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# ANALYTICAL INVESTIGATION OF ELECTRICALLY HEATED WIRE MESH FOR FLOWING GAS HEATERS

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## APPENDIX B: COMPUTER PROGRAM

By Geraldine E. Amling

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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## ABSTRACT

An analytical method is presented whereby an electrical resistance, flowing gas heater can be designed using wire mesh as the heating elements. By specifying the gas, the flow rate, the system pressure, the desired inlet and outlet gas temperatures, and the power supply characteristics, a compatible wire mesh heater element design can be determined. The calculations involve solving simultaneous equations for the heat generation rate, the convective heat transfer from the mesh to the gas, and the change in enthalpy of the gas at every axial position along the heater length. The method also enables the determination of the operating conditions of an existing mesh heater when used at some off-design condition or with another gas.

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## SUMMARY

An analytical method is presented whereby an electrical resistance flowing gas heater can be designed using wire mesh as the heating elements. By specifying the gas, the flow rate, the system pressure, the desired inlet and outlet gas temperatures, and the power supply characteristics, a compatible wire mesh heating element design can be determined. The calculations involve solving simultaneous equations for the heat generation rate, the convective heat transfer from the mesh to the gas, and the change in enthalpy of the gas at every axial position along the heater length. By varying the wire diameter, pitch, and size of the wire mesh, the designer is able to match the heater conditions to practically any type of power supply. The analytical method permits optimizing the heater design for compactness for specified operating conditions and limiting conditions such as maximum surface temperature or heat flux. It also enables one to determine the operating conditions of an existing mesh heater when used at an off-design condition or with another gas.

## INTRODUCTION

High temperature, out-of-pile tests of nuclear fuel elements have been conducted at the Lewis Research Center using hot flowing gas to simulate reactor operating conditions. Electrical resistance heaters were developed to heat the flowing gas. One type of heater consisted of electrically heated wire mesh through which the gas flows. The analytical investigation leading to the design of the wire mesh heating elements is the subject of this report.

The specific requirement was to design a heater utilizing an existing power supply to heat hydrogen, helium, and nitrogen gases at specified flow rates to temperatures up to $2780^{\circ}$ K. The search for a suitable heating element led to a commercially available tungsten wire mesh made of helical coils. The mesh provided the capability of obtaining electrical resistance compatible with the current and voltage ratings of available power supplies and also possessed a large surface area for heat transfer. Tungsten with its high melting point was chosen because of the high gas temperature requirement. A literature survey revealed only a limited amount of low temperature experimental heat transfer data for wire mesh. References 1 and 2 report the results of a Lewis experimental program to establish high temperature forced convection heat transfer correlations for electrically heated wire mesh.

After a heat transfer correlation was established, the task of using the mesh to design a heater capable of delivering gas at the desired flow rate and temperature remained. This involved solving simultaneous equations for the heat generation rate, the convective heat transfer from the mesh to the gas, and the change in enthalpy of the gas at every axial position along the heater length. This report investigates the variables in mesh geometry that can be utilized to achieve compact heater designs for limiting conditions such as maximum mesh surface temperature or heat flux. It defines reasonable limits within which a mesh heating element can be expected to operate satisfactorily. Two power supplies representing high and low electrical resistances are considered to illustrate how a mesh can be adapted to each. Experimental data from an operating mesh heater are presented to corroborate the analytical results.

A computer program by Geraldine E. Amling is included as appendix B.

## METHOD OF ANALYSIS

In designing an electrical resistance gas heater certain operating conditions must be specified. These include the type of gas, the gas flow rate and pressure, the initial and final gas temperature, and the current and voltage rating of the power supply. The next step then is to design a heating element that can generate and transfer heat to the flowing gas at a reasonable heat flux and at a surface temperature that would ensure a reasonable heater life. For this investigation, two different power supplies are considered. One represents a high resistance system in which the current can be maintained between 150 and 1500 amperes at voltages up to 3750 volts. The second represents a low resistance system whereby the voltage can be controlled between 10 and 50 volts at currents up to 60 000 amperes. The working gas is hydrogen at a flow rate of 0.0453 kilogram per second with an inlet temperature of $278^{\circ}$ K and a desired outlet temperature of $2780^{\circ}$ K.

### Mesh Heating Element

Tungsten wire mesh that can be electrically heated to surface temperatures greater

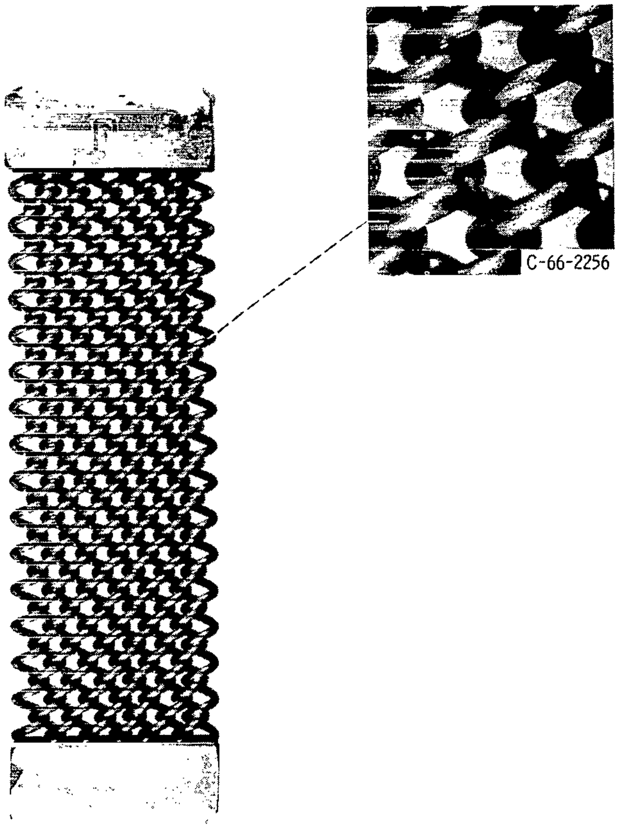


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Figure 1. - Mesh heating element.

than 2780° K becomes a unique heater element when a nonelectrically conductive fluid flows through it. The mesh provides a large heat transfer surface area per unit volume of heater element that results in high power densities and small compact heaters. The 7. 6- by 2. 5- by 0. 36-centimeter mesh shown in figure 1 has a surface area to volume ratio of 19 ($cm^2/cm^3$). The surface area of this mesh is equivalent to that of a 2. 54-centimeter-diameter tube, 16. 3 centimeters long. The chief disadvantage of a mesh element, as with any porous media, is the pressure drop restriction it places on fluid flowing through it. If relatively high pressure drops can be tolerated, then wire mesh provides many of the features necessary in a good heater element.

