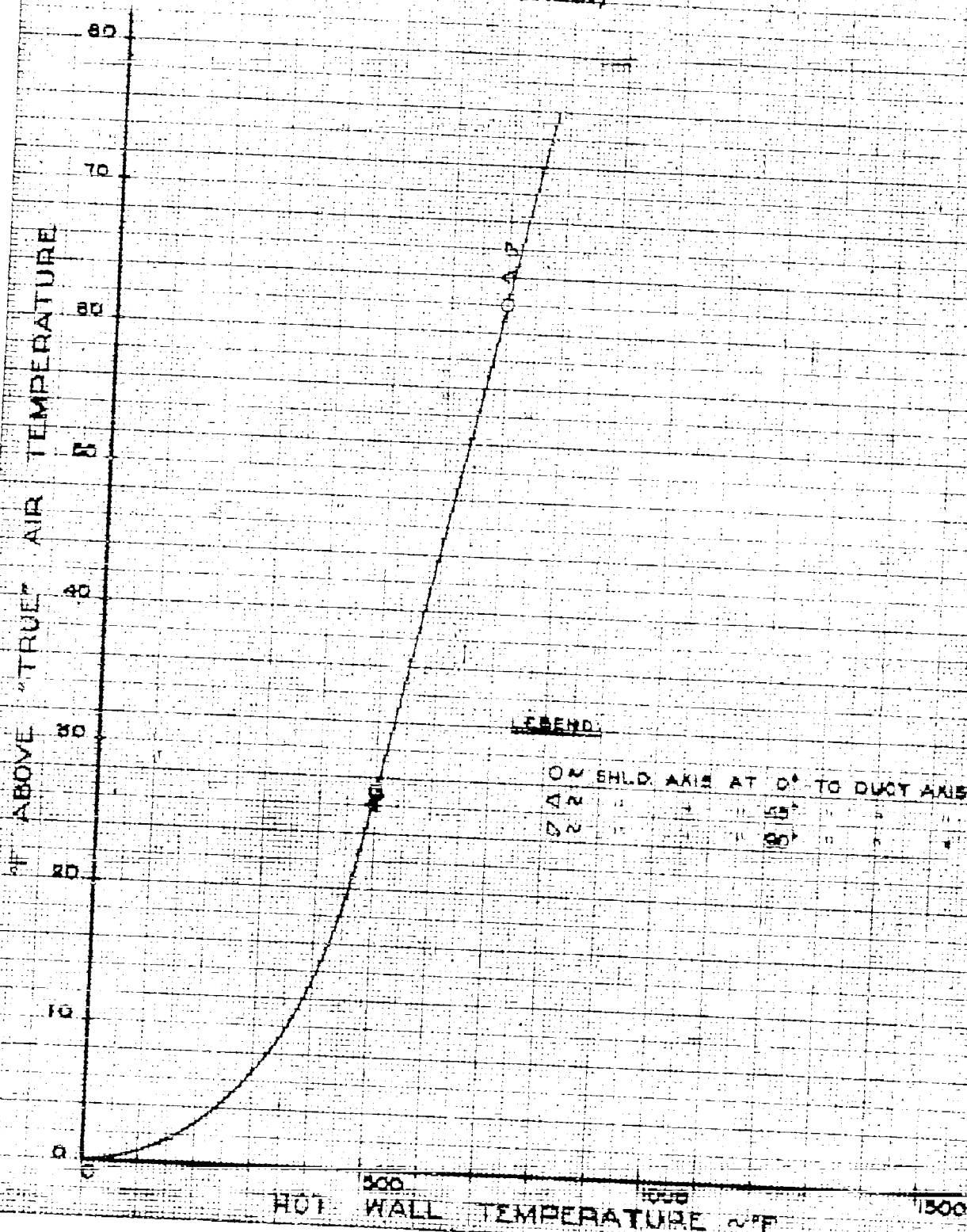
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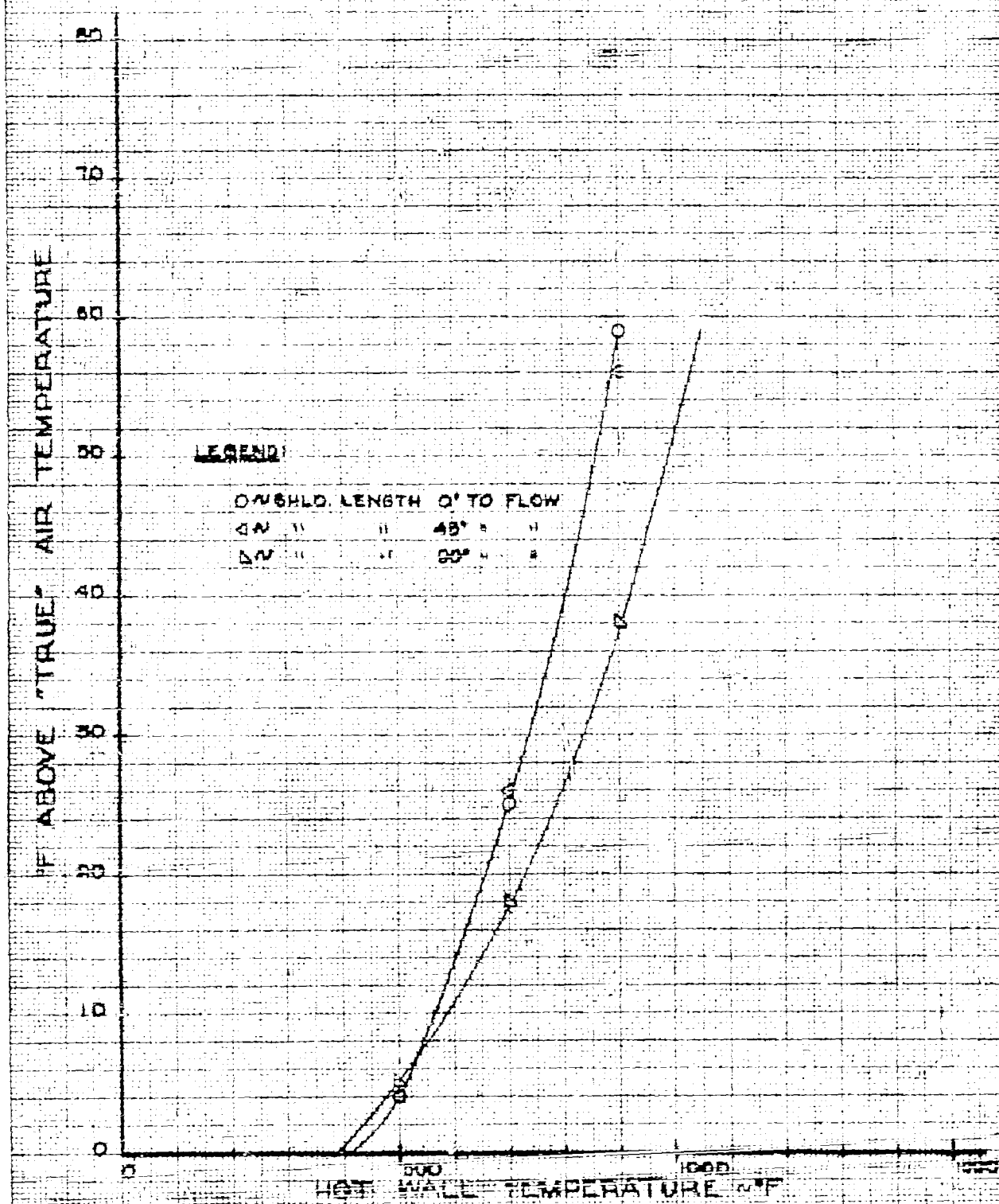
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FIG. 3H: EFFECT OF ORIENTATION ON TEST
THERMOCOUPLE READING AT ZERO FLOW.
(2" SBL, SHLD.)



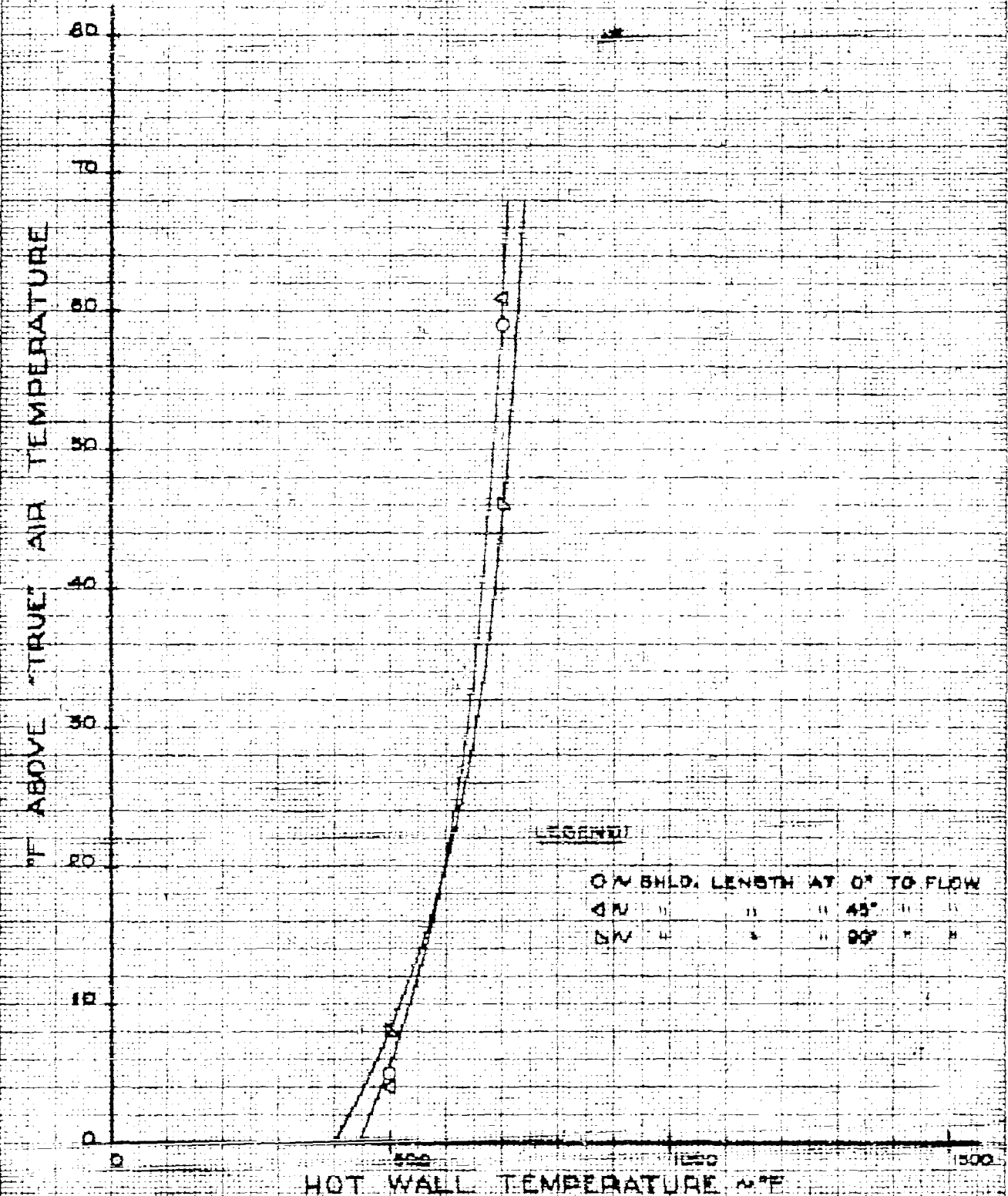
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FIG. 31: EFFECT OF ORIENTATION TO $4818\text{-MIN}^{-1}\text{-FT}^{-2}$ FLOW ON TEST THERMOCOUPLE READING. (HALF SHLD. SPECIMEN #9)



