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I. INTRODUCTION

This study of heat-sensitive radioisotopes for temperature measurement is an extension of the RMS-3A Radioactive Ablation Sensor System which is based upon a radioactive source emitting gamma rays, a Geiger-Muller detector tube, and solid state electronic circuits forming a system which converts the gamma ray field intensity into material thickness information continuously as a function of time. The operational elements of this system are illustrated in Fig. 1. The radioactive source is made part of an activated plug inserted into the ablating nose cone in the desired location. Gamma rays from the uniformly linear radioactive source pass through intervening material and trigger the detector, which supplies pulses to the electronic "black box", which converts these pulses to a DC output proportional to the strength of the source remaining in the nose cone, and thus proportional to nose cone thickness. Ground recording stations using standard telemetry equipment collect this information for analysis (Fig. 2). A gamma ray radioactive source must be used because alpha and beta particles cannot penetrate the structural material existing between the detector and the radioactive plug.

Before launch, the radioactive source is at full strength (6 to 30 millicuries dependent upon source isotope), which results in a full scale output of five volts DC from the sensing system. During re-entry, the nose cone ablation material and the radioactive material of the activated plug are eroded. This reduces the radioactive source which the detector "sees" and in turn reduces the DC output of the system. Thus, the DC output is a direct measure of the thickness of the nose cone at the particular location of the activated plug. The thickness remaining is recorded as a function of time from which absolute ablation amount and rate data are obtained from calibration curves.

Essentially the same system can be employed to sense a temperature front rather than an ablation front by using a linear radioactive source which decomposes at a given temperature below the surface instead of the high temperature

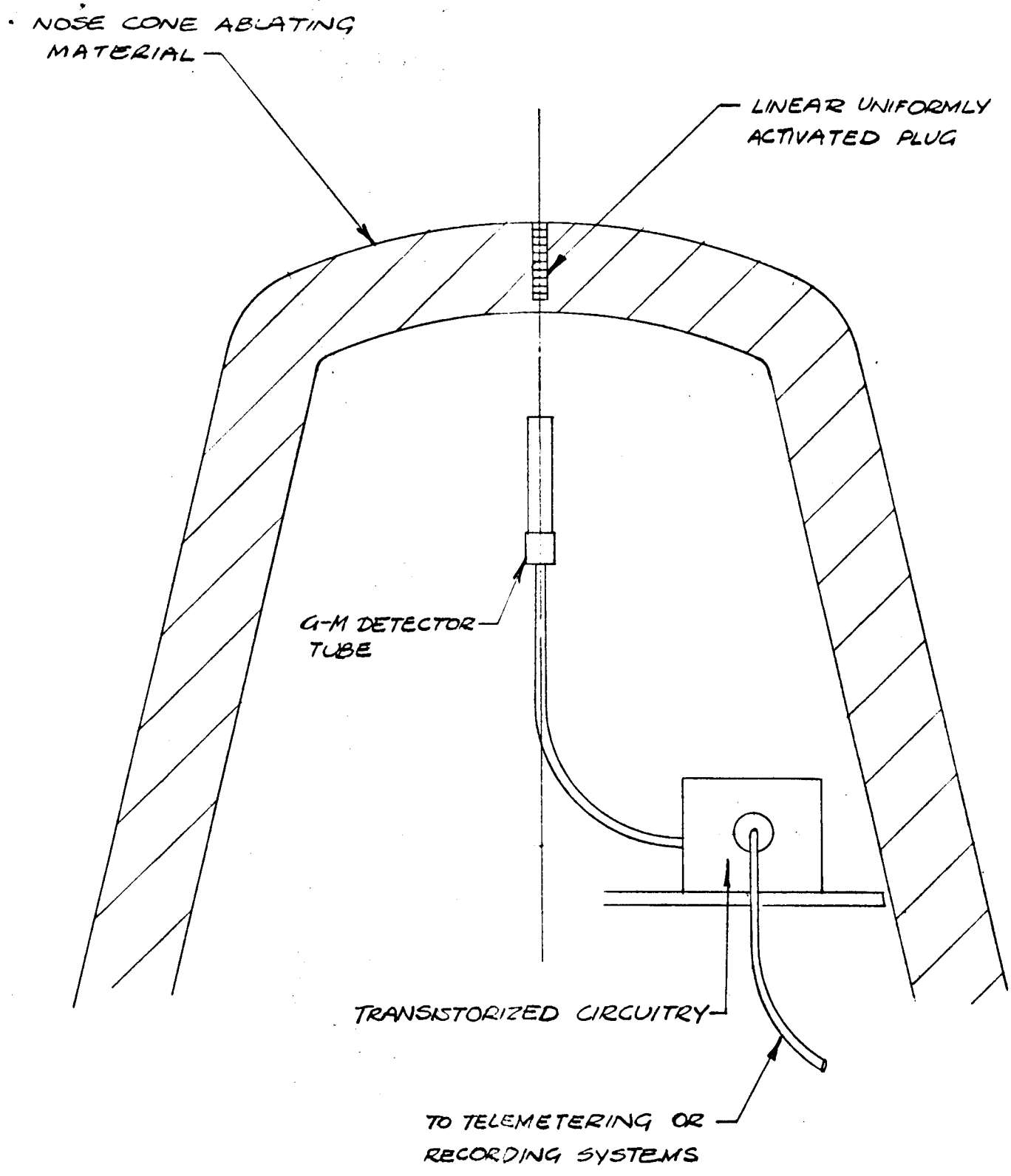
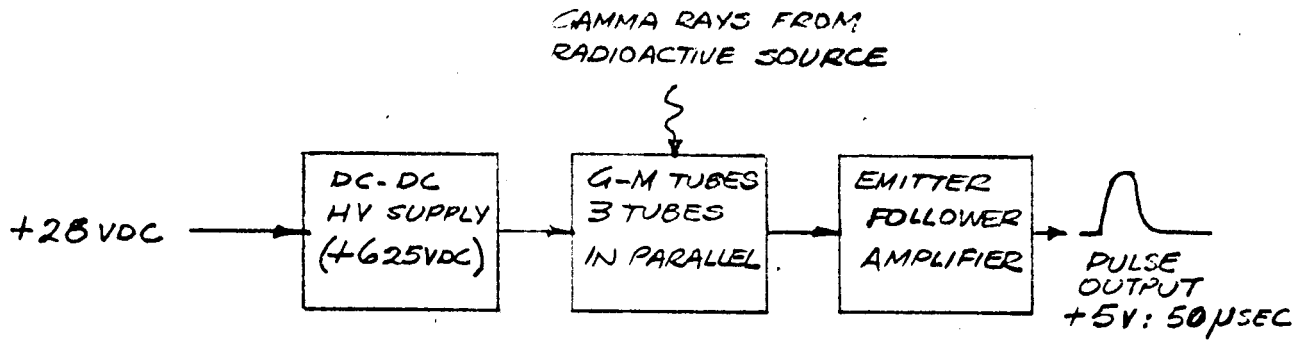


FIG 1 - SCHEMATIC OF RADIOACTIVE TYPE ABLATION SENSOR SYSTEM

HV POWER SUPPLY & G-M DETECTOR MODULE



SIGNAL CONDITIONER MODULE

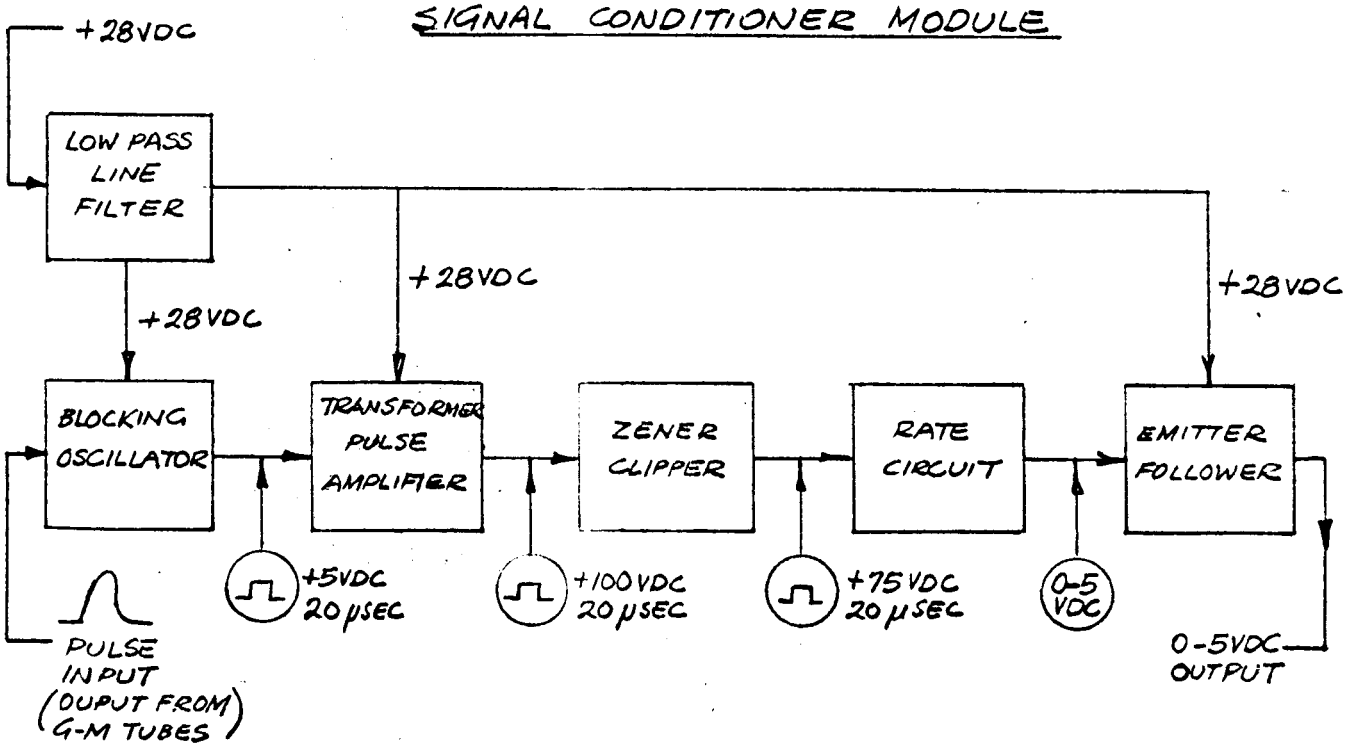


FIG 2 - RMS-3A ELECTRICAL SYSTEM BLOCK DIAGRAM

encountered at the ablation surface. Previous research and development work conducted as part of the RMS-1A, 2A, and 3A systems optimized the radioactive source configuration. The final form consists of a 0.0625 inch O.D. by 0.0312 inch I.D. alumina tube 1.5 inches long. The interior of the tube is filled with a small amount, e.g., 10 to 20 milligrams of an inert metal powder uniformly mixed in a carrier material. The ablation sensor system utilizes a high temperature (4000°F) carrier material which is not decomposed until it is exposed to the external ablating plasma environment. The purpose of this research program is to attempt to select experimentally a series of carrier materials which decompose at fixed temperatures in the range 300°F to 1200°F, thus providing a means of continuously tracking the propagation front of an isothermal surface through the virgin nose cone material, Fig. 3.

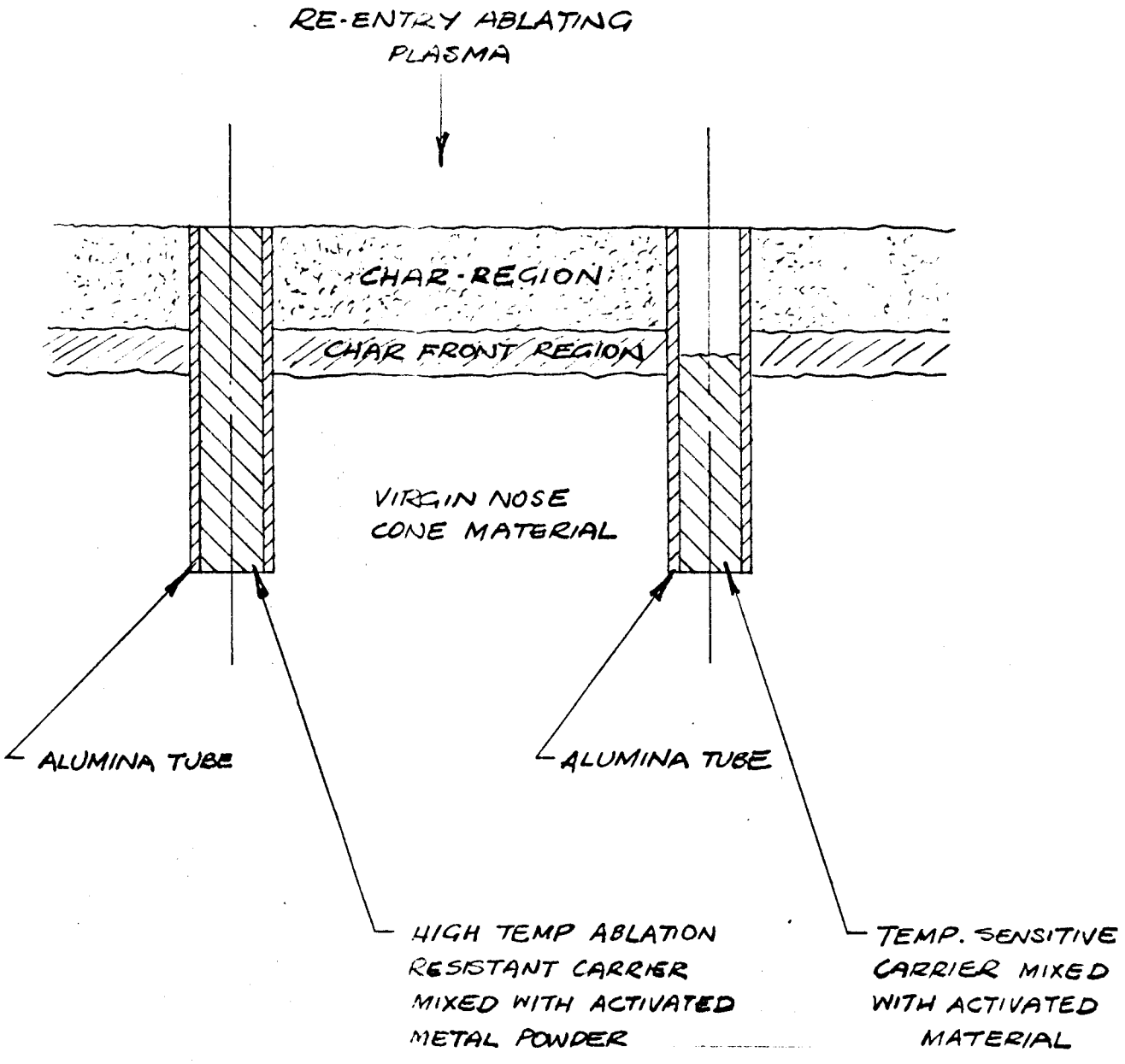


FIG 3 - RADIOACTIVE SOURCE CONFIGURATION FOR NOSE CONE ABLATION & TEMPERATURE FRONT PROPAGATION MEASUREMENT

II. SELECTION OF TEMPERATURE SENSITIVE CARRIER MATERIALS

Ideally, a temperature-sensitive carrier material, is in the solid state until its temperature is raised to a particular and repeatable value at which it decomposes into a gas which exhausts out the open end of the alumina tube. Activation of one or more elements of the carrier material is a most desirable condition, however, a difficult one to achieve because of simultaneous requirements of thermal neutron activation cross section, half-life, isotope concentration, gamma ray energies, and decay modes. A second approach is to add a small quantity of a particular source element to a temperature-sensitive carrier material which contributes negligible gamma ray radiation relative to the source element. This procedure allows separation of the numerous simultaneous requirements into two manageable and independent groups, i.e., one group containing optimized source elements, and a second group containing optimized carrier materials. Literature search for suitable source elements and carrier compounds was made, together with an experimental evaluation of some 80 different carrier materials.

