TD/M/8

A REVIEW OF SOME TEMPERATURE AND THERMAL STRESS CONSIDERATIONS RELATED TO SUPERSONIC AIRCRAFT DESIGN AS DERIVED FROM EXPERIENCE IN THE DESIGN OF THE ARROW.

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S U M M A R Y

The AGARD report No. 208 on "Some Effects of Internal Heat Sources on the Design of Flight Structures" presented the problem in general and that of an engine bay in detail. In this report, the discussion is extended to the kinetic heating of external surfaces.

The experience acquired on the CF.105 in the field of thermoelastics is reviewed, some of the conclusions and recommendations which resulted from the study of this design are listed. The review is extended into allied fields which had also been analysed in some detail.

C O N T E N T S

1.0 INTRODUCTION

This report discusses some general temperature and thermal stress considerations which arose during the design of the Mach 2 Avro Arrow interceptor. The related analytical investigations are contained in the references.

2. REQUIREMENTS & LIMITATIONS

As the structural integrity of the aircraft depends upon material strength which in turn depends upon temperature, it is essential that a maximum temperature concept be introduced. It is not adequate to set a maximum Mach number to define this limitation, for in such a case we can exceed the temperature and not make full use of the aircraft potential. As shown in fig. 1, where the limitations are 700 kts and M=2.0, we can overheat the structure by flying at M=1.9 and 30,000 ft. in a standard hot day atmosphere and yet we could fly at M=2.5 and 60,000 ft. on a standard cold day. Various proposals have been put forward to cater to this situation, one would consist of a gauge which measured the skin temperature, the other would be a "bug" on the Mach meter to indicate the maximum permissible (or cruising) Mach number for any ambient temperature.

The effect of elevated temperatures on the structure is to produce thermal stresses and decrease the material strength properties. Some of this strength is however "recovered" upon return to room temperature, but its value is a function of the time spent at elevated temperatures. An estimate of this time can be made by analysing the missions the aircraft is likely to perform and if the thermal stress problem is neglected for the time being, it is possible to draw flight envelopes which cater to the strength decrease at temperature.

For example in figure 2, a load factor of 7.33 at low speeds would be reduced to 6g at the top speed.

3. STRUCTURE

The effect of decrease in material strength being accounted for by the reduction in "g" at high speeds, it now remains to investigate the thermal stress problem both on its own and when combined with "g" loadings.

First it is necessary to enquire into the accuracy of the inputs to this problem. Next, to evaluate the importance of the various parameters so that finally an analytical approach compatible with the validity of the final results be derived.

The temperature and thermal stress responses are dependent upon the following factors:

3.1 Heat transfer coefficients

3.1.1 The surface convective transfer coefficient is a function of local Reynolds & Prandtl numbers as well as skin to ambient temperature ratios. The determination of the local flow properties is lengthy and depends on aircraft altitude, location of transition point, etc. An analysis[6] of this problem has shown that for a particular case we could assume that over the main structure area the flow was turbulent, equal on top and bottom surfaces and that the variation along the chord was small (± 10%).

The temperature ratio effect can be minimized by making the assumption that the skin temperature response is immediate where it is not affected by powerful heat sinks close by.

3.1.2 The transfer of heat from the skin to the web is controlled by the joint conductivity. If the mating surfaces provide a difficult heat path, there will be a temperature jump at this point and consequently the web will tend to have a slower temperature response, hence higher thermal stresses. The importance of this parameter is also dependent upon the convective heat transfer and some geometrical parameters[14], see figure 3.

3.1.3 As the heat transferred by radiation is small, for the temperatures considered, only the problem of heat transfer to fuel remains. The dependance of the skin temperature was investigated briefly, the results showing that a 10% change in transfer coefficient altered the skin temperature by approximately 5%. At this stage representative tests were required to investigate this problem and determine an accurate transfer coefficient.

3.2 Material Properties

The physical properties of the material being heated affect the thermal analysis. A review[12] of the relevant properties (k, C_p, α, E, geometry) shows that the scatter can be fairly large, (see figures 4 and 5), therefore the cumulative effect is instrumental in producing a large scatter in the final results.

3.3 Missions

The type of missions, their frequency and the total life of the aircraft, all play a part in introducing some doubtful parameters in the calculation. To make the analysis possible it is necessary to simplify the problem.

An investigation[10] into the effect of rates of acceleration between 0-2 minutes shows that the structure temperature and free thermal stresses are not altered appreciably. Therefore in all the mission we can safely replace the actual acceleration by a step function. This, together with a reasonable assumption of the time at high speed produces a simplified mission which is comparatively easy to analyse.