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FIG. 50: EFFECT OF ORIENTATION TO 19 LB-MIN⁻¹-FT.²
FLOW ON TEST THERMOCOUPLE READING
(HALF SHLD SPECIMEN #2)



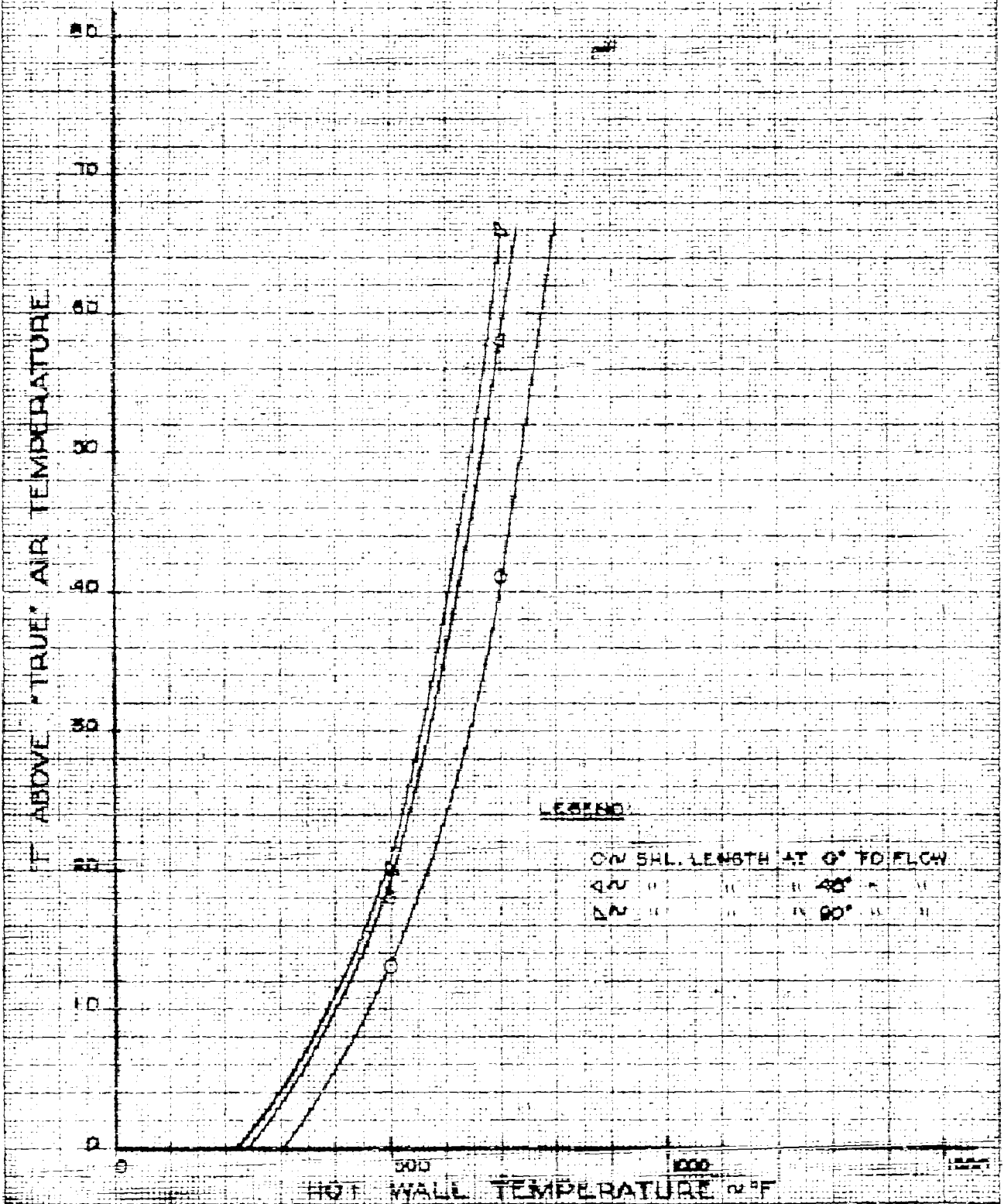
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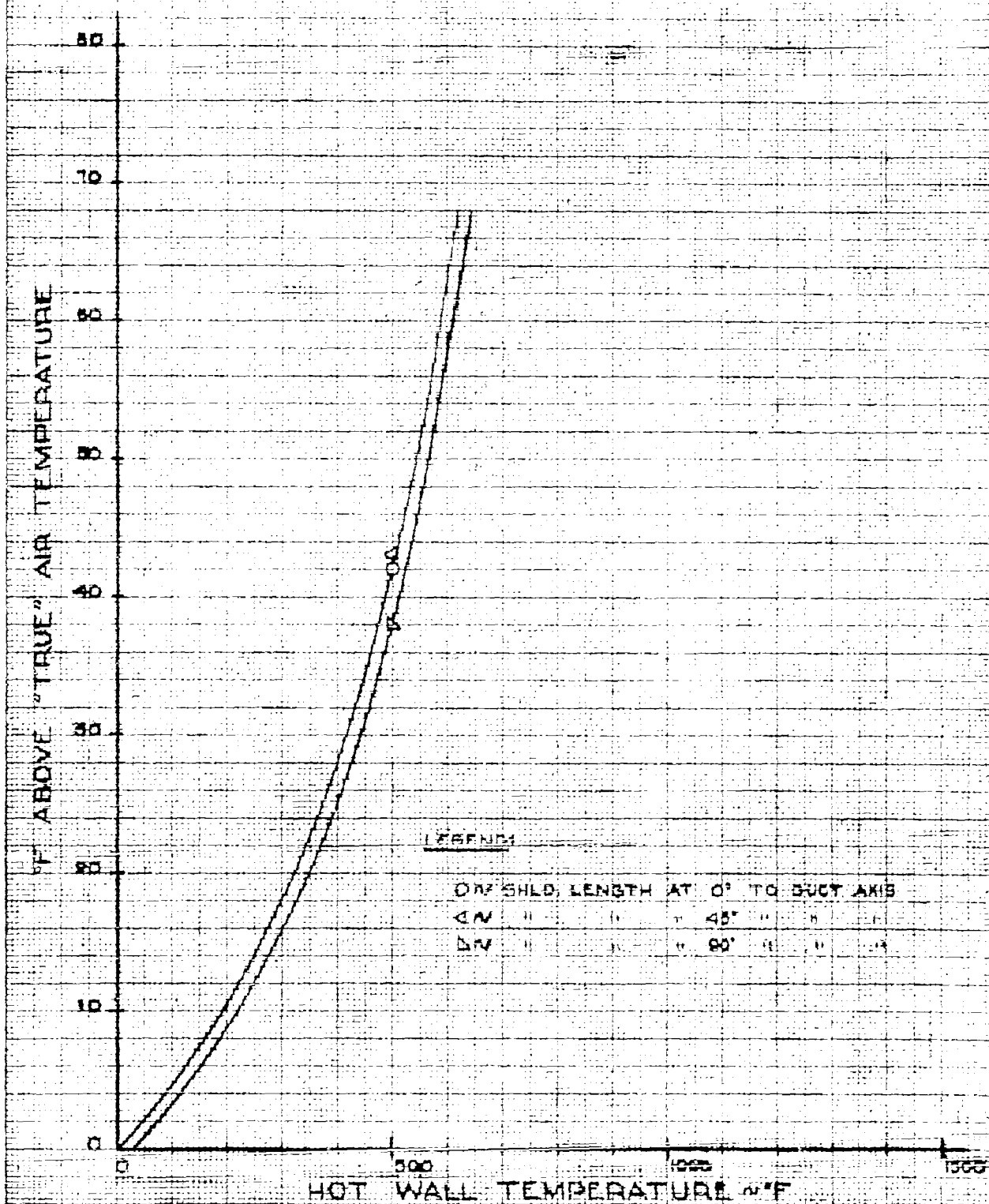
DATE
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FIG. 3K: EFFECT OF ORIENTATION TO 40 LB-MIN-FT²
FLOW ON TEST THERMOCOUPLE READING
(HALF SHLD. SPECIMEN #2)



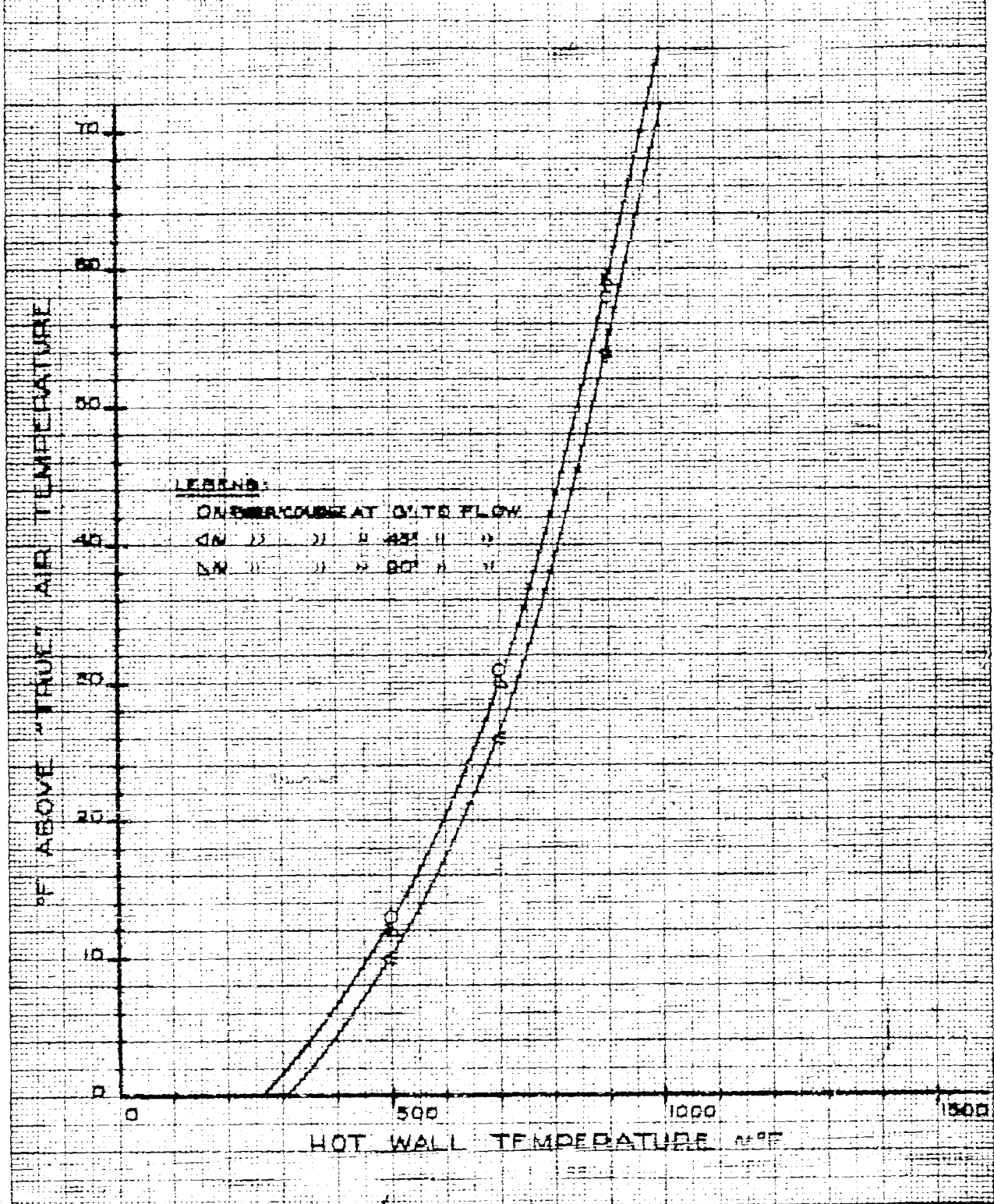
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FIG. 31: EFFECT OF ORIENTATION ON TEST THERMO-
COUPLE READING AT ZERO FLOW.
(HALF SHLD. SPECIMEN "D")