STUDY OF HEAT SENSITIVE RADIOISOTOPES FOR TEMPERATURE MEASUREMENT APPLICATION

Final Report

Prepared for
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

Contract NAS 9-3403

by
H. D. Hutchinson

Meteorology Research, Inc.
2420 North Lake Avenue
Altadena, California

July 1965

III. SOURCE ELEMENTS

Source element candidates must possess several physical and nuclear properties to perform the desired function satisfactorily. For example, they must have a high isotope concentration in the natural state, a reasonable thermal neutron activation cross section and half-life, a high percentage of energetic gamma rays, be chemically stable at room temperature, and obtainable in uniform finely powdered form. Table I lists acceptable ranges of values for these parameters.

The specific activity of an element placed in a nuclear pile for a time (t) is given by

$$A_{sp} = \frac{Nf\sigma}{A}\left(1 - e^{\frac{-0.693t}{T_{1/2}}}\right)$$

where

- N = Avogadro's number (6.02×10^{23})
- f = Thermal neutron flux in number of neutrons per square cm per sec
- σ = Thermal neutron cross section of element in cm^2
- A = Atomic wt. of element in grams
- t = Time
- T = Half-life in same units as t

For limited irradiation times: $t << T_{1/2}$ and $e^{-\frac{0.693t}{T_{1/2}}} < 1$ thus this exponential can be replaced by the first two terms of its series expansion, i.e.,

$$e^{-\frac{0.693}{T_{1/2}}} \cong 1 - \frac{0.693}{T_{1/2}}$$

Thus

$$A_{sp} = \frac{Nf\sigma\ 0.693t}{AT_{1/2}}$$

The initial strength of the source when removed from the reactor in millicuries is given by

$$A_i = \frac{A_{sp} \cdot W_E \cdot C_I}{3.7 \times 10^7}$$

TABLE 1

PHYSICAL AND NUCLEAR PROPERTY LIMITS
OF SOURCE ELEMENTS

PROPERTY		
Thermal Neutron Cross Section	$>3x10^{-24}cm^2$ (Half-Life Less Than One Year) $>15x10^{-24}cm^2$ (1 Year<Half-Life < 3 years) $>30x10^{-24}cm^2$ (3 Years<Half-Life < 5 Years)	The cross section and half-life have an inverse relationship such that a limited irradiation time necessitates shifting the limiting cross section value with half-life.
Isotope Concentration	>30%	Highest possible concentration of the desired isotope is required to minimize conflicting nuclear reactions and concentration of source elements relative to carrier materials.
Half-Life	>30 Days < 5 Years	Lower limit determined by operational requirements of user. Upper limit determined by activation limitations, i.e., neutron flux, cross section, half-life, available reactor time, etc.
Chemical Form	Pure Element	See isotope concentration discussion.
Physical Form	Fine Powder >350 Mesh	Uniform powder equal to or finer than common face powder.
Gamma Ray Exposure Rate	Approximately Equal to Co 60 Value of 12.8 r/hr/mc @ 1 cm	The energy of the gamma rays should be in the range 0.5 Mev to 3 Mev to limit exposure rate changes due to attenuation dependance upon gamma ray energy. The disintegration energy and scheme of each isotope must be analyzed and appropriate calculations made to determine the exposure rate which is compared to the Co 60 value to determine the source strength required to give the equivalent exposure.

where

W_E = wt. of element placed in the reactor in grams

C_I = concentration of isotope in element used.

The exposure rate for a point source is given by

$$I_\gamma = 0.156\ nE(10^5\ \mu_a)$$

where

I_γ = mr/hr at 1 meter per millicurie

n = gamma quanta per disintegration

E = energy of gamma quanta in Mev

μ_a = energy absorption coefficient for gamma rays in air (STP) in cm^{-1}.

Equation assumes that one ion pair in air causes an average energy expenditure of 32.7 electron volts. At a distance of 1 meter in air, this equation reduces to the approximate form

$$\text{mr/hr/mc at 1 meter} \cong 0.5\ nE$$

The integrated value for multiple gamma ray decay schemes is obtained by summing over the various gamma quanta emitted, thus

$$I'_\gamma = \int (\text{mr/hr/mc at 1 meter}) = \sum_i 0.5\ n_i E_i$$

The source strength of each particular isotope required to provide equivalence to a standard Co 60 source of 6 mc is given by

$$A_i = 6\ \frac{I'_\gamma(\text{Co 60})}{I'_\gamma(\text{isotope})}$$

IV. CARRIER MATERIALS

The literature search for carrier materials was divided into two broad chemical classifications, plus three thermal property subclassifications, namely, inorganic, organic, and melting, sublimating, and decomposition temperature, respectively. Initial search involved selecting materials with physical and thermal properties which fell within the limits indicated in Table II.

Materials which satisfied the conditions of Table II were subjected to laboratory tests in which a temperature gradient is made to propagate along the axis of a 1.0 inch O.D., 1.125 inch long cylinder of nose cone ablation material. The cylinder is thermally shielded along its outer wall and one end, and a flame or hot air applied to the exposed end, resulting in a temperature distribution which is axially symmetric and planar near the axis of the cylinder, i.e., within 0.250 radii of the axis. The sample material is placed in an alumina cylinder 0.0625 inch O.D.x0.0325 inch I.D.xl.125 inch long along the axis of the test cylinder. Numerous chromel-alumel thermocouples are placed along the length of the alumina rod, and at various radii, and longitudinal positions per Fig. 4. A block diagram of the complete instrumentation system is shown in Fig. 5, photographs in Fig. 6. Several temperature versus time calibration runs were conducted to establish the propagation of heat and the resulting temperature distribution as a function of time. The results are summarized in Figs. 7,8, and 9.

TABLE II

CARRIER MATERIAL PROPERTY LIMITS

PROPERTY	LIMITING VALUE OR RANGE OF VALUES	DISCUSSION
Melting Point and Boiling Point	300°F to 1200°F	Materials were tested with various combinations of melting and boiling points inside and outside the limits.
Sublimation Temperature	300°F to 1200°F	Literature generally indicated sublimation temperatures under standard conditions. The sublimation rate as a function of pressure and over temperature were not given.
Decomposition Temperature	300°F to 1200°F	Decomposition temperature was given at STP only. No information concerning decomposition products or rate as a function of pressure or atmosphere composition was available.
Chemical Form	Fine Powder $\geq$350 mesh	Materials were selected which were obtainable in powder form or could be ground into fine powder using a mortar and pestle. Hygroscopic materials were not used because water content increase causes the partially ground material to form a gummy mass. In addition, variation in water content alters their thermal characteristics.
Toxicity	Less Toxic Than 0.01 mg Hg per m^3	Because of the necessity to vaporize and/or decompose the carrier material, their toxicity was limited to values approaching mercury compounds.
Stability	Non-Combustible and Non-Explosive	Materials which ignited when subjected to an open flame were rejected as well as material which decomposed in an explosive manner. Burning of the decomposition products was considered a favorable condition if the combustion products remained in a gaseous state.

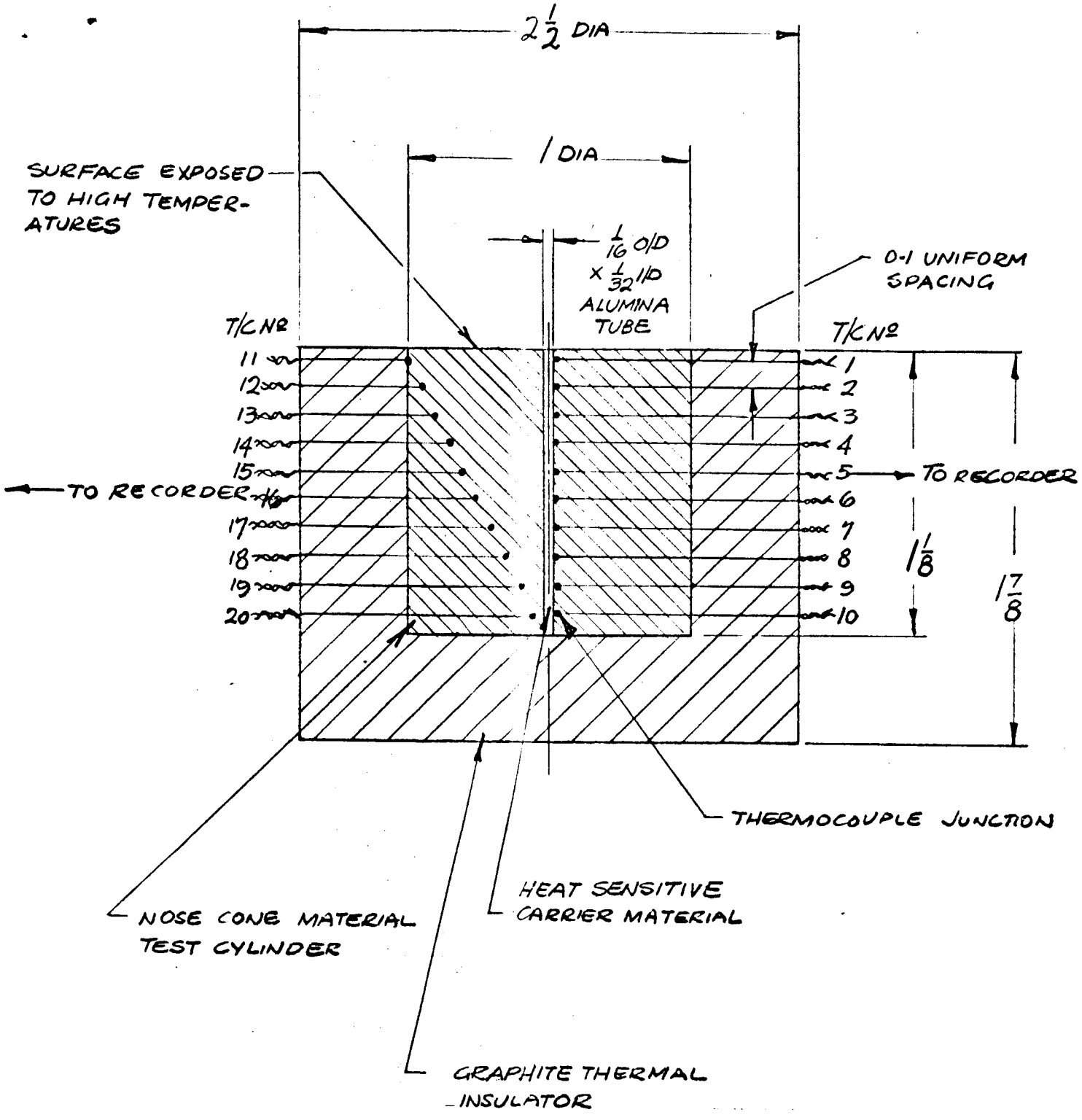
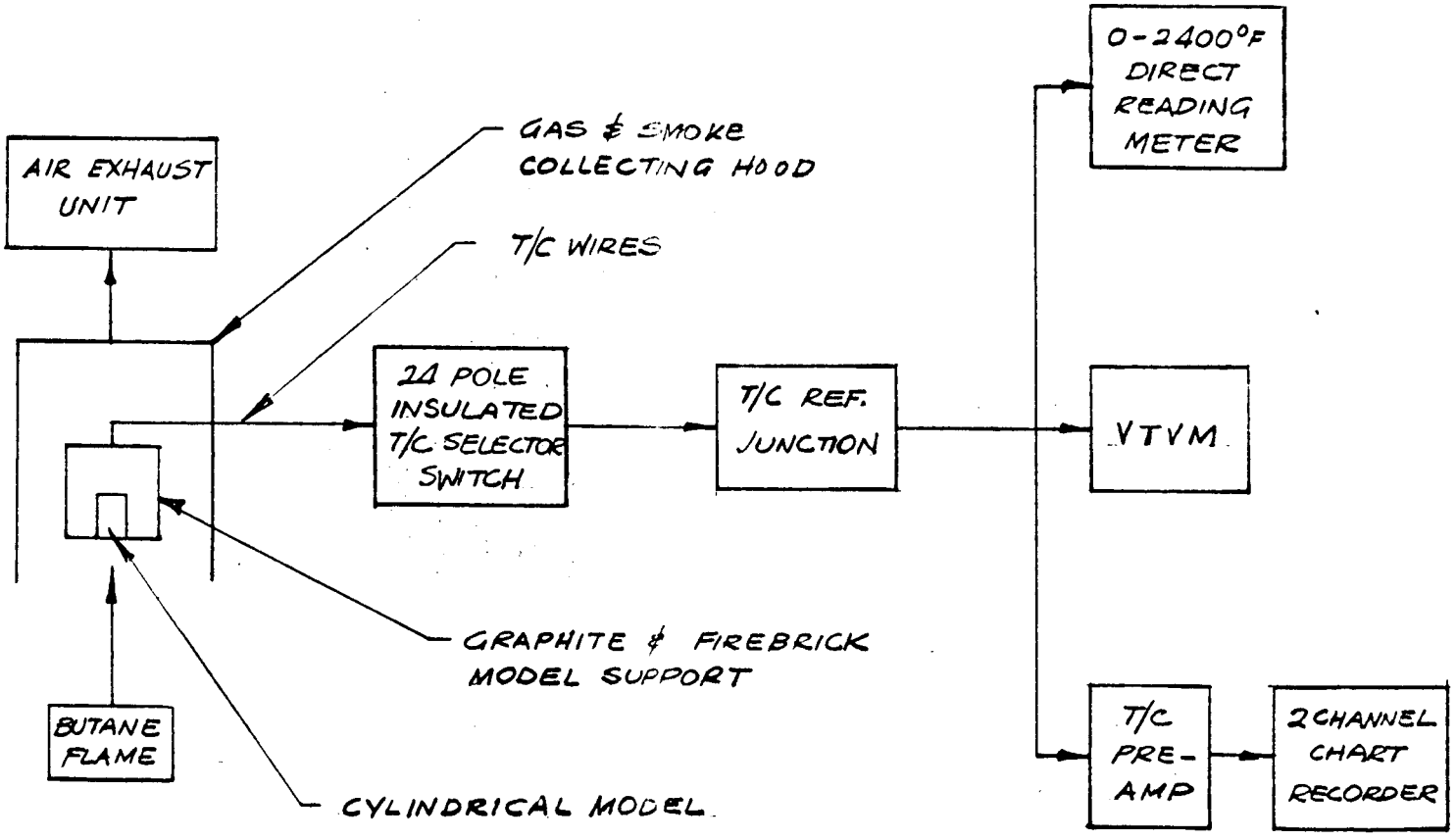


FIG 4 - INSTRUMENTED NOSE CONE MATERIAL MODELS



NOTE : NON-RADIOACTIVE MATERIALS USED IN THESE LABORATORY TESTS.

