# REON

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REPORT NO. RN-S-0297

TO

AEC - NASA SPACE NUCLEAR PROPULSION OFFICE

THRUST CHAMBER TEMPERATURE PROFILE PROBE
SUMMARY REPORT

JUNE 1966
NERVA PROGRAM
CONTRACT SNP-1

MASTER

AEROJET
GENERAL TIRE
GENERAL

AEROJET-GENERAL CORPORATION
SACRAMENTO, CALIFORNIA

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**AEROJET GENERAL**

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# THRUST CHAMBER TEMPERATURE PROFILE PROBE
## SUMMARY REPORT

### JUNE 1966

ROCKET ENGINE OPERATIONS – NUCLEAR

NERVA PROGRAM                    CONTRACT SNP-1

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## CLASSIFICATION CATEGORY

### UNCLASSIFIED

S K Yoder                              6-30 '66

**CLASSIFYING OFFICER**            **DATE**

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# ABSTRACT

This document presents the summary of a feasibility study conducted in
CY '65 for a proposed device to measure the exit gas temperature profile in the
convergent area of the NERVA thrust chamber.

This report is submitted in partial fulfillment of Subtask 2.4, Contract
SNP-1.

C. M. Rice
Program Manager - REON

# TABLE OF CONTENTS

# LIST OF FIGURES

I.     INTRODUCTION

This report presents a summary of a feasibility study for a device for measuring
the profile of the NERVA thrust chamber gas temperatures in approximately half of the
cross-sectional plane near the hot bleed port.  The proposed device consists of a
streamlined tubular arm mounted on a pivot in the hot bleed port, six tungsten-
rhenium thermocouples protruding from the front edge of the arm, and a drive mechanism
to swing the arm back and forth across the thrust chamber.  Measurements obtained with
this profile probe would determine the temperature gradients in the convergent section
of the thrust chamber and the validity of measuring the thrust chamber gas tempera-
ture with thermocouples that extend 1.4-inch into the hot gas stream at four to five
angular positions around the thrust chamber.

II.    CONCLUSIONS AND RECOMMENDATIONS

The proposed device is technically feasible.  The drive mechanism, thermocouples,
and arm structure represent direct applications, or extensions, of existing hardware
or techniques and all stresses are within limits of a high temperature alloy such as
tungsten 26% rhenium.  Building and testing this device would require about one to two
years and cost about $250,000.00.  Extensive nonnuclear testing would be necessary to
demonstrate the adequacy of the design prior to testing in the NRX or XE vehicle.

In view of the close agreement between the individual thermocouples used on
all NRX tests conducted to date, and in view of the agreement between the average
measured and calculated temperatures (shown below), it is considered improbable
that large temperature gradients exist across the nozzle.  Because of this improba-
bility, the large expenditures required to make temperature profile probe type
measurements may not be justified at this time.

III. DISCUSSION

A. BACKGROUND

The anticipated need for this profile measurement arose as a result of the difference between calculated and measured temperatures and the differences between the individual thermocouple readings on NRX-A2. Improved analytical models now used to predict the nozzle gas temperatures yield results which agree with measured temperatures and the measured temperatures are now accepted as "ture" on all tests.

|  | NRX-A2 | | NRX-A3 | | NRX/EST | | NRX-A5 | |
|---|---|---|---|---|---|---|---|---|
| TEST | EP-IVA | | EP-IV | EP-V | EP-III | EP-IV | EP-IV | EP-III |
| TIME | (13900) | (13985) | (21525) | (12830) | (22366) | (11895) | (14460) | (26120) |
| T AVG MEASURED | 3130 | 3350 | 3821 | 3860 | 4130 | 3940 | 4037 | 3988 |
| T AVG CALCULATED | 3546* | 3801* | 3797*** | 3833*** | 4140*** | 3980*** | ** | ** |
| AGREEMENT | 416 | 451 | 24 | 27 | 10 | 40 | ---- | ---- |

*Published value found to contain an error in calculations. The corrected value is in agreement with the measured value by less than 100°F.

**Average Nozzle Gas Temperature not calculated but used "As Measured" to determine Flow Rates.

***Calculations show evidence of "Correction Factors" based upon temperature measurements.

As for the differences between thermocouples, improvements in thermo-couple calibration and fabrication have reduced these differences to near the expected overall ± 100°F uncertainty at 4000°R so that the differences that remain are not particularly significant. These differences, as obtained from the Cal-Comp recordings along with the maximum average temperature and number of thermocouples involved, are listed for each of the NRX tests to date.

| Test | Number of Thermocouples Used | Maximum Average Measured Temperature °R | Maximum Measured Difference °R |
|---|---|---|---|
| NRX-A2 | 4 | 3560 | 300 |
| NRX-A3 | 4 | 3810 | 150 |
| NRX-EST | 5 | 4150 | 200 |
| NRX-A5 | 4 | 4100 | 75 |

On NRX-EST, the 200°R spread was caused by one thermocouple (T-139) located in a hot sector found to be present near the hot bleed port. Further details are given in NRX/EST DRAGON Memorandum 138. The other four thermocouples agreed within 75°R.