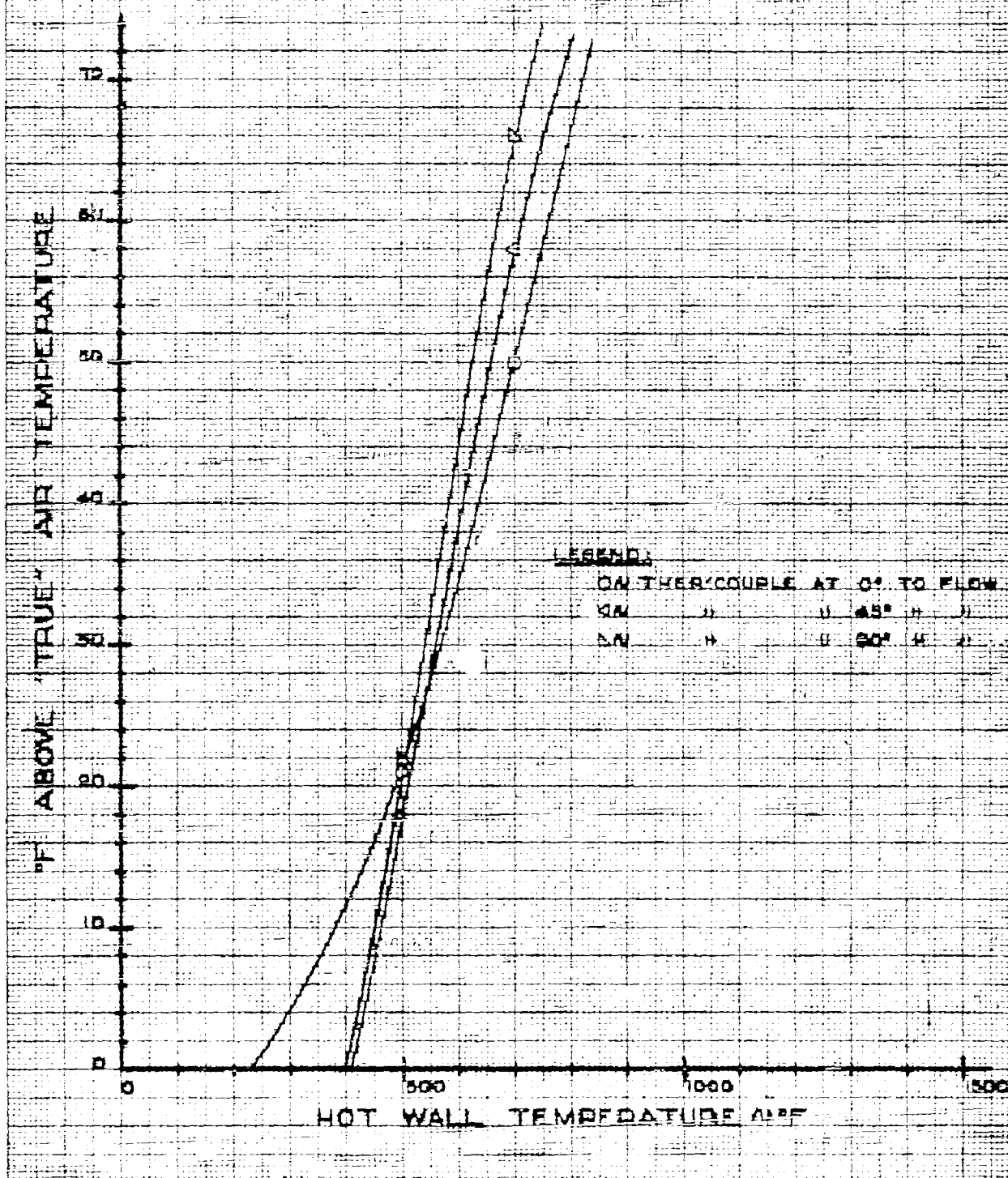
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FIG. 5N. EFFECT OF ORIENTATION TO 10 LB-MIN³-FT.³
FLOW ON TEST THERMOCOUPLE READING.
(2"x2" UMBRELLA)



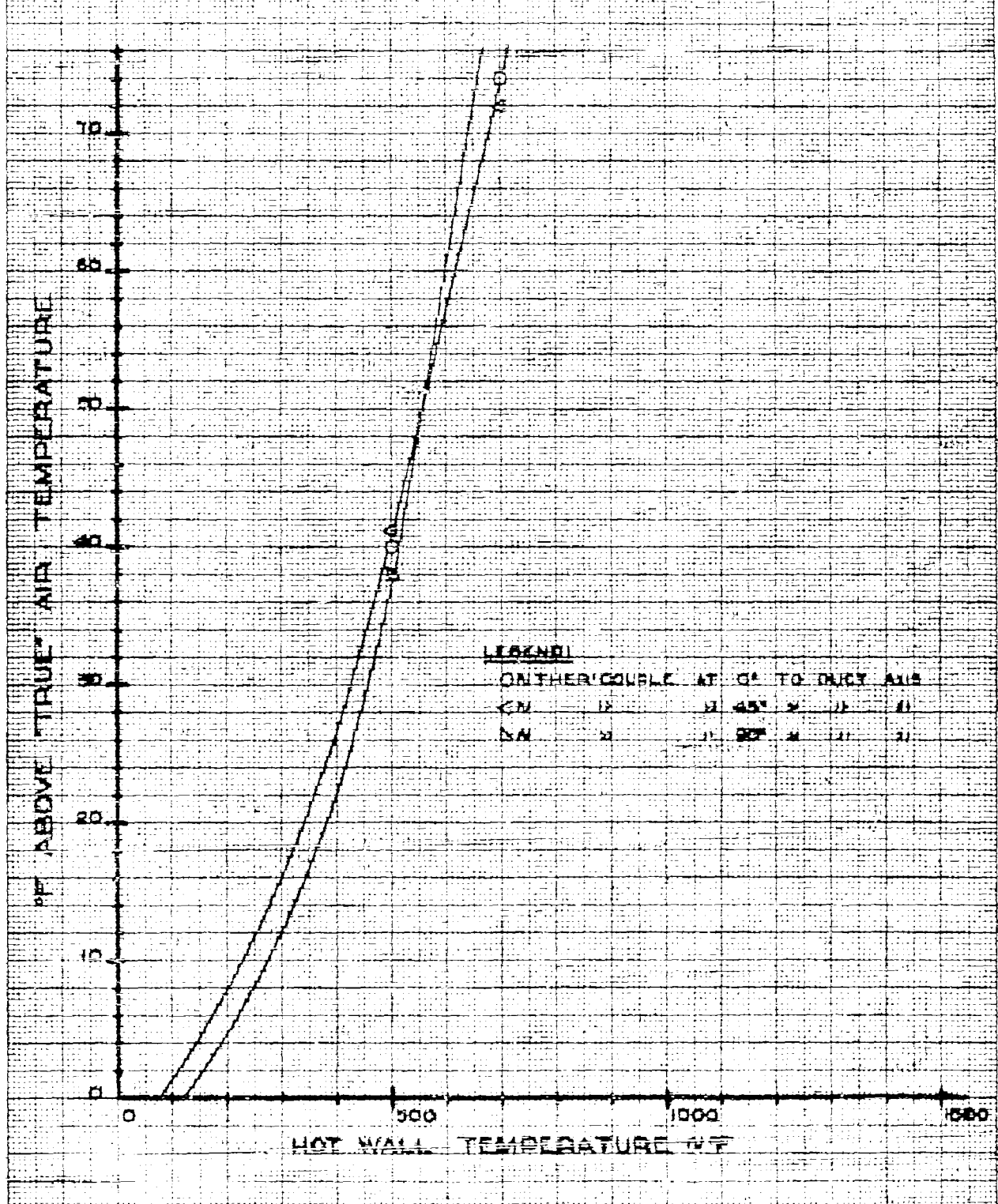
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FIG. 10: EFFECT OF ORIENTATION TO 9.6 LB-MIN-FT² FLOW ON TEST THERMOCOUPLE READING (2"x2" UMBRELLA)



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FIG. 30. EFFECT OF ORIENTATION ON TEST THERMOCOUPLE READING AT ZERO FLOW.
(2" x 2" UMBRELLA)