The wire mesh heater element considered herein is represented by figure 1. The element consists of helical coils of tungsten wire interwound into a mesh. Both ends of the coils are sandwiched between two tungsten plates each 0. 153 centimeter thick. The plates and the coil ends are heliarc welded together at both ends of the mesh. The plates provide electrical bus connections for directing current through the coils. The total current to the end plates will distribute itself into each wire coil according to the resistance of that coil. If the coolant flow distribution is uniform throughout the mesh, then the heat flux will be uniform and each coil will carry an equal amount of current. This is a necessary assumption for the analysis made herein although experimental results indicate that such is not always true. Reference 2 states that interwound mesh heating elements are susceptible to hot spotting and subsequent burnout at conditions of high heat flux with a nondissociating gas such as helium. This is believed to be caused by slight nonuniformities in the interwound geometry resulting in flow maldistribution within the mesh. If the mesh heat flux is maintained below some predetermined critical value, then the previous assumption is correct.

In order to calculate the heat transfer from a mesh it is necessary to know such geometrical parameters as surface area, current cross-sectional area, current path length, porosity, and equivalent diameter. These will be defined in terms of wire diameter, inside coil diameter (commonly referred to as mandrel diameter), coil pitch, number of parallel coils per width of mesh, and mesh length. The length S of wire in a single helical coil is given in reference 3 as

$$S = \frac{b}{p}\sqrt{\pi^2(D + d)^2 + p^2} \tag{1}$$

where b is the mesh length between end plates, p is the coil pitch, D is the inside coil diameter, and d is the wire diameter. (All symbols are defined in appendix A.) The total heat transfer surface area for N parallel coils is

$$A_s = \pi dSN \tag{2}$$

This was the area used in determining the heat transfer coefficients of references 1 and 2. The total current cross-sectional area for N parallel coils is

$$A_c = \frac{\pi d^2}{4} N \tag{3}$$

The average mesh porosity is defined as the ratio of void volume to total volume or

$$\epsilon = \frac{bw(D + 2d) - \frac{\pi d^2}{4} SN}{bw(D + 2d)} \tag{4}$$

where w is the mesh width and (D + 2d), a coil diameter, respresents the thickness in the flow direction. The equivalent diameter for a porous structure is usually defined as

$$D_e = \frac{4(\text{void volume})}{\text{surface area}} = \frac{4bw(D + 2d)\epsilon}{A_s} \tag{5}$$

The mass velocity of fluid through the element is based on an average flow area within the mesh as defined by the product of frontal area and porosity; that is,

$$G = \frac{W}{bw\epsilon} \tag{6}$$

For this analysis the mesh completely fills the flow passage so that there are no fluid by-pass effects as discussed in reference 1.

For this study, certain ground rules were established so that the mesh designs used were as compact as possible within reasonable limits for fabrication and assembly. For this reason the interwound helically coiled mesh of reference 1 was specified. The inside diameter of the coils was defined as 2d + 0.005 centimeter. The 0.005 centimeter allowed clearance for interwinding the coils. The coil pitch was defined as 3d which represents the minimum allowable pitch for interwinding. The number of coils N can be expressed in terms of mesh width and the wire and mandrel diameters according to the following empirically derived equation:

$$N = 3\left[\frac{w - (2d + D)}{2d + D}\right] \tag{7}$$

This relation states that for a width w, less a half coil width on each side, the number of interwound parallel coils is three times the number that would be available if the coils were just placed side by side. Equation (7) is an approximation which is only to be used when coil pitch and mandrel diameter are defined as done previously. It is necessary that N always be evaluated as a whole number for any actual design.

With the foregoing set of rules different meshes having the same frontal dimensions were developed merely by changing the wire diameter, the other parameters all being defined in terms of this variable. Wire diameters from 0.036 to 0.127 centimeter were used for this study. A mesh made from wires smaller than 0.036 centimeter in diameter was considered from previous operating experience to be too flimsy, while a mesh made from wires having a diameter greater than 0.127 centimeter was considered too rigid for tungsten fabrication. The geometrical properties of representative meshes are given in table I for a 6.5-square-centimeter mesh (2.54 cm wide by 2.54 cm long). Prop-

TABLE I. - MESH GEOMETRY PARAMETERS

| Wire diameter, d, cm | Mandrel diameter, D, cm | Number of parallel coils, N, coils/2.54 cm | Coil pitch, p, cm/turn | Mesh porosity, $\epsilon$ | Ratio of total surface to frontal area, $A_s/A_f$, $cm^2/cm^2$ | Ratio of total wire length to current cross-sectional area, $S/A_c$, $cm/cm^2$ | Equivalent diameter, $D_e$, cm |
|---|---|---|---|---|---|---|---|
| 0.036 | 0.076 | 49 | 0.107 | 0.56 | 7.37 | 180 | 0.045 |
| .051 | .107 | 34 | .152 | .56 | 7.17 | 127 | .066 |
| .076 | .157 | 22 | .228 | .58 | 6.84 | 87 | .105 |
| .102 | .208 | 16 | .304 | .60 | 6.52 | 68 | .151 |
| .117 | .239 | 13 | .350 | .61 | 6.34 | 60 | .181 |
| .127 | .259 | 12 | .381 | .62 | 6.21 | 56 | .204 |

erties such as surface area, equivalent diameter, and porosity relate to the heat transfer characteristics of the element while $S/A_c$ is a measure of the electrical resistance.

## Mathematical Model

A physical model of two typical mesh stages is shown in figure 2. The gas enters

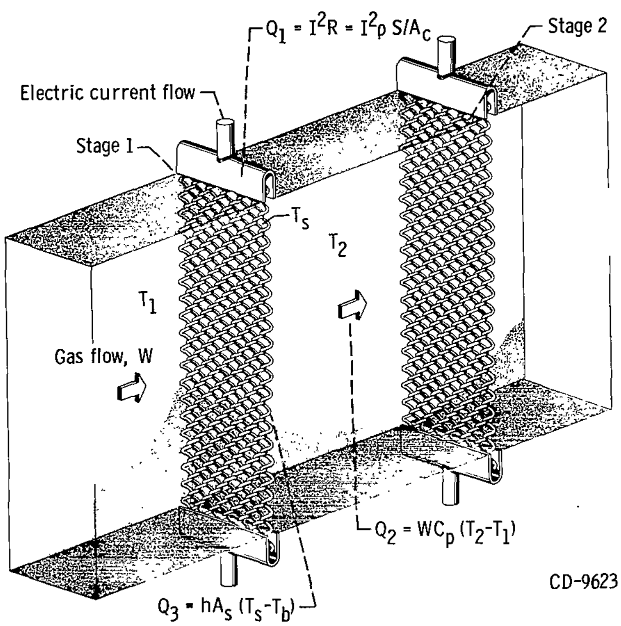



Figure 2. - Physical model.

upstream of stage 1 at temperature $T_1$. On passing through the electrically heated mesh of stage 1, heat is transferred to the gas by forced convection and exits at $T_2$; that is,

$$Q = hA_s(T_s - T_b) \tag{8}$$

where

$$T_b = \frac{T_1 + T_2}{2} \tag{9}$$

The heat transfer coefficient h for interwound mesh was experimentally determined in reference 1 to be of the following form:

$$h = C \frac{k}{D_e}\left(\frac{GD_e}{\mu}\right)^n \left(\frac{C_p\mu}{k}\right)^{0.4} \tag{10}$$