Having largely reconciled the two differences - the difference between calculated and measured temperature and the differences between the individual thermocouples - much of the need which prompted the original study has been removed.

Figure 1 is the diagram for the thrust chamber profile probe originally considered. Figure 2 shows the probe design resulting from the present study. The only differences between the two designs are in the position of the arm within the thrust chamber and in the technique of cooling the **inner core rather than the outer** surface. This latter change is especially important because computer studies using the various regeneratively cooled nozzle equations indicated that the original arm probably could not be adequately cooled. Thermally insulating with reflective foil and cooling just the inside circumvents this coolant problem so that the other aspects of the design could be investigated.

B. DESCRIPTION

Primary elements of the design shown in Figure 2 are the tubular arm, the support bearings, and the drive mechanism.

The tubular arm would be a tapered, streamlined, double-walled tube made of W 25%Re. Multiple layers of tungsten-foil reflective insulation between the walls would reduce the heat transfer between the tubes. In this way the passage through the inner tube could be cooled to below 1500°R by flowing cold gaseous hydrogen into the support axle through the inner tube and out the end of the inner tube into the thrust chamber. Cooling the inner tube greatly increases the strength of the arm at operating temperature and virtually eliminates all shunt electrical leakage that would otherwise occur in hot, long thermocouple extension leads.
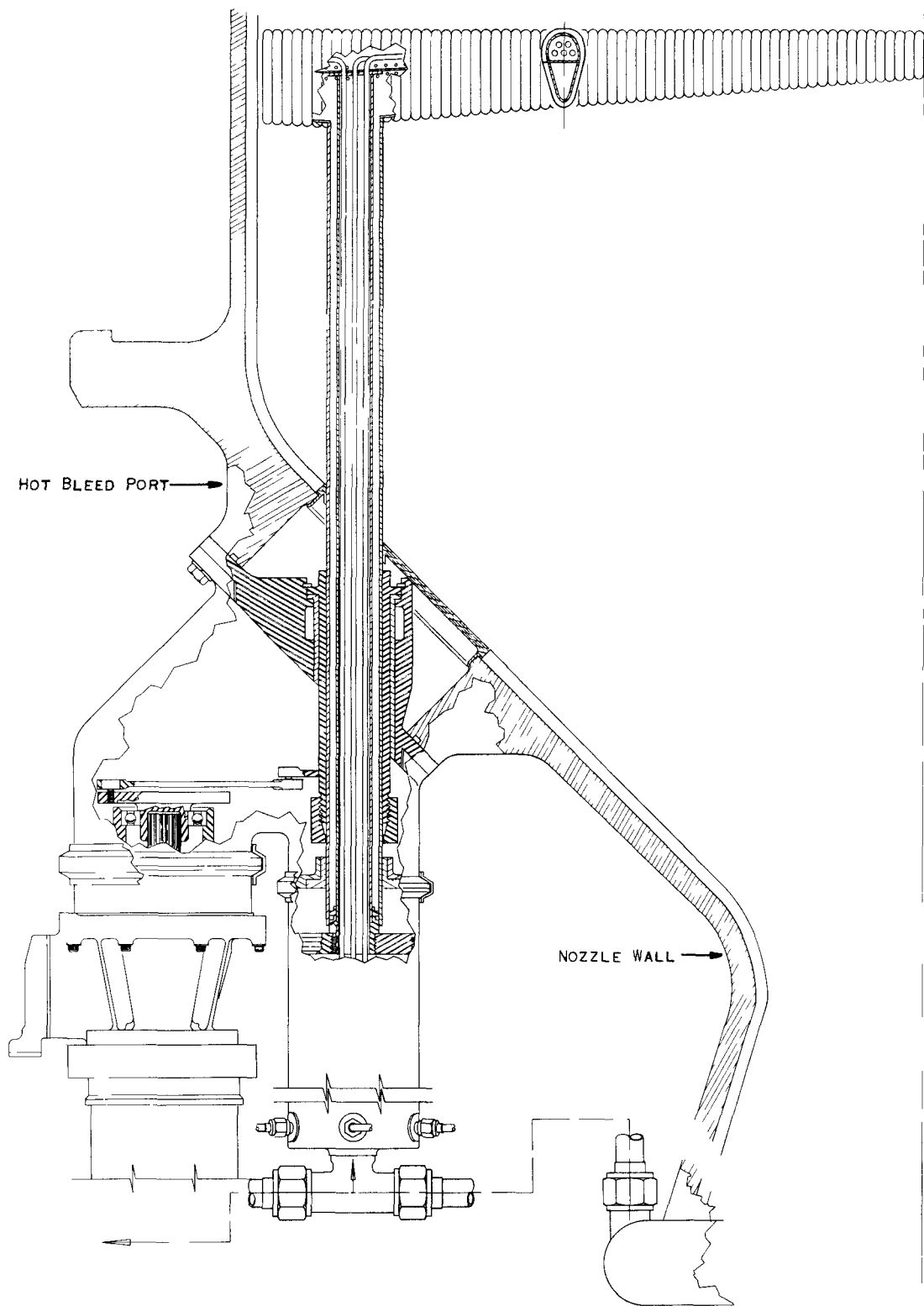
HOT BLEED PORT