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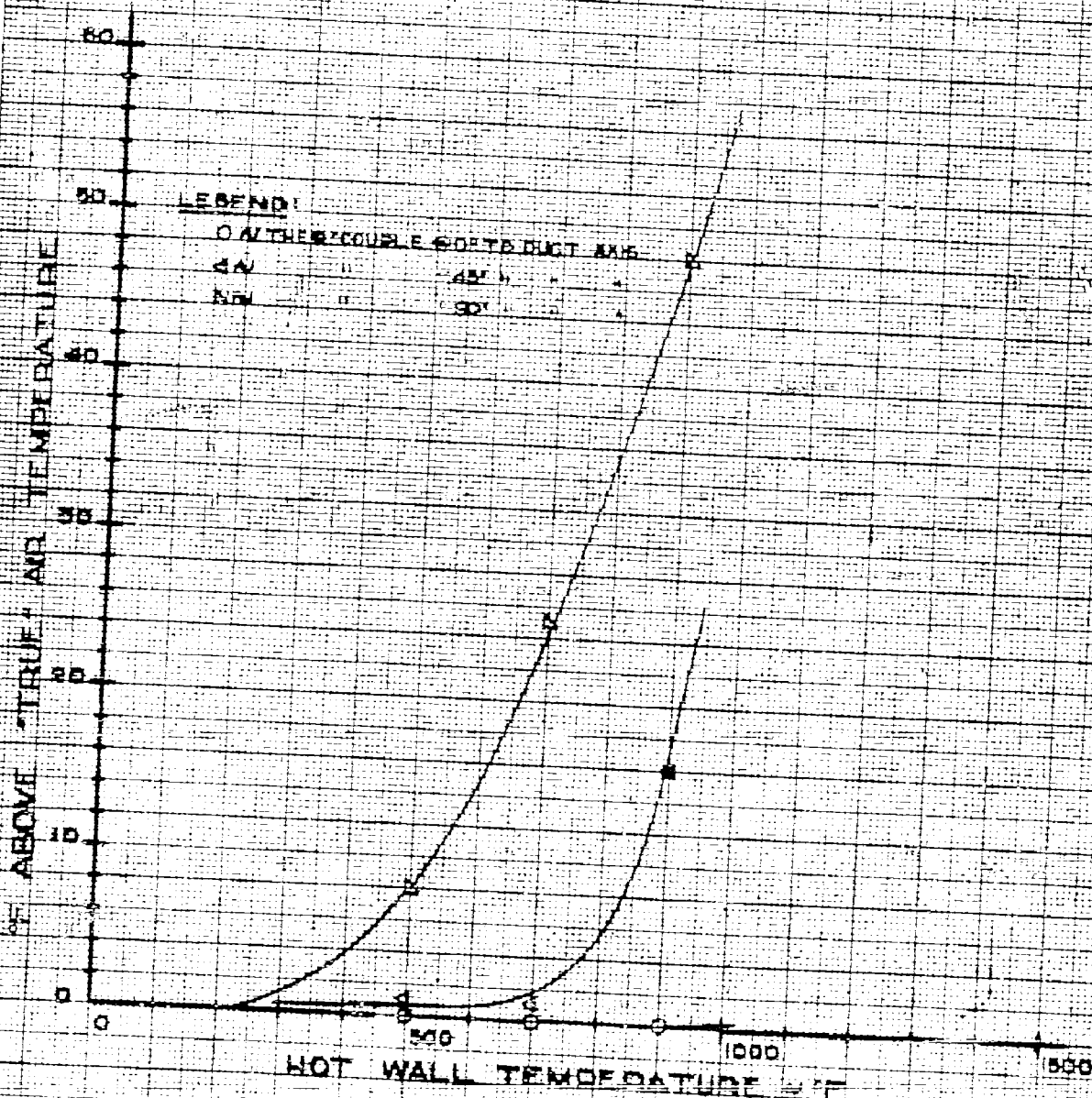
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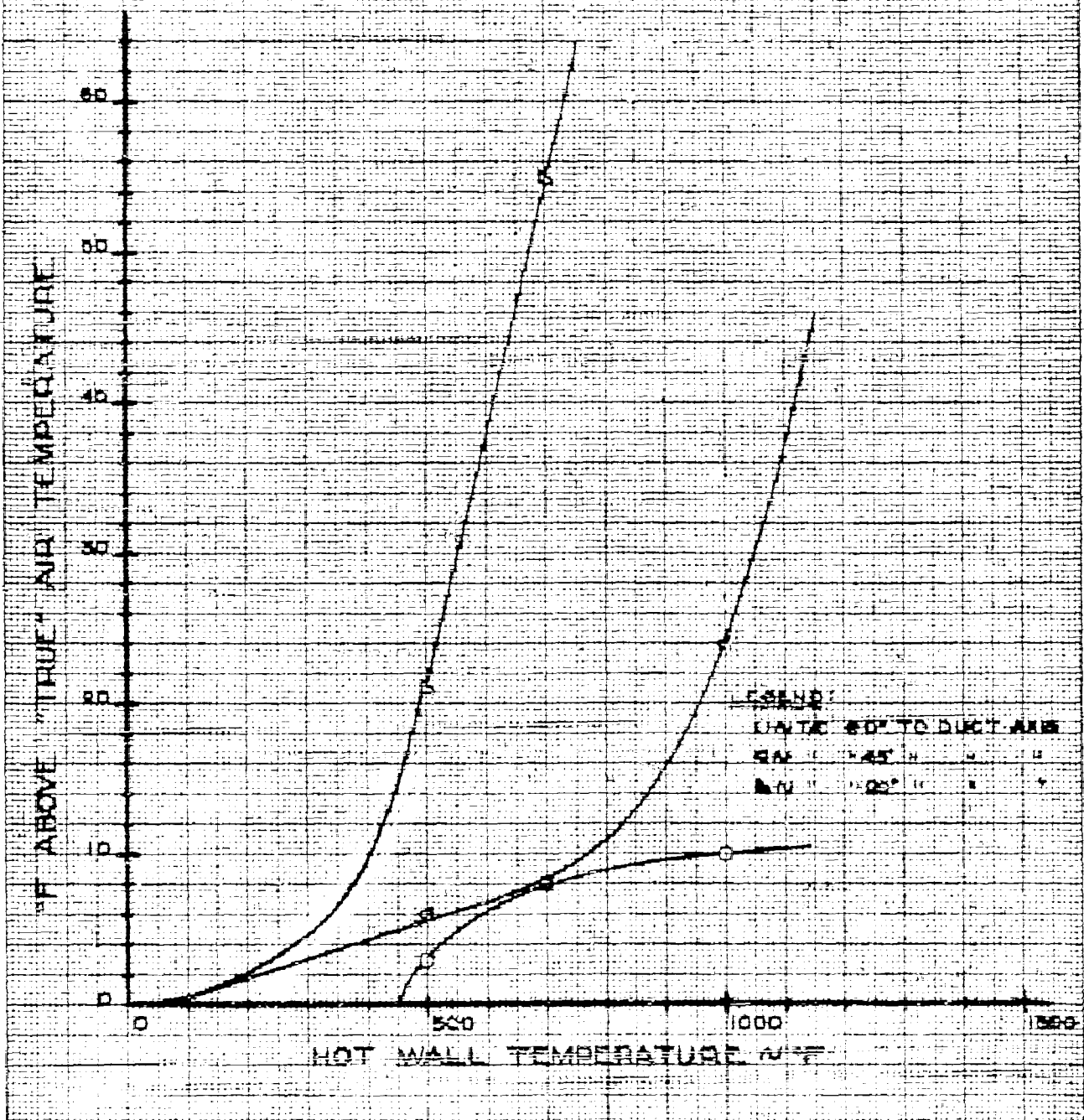
MODEL

**FIG. 30. EFFECT OF ORIENTATION TO 48 LB-MIN-FT⁻²
ON TEST THERMOCOUPLE READING
(2" INNER-3" OUTER-SHIELD)**



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FIGURE: EFFECT OF ORIENTATION TO $1918\text{-MIN}^{-1}\text{FT}^{-2}$
ON TEST THERMOCOUPLE READINGS.
(2" INNER - 3" OUTER - SHIELD)

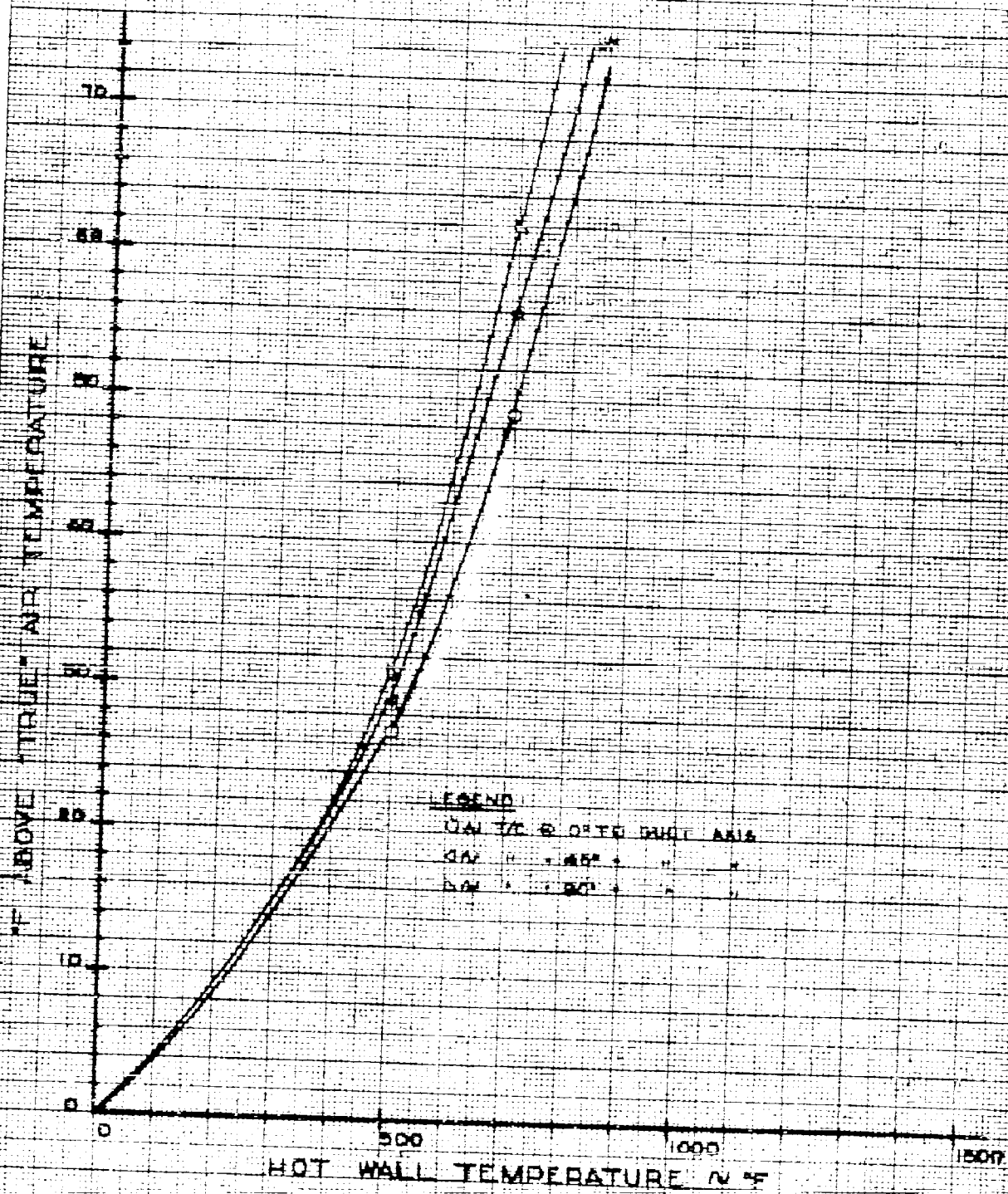


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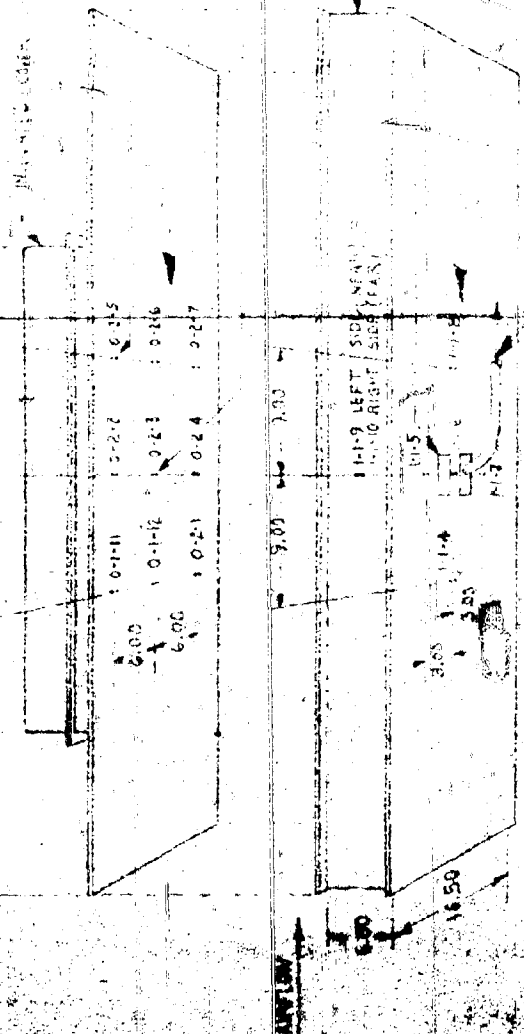
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FIG. 3T. EFFECT OF ORIENTATION ON TEST
THERMOCOUPLE READING AT ZERO FLOW
(2" INNER - 3" OUTER - SHIELD)



ENGINEER V. A. [unclear] 64
 CHECKED [unclear]
 DATE 15 APRIL 1955
 NORTHROP AIRCRAFT, INC.
 TYPICAL WALL TEMPERATURES



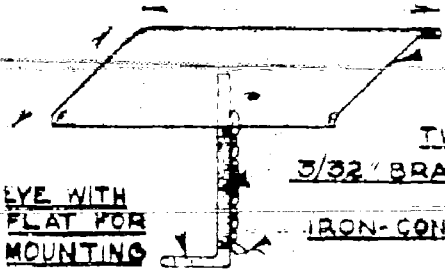
Notes: Airflow through the aspirated thermocouple affected the temperature of the specimen and thus required correction. Determination of specimen and aspirator thermocouple temperatures was therefore first established for the specimen with the aspirator off (upper line) and corrected for the aspirated thermocouple with the aspirator on (lower line).