FIG 5 - BLOCK DIAGRAM OF TEST SYSTEM FOR HEAT SENSITIVE RADIOISOTOPES FOR TEMPERATURE MEASUREMENT

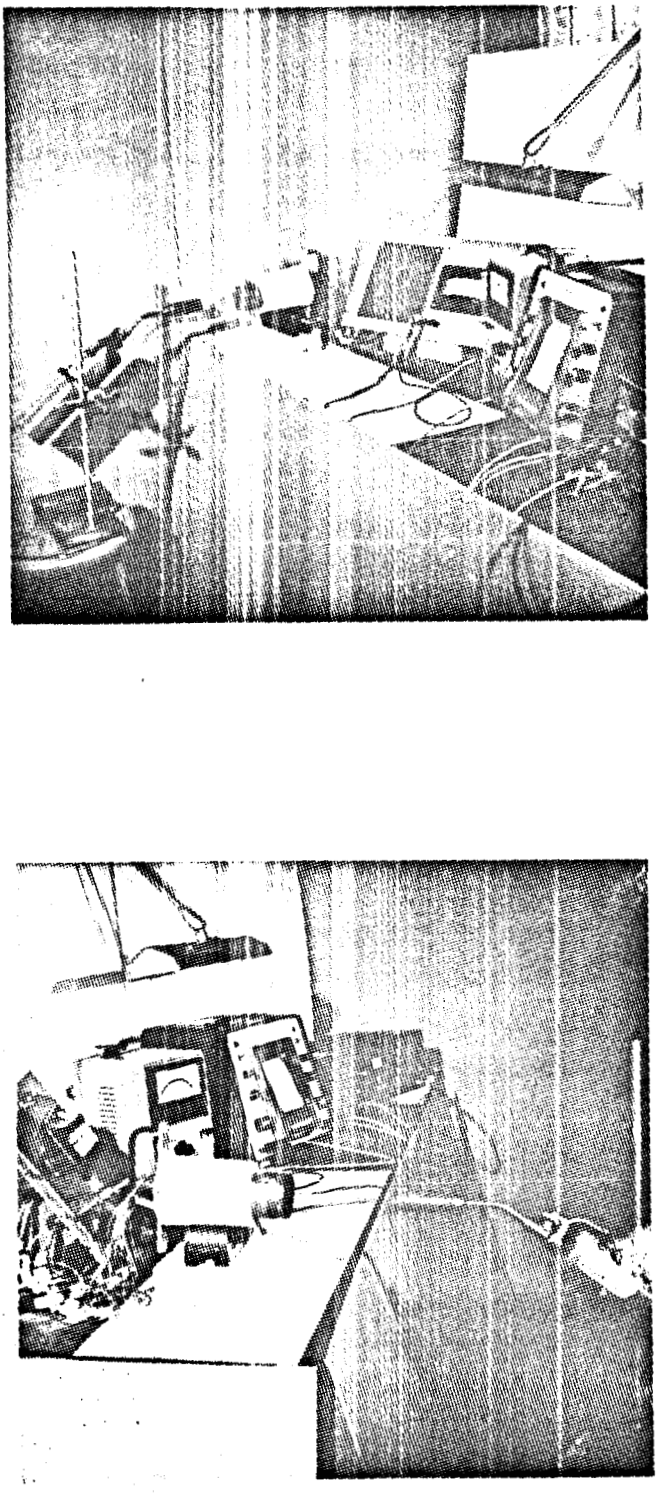


Fig. 6

LABORATORY TEST SYSTEM

FIG 7 - TEMPERATURE Vs. TIME AS A FUNCTION OF DEPTH ALONG ALUMINA TUBE

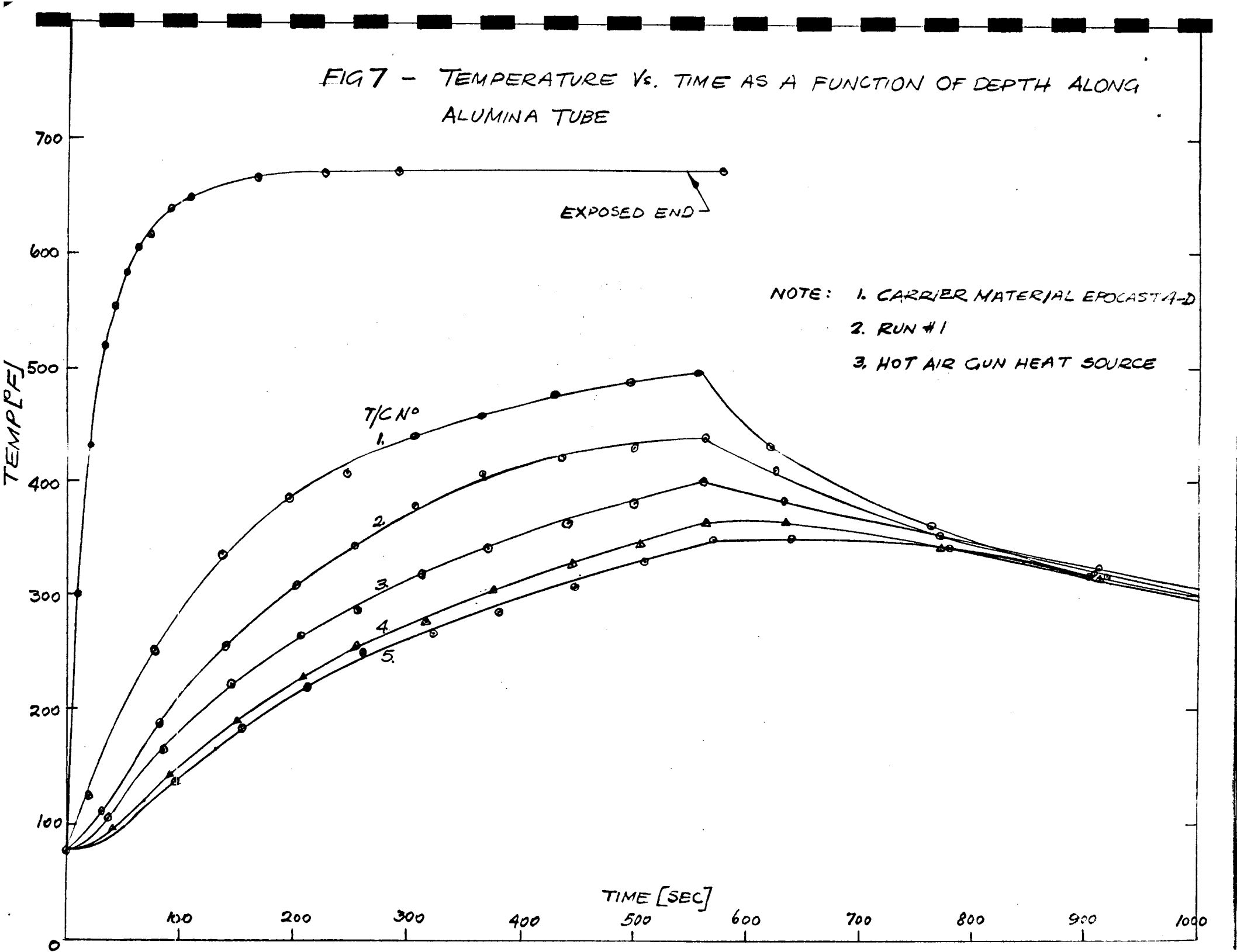


FIG 8 - TEMPERATURE Vs. TIME AS A FUNCTION OF DEPTH

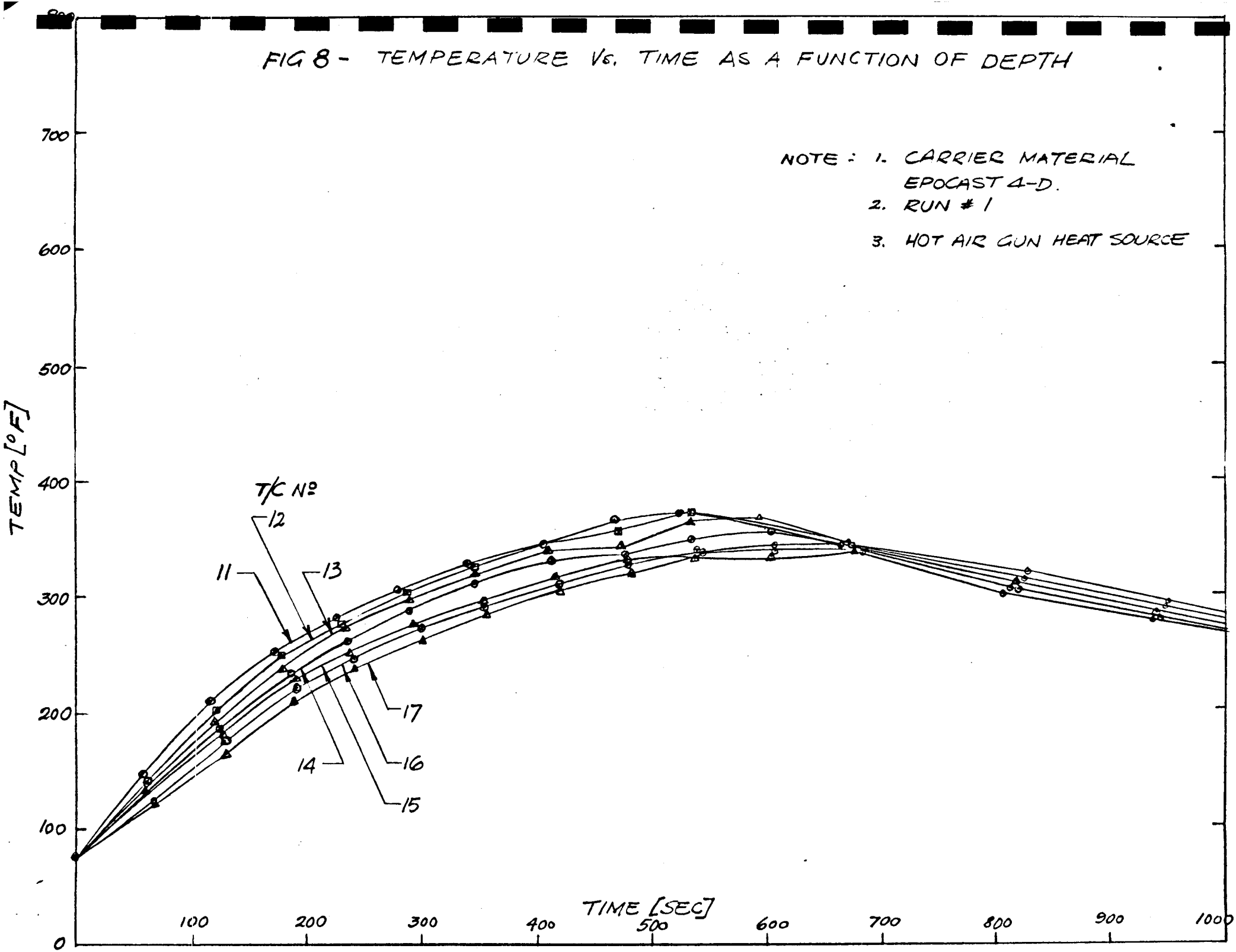
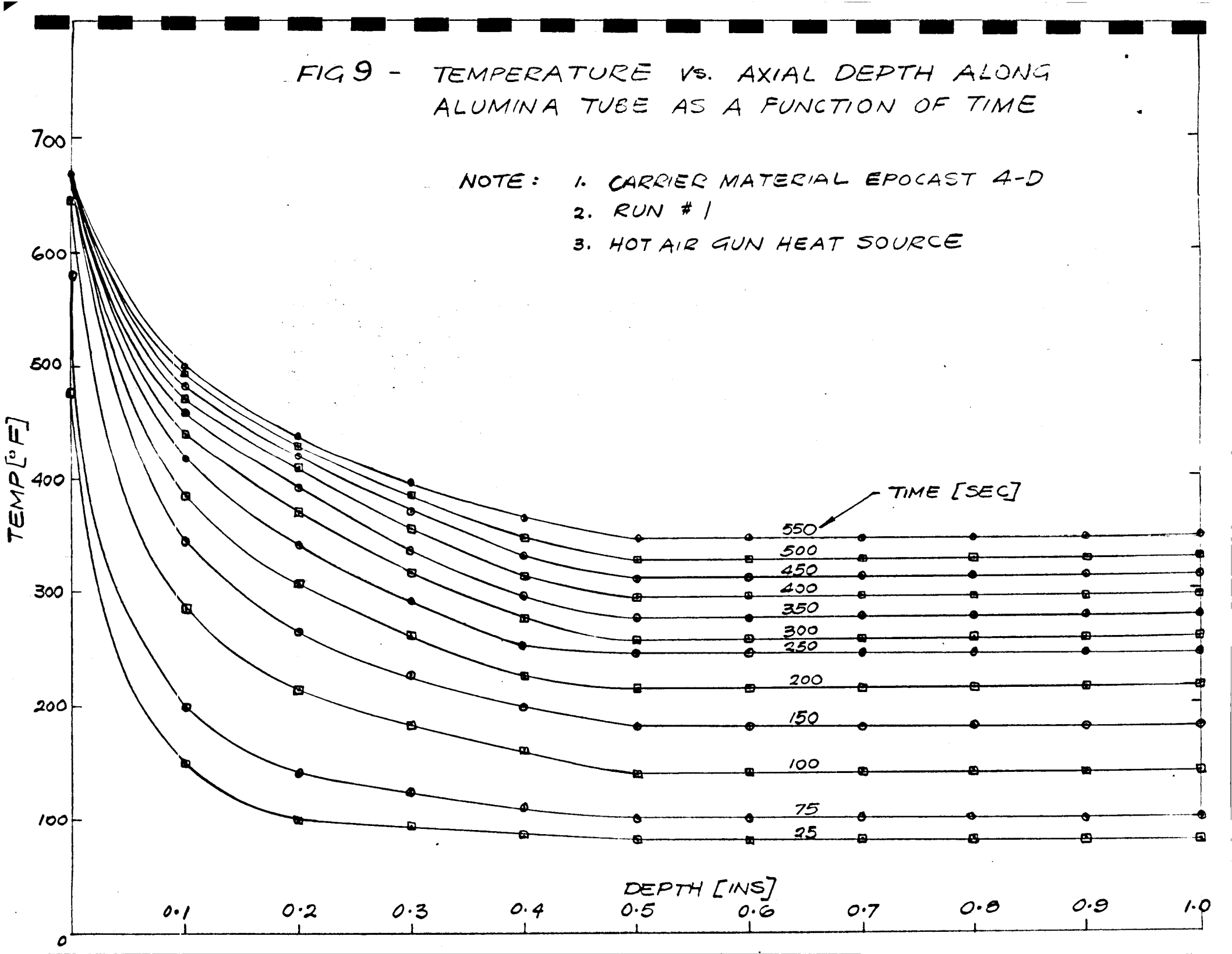