NOZZLE WALL

Figure 1

Originally Proposed Thrust Chamber Profile Probe

4

W-Re THERMOCOUPLES

0.1" THICK W-26% Re

HYDROGEN-COOLED INNER TUBE
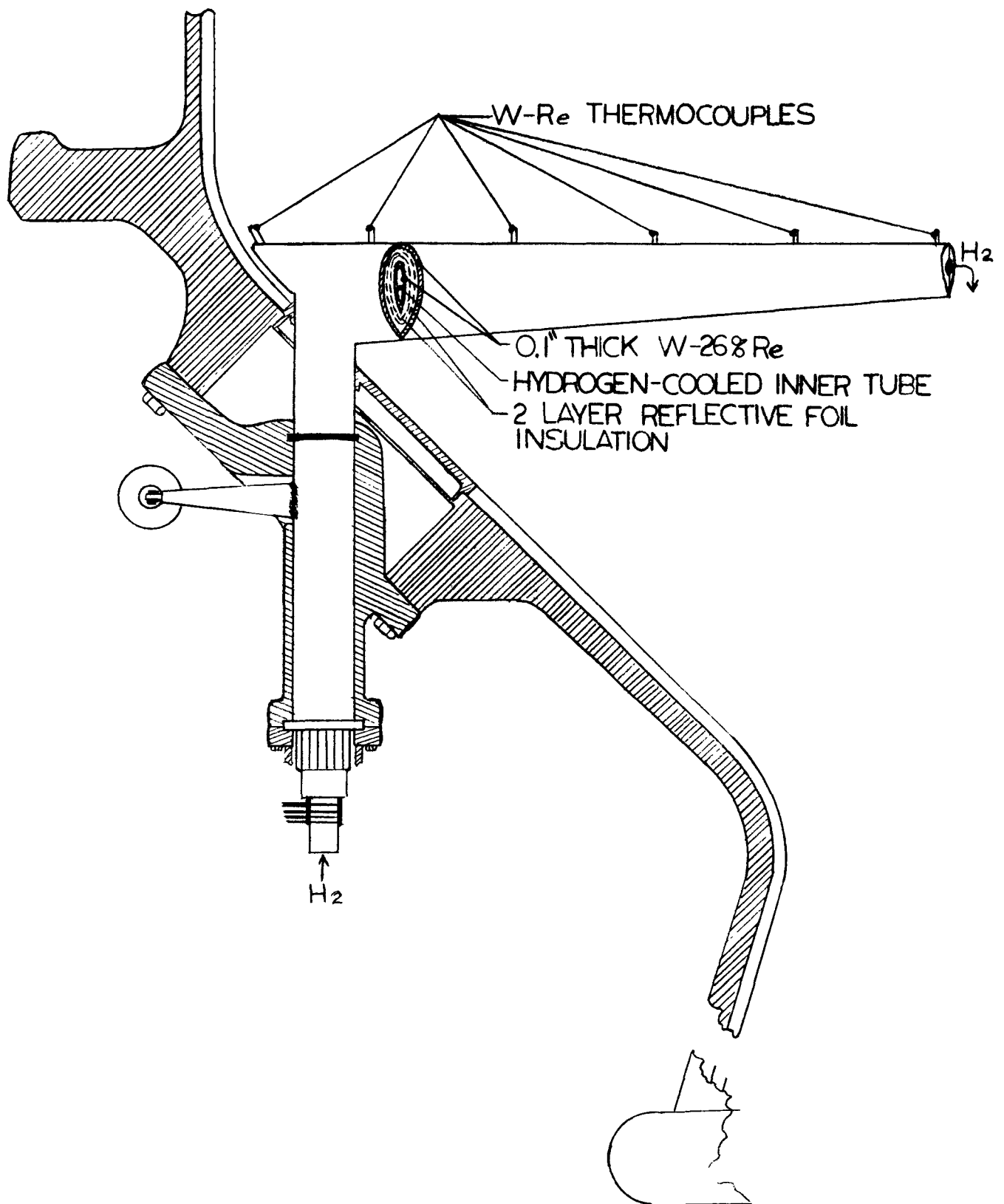
2 LAYER REFLECTIVE FOIL
INSULATION

H₂

H₂

Figure 2

Thrust Chamber Profile Probe

5

The tubular arm would be tapered and streamlined as shown to maximize strength and to minimize drag and vibrational stresses. Fabrication could be accomplished by an alloy vapor deposition technique developed by the San Fernando Laboratories of Pacoima, California. This laboratory has been contacted and they can build the described arm.