Substituting equations (9) and (10) into equation (8) gives

$$Q = C \frac{k}{D_e}\left(\frac{GD_e}{\mu}\right)^n \left(\frac{C_p\mu}{k}\right)^{0.40} A_s\left(T_s - \frac{T_1 + T_2}{2}\right) \tag{11}$$

Viscosity $\mu$ and thermal conductivity k values were obtained as functions of temperature and pressure from reference 4. Specific heat at constant pressure was evaluated at the stage inlet gas temperature using the specific heat-temperature correlation of reference 5. The electrical power input to the mesh heating element is given by the following equation in which either the voltage or current is specified depending upon the type of power supply available:

$$Q = \frac{V^2}{R} = I^2R \tag{12}$$

where

$$R = \rho \frac{S}{A_c} \tag{13}$$

Resistivity $\rho$ for most metals can usually be expressed as some function of temperature (ref. 6). Substituting equation (13) into equation (12) gives

$$Q = \frac{V^2}{\rho \frac{S}{A_c}} \tag{14}$$

The enthalpy rate increase of the gas is given by

$$Q = WC_p(T_2 - T_1) \tag{15}$$

The simultaneous solution of equations (11), (14), and (15) for a given set of conditions establishes the steady state heat transfer for the mesh-gas-power system. The three unknowns in these equations are the surface temperature $T_s$, the outlet gas temperature from stage 1 $T_2$, and the rate of heat transfer $Q$. The numerical method of reference 7, chosen to solve these equations, was adapted to a digital computer. Appendix B presents details of the method as well as the computer program used. This analysis assumes an adiabatic system.

The computer program solves these equations for stage 1 and then proceeds to the next stage using the outlet gas temperature from stage 1 as the new inlet temperature. The calculations proceed stage by stage until the desired gas temperature is obtained or until certain predetermined limits such as surface temperature, heat flux, or number of stages are exceeded. When limits are reached, it is necessary to revise the mesh element design and repeat the calculations. The variables in mesh geometry that affect the calculations are discussed in the following section.

## RESULTS AND DISCUSSION

The most compact gas heater results when the heat transfer surface operates at a constant, maximum temperature. For a tube heater the equation

$$\frac{L}{D_t} = \frac{1}{2f} \ln \frac{T_w - T_{b_1}}{T_w - T_{b_2}} \tag{16}$$

gives the minimum length to diameter ratio for the case of constant wall temperature as derived by Reynold's analogy (ref. 8). For the design flow rates of this report, a tube friction factor of 0.005 is reasonable. This results in an $L/D_t$ of about 200. To electrically heat a tube of this length and maintain a constant wall temperature requires that the current cross-sectional area vary throughout the tube length. This is very difficult and impractical to do.

The advantages of a mesh heating element are compactness and design flexibility. The latter permits the designer to more or less specify the heat generation rate or the surface temperature at any axial position along the heater length. This may be accomplished by dividing the heater length into mesh stages in which the heat generation, heat transfer, and enthalpy for each stage or group of stages is specified. Then, by varying the mesh surface area, equivalent diameter, and ratio of current path length to cross-sectional area, it is possible to approximate the desired surface temperature or heat flux conditions. Referring to table I reveals that the surface area of the meshes investigated varied about 20 percent while the equivalent diameter and $S/A_c$ varied by factors of 4.6 and 3.2, respectively.

Two design cases were investigated. One required a high electrical resistance mesh heater element, while the second required a low resistance element. Both cases specified hydrogen gas at 0.045-kilogram-per-second flow rate with an inlet temperature of $278^{\circ}$ K and a desired outlet temperature of $2780^{\circ}$ K. The system pressure was 100 atmospheres so that hydrogen dissociation was not a factor. The heater flow area was 25.8 square centimeters, and the mesh stage completely filled the flow passage cross-sectional area. The surface temperature of the mesh could not exceed $3200^{\circ}$ K, and no more than 20 mesh stages were used. There was no limitation put on heat flux, but references 1 and 2 show that their maximum experimental value was about 1.24 kilowatts per square centimeter and the operating experience of reference 9 indicates that an average heat flux of 0.62 kilowatt per square centimeter seems reasonable for an extended period of operation. The heat transfer correlation of reference 1 was used for the calculations.

## High Voltage Heater Design

For a high voltage power supply the heater elements are connected electrically in series such that the same current flows in each mesh. The heat generated in each mesh stage is therefore proportional to the $S/A_c$ ratio and the resistivity of tungsten at the temperature of the element. Figure 3 represents this type of heater. For this particular design each mesh stage is segmented into four identical panels so that a high electrical resistance can be obtained. The current flows through each of the four panels in series before it passes onto the next mesh stage. Electrical insulating material (boron nitride in this case) separates the panels so that each channel directs one-fourth of the gas flow axially through the heater. Since each mesh panel in a stage is identical and the

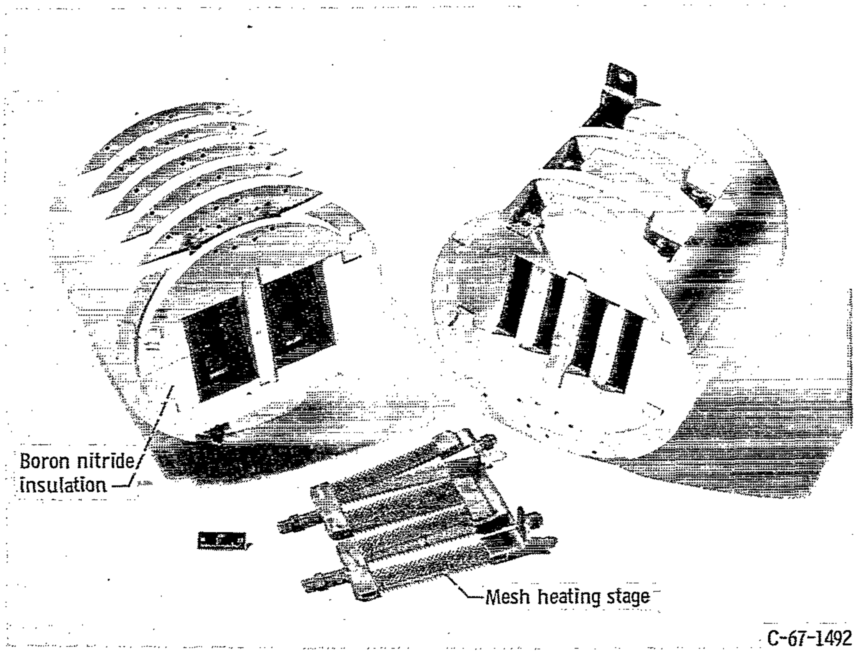



Figure 3. - Series heater.

channel flow areas are equal, the heat flux may be assumed equal throughout the stage. The mesh dimensions used were 1.27 centimeters wide by 5.08 centimeters long for each of the four flow passages in one stage for a total mesh frontal area of 25.8 square centimeters per stage.