FIG 9 - TEMPERATURE Vs. AXIAL DEPTH ALONG ALUMINA TUBE AS A FUNCTION OF TIME

NOTE:
1. CARRIER MATERIAL EPOCAST 4-D
2. RUN # 1
3. HOT AIR GUN HEAT SOURCE



V. TEST RESULTS

Visual inspection of the discoloration and char associated with the propagation of the high temperatures along the length of the test cylinder confirmed the thermocouple measurements, i.e., the isothermal surfaces at any given time after initial transients have died out are as depicted in Fig. 10. The shape and repeatability of the isothermal surfaces allowed the number of thermocouples necessary for a measurement to be reduced to five, namely, T/C no. 1-5 placed along the alumina tube 0.1, 0.2, 0.3, 0.4, and 0.5 inches below the exposed end. The experimental procedures consisted of successively recording the mv output of these five thermocouples as a function of time, from initial room temperature to maximum temperature to approximately one-half maximum temperature following removal of the heat source. A plot of the "high water mark" of the temperature depth curve is correlated with the boundary of the test material contained in the alumina tube. A typical maximum temperature versus depth curve is shown in Fig. 11. General data obtained for each material tested are contained in Table III, and maximum temperature curves versus depth are shown in Figs. 12-21 for the ten materials that gave satisfactory performance. Results are summarized in Table IV.

The ten satisfactory materials were then mixed with fine powdered gold (>400 mesh) in concentrations of 10 per cent and 20 per cent by volume and subjected to model heating tests used previously. In all cases the carrier material decomposed and exited from the tube leaving a crusty matrix of gold residue in the heated portion of the tube. Equivalent results were obtained using silver and cobalt powders.

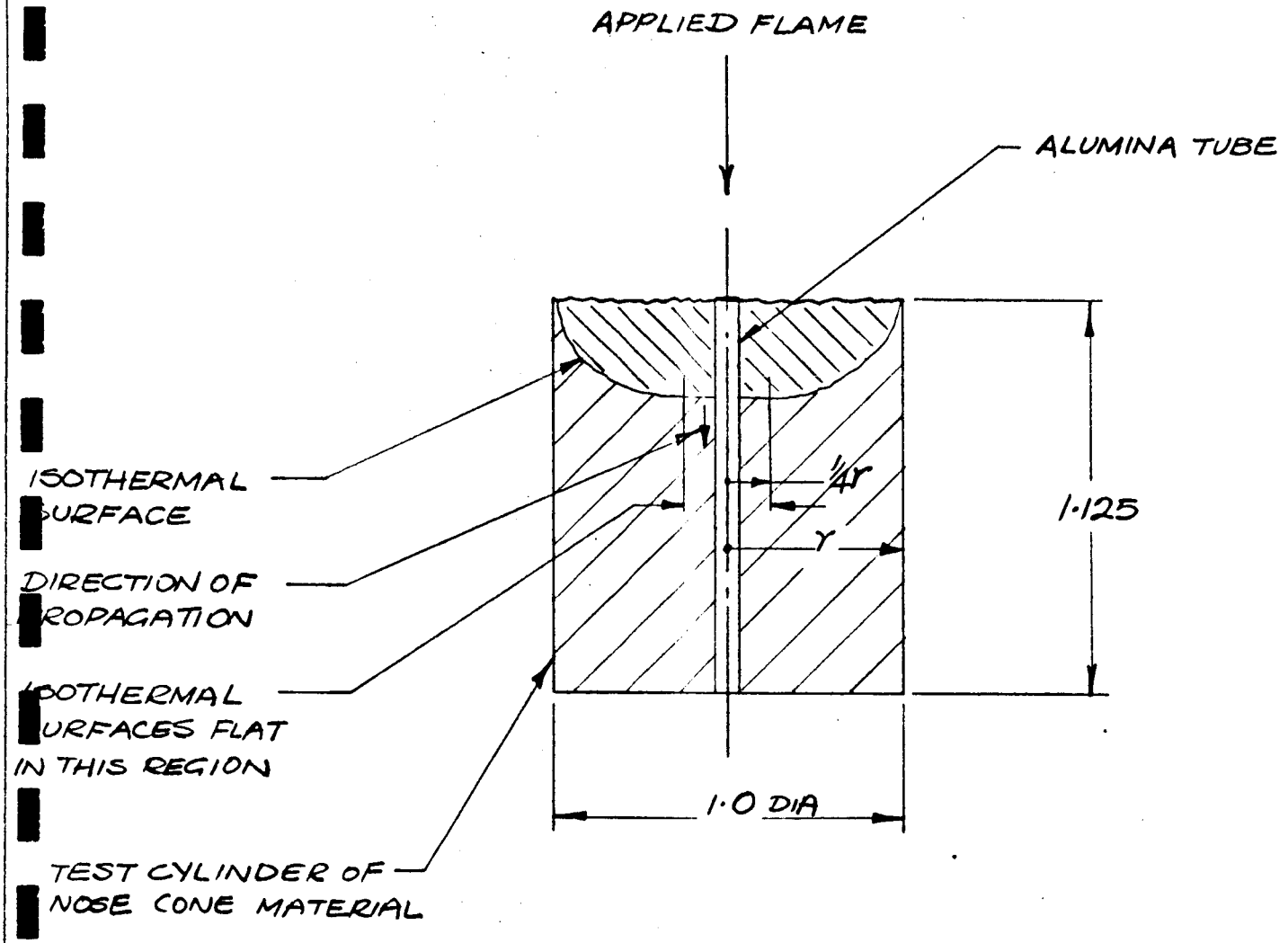


FIG 10 - SECTION OF TEST CYLINDER ILLUSTRATING ISOTHERMAL SURFACES

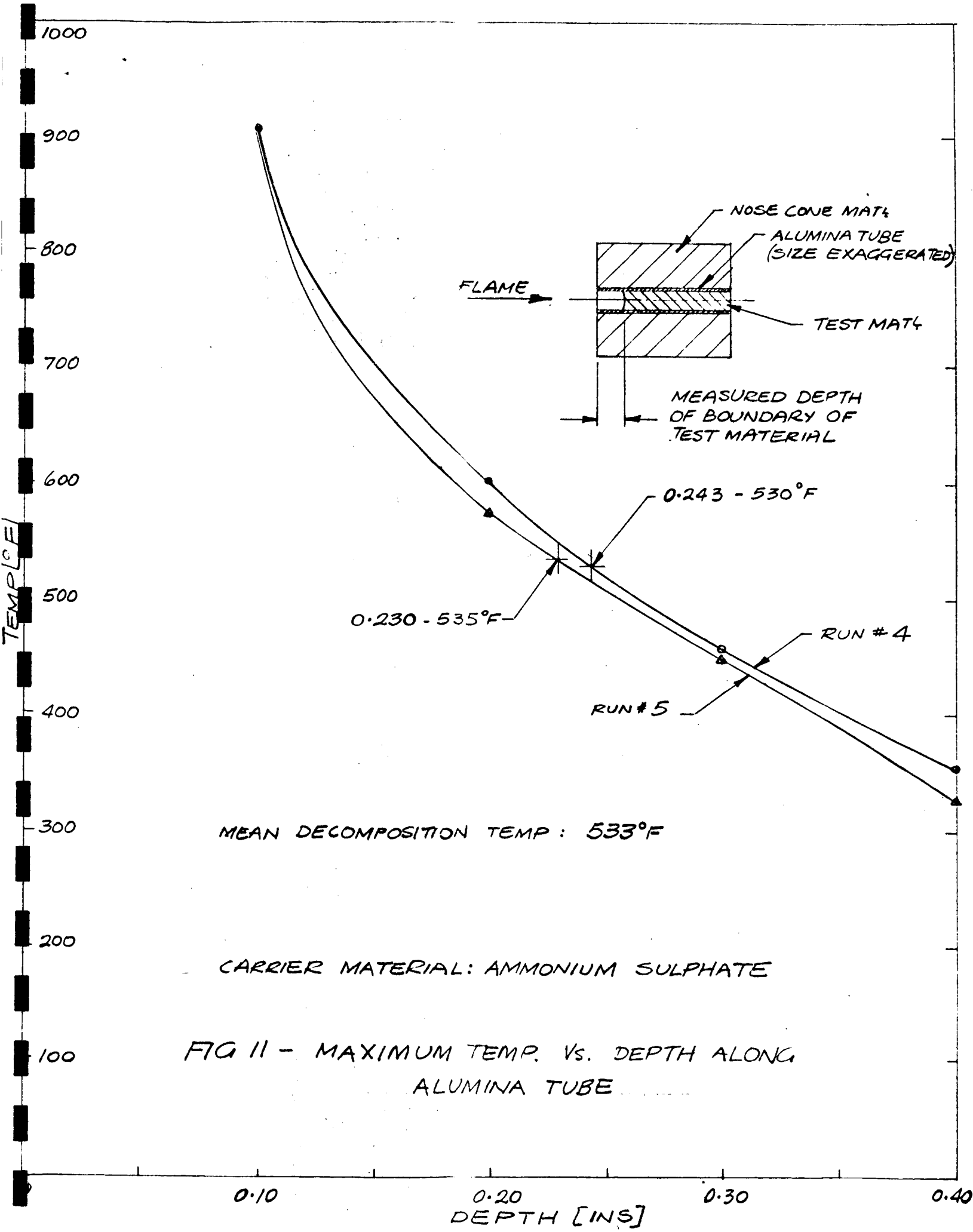


FIG 11 - MAXIMUM TEMP. Vs. DEPTH ALONG ALUMINA TUBE

TABLE III

CARRIER MATERIAL	TEST RESULTS	COMMENTS
Aluminum Filled Epocast 4-D	This material has a heat distortion temperature of 210°F. However it did not decompose at a peak temperature of 680°F. Alumina tube completely filled after test.	Not Suitable
Epocast 31A	This material has a heat distortion temperature of 375°F. However it did not decompose at a peak temperature of 700°F. Alumina tube completely filled after test.	Not Suitable
Ammonium Chloride	Decomposition temperature listed as 635°F. The first run gave a recession depth of 0.235 inches at 538°F, the second a depth of 0.277 inches at 563°F. On both runs, the recession portion of the tube was free of deposits, coke, etc.	Suitable for This Application
Ammonium Dichromate	Explosive decomposition.	Not Suitable
Ammonium Molybdate	Solid Decomposition products.	Not Suitable
Ammonium Acetate	Absorbs moisture.	Not Suitable
Ammonium Bifluoride	Absorbs moisture.	Not Suitable
Ammonium Citrate Dibasic	Inconsistent hole depth.	Not Suitable
Ammonium Oxalate		Not Suitable
Ammonium Persulfate	Combustible decomposition.	Not Suitable
Ammonium Phosphate Monobasic	Tube clogged with decomposition products.	Not Suitable
Ammonium Phosphate Dibasic	Tube clogged with melted material.	Not Suitable

TABLE III (CONTINUED)

CARRIER MATERIAL	TEST RESULTS	COMMENTS
Ammonium Tartrate	Tube free of decomposition products.	Suitable
Ammonium Iodide	Decomposition temperature listed as 1025°F. The first run gave a recession depth of 0.265 inches at 664°F, the second a depth of 0.150 inches at 673°F. In both runs the recession portion of the tube was free of deposits, coke, etc.	Suitable
Ammonium Nitrate	Explosive decomposition	Not Suitable
Ammonium Sulfate	The handbook decomposition temperature is listed as 536°F. The first test gave a recession depth of 0.243 inches at 530°F, the second a depth of 0.230 at 535°F. In both runs the recession portion of the tube was free of deposits, etc.	Suitable
Aluminum Sulfate	Solid decomposition products.	Not Suitable
Phosphorous Pentasulfide	Large random variation in hole depth.	Not Suitable
Phosphorous Pentachloride	Extremely hazardous - inadequate safety equipment available.	Not Tested
Phosphorous Pentoxide	Absorbed moisture from air and formed a gummy mass which could not be forced into alumina tube.	Not Suitable
Potassium Acetate	Absorbed moisture.	Not Suitable
Potassium Biphthalate	Tube clogged with decomposition products.	Not Suitable

TABLE III (CONTINUED)