The support bearings and drive mechanism could be patterned after the present NERVA control-drum-drive system. If need be, 1500°R dry-type bearings and pneumatic actuators developed for the SNAP program could be used. Possibly the system could be sufficiently cooled and flushed so that conventional lubricants could be used.

The six tungsten-rhenium thermocouples protruding from the arm would be similar to those used successfully on the NRX tests to date. No unusual problems are expected.

C.  ANALYSIS

For ease of calculation and as a conservative case, the arm projecting into the thrust chamber is assumed to be a straight cylinder. The tapered streamlined shape proposed is actually much stronger and has a lower loading than the assumed straight cylinder.

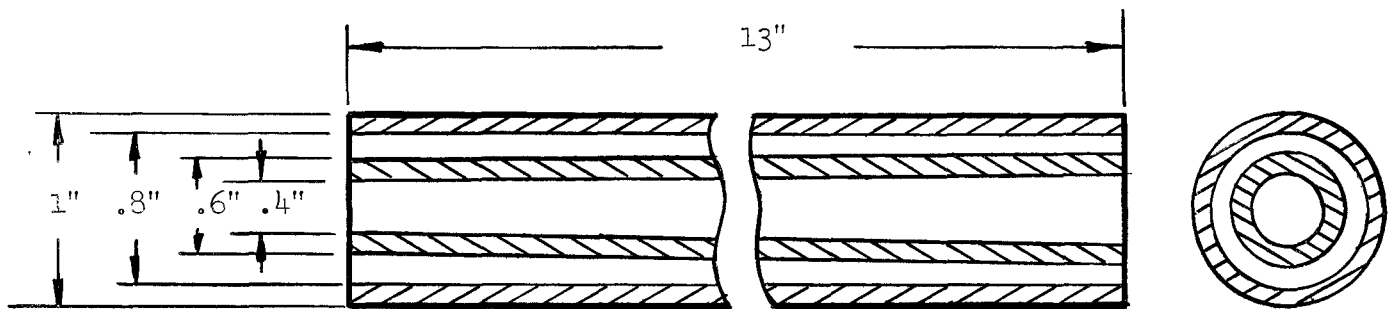Figure 3 gives the dimensions of this simplified arm.



Figure 3
Proposed Tapered Streamline Shape

Drag forces on this cylindrical arm are given by the following equation:

$$\text{Drag} = \frac{\rho V^2}{2} \, C_D \, S \tag{1}$$

where:

$\rho$ = .0257 lb/ft$^3$ = 0.0008 slugs (density of hydrogen at full power)

$\dot{w}$ = 71 lb/sec (hydrogen flow at full power)

$V$ = $\dfrac{\dot{w}}{\rho \, \text{Area}}$ = $\dfrac{71}{(.0257)(3.96)}$ = 700 ft/sec (flow velocity)

$C_D$ = 0.66 (drag coefficient for cylinder)

$S$ = Projected surface area of arm - 13" x 1" = 13-in.$^2$

Drag = $\dfrac{0.0008 \, (700)^2 \, (0.66)(13)}{2(144)}$ = 11.3 lb

Treating the profile probe arm as a cantilever beam with a distributed load, the bending stress $\sigma_B$ of the outer tube is:

$$\sigma_B = \frac{MC}{I} \tag{2}$$

where:

$M$ = $\dfrac{DL}{2}$ = $\dfrac{11.3(13)}{2}$ = 74 in-lb

$C$ = radius of arm (0.5 in.)