3.4 Methods of Analysis

Given a specific structure and all the necessary heat transfer data, it is always possible to analyse it rigourously by finite difference methods[8]. The basic differential equation, however, has to satisfy a stability criterion and for this reason it is necessary to take extremely short time intervals during the computation. A typical calculation taking approximately 2 hours on the IBM 704.

Other methods have been suggested. Amongst them the very promising method of Biot, which can be used to give practically exact results in a very short time (3-5 minutes on the IBM 704). If we allow considerable simplification in the mission and the structure, we can obtain an easy analytical solution to the problem[4,7,9,11,13]. One such method derives the skin temperature response by assuming no conduction to the web, and then calculating the web by using the skin temperature as its input.

It should be remembered that the exact thermal stresses are a function, not only of the temperature distribution, but also of the interaction of the remainder of the structure.

4. GENERAL

The following is a review of allied fields which were also investigated.

4.1 Stiffness

Calculations of the effect of thermal stresses on the stiffness[2,3] shows that this is negligible. It is therefore sufficient to assume a stiffness decrease compatible with the Young's Modulus at the control temperature.

4.2 Fatigue

This problem can be investigated[5] by making simplifying assumptions on the mission, the effect of temperature on fatigue properties, etc. The analysis showed that most of the damage appears to be produced by manoeuvres during combat. However, the assessment of the "g" loading during these manoeuvres is a point open to discussion.

4.3 Oil cooling system

Four independent oil systems exist

1. Utility hydraulics
2. Flying control hydraulics
3. Constant speed drive
4. Accessories gear box

These are cooled by means of both air and fuel. At high speeds the air cooling, due to high stagnation temperatures, is replaced entirely by fuel cooling.

The analysis was directed, first of all to the determination of the fuel temperature in the collector tank, prior to its use for cooling. A maximum temperature at the end of the high speed run was established (140°F) and from there the design and analysis proceeded.

It was found that a transient high fuel temperature condition could arise when the engines where suddently throttled back[15] (due to decrease of fuel flow). A similar condition could also arise when starting the engines on the ground if the oil systems were still hot (e.g. re-starting shortly after return from a high speed mission). These difficulties could however be overcome by suitable restrictions until the flight test results proved or disproved the theoretical analysis.

4.4 Time at high speed

It is apparent that the proper functioning of the oil cooling system depends upon the maximum fuel tank temperature. This in turn depends on the maximum speed, the time spent at that speed and the initial fuel temperature. For instance under standard conditions this temperature might be reached after 10 minutes at high speed, whereas if the initial temperature were high this time might be reduced to 5 minutes. This means in effect a limitation on the time at high speed, dependent upon the collector tank fuel temperature. It is therefore logical to introduce some means of warning when this temperature is reached.

5. CONCLUSIONS

First, it should be noted that the purpose of this report is to produce a review of the design problems associated with kinetic heating on the CF-105. The points which were made during the discussion apply specifically to that aircraft and before a conclusion is applied to another aircraft, a re-examination is required.

Certain salient points, however, will still apply to a wide range of high speed aircraft, namely:

1. The need for an instrument to indicate the structure temperature limitation under any ambient condition (e.g. "bug" on Mach meter)

2. As the input data to thermal stress calculations shows a fair amount of scatter, simplifications in the analysis are therefore permissible. This scatter can be reduced by suitable testing, but even then, it is doubtful if rigorous analysis are warranted.

3. In a similar fashion that a fuel contents gauge indirectly indicates the remaining time available for flying; an instrument must be provided to permit assessment of the remaining time available for high speed flying.

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3. 70/Elastics/10 - The effect of plasticity and building on thermal stress and stiffness.

4. 70/Thermo/8 - The effect of radiation on aircraft skin temperature

5. 70/Thermo/9 - Temperature history and
72/Thermo/10 - fatigue life of CF-105.

6. 72/Thermo/12 - Determination of heat transfer coefficients over a wing, at supersonic speeds, with reference to unequal heating rates of upper and lower surfaces, which may occur.

7. 70/Thermo/20 - A simple analytical solution for temperature response in an insulated skin.

8. 70/Thermo/22 - Calculation of two-dimensional temperature and thermal stress distribution in structures.

9. 70/Thermo/24 - An exact solution for temperature response in an insulated stab.

10. 70/Thermo/24 - Effect of acceleration on temperature and thermal stress distributions.

11. 70/Thermo/31 - An analytical solution of steady state temperature distributions in joints.

12. 70/Thermo/32 - Same considerations in establishing temperature distributions as used for thermal stressing.

13. 70/Thermo/33 - Equilibrium temperature of an isolated Skin.