Figure 4 shows the effect of wire diameter on heater design. The large diameter (0.127 cm) wire mesh has such a low electrical resistance that the heat flux is very small. A heater using this size wire throughout would be prohibitively long to achieve the desired gas temperature. The small diameter (0.036 cm) wire mesh has a much higher electrical resistance with about the same surface area. Consequently, the mesh operates at a higher surface temperature that increases exponentially with heater length. This is caused chiefly by the increase in tungsten resistivity with temperature. The result is a short compact heater in which the major portion of the heat is generated and transferred in the last few stages. This is not a good design because it is susceptible to mesh burnout. The combination of high surface temperature, high heat flux and small, hence weak, wires would probably result in a burnout in the event of any small maldistribution in gas flow through the mesh.

Figure 5 shows the effect of maximizing surface temperature. This was done by choosing mesh from table I that would give the highest electrical resistance for each stage without exceeding $3200^{\circ}$ K. The result is a very short, compact heater in which the heat flux is very high. Since these heat fluxes have not been demonstrated experi-

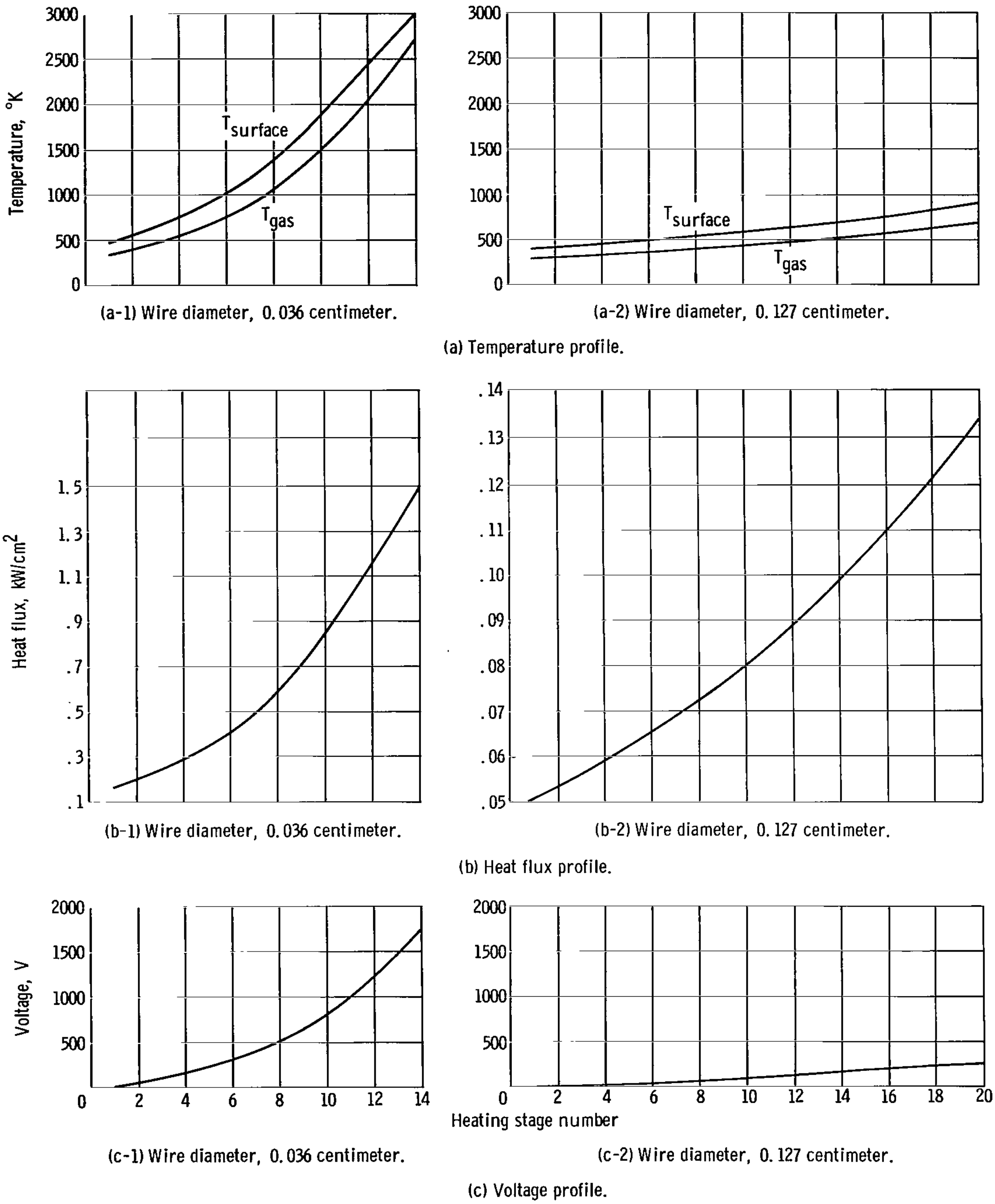
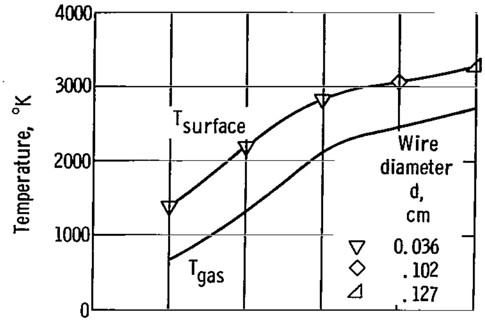
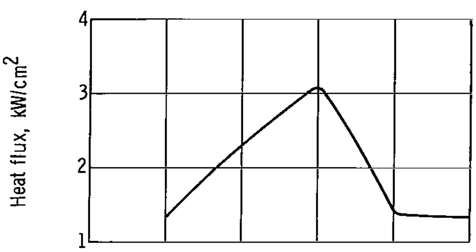


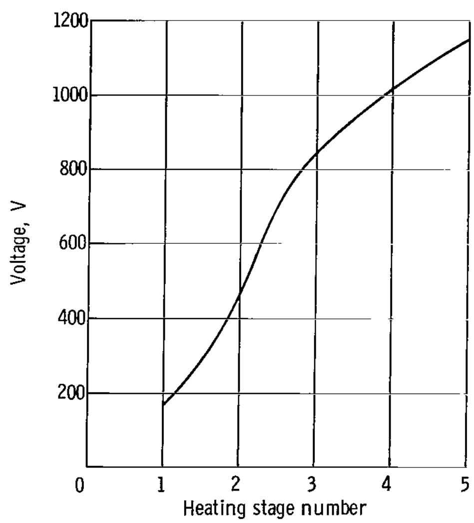

Figure 4. - Effect of wire diameter for high voltage series connected heater. Operating conditions: hydrogen gas; gas flow rate, 0.045 kilogram per second; current, 1000 amperes.




(a) Temperature profile.




(a) Heat flux profile.