$I$ = $\dfrac{\pi}{64} \, (d_o^{\,4} - d_i^{\,4})$

= $\dfrac{\pi}{64} \, (1^4 - 0.8^4)$ = 0.0289

$\sigma_B$ = $\dfrac{74 \, (0.5)}{.0289}$ = 1280 psi

Figure 4 shows the yield and ultimate strengths of W 26%Re as functions of temperature. At 4500°R, W 26%Re is shown to have a yield strength of about 10,000 psi. Hence the uncooled outer tube alone has 8 times the required strength.
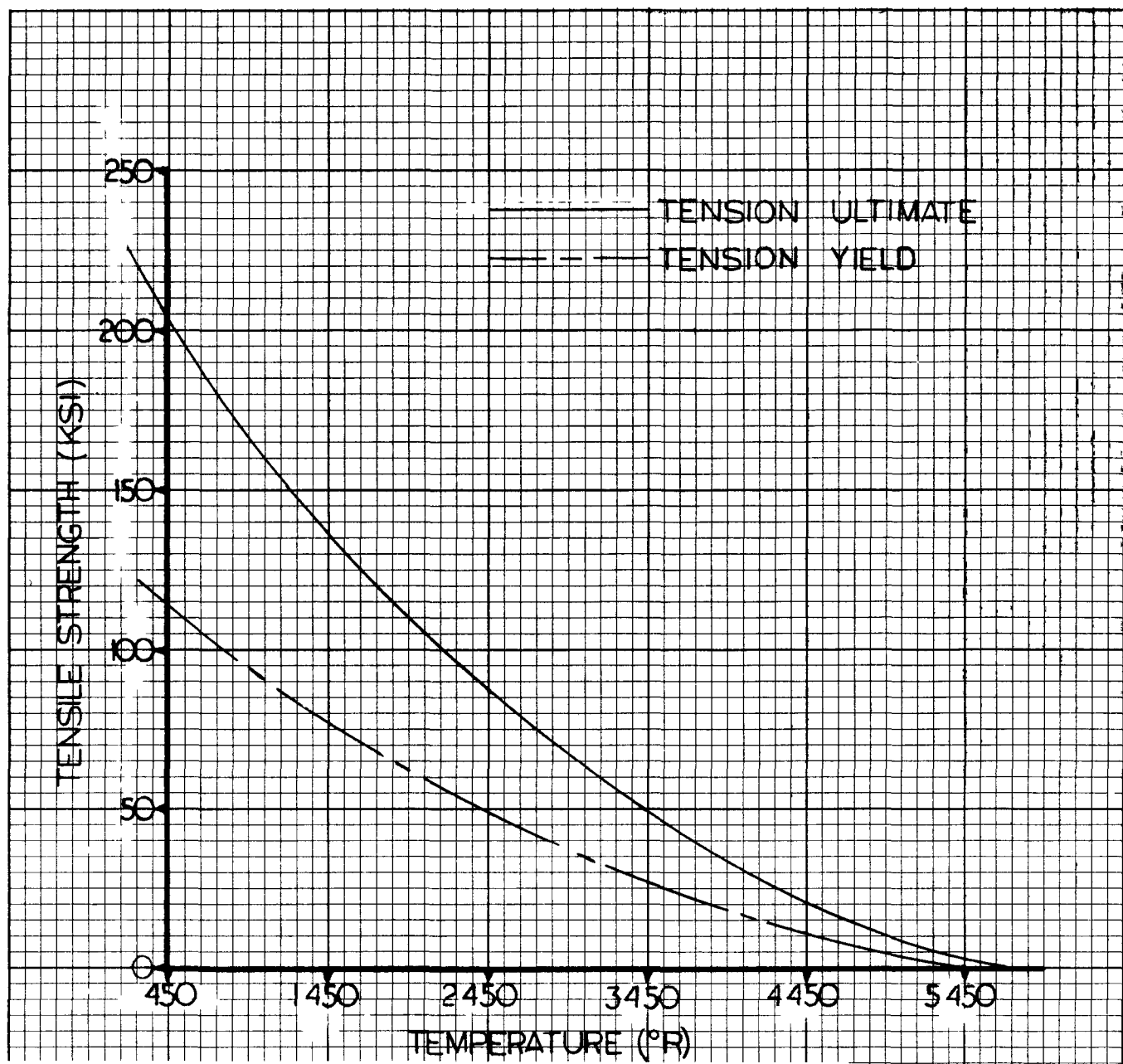
7

Figure 4

Tensile Strength VS. Temperature for Tungsten
26% Rhenium

8

Calculation of the vibrational stresses in the beam were performed taking into account the change in beam strength with temperature. Figure 5 depicts the elastic modulus - temperature relationship of tungsten 26% rhenium material. The fundamental resonant frequency of a cantilevered beam is:

$$f = \frac{3.52}{2\pi} \sqrt{\frac{EI}{\mu L^4}} \tag{3}$$

where:

$EI = E_o I_o + E_i I_i$

and $E_o$ at 4500°R from Figure 5 = $4 \times 10^6$ psi

$E_i$ at 1500°R from Figure 5 = $39 \times 10^6$ psi

$I_o = 0.0289$

$I_i = \frac{\pi}{64} (.6^4 - .4^4) = 0.0049$

$\mu$ = mass/unit length (assumed to be half void)

$$\frac{0.714 \text{ lb/in.}^3}{2 \times 32.2 \times 12} \times A = 7.27 \times 10^{-4} \text{ slugs/in.}$$

$$f = \frac{3.52}{2\pi} \sqrt{\frac{4 \times 10^6 \times 0.0289 + 39 \times 10^6 \times .0049}{7.27 \times 10^{-4} \times 13^4}} = 68 \text{ cps}$$

This 68 cps resonant frequency is for two, coupled, concentric, straight cylindrical tubes. Taking taper into account would strengthen the structure and approximately double the resonant frequency. By comparison, the nozzle vibrational acceleration frequencies on NRX/EST occurred predominantly at 33, 246, 363, 490, 643, 720, and 873 cps. The arm resonant frequency of 136 cps (2 x 68) is thus well away from the engine resonant drive frequencies.