14. - Summary of investigations - Kinetic heating.

15. 72/Thermo/30 - Analysis of transient fuel temperatures at engine inlet.

16. 72/Thermo/29 - Description and analysis of Arrow 2 oil cooling system.

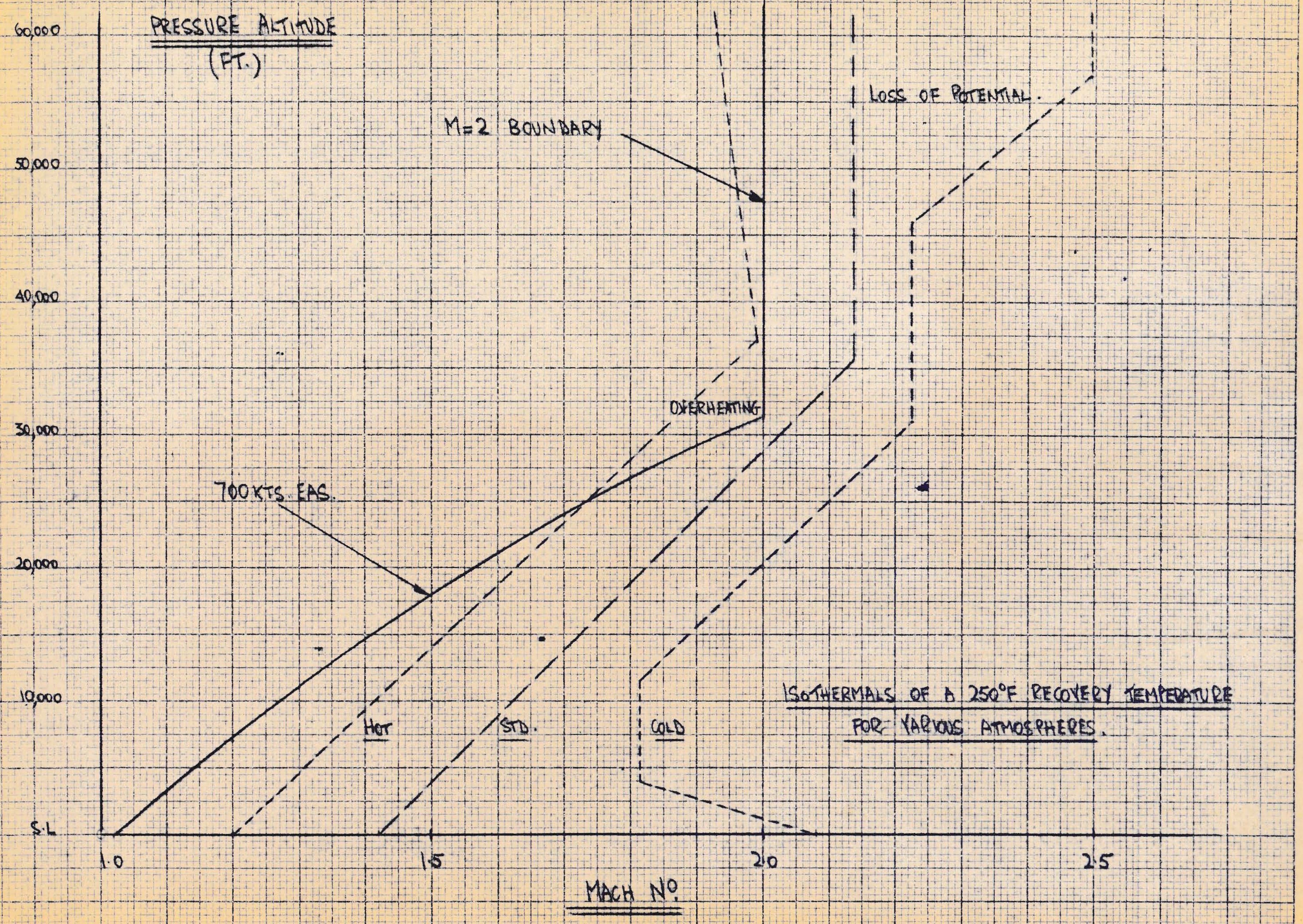

FIGURE 1 - VARIATION OF TEMPERATURE LIMITATION FOR VARIOUS ATMOSPHERES.