(c) Voltage profile.

Figure 5. - Effect of maximizing surface temperature for high voltage series connected heater. Operating conditions: hydrogen gas; gas flow rate, 0.045 kilogram per second; current, 1500 amperes.

mentally, this does not represent a practical design. Another factor that would tend to negate this design would be the high voltage drops across each mesh. For example, the maximum voltage difference between adjacent stages of figure 5 is 682 volts. Providing sufficient insulation to prevent arcing could be a limiting problem, particularly at the peak temperatures.

From the foregoing discussion it may be concluded that a practical series heater design would consist of various meshes that would all operate at a fairly uniform heat flux. The heat flux would be high enough so that the heater dimensions will remain compact but not high enough to cause burnout due to flow maldistribution. The smaller wire diameter mesh would be used at the heater inlet, and as the operating temperature increases the wire size would increase so that the mesh operating at the highest temperature is also the strongest.

## Low Voltage Heater Design

For a constant low voltage, variable high current power supply the mesh heater elements are connected electrically in parallel. Each mesh operates with the same voltage drop but the current through each varies inversely with the resistance. Consequently, the cooler elements carry more current and operate at a higher heat flux than the hotter ones, just the opposite of the series heater.

Figure 6 represents this type of parallel heater. For this analysis the mesh panels are 5.08 centimeters by 5.08 centimeters. The power is introduced through water cooled copper tubes and buses. The heater elements are bolted onto the buses which form two sides of the square flow passage. Insulating material (boron nitride) forms the other two sides of the channel. The gas flows in series through each mesh, increasing in temperature from one stage to the next.

Figure 7 shows the effect of wire diameter on heater design. The low electrical resistance of the large diameter (0.127 cm) wire mesh makes it more compatible with this type of power supply than the small wire diameter mesh. The result is a short heater operating at a high average heat flux with the 0.127-centimeter wire as compared to a long heater operating at a relatively low average heat flux for the 0.036-centimeter wire. In comparing these designs with the series heater it becomes evident that the temperature and heat flux gradients for the parallel heaters are not as severe as those of the series heaters. This is because the parallel electrical connection has an equalizing effect. Since the resistance of each mesh increases with temperature, the current will distribute itself inversely with temperature. Consequently the cooler mesh will carry more current and the hotter ones less for the same applied voltage, thereby flattening the mesh temper-

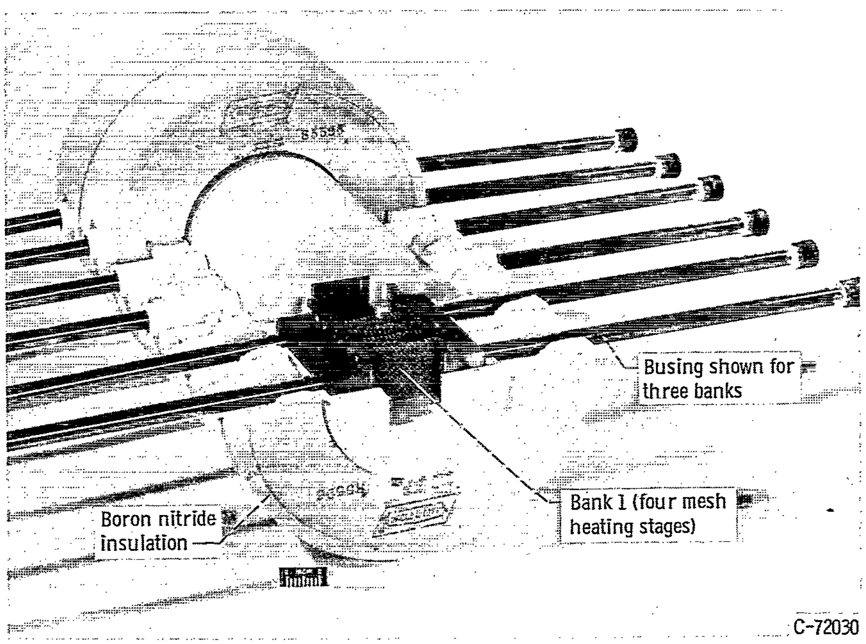
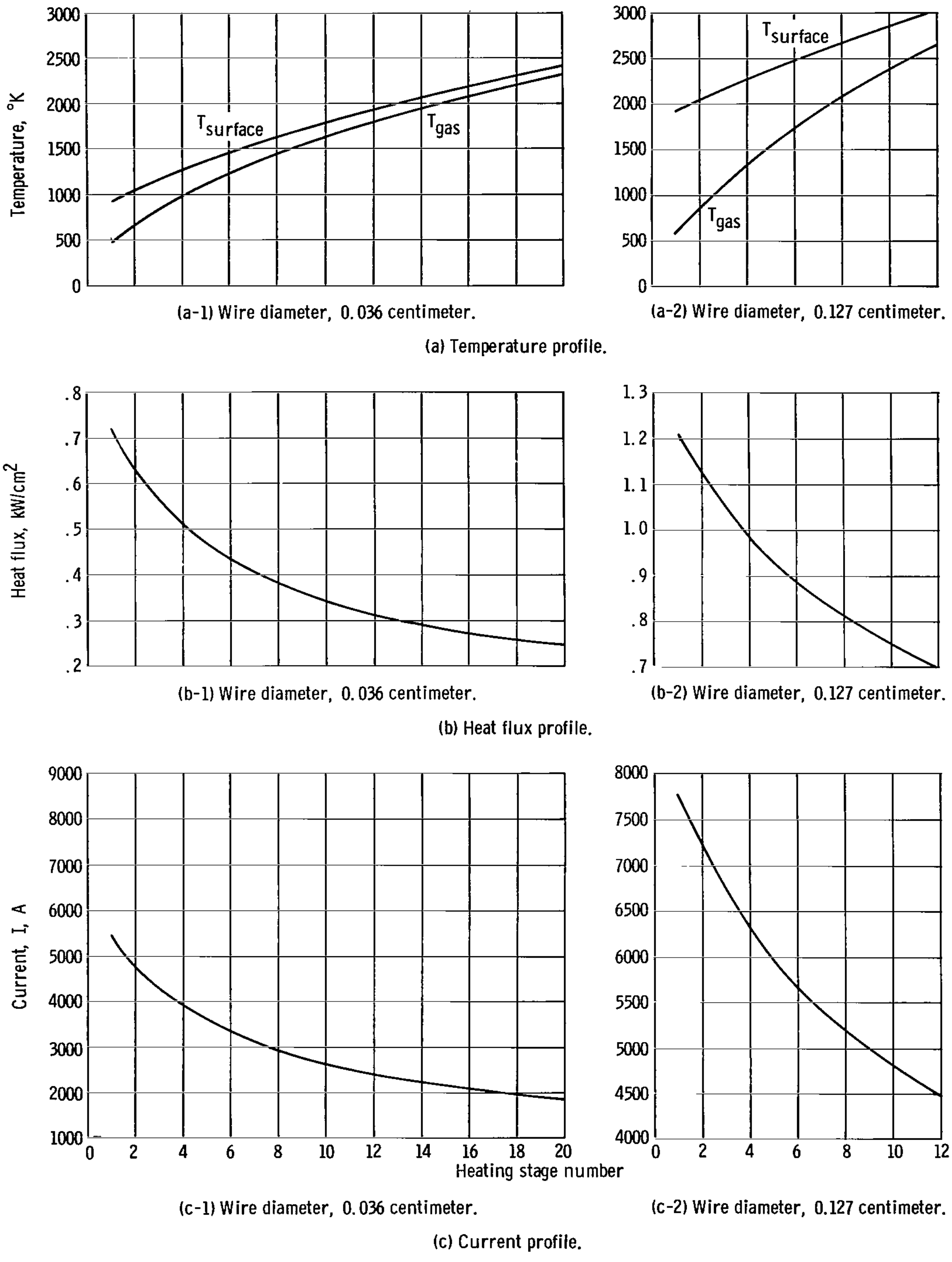



Figure 6. - Parallel heater.