CARRIER MATERIAL	TEST RESULTS	COMMENTS
Potassium Meta-Bisulfite	No loss of material below 1200°F.	Not Suitable
Potassium Bitartrate	Tube clogged with decomposition products.	Not Suitable
Potassium Bromate	Absorbed moisture.	Not Suitable
Potassium Chlorate	Tube clogged with decomposition products.	Not Suitable
Potassium Dichromate	Tube clogged with decomposition products.	Not Suitable
Lead Carbonate	Decomposition temperature listed as 599°F. Successive tests to 1000°F at a depth of 0.1 inch failed to decompose the material.	Not Suitable
Lead Chloride	Solid decomposition products.	Not Suitable
Lead Dioxide	Decomposition temperature listed as 554°F. Decomposed to hard porous coke.	Not Suitable
Lead Oxide	Decomposition temperature listed as 932°F. Decomposed to gas and solid lead.	Not Suitable
Magnesium Carbonate	Decomposition temperature listed as 662°F. Successive tests to 905°F at a depth of 0.1 inch failed to decompose material.	Not Suitable
Mercury Chloride	Poisonous vapors.	Not Suitable
Mercury Oxide	Poisonous vapors.	Not Suitable

TABLE III (CONTINUED)

CARRIER MATERIAL	TEST RESULTS	COMMENTS
Magnesium Acetate	Decomposition temperature listed as 613°F. Material decomposes and forms magnesium oxide which clogged recession portion of alumina tube.	Not Suitable
Potassium Iodate	Tube clogged with decomposition products.	Not Suitable
Potassium Nitrate	Decomposition temperature well below 300°F	Not Suitable
Potassium Nitrite	Absorbs moisture.	Not Suitable
Potassium Oxalate	No loss of material below 1200°F	Not Suitable
Potassium Perchlorate	Tube free of decomposition products.	Suitable
Potassium Meta-periodate	Tube free of decomposition products.	Suitable
Potassium Pyrosulfate	No loss of material below 1200°F.	Not Suitable
Sodium Acetate	Tube clogged with melted material.	Not Suitable
Sodium Bicarbonate	Tube clogged with decomposition products.	Not Suitable
Sodium Metabisulfite	Tube clogged with decomposition products.	Not Suitable
Sodium Citrate	Tube clogged with molten material.	Not Suitable
Sodium Nitrite	Tube clogged with melted material.	Not Suitable
Sodium Phosphate	Tube clogged with molten material.	Not Suitable
Sodium Pyrophosphate	Tube clogged with decomposition products.	Not Suitable
Sodium Sulfate	Absorbs moisture.	Not Suitable

TABLE III (CONTINUED)

CARRIER MATERIAL	TEST RESULTS	COMMENTS
Sodium Sulfide	Absorbs moisture.	Not Suitable
Sodium Bisulfite	No loss of material below 1200°F.	Not Suitable
Sodium Bisulfite	Tube free of decomposition products.	Suitable
Sodium Borate	Tube clogged with decomposition products.	Not Suitable
Sodium Carbonate	No loss of material below 1200°F.	Not Suitable
Sodium Chlorate	Duplication of ammonium iodide decomposition temperature.	Suitable
Sodium Peroxide	Strong oxidizer - unable to handle safely.	Not Suitable
Sodium Dichromate	Absorbs moisture.	Not Suitable
Sodium Nitrate	Combustible.	Not Suitable
Sulphurated Potash	Absorbs moisture.	Not Suitable
Sulphur	Molten sulphur filled tube.	Not Suitable
Anthraquinone	Tube free of decomposition products.	Suitable
Alloyan	Tube clogged with decomposition products.	Not Suitable
Alloxantin	Large random variation in hole depth.	Not Suitable
Acenapathene Quinone	Combustible.	Not Suitable
Benzil	Combustible.	Not Suitable
Benzilic Acid	Decomposes below 300°F	Not Suitable
Benzoic Acid	No loss of material below 1200°F.	Not Suitable

TABLE III (CONTINUED)

CARRIER MATERIAL	TEST RESULTS	COMMENTS
Glycine	Tube clogged with decomposition products.	Not Suitable
L (+) Glutamic Acid	Tube clogged with decomposition products.	Not Suitable
Hexamethyllene Tetramine	Duplicates anthraquinone.	Suitable
Starch	Tube clogged with decomposition products.	Not Suitable
Thionyl Chloride	Liquid.	Not Suitable
Urea	Absorbs moisture.	Not Suitable

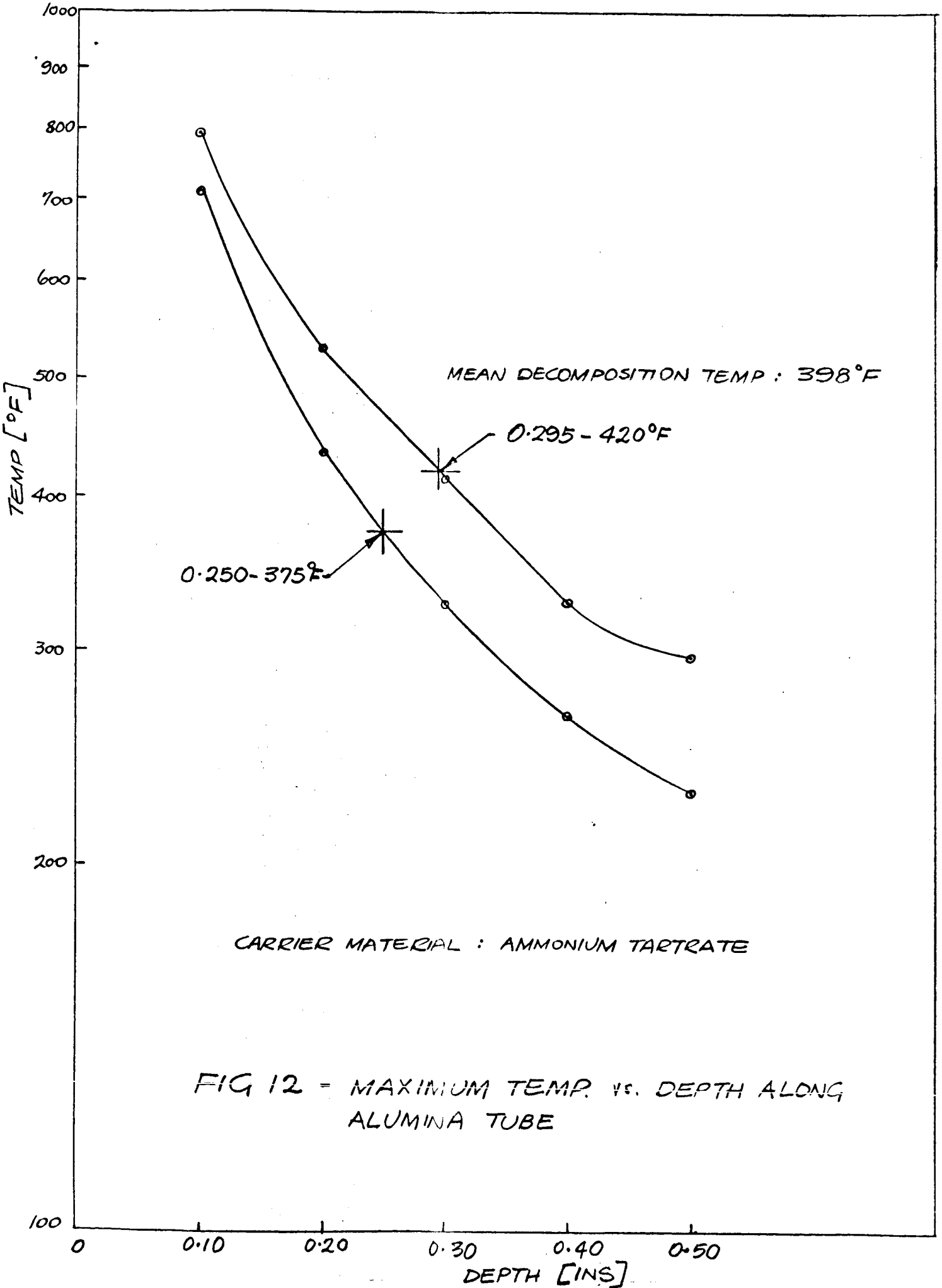


FIG 12 = MAXIMUM TEMP. VS. DEPTH ALONG ALUMINA TUBE

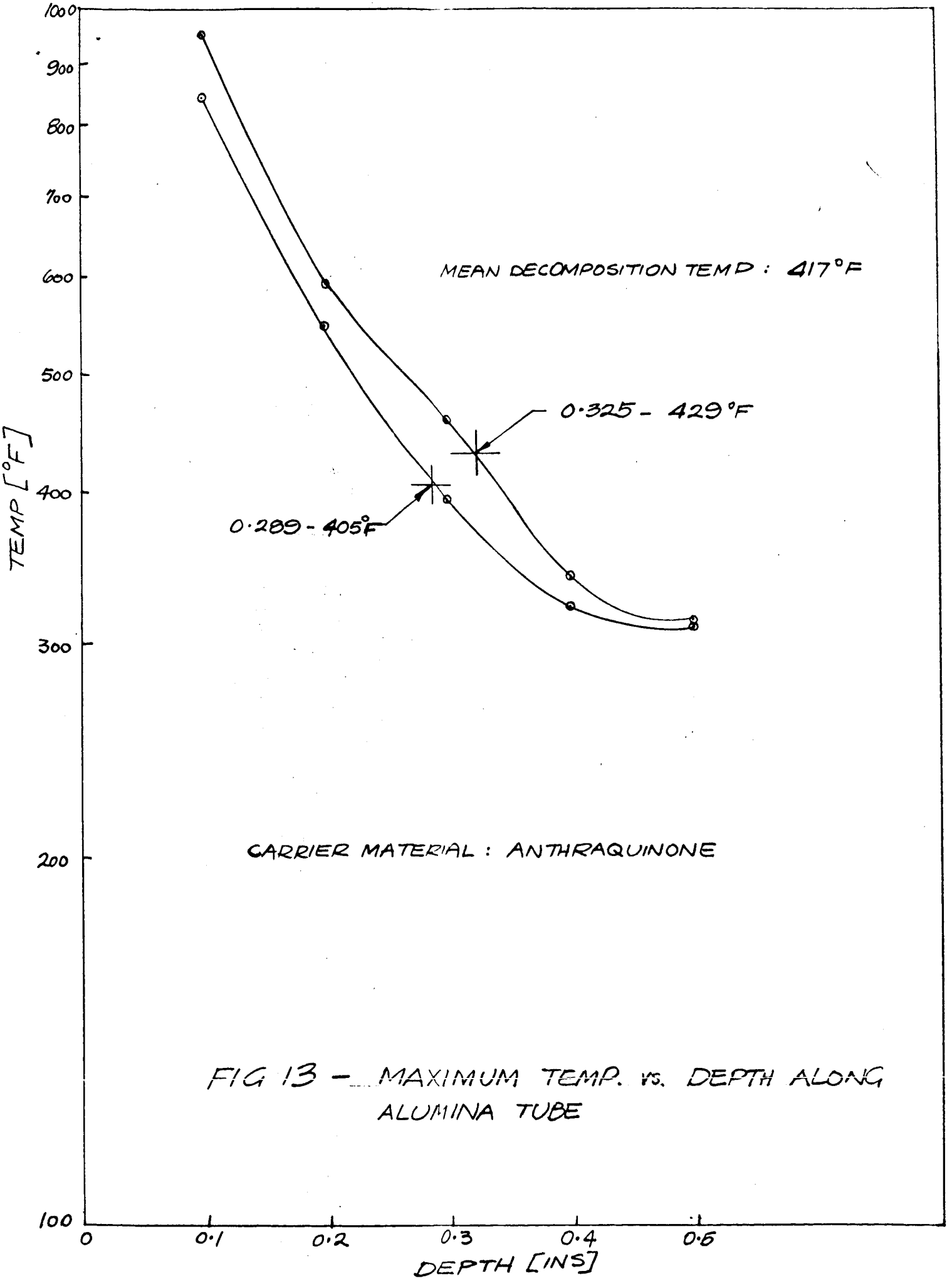
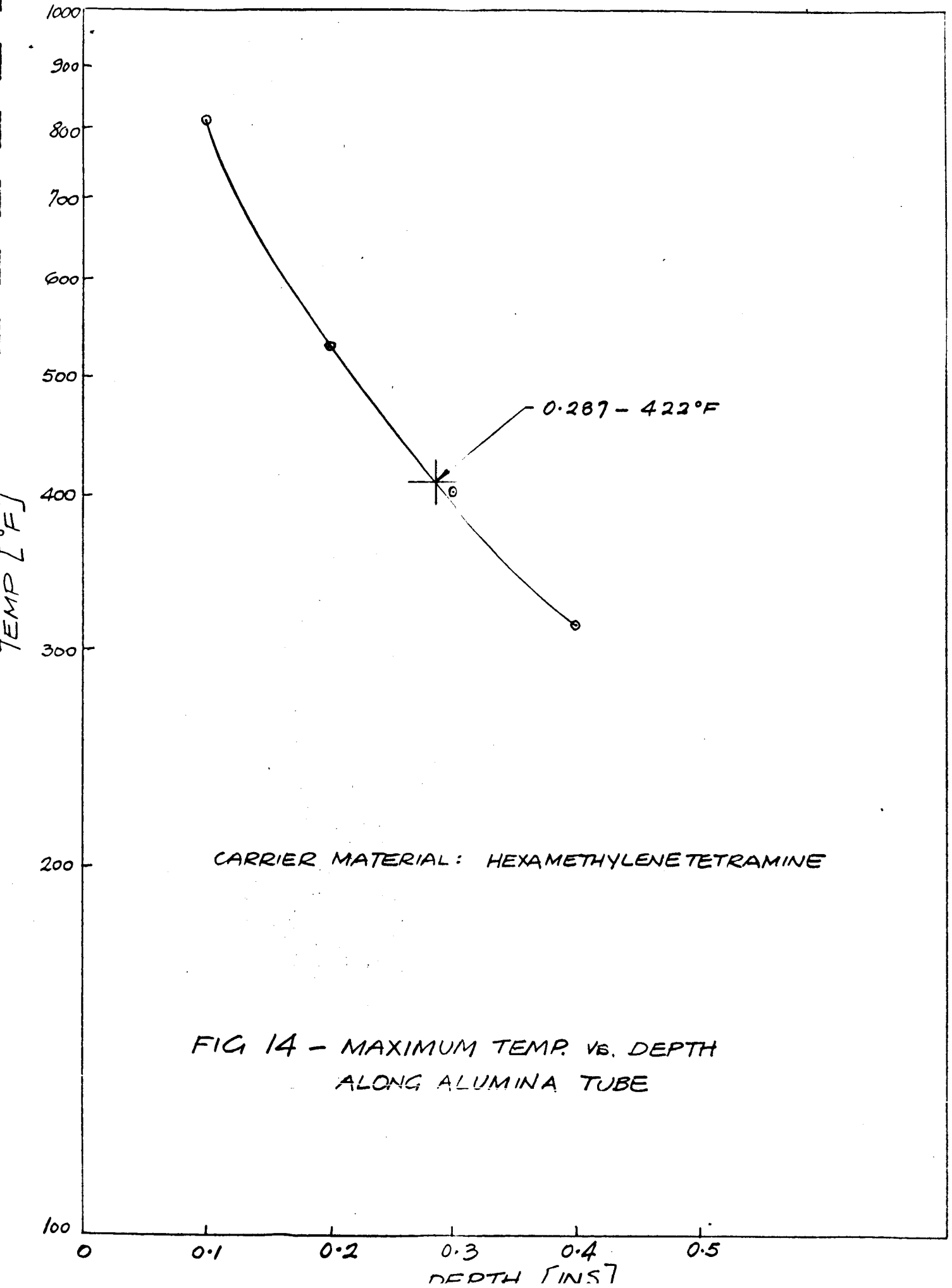