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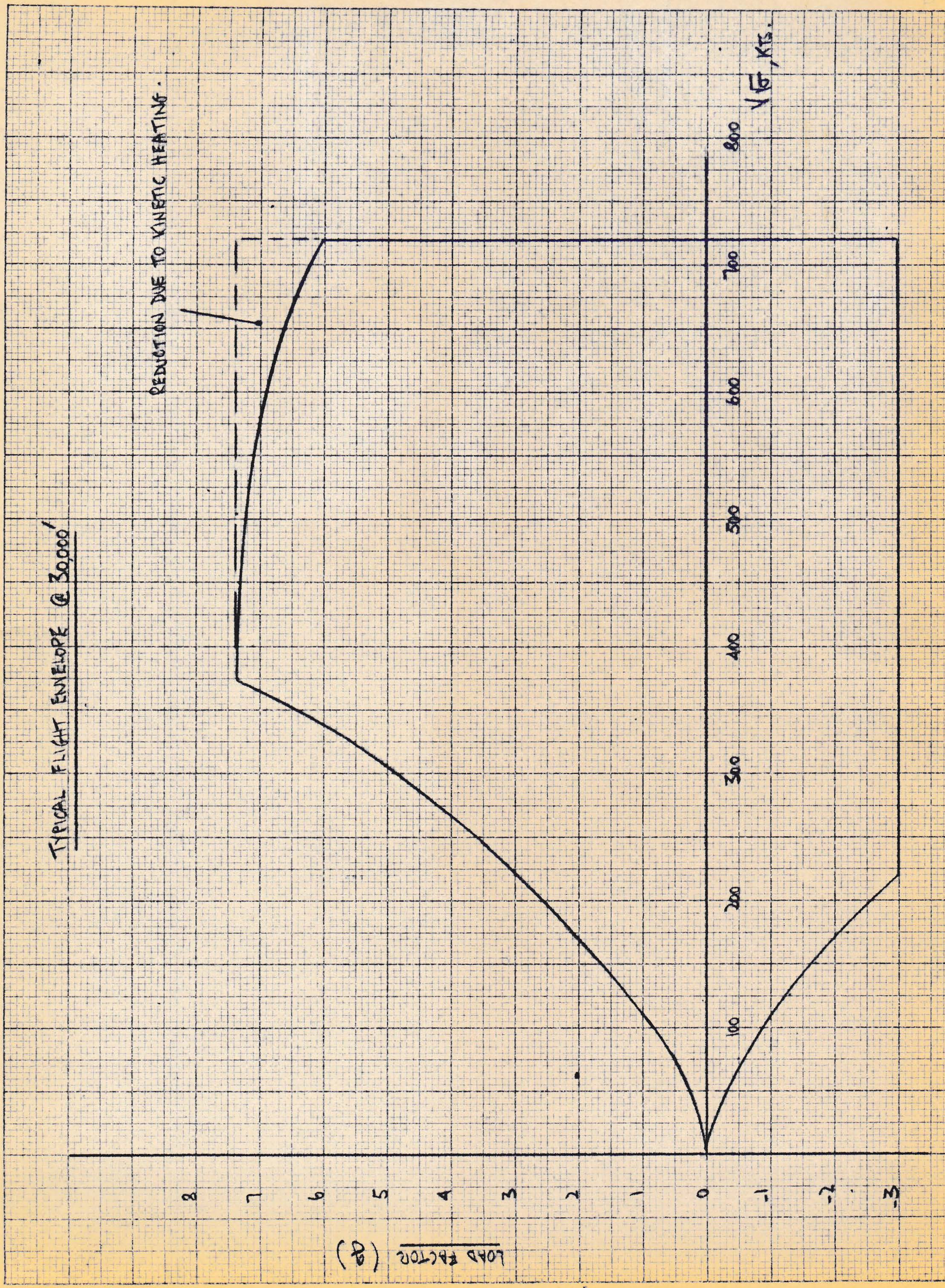
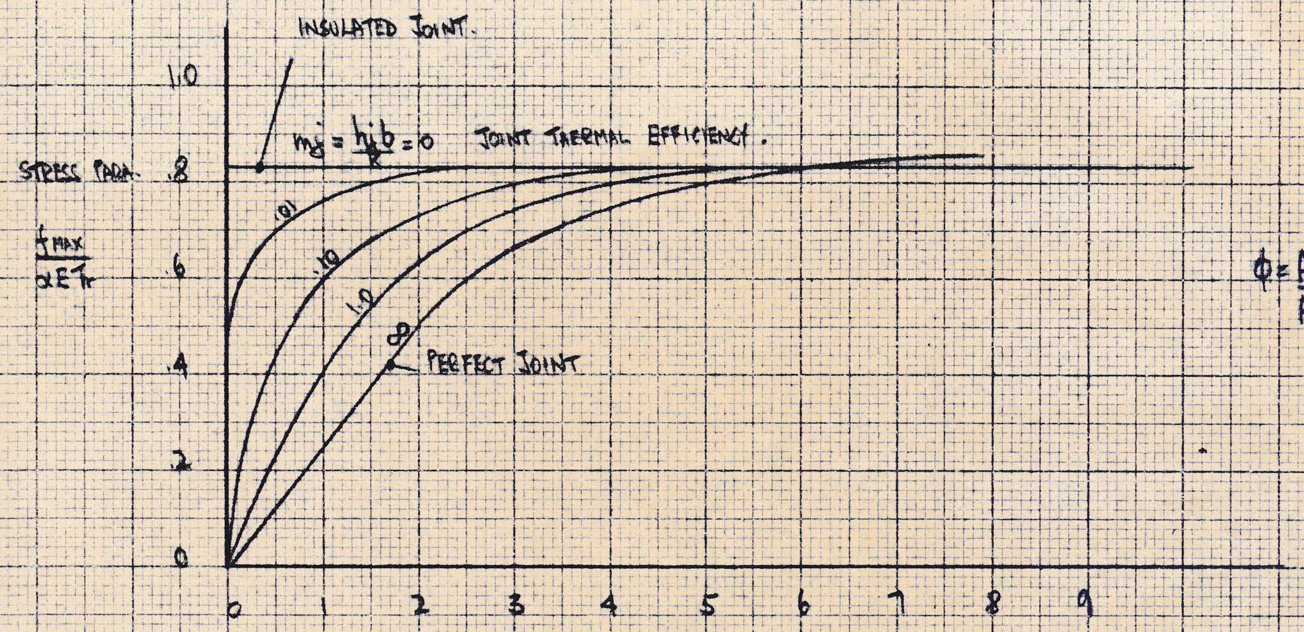