(a-1) Wire diameter, 0.036 centimeter.

(a-2) Wire diameter, 0.127 centimeter.

(a) Temperature profile.

(b-1) Wire diameter, 0.036 centimeter.

(b-2) Wire diameter, 0.127 centimeter.

(b) Heat flux profile.

(c-1) Wire diameter, 0.036 centimeter.

(c-2) Wire diameter, 0.127 centimeter.

(c) Current profile.

Figure 7. - Effect of wire diameter for high current parallel connected heater. Operating conditions: hydrogen gas; gas flow rate, 0.045 kilogram per second; voltage, 25 volts.

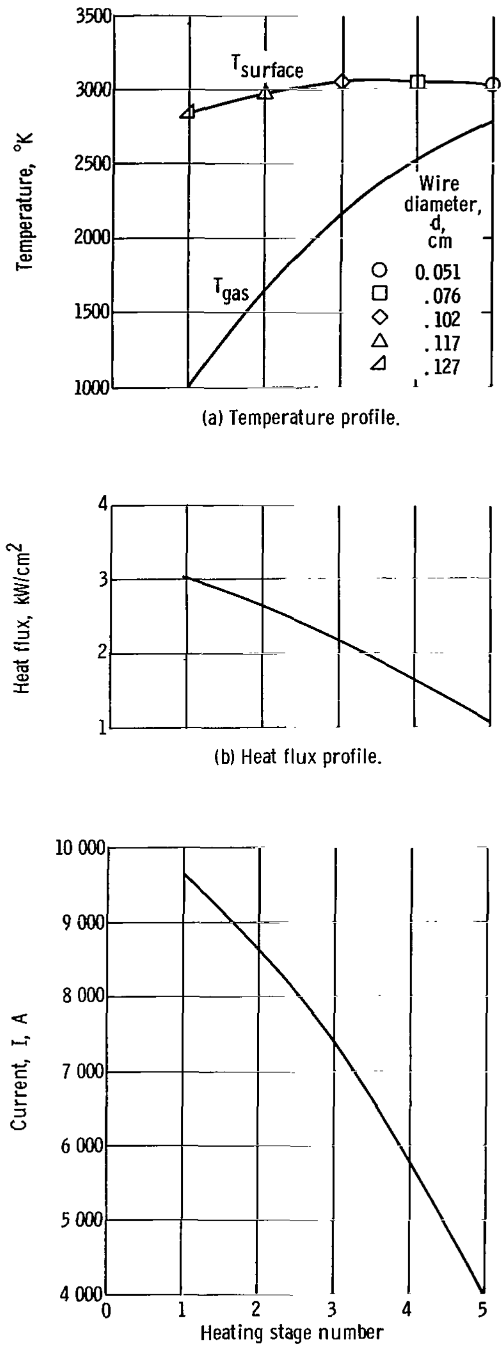



Figure 8. - Effect of maximizing surface temperature for high current parallel connected heater. Operating conditions: hydrogen gas; gas flow rate, 0.045 kilogram per second; voltage, 50 volts.

ature profile and to some extent the flux profile. Additional equalization can be achieved by varying the mesh wire diameter.

Figure 8 shows the effect of maximizing surface temperature by tailoring each mesh stage. As with the series heater, the result is a very short compact heater with the mesh operating at very high heat fluxes. In addition to being susceptible to burnout, this design would impose very large demands on the electrical busing. The necessity of delivering 40 000 amperes to these five mesh stages in a small volume of space would be a very difficult design problem.

The same general conclusion applies to the parallel heater as for the series heater. The better design is achieved by equalizing the mesh heat flux at some reasonable value and minimizing the number of mesh operating near the maximum allowable surface temperature. Reference 8 represents this type of compromise design.

## Effect of Gas

A heater designed for one gas will operate quite differently with another gas. Figure 9 compares nitrogen operation with the parallel heater designs of figure 7. The comparison is made with a nitrogen flow rate that corresponds to the same power and gas temperature rise as for the hydrogen design conditions; that is,

$$W_{N_2} = W_{H_2} \frac{C_{p,H_2}}{C_{p,N_2}} \tag{17}$$

For the same applied voltage, the mesh operate at a higher surface temperature for nitrogen than for hydrogen. This is chiefly because nitrogen has a lower thermal conductivity which causes its heat transfer coefficient to be less than that for hydrogen as seen by equation (10). By comparing thermal conductivities it is possible to predict heater behavior for gases other than the design gas. As in the previous cases, it would be necessary to operate the nitrogen heater at both a lower power level and flow rate to achieve $2780^{\circ}$ K gas. However, in order to accurately predict the flow rate and power level, it would be necessary to use the computer program described in appendix B.