Without resonant amplification, vibrational stresses in the arm produced by the measured 20 g accelerations of the engine are:

$$F_v = \text{Wt/in.} \times 20 = 5.6 \text{ lb/in.} \tag{4}$$

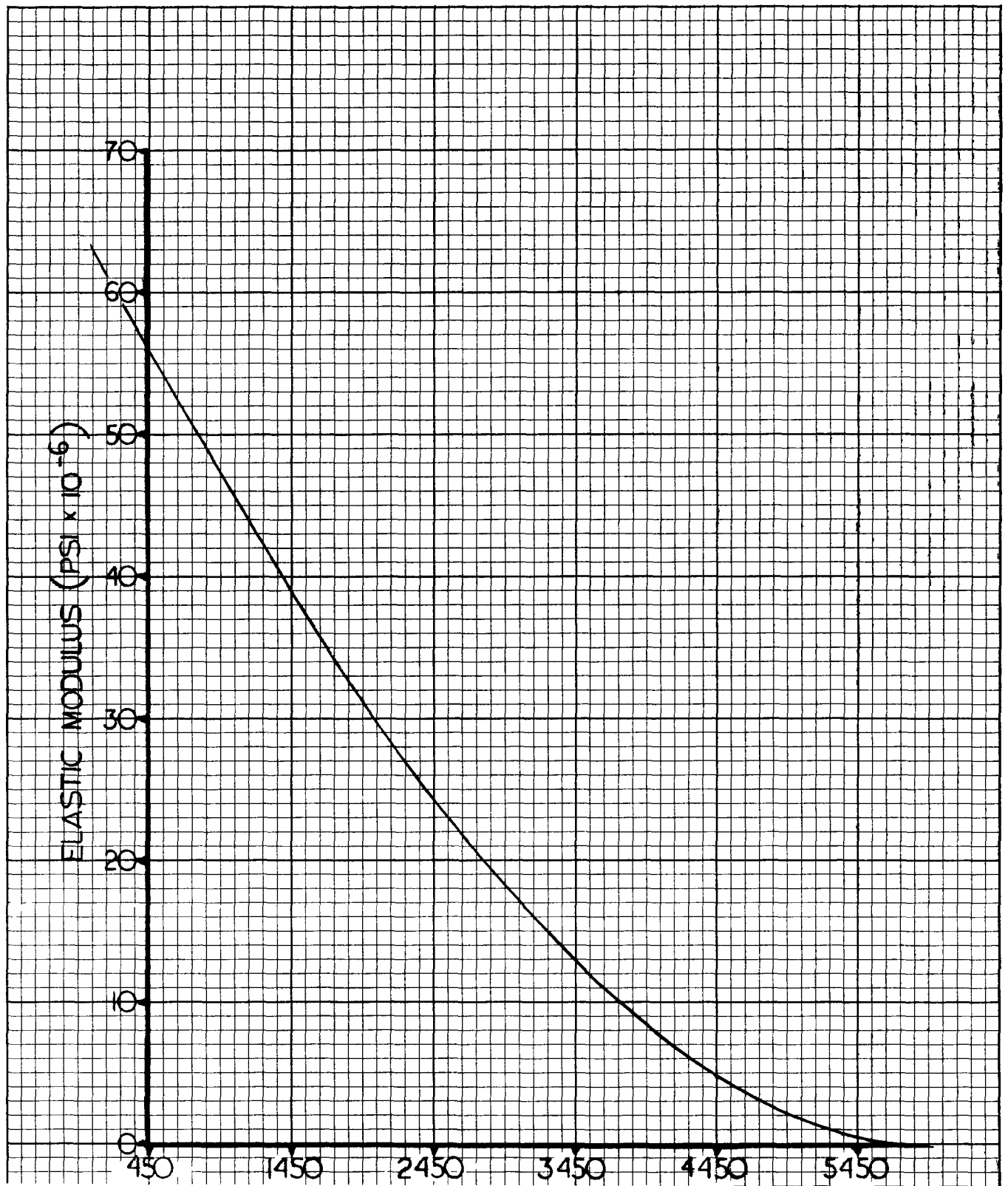$$\sigma_v = \frac{MC}{I} \tag{5}$$

Figure 5

Elastic Modulus VS. Temperature for Tungsten
26% Rhenium

10

where:

$$M = \frac{FL}{2} = \frac{(5.6 \times 13)\ 13}{2} = 473 \text{ in/lb.}$$

$$C = 0.5" \text{ radius of outer tube}$$

$$I = I_o + I_i = 0.0338 \text{ total moment}$$

$$\sigma_v = \frac{473\ (0.5)}{.0338} = 7,000 \text{ psi}$$

This simplified analysis neglects the fact that the inner 1500°R tube has a higher Young's Modulus than the 4500°R outer tube (39 x 10$^6$ compared to 4 x 10$^6$ psi). Even so, the calculated 7,000 psi stress is less than the allowed yield strength of 10,000 psi for W 26%Re at 4500°R. Tapering would provide an additional safety factor by reducing the vibrational load and strengthening the structure where stresses are highest. The net result of this simplified analysis is that the arm has adequate strength to resist the measured nozzle accelerations provided high resonance amplifications are not permitted to occur. Such amplifications can be prevented by internal dampening. Figure 6 shows the ductility of W 26%Re as a function of temperature.

As for the effectiveness of reflective foil insulation between the two tubes, the following simplified analysis considers 2 layers between 2 flat surfaces as shown in Figure 7.
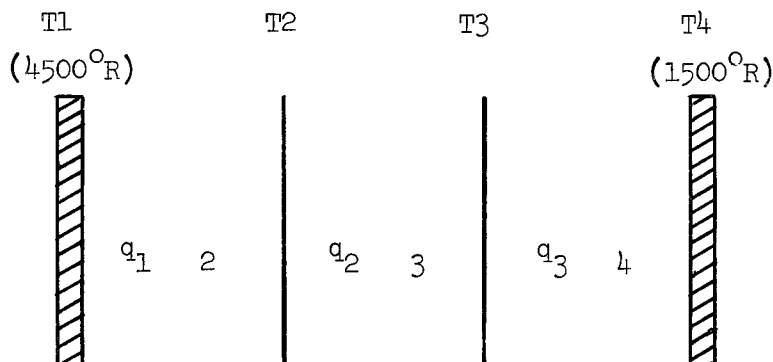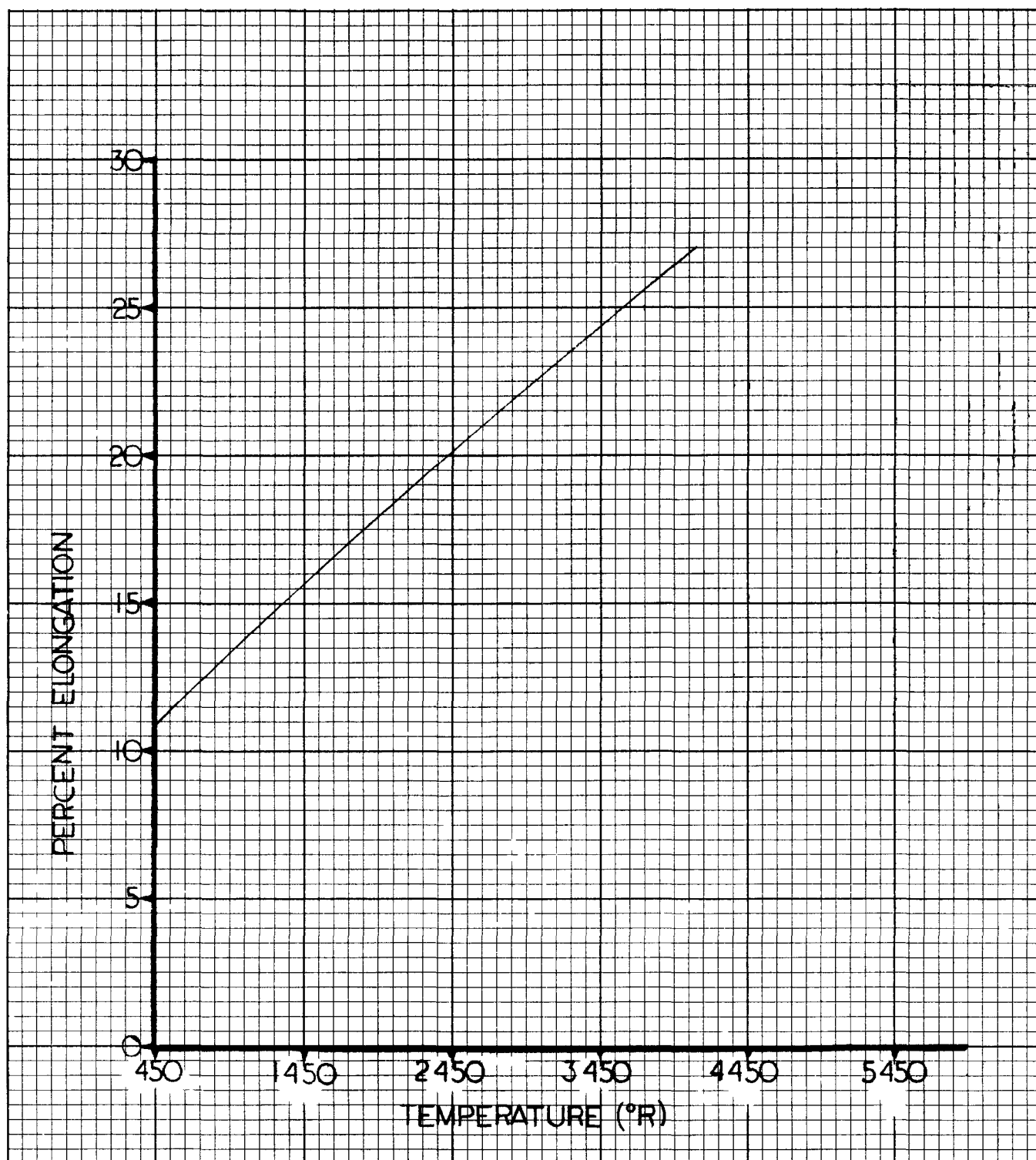