FIG. 2. TYPICAL FLIGHT ENVELOPE AT 30,000' SHOWING DECREASE OF LOAD FACTOR DUE TO KINETIC HEATING.



$$q = b\sqrt{\frac{h}{k t_s}}$$ HEATING PARAMETER.

$\phi = \frac{A_S}{A_W} = 5$ = AREA $\frac{SKIN}{WEB}$

b = 1/2 WEB DEPTH
h = CONVECTIVE HEAT TRANSFER COEF.
K = MATERIAL THERMAL CONDUCTIVITY
t_s = SKIN THICKNESS.
f_{max} = MAXIMUM STRESS
α = COEFFICIENT OF EXPANSION
E = YOUNG'S MODULUS.
h_j = JOINT CONDUCTIVITY.
T_r = RECOVERY TEMPERATURE.

REF. "GATEWOOD" THERMAL STRESSES.

FIG 3. MAX. WEB STRESSES FOR VARIOUS JOINT THERMAL RESISTANCES.

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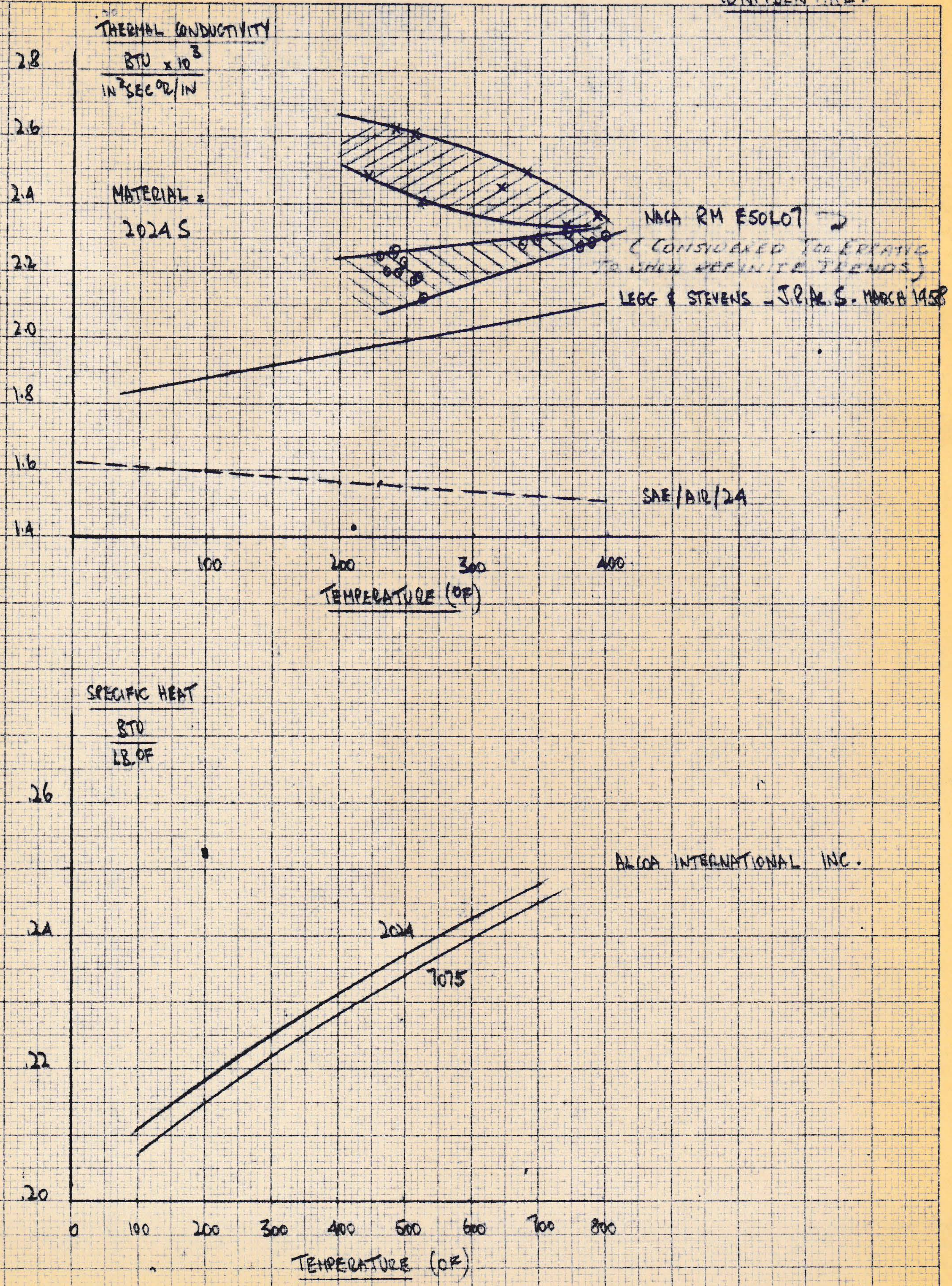

FIG 4. VARIATION WITH TEMPERATURE OF: 1. THERMAL CONDUCTIVITY 2. SPECIFIC HEAT.

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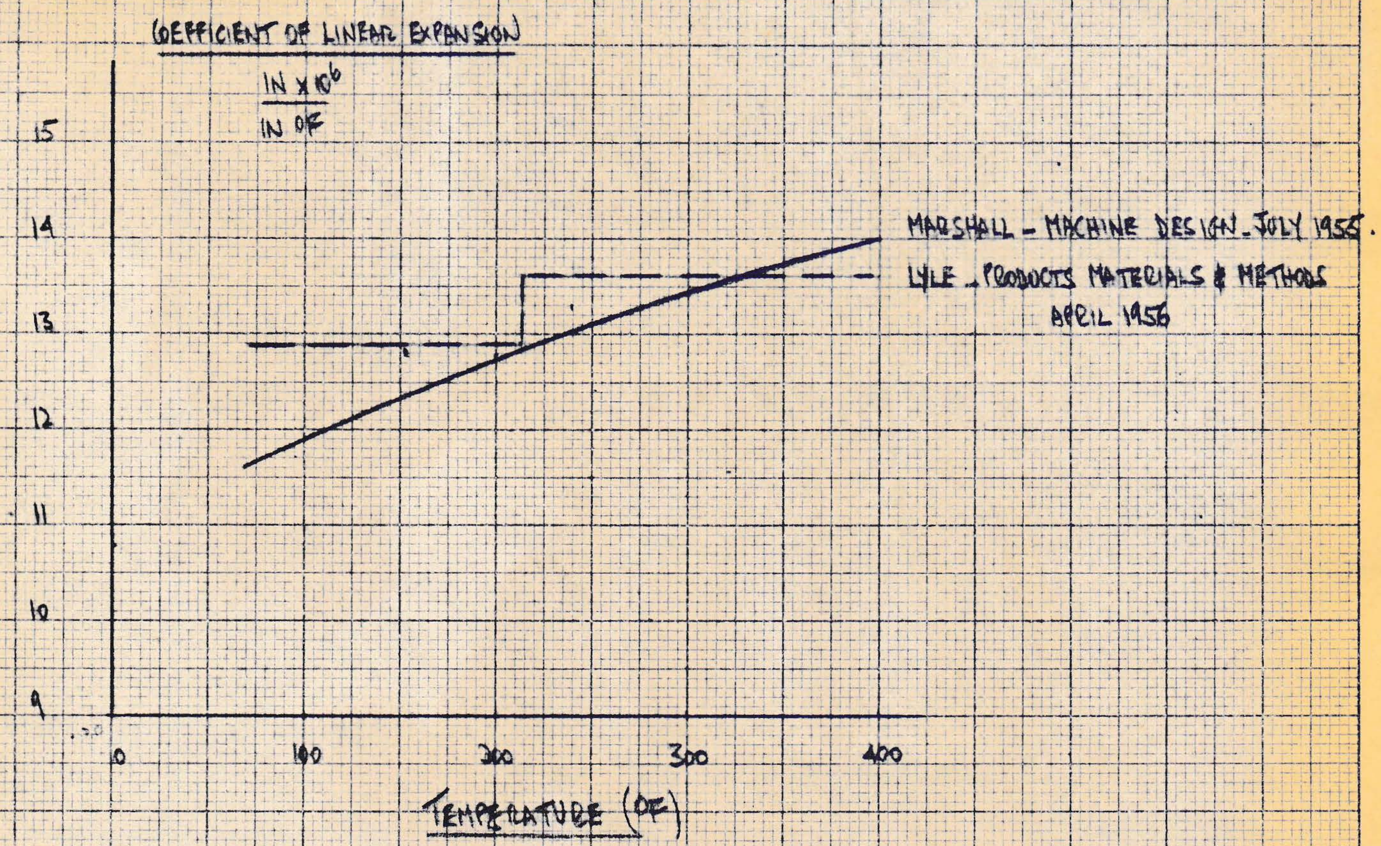