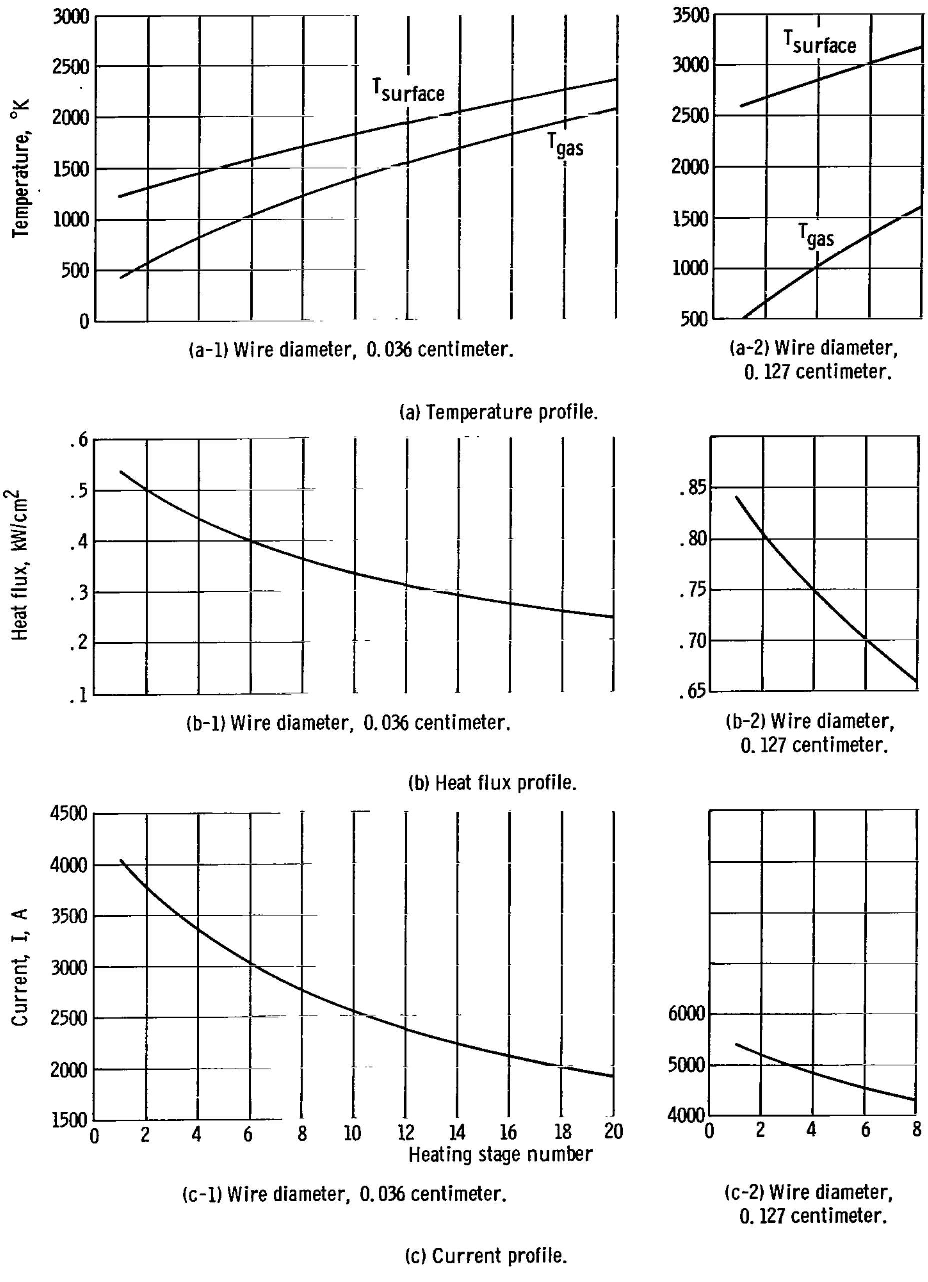



Figure 9. - Effect of nitrogen gas on operation for high current parallel connected heater. Operating conditions: nitrogen gas; gas flow rate, 0.63 kilogram per second; voltage, 25 volts.

## Experimental Results

An electrical resistance wire mesh gas heater has been designed and built with the aid of the analytical program described herein. A detailed description of this heater is presented in reference 9. The heater was originally designed for hydrogen but has been used both as a nitrogen and hydrogen heater. It consists of four banks of mesh stages similar to the three banks shown in figure 6. Each bank represents a different mesh geometry and each is powered by a separate low voltage power supply. The mesh heating elements are connected in parallel as in figure 6. Figure 10 compares experimental results for nitrogen operation with the calculated conditions from the analytical program. The calculated average surface temperatures were 1 to 9 percent higher than the experimental average values determined from resistivity measurements but the calculated and measured outlet gas temperature differed by less than 5 percent. These differences are within experimental error and do not detract from the significance of the analytical results.

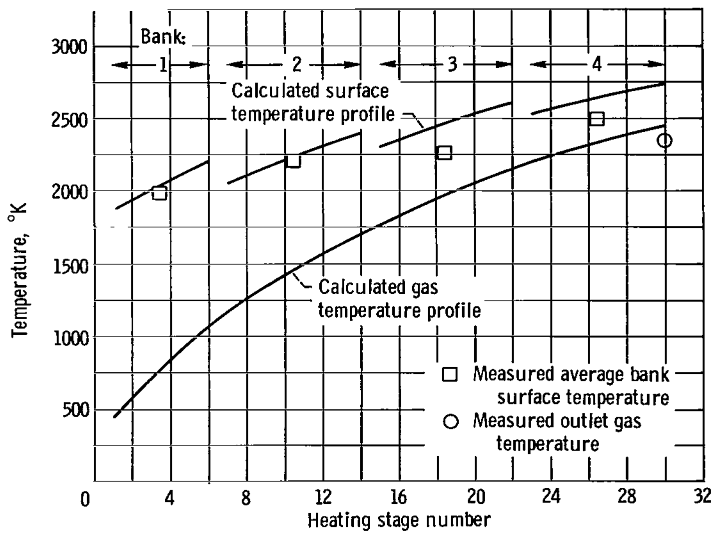



Figure 10. - Comparison of calculated to experimental results for high current parallel connected heater. Operating conditions: nitrogen gas; gas flow rate, 0.313 kilogram per second.

## SUMMARY OF RESULTS

An analytical method is presented whereby an electrical resistance gas heater can be designed using wire mesh as the heating elements. By specifying the type of gas, the flow rate, the system pressure, the desired inlet and outlet temperatures, and a power supply of sufficient capacity and known voltage and current rating, a compatible wire mesh design can be determined. The calculations involve solving simultaneous equations for the heat generation rate, the convective heat transfer from the mesh to the gas, and the change in enthalpy of the gas at every axial position along the heater length.

Wire mesh heating elements provide the designer with compactness and the flexibility to match the heater conditions to practically any type of power supply. For low voltage power supplies, the mesh are connected electrically in parallel while for high voltage power supplies, a series electrical connection is desirable. In both cases the mesh geometry parameters change with heater length to comply with the varying heat transfer conditions throughout the system. High heat fluxes and surface temperatures should be avoided since they increase the chance of mesh burnout because of slight flow maldistributions that are inherent with any porous geometry.

Given specific operating conditions and limiting conditions such as surface temperature and heat flux, the analytical method permits one to optimize the heater design for compactness. It also permits one to determine the operating conditions for the heater when it is used for a different purpose such as with another gas or at some off-design condition with the same gas. Comparing the results from the analysis with actual experimental results of an operating heater demonstrates the usefulness of this analytical method.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 23, 1968,
120-07-04-54-22.