TABLE I. REPRESENTATIVE TEST CHAMBER TEMPERATURES

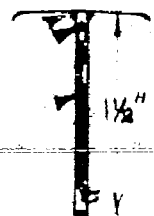
DUCT AIR FLOW PPM	DUCT AIR INLET TEMP-F	ASPIRATED THERMO-COUPLE	TEMPERATURES - DEGREES FAHRENHEIT																																																																																																																																																																																																																																																																																																																																																																																																																																																																																										
			DUCT WALL				SIDE WALL				COLD WALL																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
			0-1-11	0-1-12	0-2-1	0-2-2	0-2-3	0-2-4	0-2-5	0-2-6	0-2-7	1-1-9	1-1-10	1-1-11	1-1-12	1-1-13	1-1-14	1-1-15	1-1-16	1-1-17	1-1-18																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
30	74	OFF	345	335	351	357	361	365	368	372	376	380	384	388	392	396	400	404	408	412	416	420	424	428	432	436	440	444	448	452	456	460	464	468	472	476	480	484	488	492	496	500	504	508	512	516	520	524	528	532	536	540	544	548	552	556	560	564	568	572	576	580	584	588	592	596	600	604	608	612	616	620	624	628	632	636	640	644	648	652	656	660	664	668	672	676	680	684	688	692	696	700	704	708	712	716	720	724	728	732	736	740	744	748	752	756	760	764	768	772	776	780	784	788	792	796	800	804	808	812	816	820	824	828	832	836	840	844	848	852	856	860	864	868	872	876	880	884	888	892	896	900	904	908	912	916	920	924	928	932	936	940	944	948	952	956	960	964	968	972	976	980	984	988	992	996	1000																																																																																																																																																																																																																																																																																																																						
12	71	OFF	349	339	355	361	365	369	372	376	380	384	388	392	396	400	404	408	412	416	420	424	428	432	436	440	444	448	452	456	460	464	468	472	476	480	484	488	492	496	500	504	508	512	516	520	524	528	532	536	540	544	548	552	556	560	564	568	572	576	580	584	588	592	596	600	604	608	612	616	620	624	628	632	636	640	644	648	652	656	660	664	668	672	676	680	684	688	692	696	700	704	708	712	716	720	724	728	732	736	740	744	748	752	756	760	764	768	772	776	780	784	788	792	796	800	804	808	812	816	820	824	828	832	836	840	844	848	852	856	860	864	868	872	876	880	884	888	892	896	900	904	908	912	916	920	924	928	932	936	940	944	948	952	956	960	964	968	972	976	980	984	988	992	996	1000																																																																																																																																																																																																																																																																																																																							
6	72	OFF	368	358	374	380	384	388	392	396	400	404	408	412	416	420	424	428	432	436	440	444	448	452	456	460	464	468	472	476	480	484	488	492	496	500	504	508	512	516	520	524	528	532	536	540	544	548	552	556	560	564	568	572	576	580	584	588	592	596	600	604	608	612	616	620	624	628	632	636	640	644	648	652	656	660	664	668	672	676	680	684	688	692	696	700	704	708	712	716	720	724	728	732	736	740	744	748	752	756	760	764	768	772	776	780	784	788	792	796	800	804	808	812	816	820	824	828	832	836	840	844	848	852	856	860	864	868	872	876	880	884	888	892	896	900	904	908	912	916	920	924	928	932	936	940	944	948	952	956	960	964	968	972	976	980	984	988	992	996	1000																																																																																																																																																																																																																																																																																																																												
0	-	OFF	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435	435

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DATE April 1955	FIG. 4: TEST SPECIMENS	REPORT NO. NAI 55-278
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A. UMBRELLA SHIELD

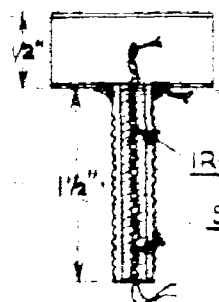


POLISHED ST. STL.
SILVER SOLDER
TWIST ENDS - SILVER SOLDER
3/32" BRASS ROD
EYE WITH FLAT FOR MOUNTING
WOUND MASKING TAPE
IRON-CONSTANTAN-INSUL. STRANDED WIRE



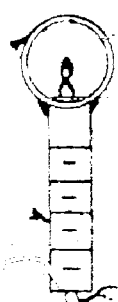
1 1/2"

B. 1" LONG SINGLE SHIELD (REF. DWG. #2005391)



1/2"
1 1/2"

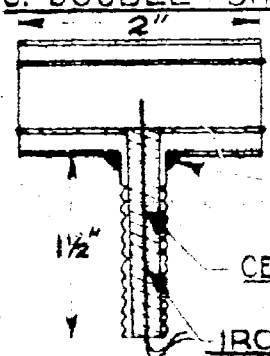
TWISTED ENDS; FLASH WELDED
SHIELD, STAINLESS STEEL TUBE, 0.035 WALL
SILVER SOLDER
1/4 - 28NF3
IRON-CONSTANTAN, INSUL. STRANDED WIRE
SAUERLEISEN #7 PASTE



1/2"

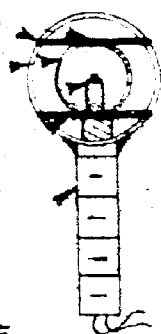
NOTE: 2" LONG SPECIMEN SAME EXCEPT SHIELD HAS 0.028 WALL AND STEM CONTAINS 2-HOLE CERAMIC INSULATOR (REF. DWG. #5206655).

C. DOUBLE SHIELD (REF. DWG. #5206655)



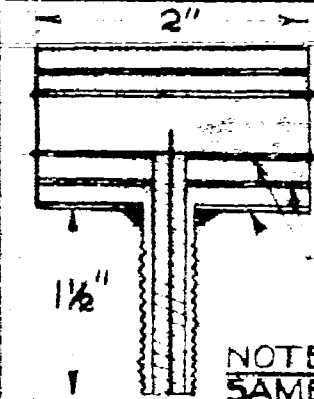
2"
1/2"
1 1/2"

SILVER SOLDER - 12 PLACES
1/2" 1" ST'LESS. ST'L. 0.028 WALL
BUTT WELD, SILVER SOLDER
SILVER SOLDER
SHIELD SUPPORT - 0.034 MCNEL
CERAMIC INSULATOR
3/8 - 24NF3
IRON-CONSTANTAN, INSUL., STRANDED WIRE



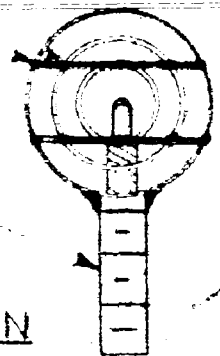
1/2"

D. TRIPLE SHIELD (REF. DWG. #5206655)



2"
1/2"
1 1/2"

SILVER SOLDER
20 PLACES
0.028 WALL
0.035 WALL
3/8 - 24NF3



1 1/2"

NOTE: DETAILS OF CONSTRUCTION SAME AS SPECIMEN "C".

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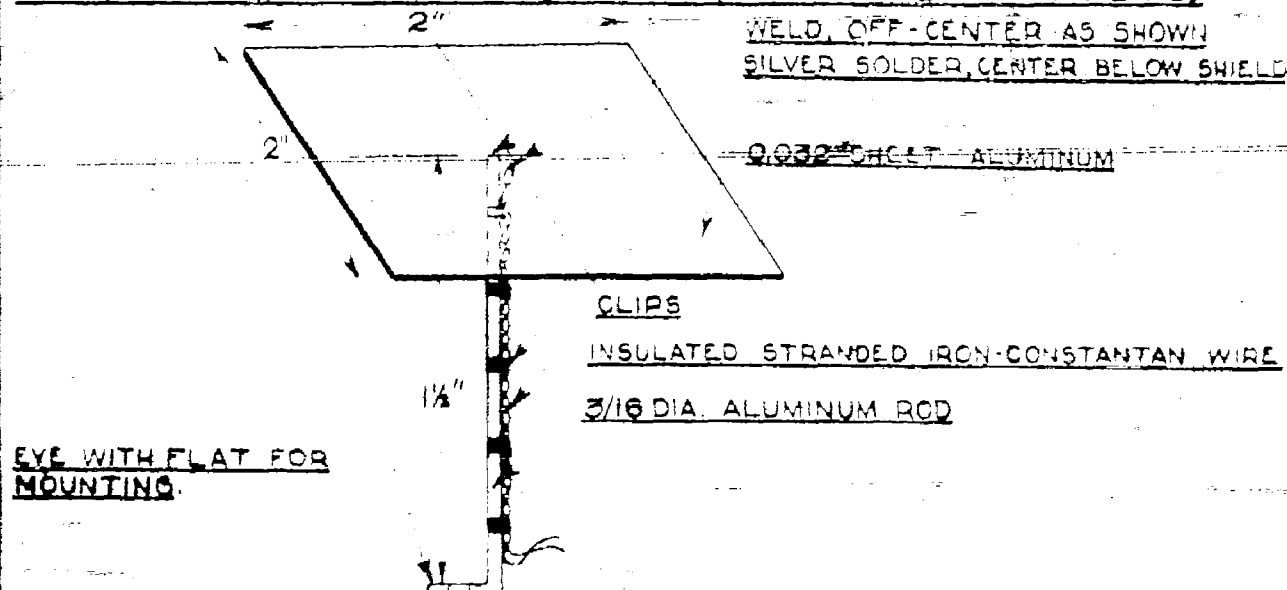
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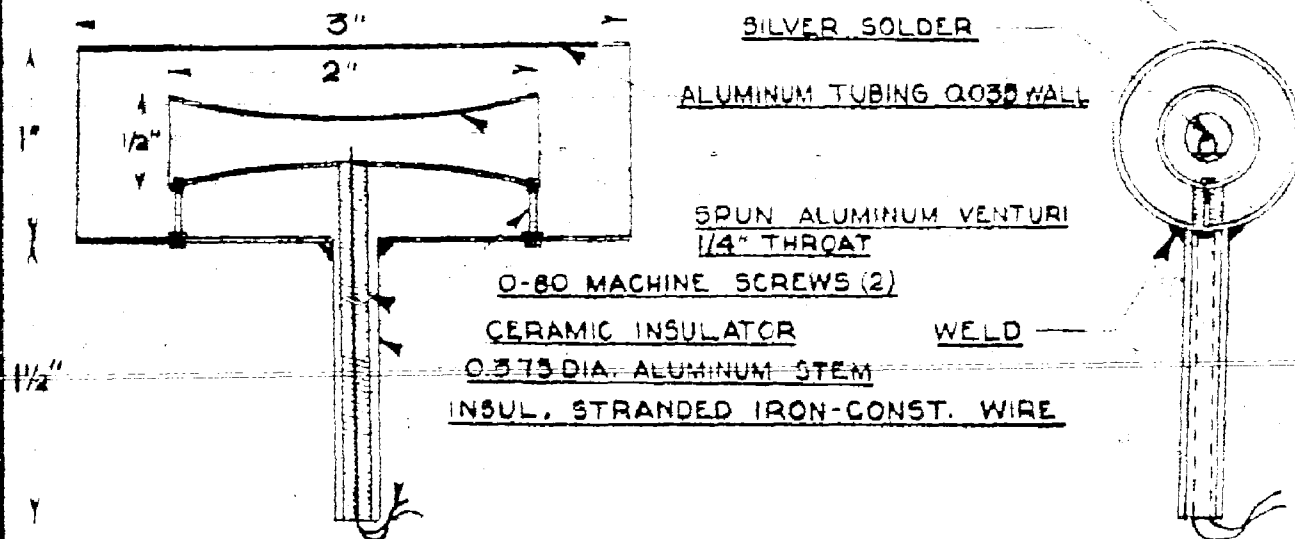
FIG. 4: TEST SPECIMENS

E. FLAT UMBRELLA SHIELD (REF. DWG. #5206959)



NOTE: ONE ADDITIONAL, EXACTLY AS ABOVE AND WITH 2-2" $\frac{1}{16}$ " THICK SHEET ASBESTOS COVERED WITH ALUMINUM FOIL.