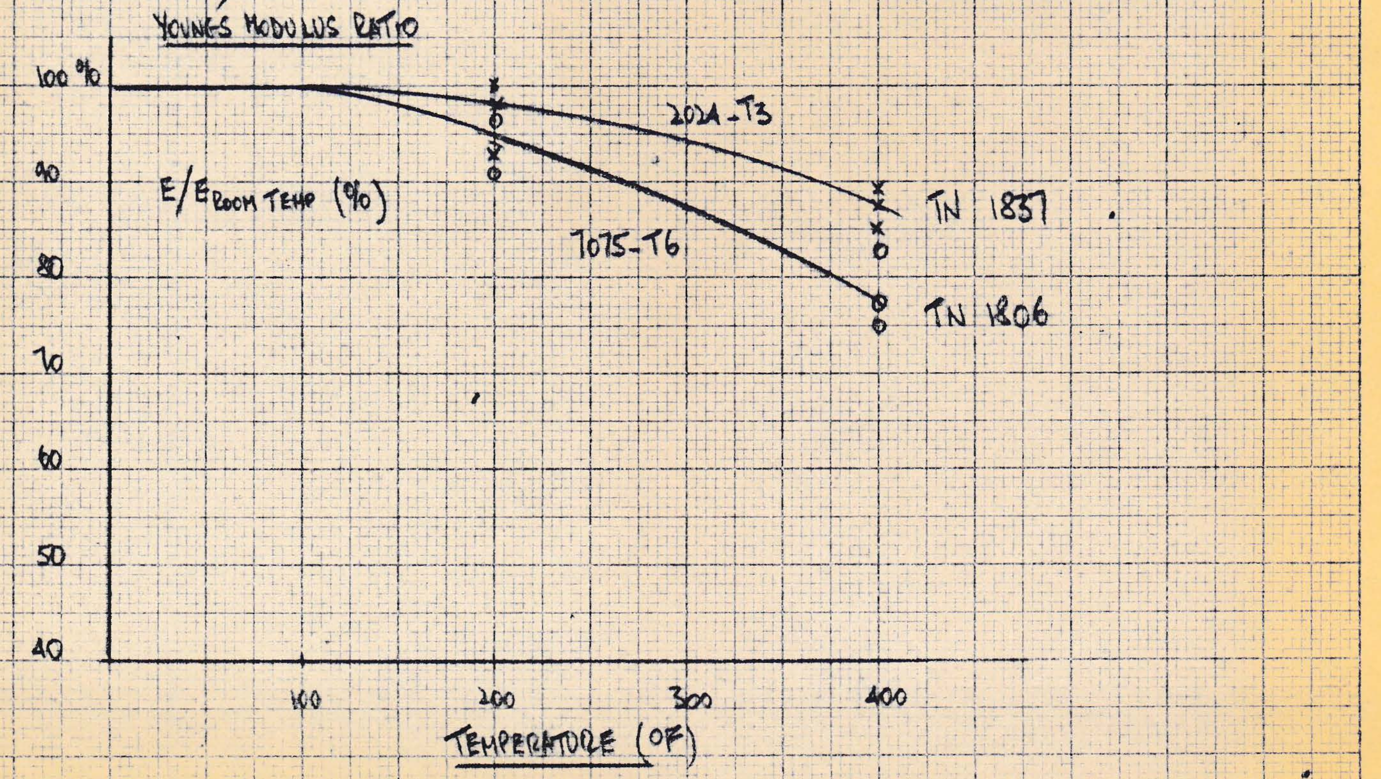

FIG 5. VARIATION WITH TEMPERATURE OF: 1. COEFFICIENT OF LINEAR EXPANSION 2. YOUNG'S MODULUS.