Figure 7
Insulation Between Flat Surfaces

11

Figure 6

Percent Elongation VS. Temperature for Tungsten
26% Rhenium

12

$$q_{1 \to 2} = \varepsilon \sigma \quad (T_1{}^4 - T_2{}^4) \tag{6}$$

$$q_{2 \to 3} = \varepsilon \sigma \quad (T_2{}^4 - T_3{}^4) \tag{7}$$

$$q_{3 \to 4} = \varepsilon \sigma \quad (T_4{}^4 - T_3{}^4) \tag{8}$$

at steady state,

$$q_{1 \to 2} = q_{2 \to 3} = q_{3 \to 4} \tag{9}$$

$$\varepsilon \sigma \ (T_1{}^4 - T_2{}^4) = \varepsilon \sigma \ (T_2{}^4 - T_3{}^4) \tag{10}$$

$$T_3{}^4 = 2 T_2{}^4 - T_1{}^4 \tag{11}$$

$$\varepsilon \sigma \quad (T_2{}^4 - T_3{}^4) = \varepsilon \sigma \ (T_4{}^4 - T_3{}^4) \tag{12}$$

$$T_2{}^4 = 2T_3{}^4 - T_4{}^4 \tag{13}$$

$$T_2{}^4 = 2 \ (2T_2{}^4 - T_1{}^4) - T_4{}^4 \tag{14}$$

$$3 \ T_2{}^4 = 2 \ T_1{}^4 - T_4{}^4 \tag{15}$$

By the statement of problem, $T_1 = 4500°R$ and $T_4 = 1500°R$

Substituting for $T_1$ and $T_4$,

$$3 \ T_2{}^4 = 2(4500)^4 - 1500^4 \tag{16}$$

$$T_2 = 4070°R$$

Substituting this value for $T_2$ into Equation (6) enables $q_{1\to 2}$ to be calculated,

$$q_{1\to 2} = \varepsilon \sigma \left(T_1^4 - T_2^4\right) \tag{17}$$

where:

$\varepsilon$ for tungsten = 0.3

$\sigma$ is the Stefan-Boltzmann constant ($0.173 \times 10^{-8}$ BTU/ft$^2$=hr=°R$^4$)

$$q_{1\to 2} = 0.3 \, (0.173 \times 10^{-8}) \, (4500^4 - 4070^4)$$

$$q_{1\to 2} = 70{,}000 \text{ BTU/hr-ft}^2$$

This is a small heat load which, assuming a total surface area of one square foot, could be handled by a hydrogen flow of only 20 lb/hr or about 3 grams per second.

IV.    SUMMARY

This analysis and a flutter analysis, which is not repeated here, show that the stresses and thermal load are well within the range of available materials and existing techniques. The profile probe is therefore technically feasible. Whether or not the information which can be gained is worth the $250,000.00 to build the probe and the cost of a special reactor test must be decided on the basis of the validity of the temperature data obtained during the NRX-A reactor test series.

# REFERENCES

1.  Timoshenko, S., <u>Vibration Problems in Engineering</u>, Second Edition,
    D. Van Nostrand Co., New York, 1937.

2.  Bower, R. L., <u>Stress Analysis of NRX-A2 Thermocouple Probes</u>, dated 5-17-64.

3.  <u>Tungsten-Rhenium Thermocouple Alloys</u>, Hoskins Mfg. Co., Detroit, Michigan.

4.  Materials and Fabrication Data Sheets issued by Materials and Fabrication
    Division, Solid Rocket Plant, Aerojet-General Corp., Sacramento, Calif.,
    6 Nov 1962.

5.  DRAGON Memoranda - NRX/EST Performance Evaluation, EP III, 6 March 1966.