F. VENTURI DOUBLE SHIELD (REF. DWG. #5206959)



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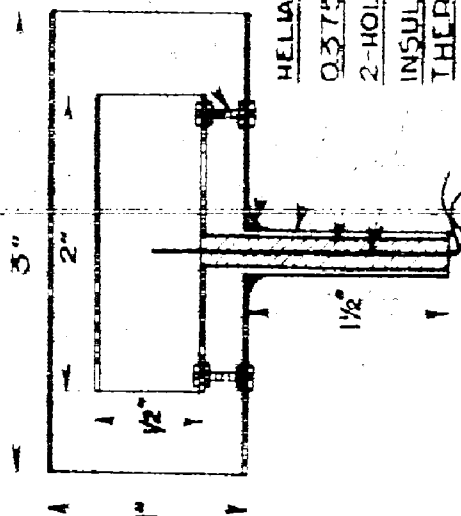
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FIG. 4: TEST SPECIMENS

MODEL

6. 3" OUTER - 2" INNER - DOUBLE SHIELD



BUTT WELD - SILVER SOLDER.

ALUMINUM TUBING - 0.003 WALL.

0-80 MACHINE SCREWS (2).

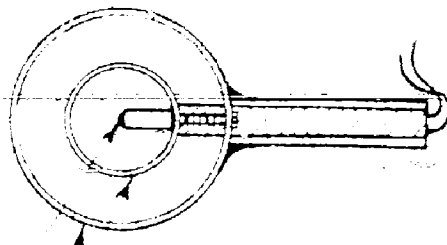
HELLARC WELD.

0.375 DIA. ALUMINUM STEM.

2-HOLED CERAMIC INSULATOR.

INSULATED STRANDED IRON-CONSTANTAN

THERMOCOUPLE WIRE.



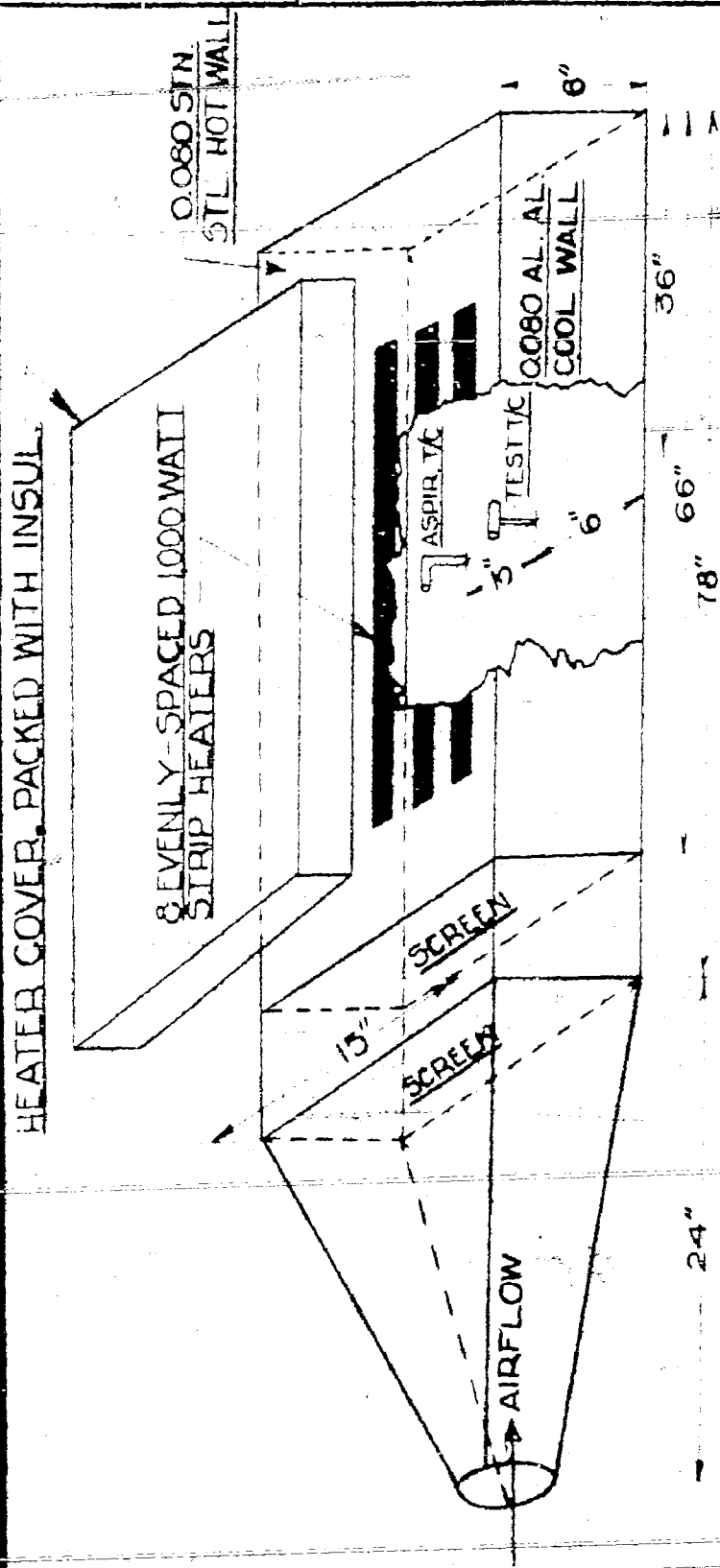
REF. DWG. #3208959

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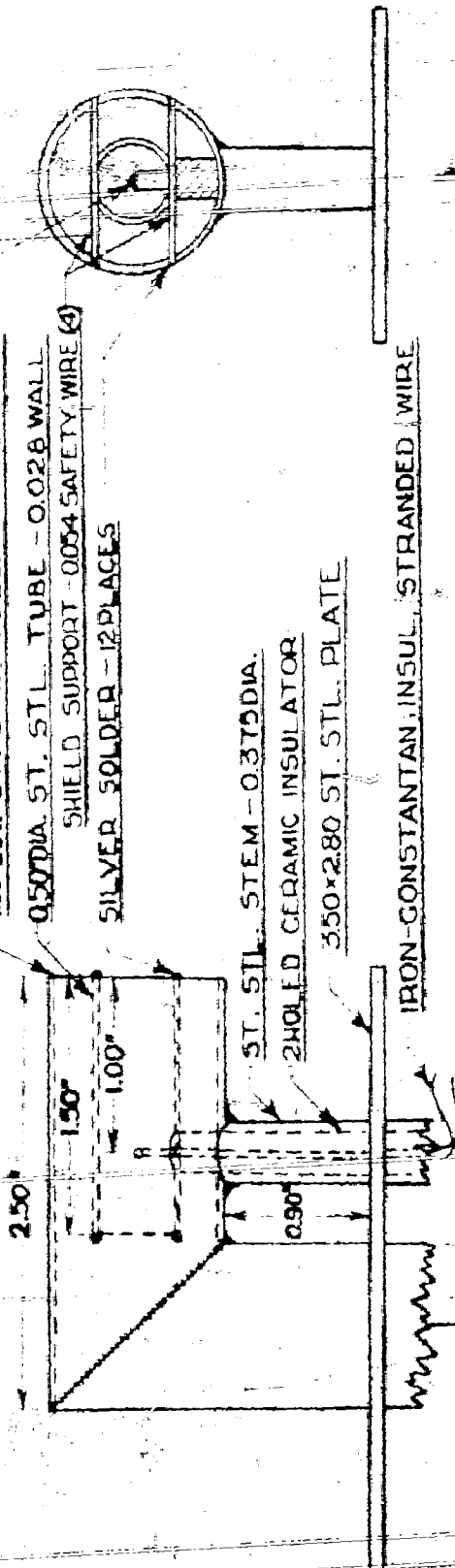


REF. DWS. 2206856

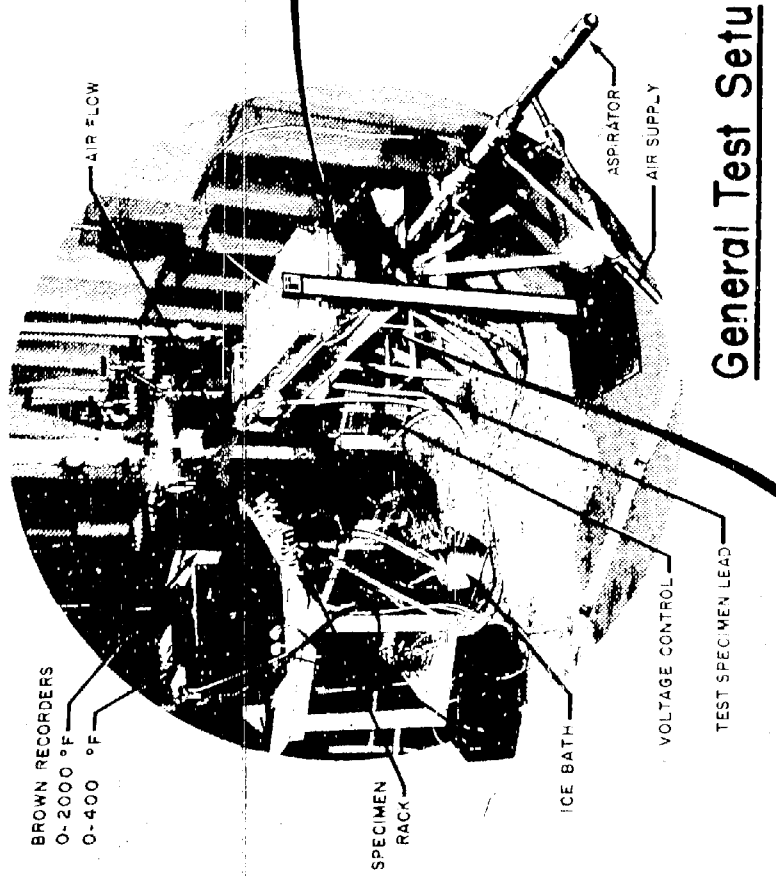
FIG. 5: TEST CHAMBER

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		MODEL

BUTT WELD - SILVER SOLDER
1.00" DIA. ST. STL. TUBE - 0.028 WALL
0.507 DIA. ST. STL. TUBE - 0.028 WALL
SHIELD SUPPORT - 0054 SAFETY WIRE (4)
SILVER SOLDER - 12 PLACES
ST. STL. STEM - 0.375 DIA.
2 HOLED CERAMIC INSULATOR
350 x 280 ST. STL. PLATE
IRON-CONSTANTAN-INSUL. STRANDED WIRE