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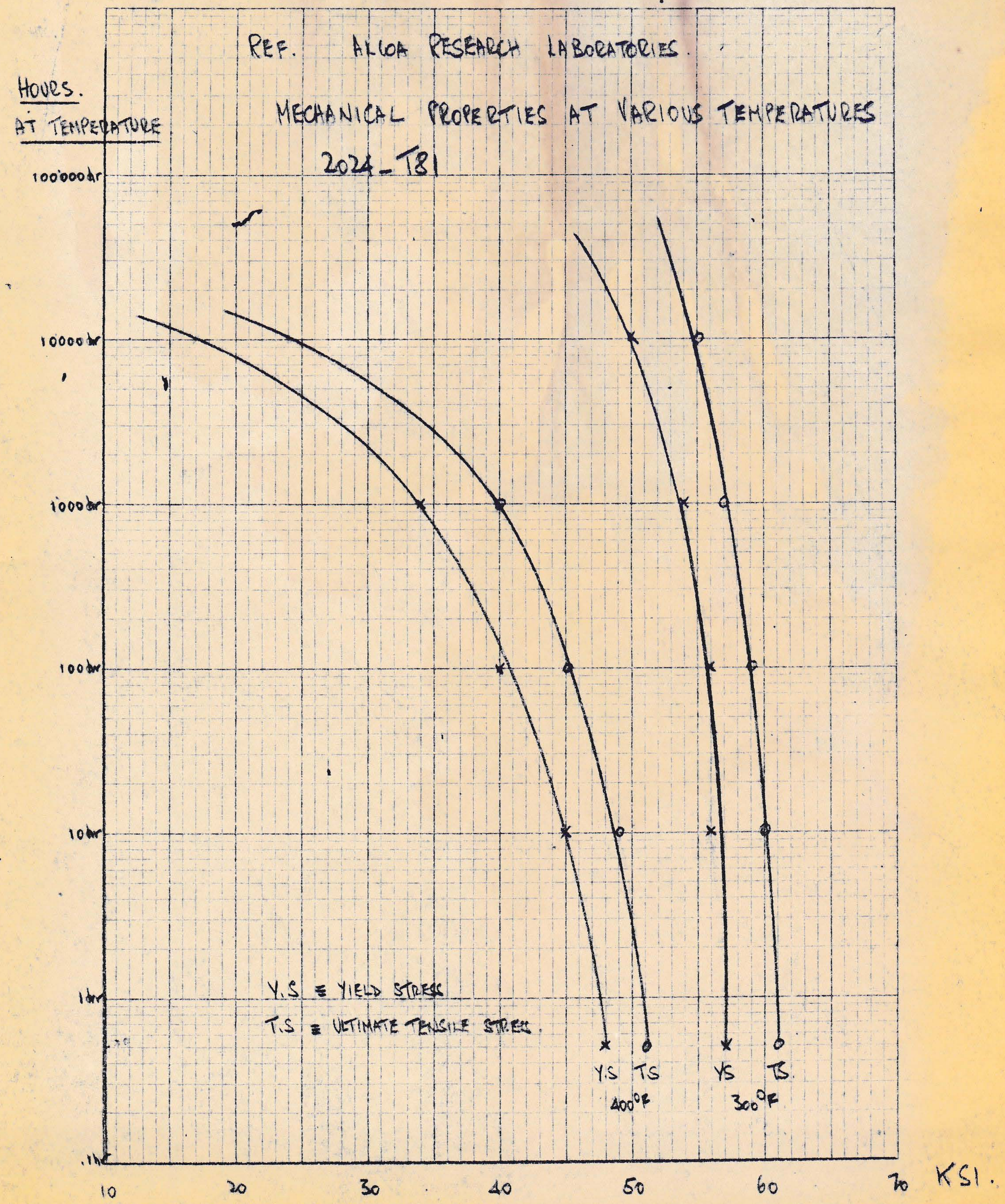

FIGURE 6. MECHANICAL PROPERTIES OF 2024-T81 @ 300 & 400°F.

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