FIG 13 - MAXIMUM TEMP. vs. DEPTH ALONG ALUMINA TUBE



CARRIER MATERIAL: HEXAMETHYLENETETRAMINE

FIG 14 – MAXIMUM TEMP. VS. DEPTH ALONG ALUMINA TUBE

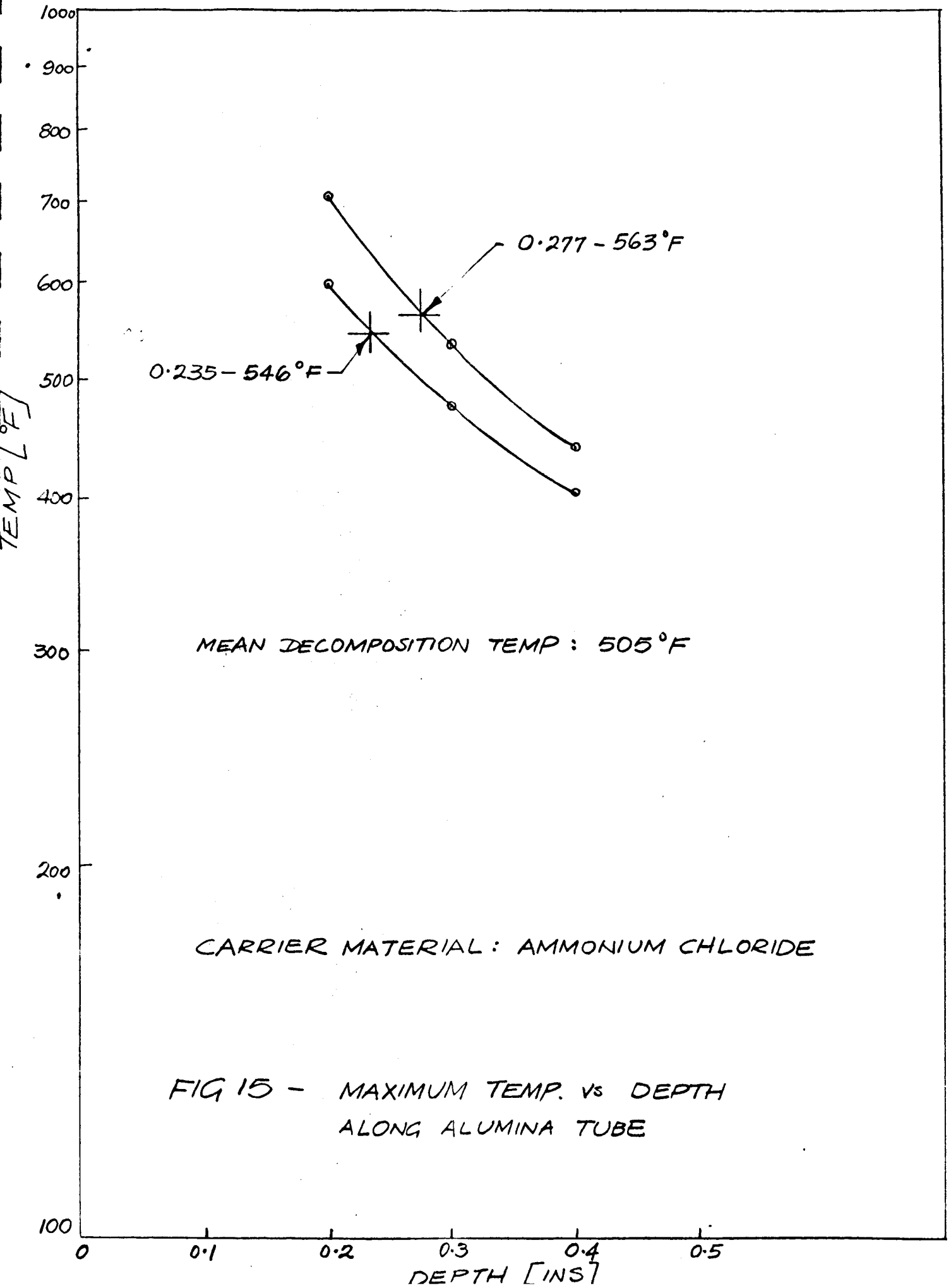


FIG 15 - MAXIMUM TEMP. Vs DEPTH ALONG ALUMINA TUBE

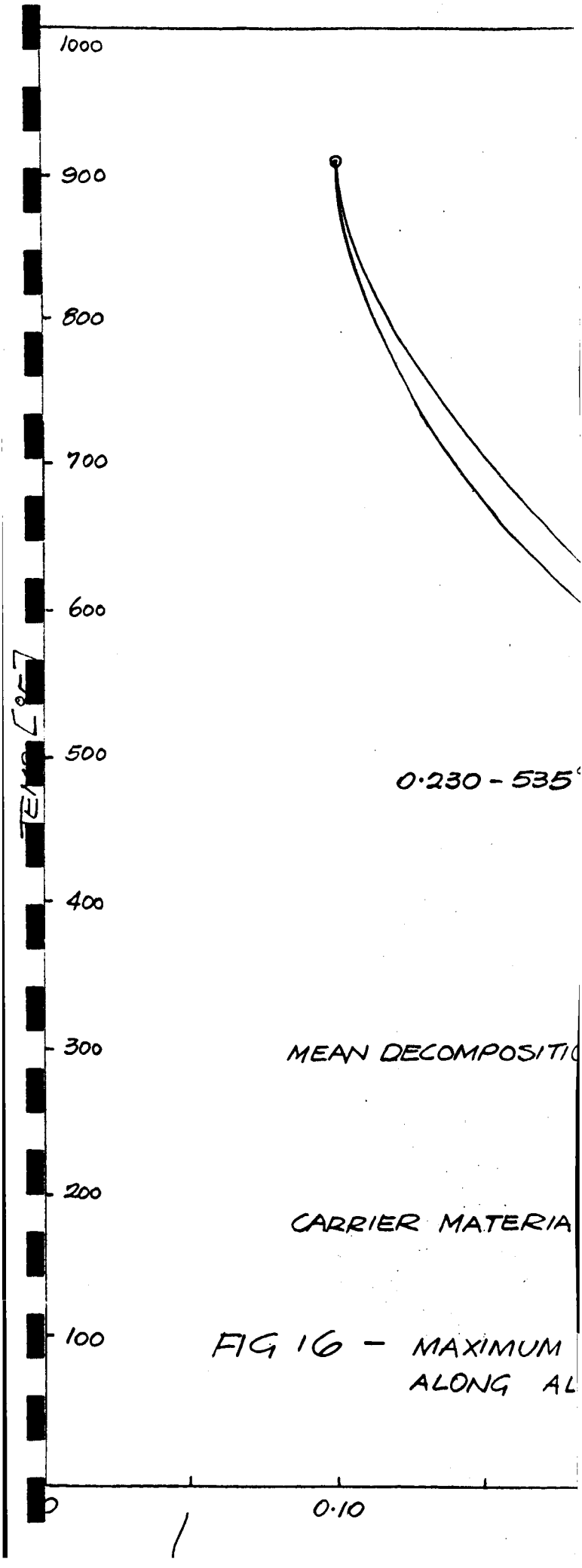
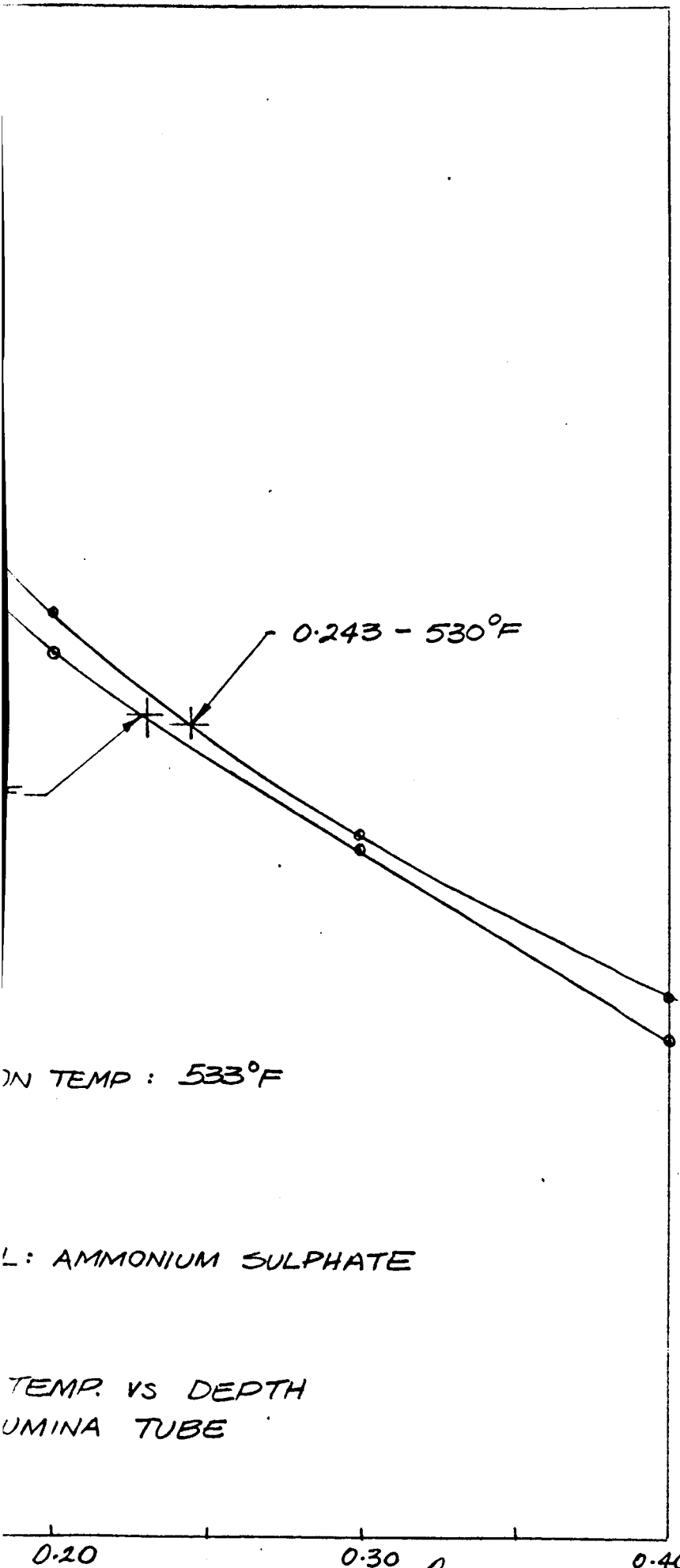