REF. DWG. 5206652



BROWN RECORDERS
0-2000 °F
0-400 °F

SPECIMEN
RACK

ICE BATH

VOLTAGE CONTROL

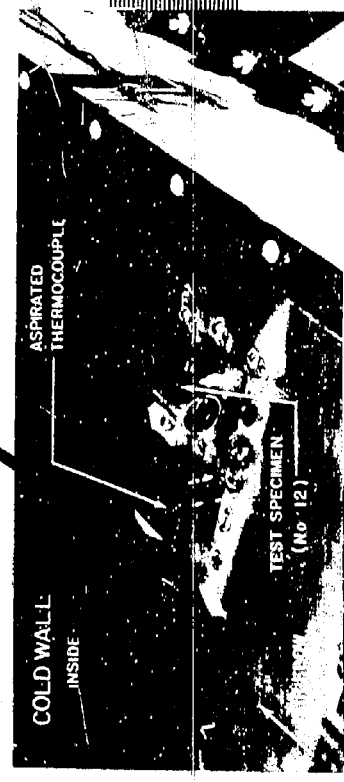
TEST SPECIMEN LEAD

ASPIRATOR

AIR SUPPLY

AIR FLOW

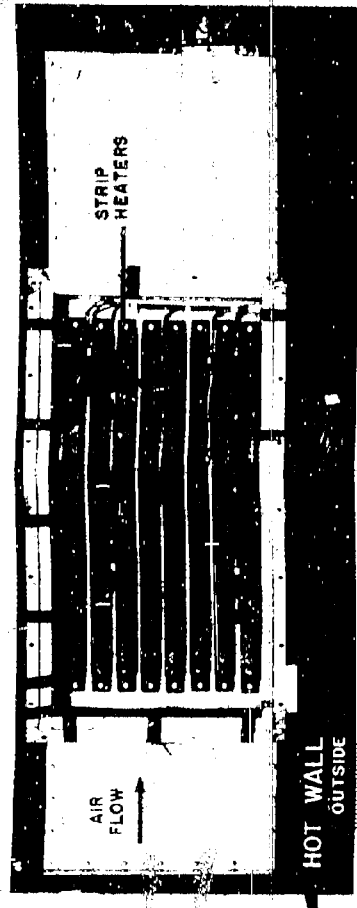
General Test Setup



COLD WALL
INSIDE

ASPIRATED
THERMOCOUPLE

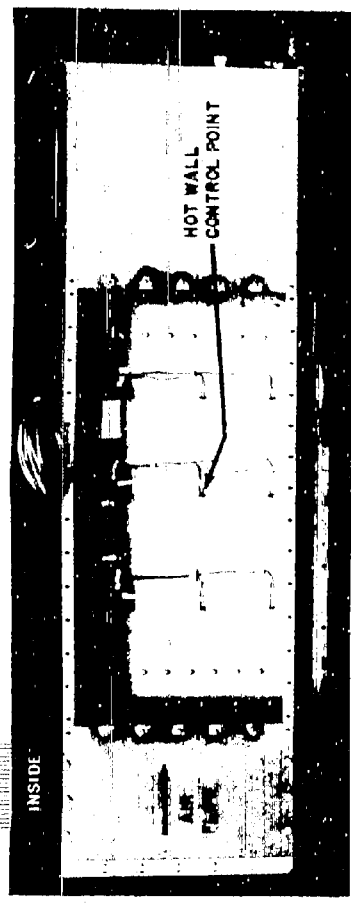
TEST SPECIMEN
(No. 12)



STRIP
HEATERS

AIR
FLOW

HOT WALL
OUTSIDE



HOT WALL
CONTROL POINT

INSIDE

AIR
FLOW

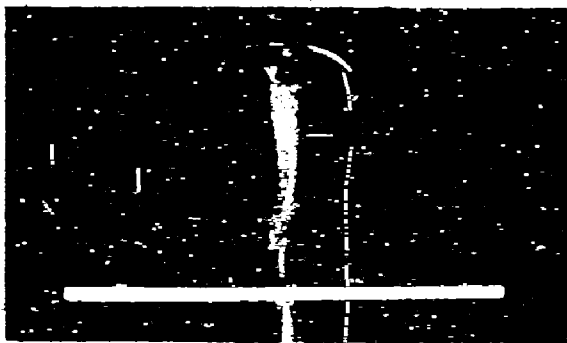


TEST SPECIMEN

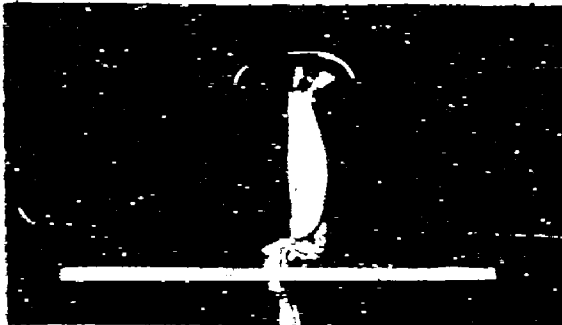
HOT

ASPIRATED
THERMOCOUPLE

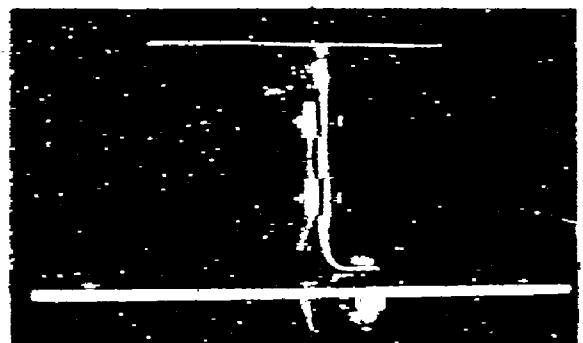
COLD WALL
OUTSIDE



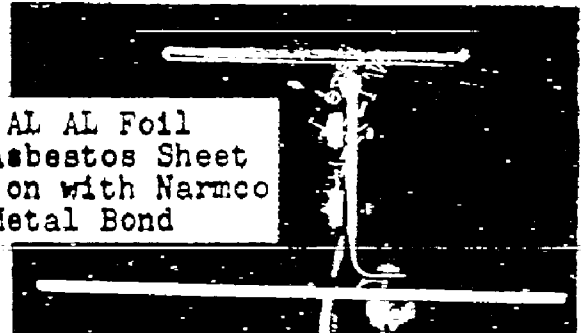
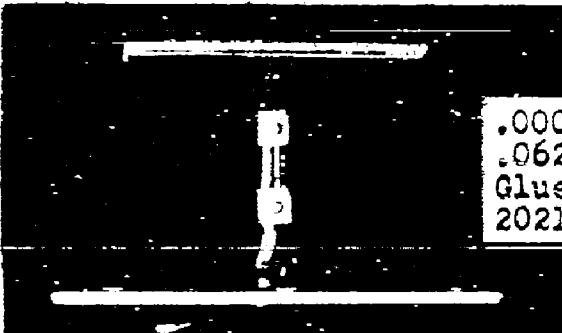
No 8- 1.00 SQUARE STN STL No 1



No 9- 1.00 SQUARE STN STL No 2



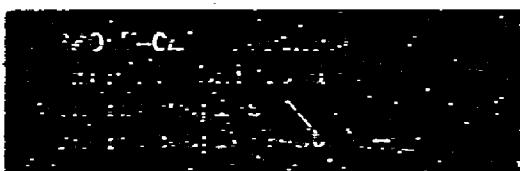
No 10- 2.00 SQUARE AL AL

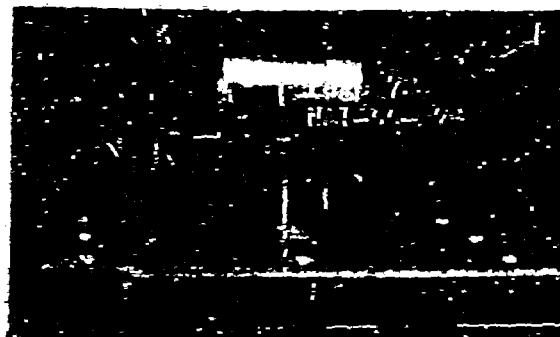
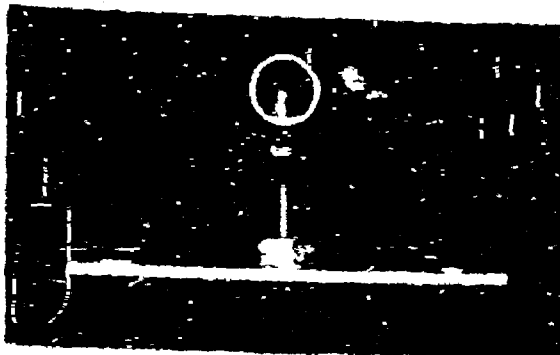


No 11- 2.00 SQUARE AL A-

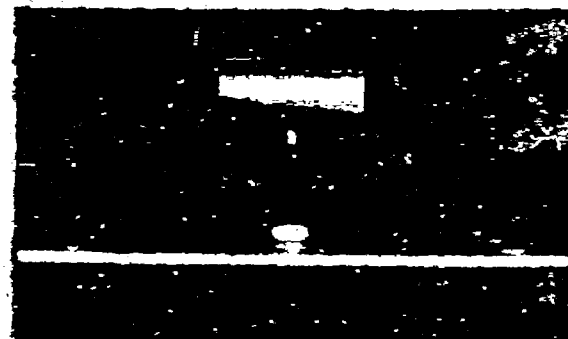
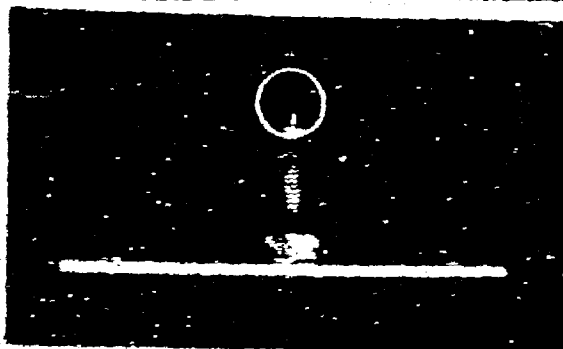
.0008 AL AL Foil
.062 Asbestos Sheet
Glued on with Narmco
2021 Metal Bond

(Similar to No 10 except
as noted)

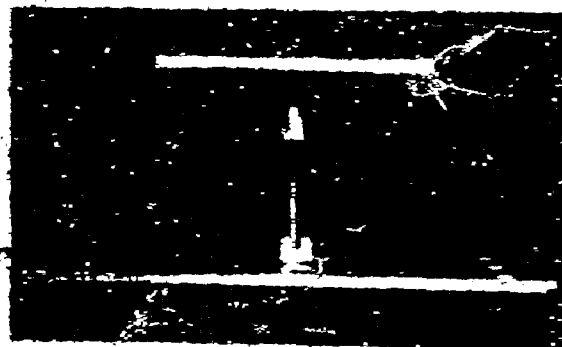
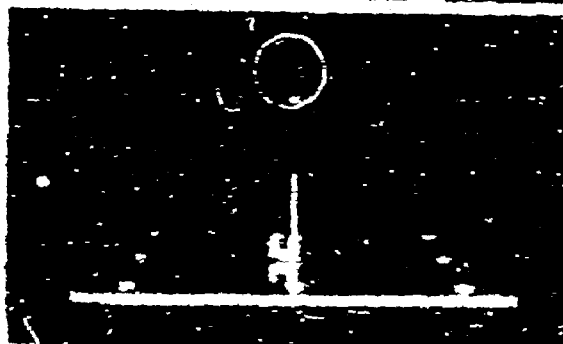




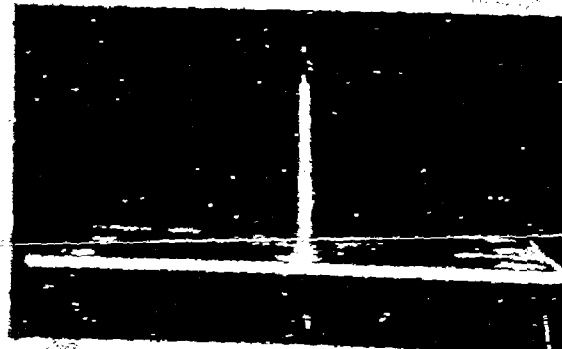
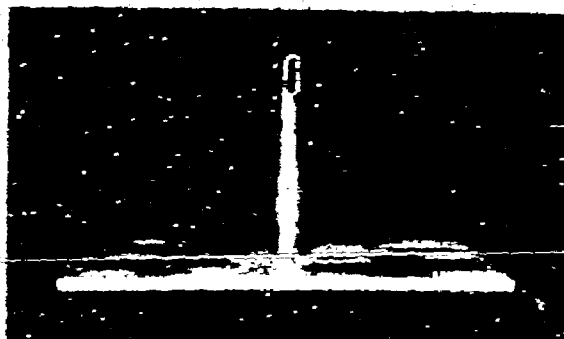
No 1- 1.00 LONG STN STL No 1



No 2- 1.00 LONG STN STL No 2

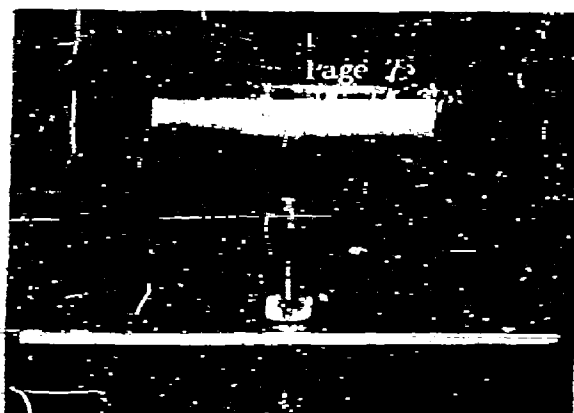
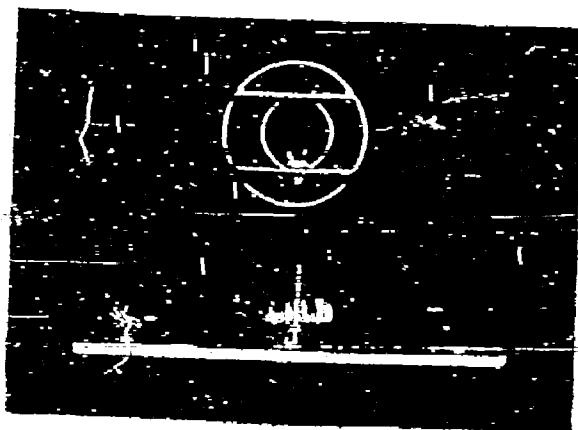


No 3- 2.00 LONG STN STL

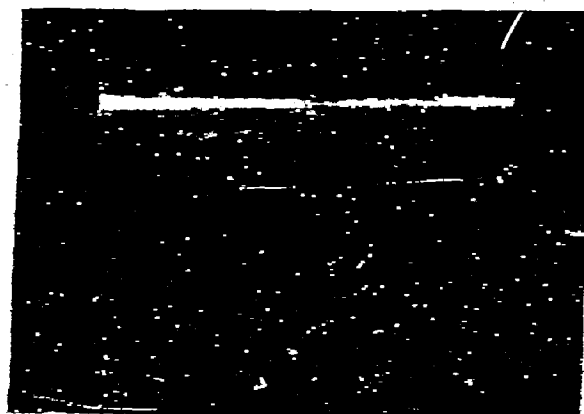
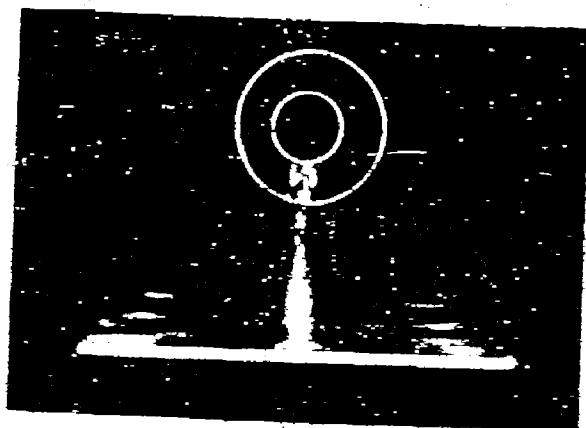


No 7- BARE

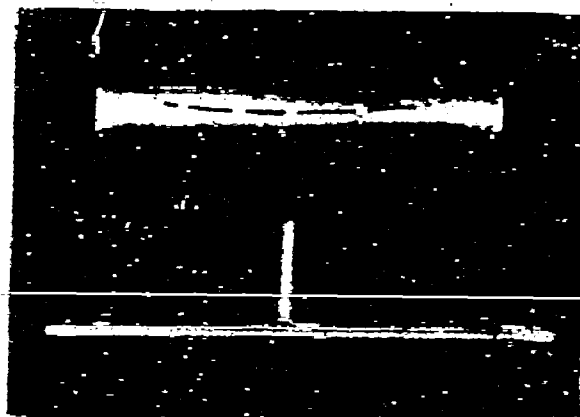
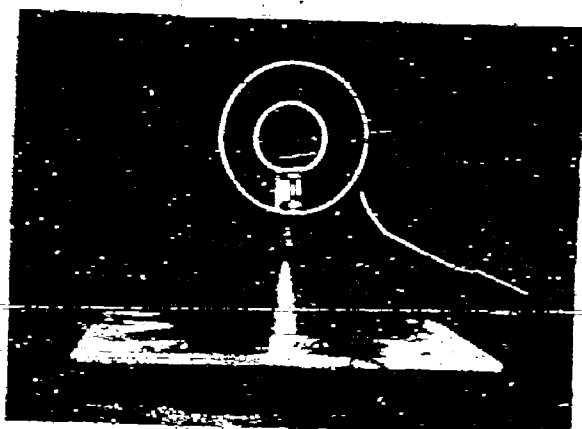
200-445 Forting
Single shielded and
unshielded
for example



No 4- 2.00 LONG STN STL



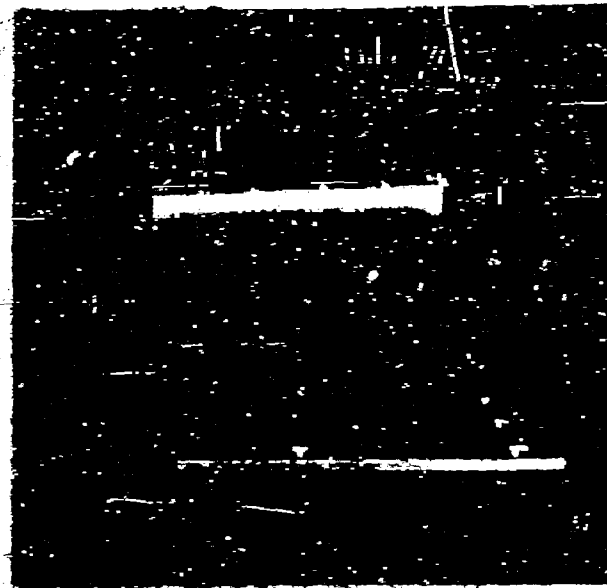
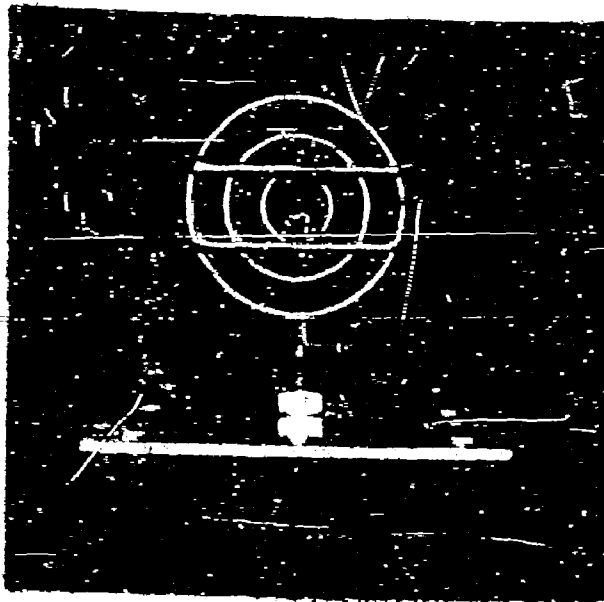
No 12- 3.00 LONG AL AL



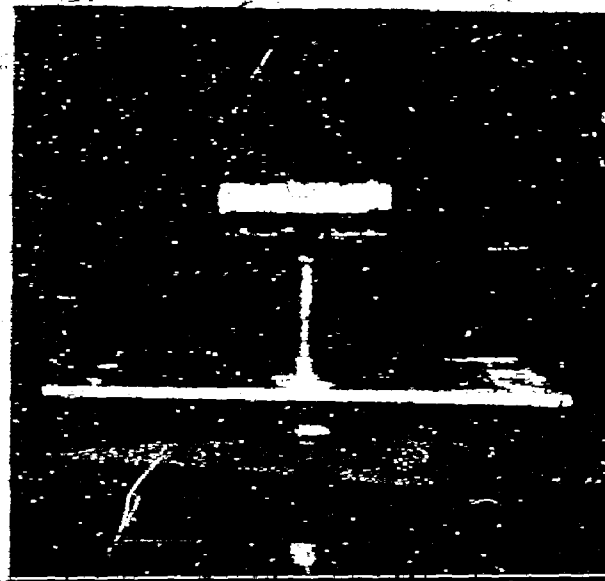
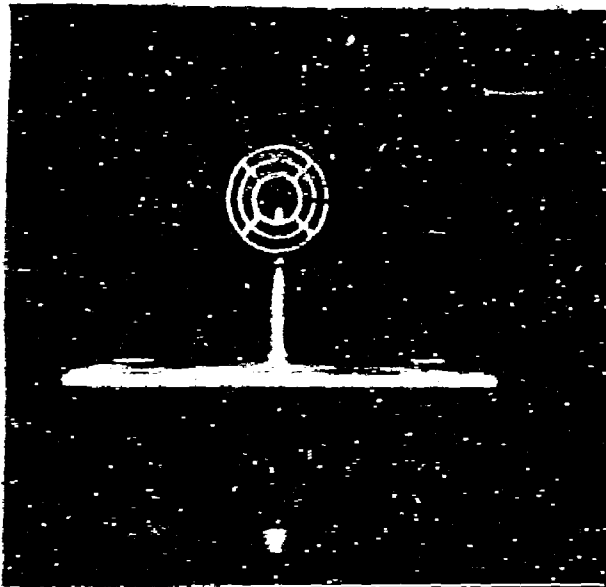
No 13- 3.00 LONG AL AL

(Venturi)

88056-445 Venturi
Double 3.00 AL AL
Therocouple
Therocouple set 100

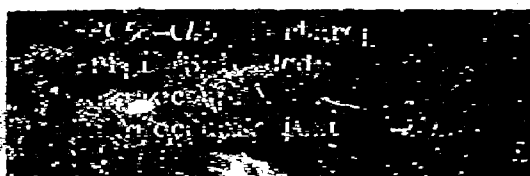


No 5- 2.00 LONG STN STL



No 6- 1.25 LONG STN STL

(Revere Corp)



AD 80593

Armed Services Technical Information Agency

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