FIG 16 – MAXIMUM
ALONG AL

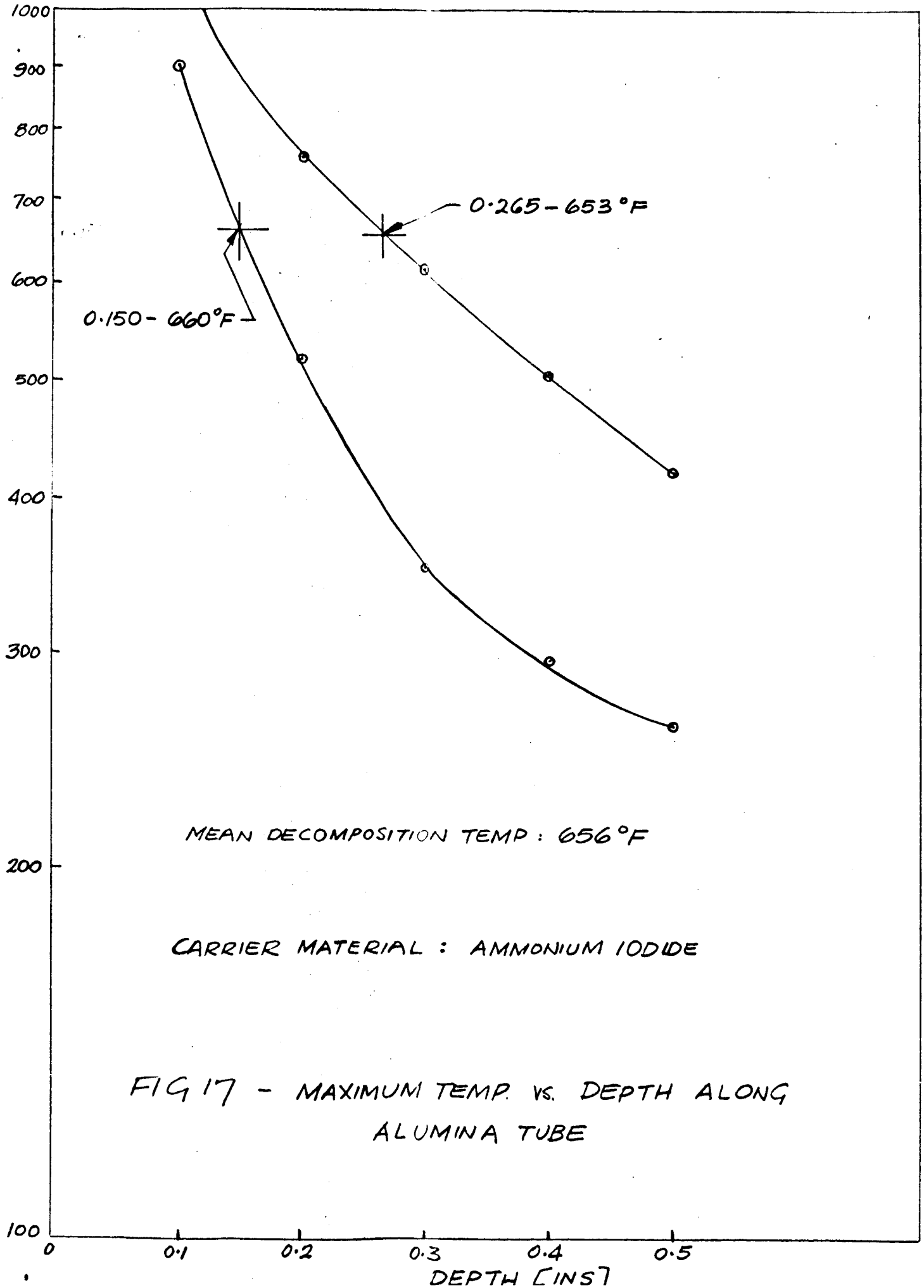


ON TEMP : 533°F

L : AMMONIUM SULPHATE

TEMP. VS DEPTH
UMINA TUBE

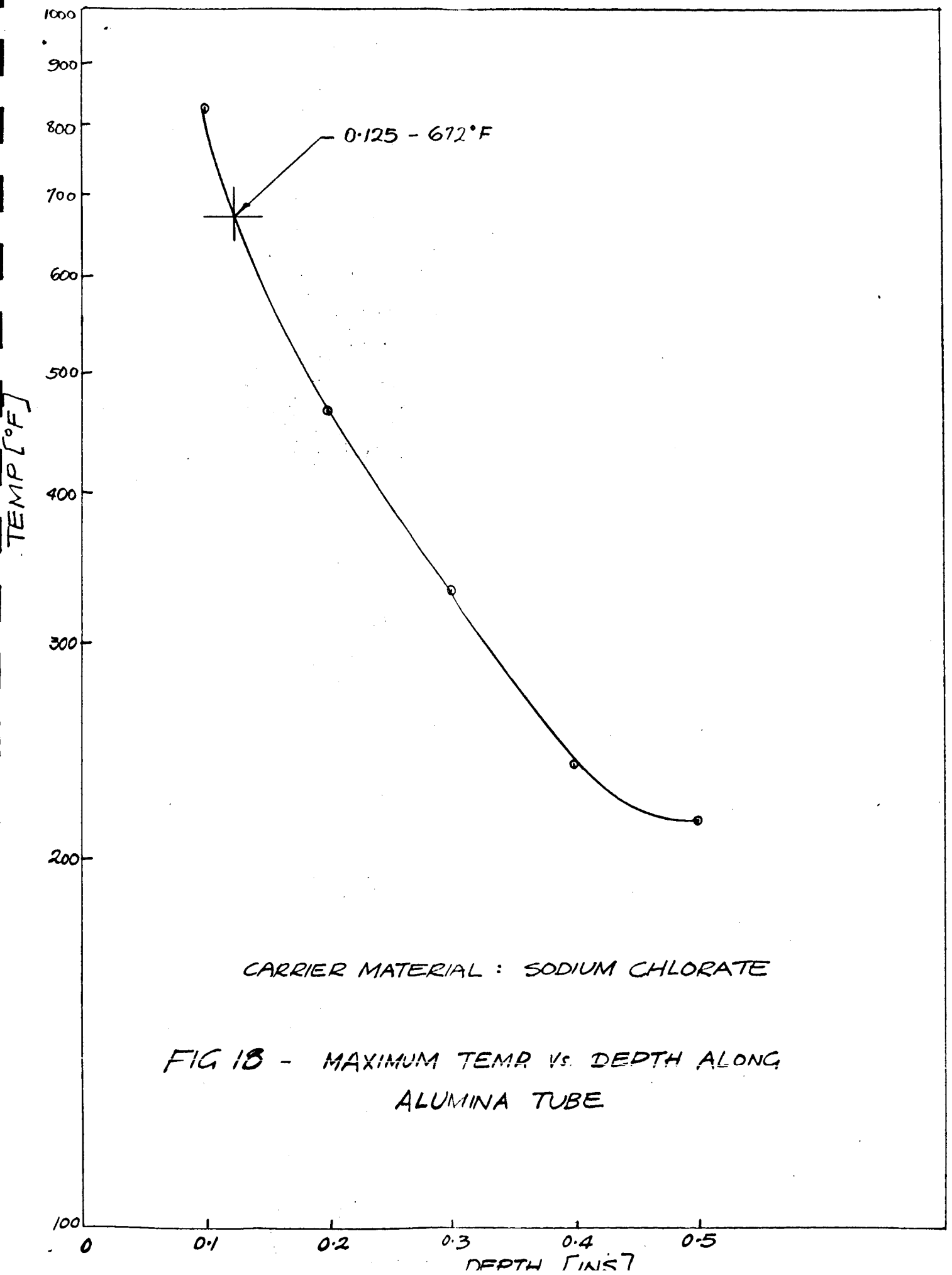
2



MEAN DECOMPOSITION TEMP : 656 °F

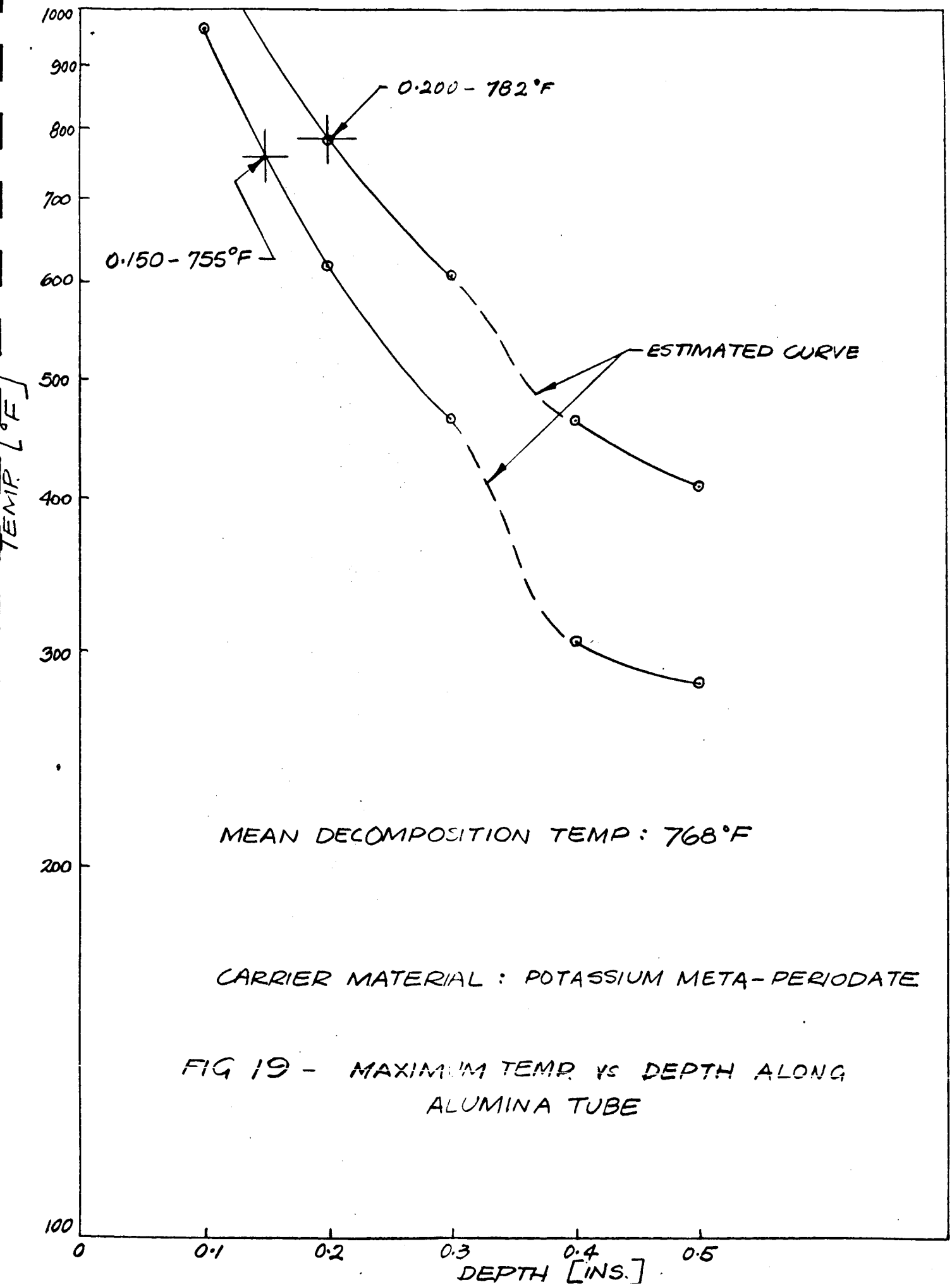
CARRIER MATERIAL : AMMONIUM IODIDE

FIG 17 – MAXIMUM TEMP. VS. DEPTH ALONG ALUMINA TUBE



CARRIER MATERIAL : SODIUM CHLORATE

FIG 18 - MAXIMUM TEMP Vs. DEPTH ALONG ALUMINA TUBE



MEAN DECOMPOSITION TEMP : 768°F

CARRIER MATERIAL : POTASSIUM META-PERIODATE

FIG 19 - MAXIMUM TEMP. VS DEPTH ALONG ALUMINA TUBE

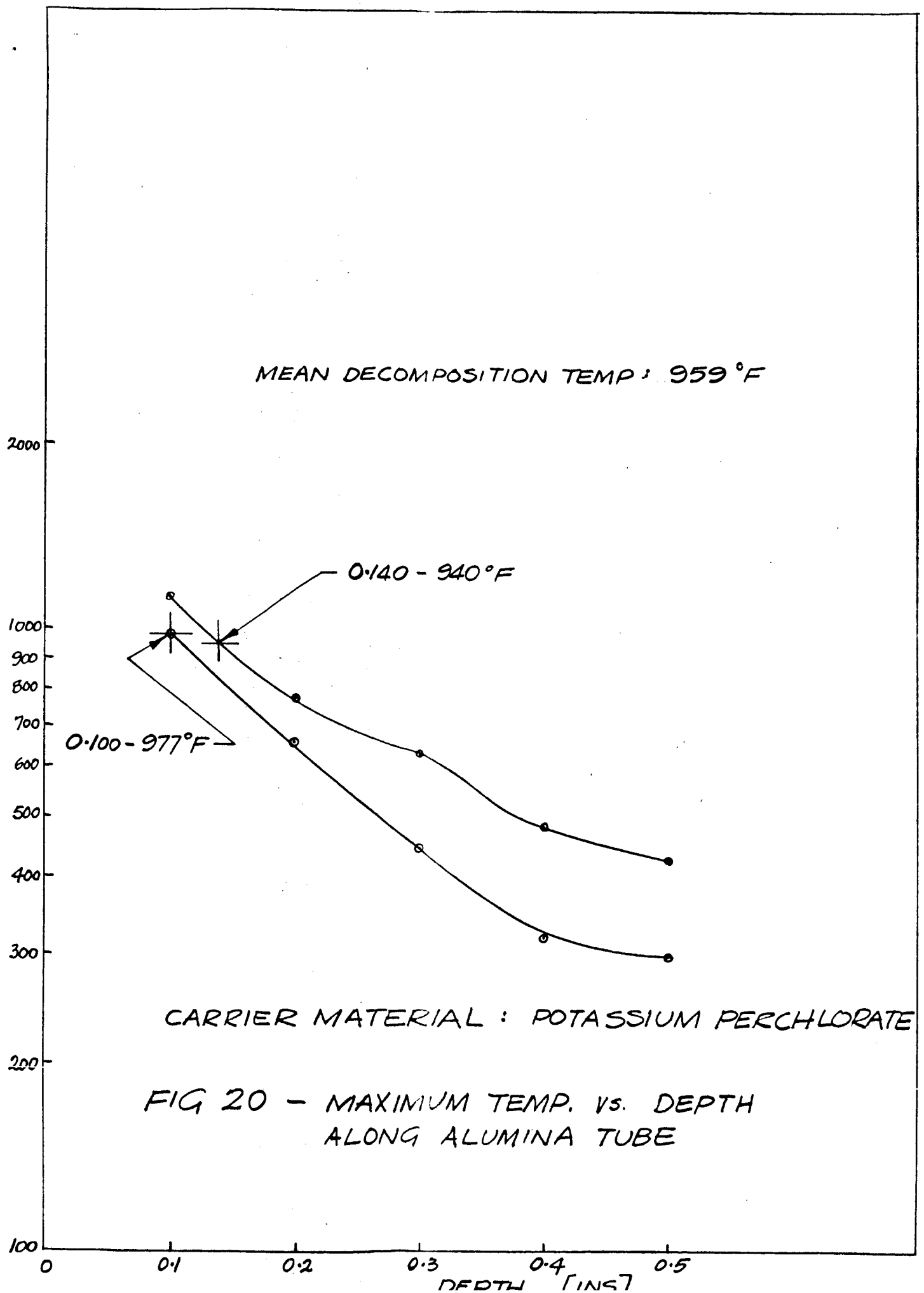


FIG 20 – MAXIMUM TEMP. Vs. DEPTH ALONG ALUMINA TUBE

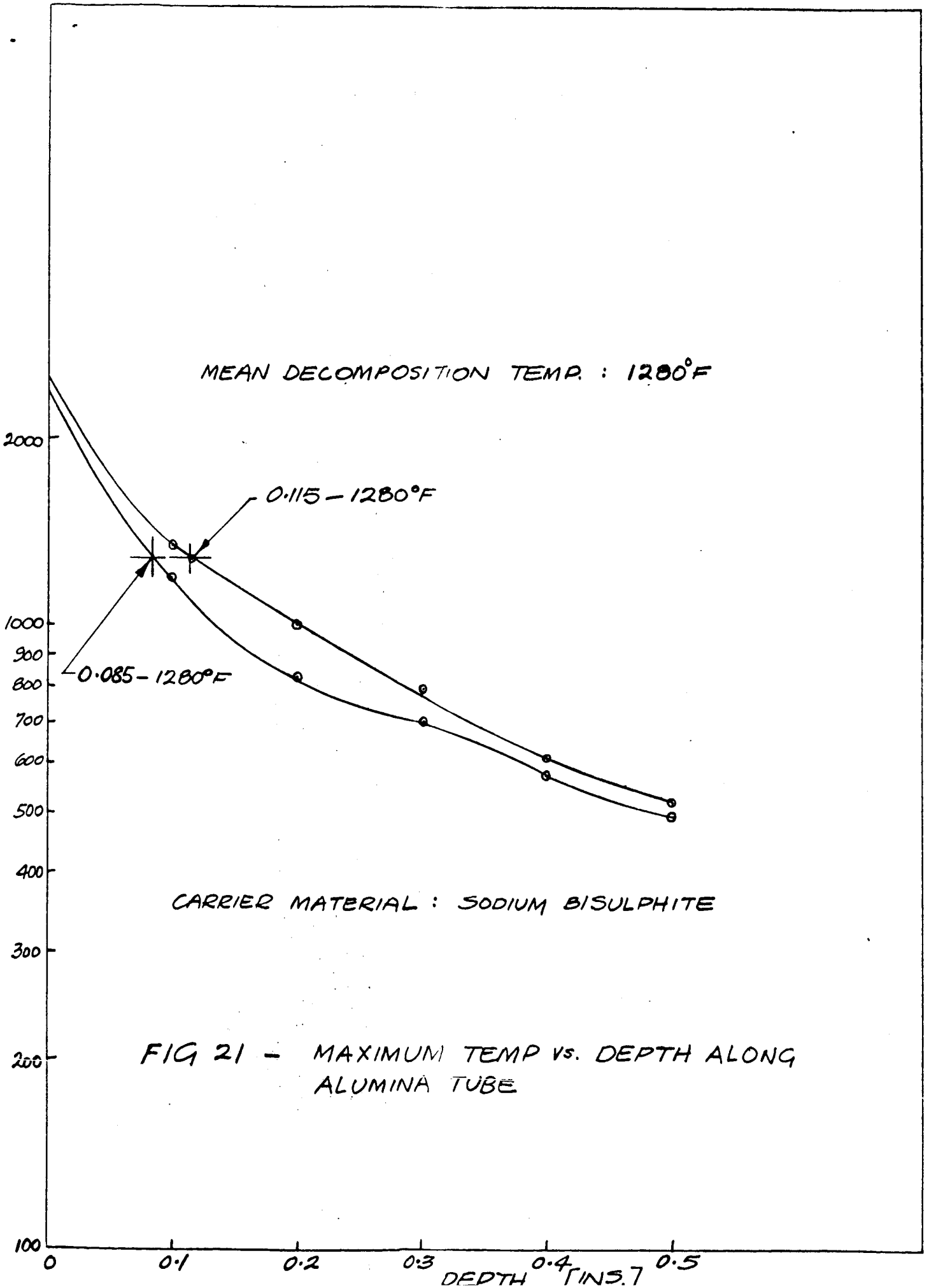
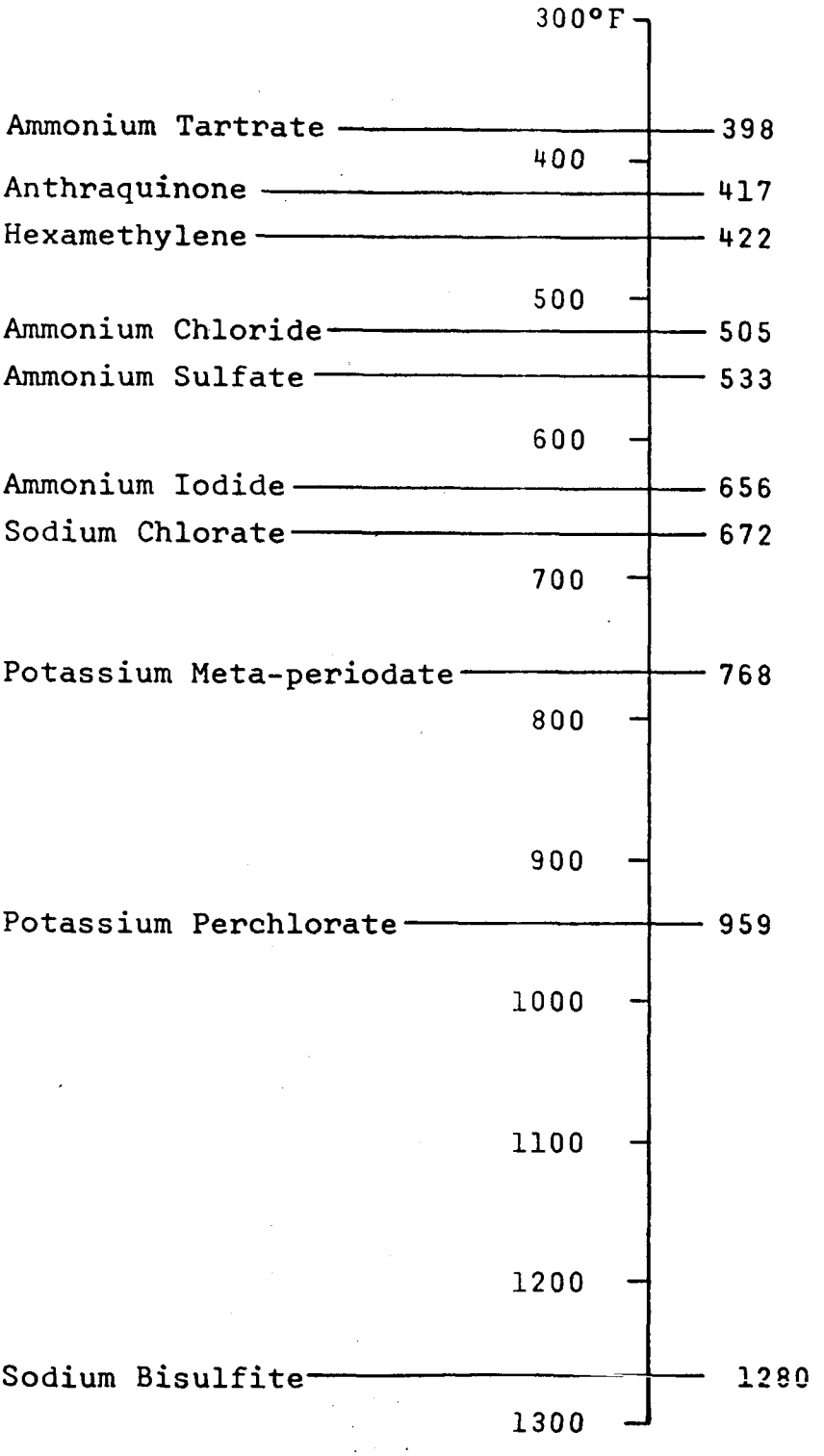


FIG 21 – MAXIMUM TEMP Vs. DEPTH ALONG ALUMINA TUBE

TABLE IV.

SUMMARY OF SUITABLE HEAT SENSITIVE CARRIER COMPOUNDS



VI. ANALYSIS AND SUMMARY

The negative results obtained using metal powders dispersed in decomposable carriers reopened the search for alternate source material and methods. One obvious avenue was to look at the carrier materials themselves to determine whether or not constituent isotopes can be activated. A second approach was to search for a compound which can be activated and which decomposes at temperatures $\leq$ 300°F. A reasonable concentration (10 to 20 per cent by volume) of this compound would be held in place by the carrier material for limited times (less than one minute) at temperatures $\geq$ 300°F., i.e., until the carrier material itself decomposes.

Isotopes contained in the ten carrier materials are listed in Table V, with pertinent activation data. Three useful isotopes occur as natural constituents of these heat sensitive carrier materials, namely, Na23, K39, and K41. Fortunately, the gamma ray energies are high (1.5 to 2.7 Mev) and the half-life range is broad (12h to 1.3×10^9y). Sodium is contained in sodium chlorate which decomposes at a temperature of 672°F, which unfortunately is near the middle of the temperature range of interest. Potassium is contained in potassium meta-periodate, which decomposes at 768°F. Both compounds would be suitable in the pure state as activated source materials or as additives to carrier materials which decompose at higher temperatures. Tests run using ammonium tartrate as the low temperature activated compound and ammonium perchlorate as the high temperature carrier material gave inconsistent results. That is, one run gave depth versus temperature points corresponding to pure potassium perchlorate, and two successive runs produced partially clogged tubes. An additional run employing cooling of the model immediately after removal of the flame gave improved results and confirmation of an explanation of the inconsistent clogging of the tube. The low temperature material is subjected to baking at temperatures above its decomposition temperature after removal of the ablative flame, and the combined effect of high

TABLE V

ACTIVATION DATA OF CONSTITUENT ISOTOPES
OF TEN SATISFACTORY CARRIER MATERIALS

TARGET ISOTOPE	THERMAL NEUTRON REACTIONS	REACTION CROSS-SECTION (BARNS)	NATURAL OCCURRENCE OF TARGET ISOTOPE	RADIOACTIVE PRODUCT		COMMENTS
				γ-RAY ENERGY AND % OCCURENCE	HALF-LIFE	
H^1	none	----	----	----	----	not suitable - no reaction
H^2	$H^2(n,\gamma)H^3$	0.57 mb	0.0139%	none	----	not suitable - no gamma rays
C^{12}	$C^{12}(n,\gamma)C^{13}$	3.3 mb	98.9%	none	----	not suitable - no gamma rays
C^{13}	$C^{13}(n,\gamma)C^{14}$	0.9 mb	1.108%	none	----	not suitable - no gamma rays
N^{14}	$N^{14}(n,P)C^{14}$	1.75 b	99.6%	none	----	not suitable - no gamma rays
N^{14}	$N^{14}(n,\gamma)N^{15}$	0.08 b	99.6%	none	----	not suitable - product stable
O^{16}	none	----	----	----	----	not suitable - no reaction
O^{17}	none	----	----	----	----	not suitable - no reaction
O^{18}	$O^{18}(n,\gamma)O^{19}$	0.21 mb	0.204%	1.36 (67%)	29 sec	not suitable - natural occurrence;

TABLE V (continued)

ACTIVATION DATA OF CONSTITUENT ISOTOPES
OF TEN SATISFACTORY CARRIER MATERIALS

TARGET ISOTOPE	THERMAL NEUTRON REACTIONS	REACTION CROSS-SECTION (BARNS)	NATURAL OCCURRENCE OF TARGET ISOTOPE	RADIOACTIVE PRODUCT γ-RAY ENERGY AND % OCCURRENCE	RADIOACTIVE PRODUCT HALF-LIFE	COMMENTS
Na^{23}	$Na^{23}(n,\gamma)Na^{24}$	0.536 mb	100.0%	1.368 (100%) 2.754 (100%)	15 hr	suitable - somewhat limited by a short half-life and small cross-section
Cl^{35}	$Cl^{35}(n,\gamma)Cl^{36}$	39 b	75.5%	none	----	not suitable - no gamma rays
Cl^{37}	$Cl^{37}(n,\gamma)Cl^{38}$	90 b	24.5%	1.59 (31%) 2.16 (16%)	37.3 min	not suitable - short half-life
Cl^{38}	$Cl^{38}(n,\gamma)Cl^{39}$	----	----	1.52 (85%)	55.5 min	not suitable - short half-life
K^{39}	$K^{39}(n,\gamma)K^{40}$	3 b	93.0%	1.46 (11%)	1.3×10^{9} yr	suitable
K^{40}	$K^{40}(n,\gamma)K^{41}$	3.8 b	0.0119%	1.29 (100%)	6.6×10^{-9} sec	not suitable - short half-life
K^{41}	$K^{41}(n,\gamma)K^{42}$	1.3 b	6.91%	1.53 (18%)	12 hr	suitable
I^{127}	$I^{127}(n,\gamma)I^{128}$	5.6 b	100.0%	0.45 (16%)	25 min	not suitable - short half-life

TABLE V (continued)

ACTIVATION DATA OF CONSTITUENT ISOTOPES
OF TEN SATISFACTORY CARRIER MATERIALS

TARGET ISOTOPE	THERMAL NEUTRON REACTIONS	REACTION CROSS-SECTION (BARNS)	NATURAL OCCURRENCE OF TARGET ISOTOPE	RADIOACTIVE PRODUCT γ-RAY ENERGY AND % OCCURRENCE	RADIOACTIVE PRODUCT HALF-LIFE	COMMENTS
S^{32}	$S^{32}(n,\gamma)S^{31}$	1.8 mb	95.0%	1.264 (0.07%)	2.6 hr	not suitable - short half-life, low spec. activity
S^{33}	$S^{33}(n,\gamma)P^{33}$	15 mb	0.75%	none	----	not suitable
S^{34}	$S^{34}(n,\gamma)S^{35}$	0.26 b	4.215%	none	----	not suitable
S^{36}	$S^{36}(n,\gamma)S^{37}$	0.14 b	0.017%	3.09 (90%)	5.04 min	not suitable - short half-life

vapor pressure and softened carrier material allows some of the combined material to flow into the open end of the tube. Rapid cooling of the tube minimizes this effect in laboratory studies. In operational use this effect would not be significant because the isothermal surface is advancing into cooler material, and all material behind the front would be subjected to higher temperatures due to the temperature gradient. Thus, a combination of 20 per cent or less by volume of a low decomposition temperature activated element or compound uniformly mixed with a higher decomposition temperature carrier material will act under dynamic temperature front propagation conditions as if the carrier were a pure material. This considerably broadens the list of possible elements and compounds which can be considered for activation, e.g., bromine, iodine, and mercury.

The performance of the carrier materials has been sufficiently satisfactory to establish this method firmly for continuously following the dynamic motion of an isothermal temperature point along a given line. Impregnating the carrier material with a small quantity of radioactive material in order to measure the progress of the temperature-determined decomposition point along the given line has not been satisfactory. The critical problem is to obtain an element or compound which has the required radioactive and thermal properties as well as gaseous decomposition products. It appears that a solution to this problem is to add small amounts (< 20 per cent by volume) of a low decomposition temperature (< 300°F) compound to a temperature sensitive carrier material. Additional inert experimentation would be required to select the optimum activated compounds and minimum concentrations followed by full scale dynamic tests using radioactive compounds to evaluate fully the performance of the complete system.

VII. ACKNOWLEDGMENTS

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