# APPENDIX A

## SYMBOLS

$A_c$ total current cross-sectional area, $cm^2$

$A_f$ total frontal area, $cm^2$

$A_s$ total surface area, $cm^2$

b length of coil, cm

C coefficient in eq. (10)

$C_p$ specific heat of gas at constant pressure, $J/(kg)(^oK)$

D mandrel diameter, cm

$D_e$ equivalent diameter, cm

$D_t$ tube diameter, cm

d wire diameter, cm

f friction factor

G average mass velocity, $(kg/sec)/cm^2$

h average heat transfer coefficient, $J/(sec)(cm^2)(^oK)$

I current, A

k thermal conductivity of gas, $J/(cm)(sec)(^oK)$

L tube length, cm

N number of parallel coils

n exponent in eq. (10)

p coil pitch, cm/turn

Q rate of heat transfer to gas, J/sec

R electrical resistance, ohm

S total wire length of helical coil, cm

$T_b$ average bulk temperature, $^oK$

$T_s$ average surface temperature, $^oK$

$T_w$ wall temperature, $^oK$

$T_1$ stage inlet gas temperature, $^oK$

$T_2$ stage outlet gas temperature, $^oK$

V voltage, V

W gas flow rate, kg/sec

w mesh width, cm

$\epsilon$ mesh porosity

$\mu$ absolute viscosity of gas, kg/(sec)(cm)

$\rho$ resistivity of tungsten, ohm-cm

# APPENDIX B

## COMPUTER PROGRAM

by Geraldine E. Amling

The computer program presented herein was written for the purpose of designing wire mesh heating elements for an electrical resistance flowing gas heater. If the gas, the flow rate, the system pressure, the desired inlet and outlet gas temperatures, and the power supply characteristics are known, a compatible wire mesh heater element can be determined. Basically, this program solves the following three simultaneous equations having three unknowns, surface temperatures TS, outlet gas temperature T2, and the rate of heat transfer to gas Q: (English units, as defined in the section Computer Code Symbols of this appendix, are used throughout.)

$$Q = \frac{0.948\times10^{-3}\ E^2}{5.2\times10^{-6}\left(\frac{TS}{1000}\right)^{1.185} XLA\cdot XL} \tag{B1}$$

$$Q = FR\cdot\ CP(T2 - T1) \tag{B2}$$

$$Q = \frac{AR}{144}\ (ASF)\left[0.364\left(\frac{144\ FR\cdot DE}{P\cdot AR\cdot XMU}\right)^{0.542}\frac{XK}{DE}\right]\left[TS - \left(\frac{T1 + T2}{2}\right)\right] \tag{B3}$$

If current is to be specified instead of voltage, equation (B1) would be changed to

$$Q = I^2(5.2\times10^{-6})\left(\frac{TS}{1000}\right)^{1.185}(XLA)(XL) \tag{B4}$$

The resistivity of tungsten, $5.2\times10^{-6}(TS/1000)^{1.185}$, is from reference 6. Since the Prandtl number in reference 1 is nearly a constant, it was not included in the correlation presented in equation (B3). The method used to solve these equations was the Newton-Raphson iteration process (ref. 7) with Gauss double precision routine to solve the matrix. For the specific case presented, gas properties are evaluated at the mesh surface temperature; however, evaluation could be at any specified temperature with only minor changes to the program. The solution requires an initial estimate of TS, Q, and T2 in the region of convergence of the functions used. Corrections are then repeatedly calculated and added to the values until the desired accuracy is obtained. If AH, AL, and

AK are corrections to the initial estimate for Q, T2, and TS, respectively, then

$$Q1 + AH = Q'1 \tag{B5}$$

$$T2 + AL = T'2 \tag{B6}$$

$$TS + AK = T'S \tag{B7}$$

The new, more exact values are then used to calculate new corrections.

In the program, preliminary estimates of starting values are obtained by using a single iterative process to determine, within $100^{\circ}$ R, the value of TS, and the corresponding values of T2 and Q. The approximation is further refined using the subroutine MGAUSD to obtain a TS value which is within 1 percent of the true value.

Starting values used in this program are approximations, and although satisfactory results were obtained in all cases run, there is a possibility that the Newton-Raphson method will not converge for a given set of values.

Hydrogen, nitrogen, and helium properties have been curve fitted in the range of $500^{\circ}$ to $6000^{\circ}$ R. The coefficients of the curves are included in the main program as data, where the units of these properties are as follows:

Temperature, $^{\circ}$R; thermal conductivity XK, Btu/(ft)(sec)($^{\circ}$R); viscosity XMU, lb/(ft)(sec); specific heat CP, Btu/(lb)($^{\circ}$R).

If the surface temperature TS becomes negative, a print out of TS is given, computation is terminated. and program reads in a new case.

Accuracy of the approximations using Newton-Raphson technique was established by convergence of Q values at the 1.0 percent level. However, the percent error may be increased or decreased according to the user's needs. Percent error tests are made at statement number 14 and statement number 16. If specified accuracy is not achieved after 50 iterations, a print out of TS, T2, and Q is given, computation is terminated, and program reads in a new case.

## Input

The input format sheet is shown in table II. The quantities filled in are for a sample problem. The output for this sample problem will be presented subsequently.

# TABLE II. - INPUT FORMAT FOR FORTRAN COMPUTER PROGRAM

TITLE | PROJECT NUMBER | ANALYST | SHEET ____ OF ____

STATEMENT NUMBER | CONT | FORTRAN STATEMENT | IDENTIFICATION FORMAT

| CODE | NN | FORMAT |
|---|---|---|
| N2 | 4 | (A2,I2) |

| D | | E | ASF | DE | P | XLA | XIT | FORMAT |
|---|---|---|---|---|---|---|---|---|
| 30000 | -1 | 17970+2 | 55200+1 | 59400-2 | 70400+0 | 27400+3 | 60000+1 | (7E8.5) |
| 30000 | -1 | 15200+2 | 55200+1 | 59400-2 | 70400+0 | 27400+3 | 14000+2 | (7E8.5) |
| 35000 | -1 | 11720+2 | 60400+1 | 53800-2 | 65000+0 | 18700+3 | 22000+2 | (7E8.5) |
| 35000 | -1 | 98200+1 | 60400+1 | 53800-2 | 65000+0 | 18700+3 | 30000+2 | (7E8.5) |

| PCE | | AR | XL | FR | T11 | FORMAT |
|---|---|---|---|---|---|---|
| 10000 | -1 | 42500+1 | 10625+1 | 69000+0 | 50000+3 | (7E8.5) |

Instructions for preparing the input are given in table III.

TABLE III. - INSTRUCTIONS FOR PREPARING INPUT

| Card type | Number | Columns | Description of variables | |
|---|---|---|---|---|
| 1 | 1 | 1 to 2 | CODE | two-letter code for type gas (H2, HE, or N2) |
| | | 3 to 4 | NN | number of stage groups |
| 2 (constants for each stage) | NN | 1 to 8 | D | wire diameter, in. |
| | | 9 to 16 | E | voltage, V |
| | | 17 to 24 | ASF | $A_s/A_f$, total surface area/total frontal area |
| | | 25 to 31 | DE | equivalent diameter, ft |
| | | 33 to 40 | P | mesh porosity, percent |
| | | 41 to 48 | XLA | $S/A_c$, total wire length/total current cross-sectional area (for 1 sq in. of mesh) |
| | | 49 to 56 | XIT | last mesh number of each stage |
| 3 (data for one case) | 1 | 1 to 8 | PCE | percent error |
| | | 9 to 16 | AR | total frontal area, $in.^2$ |
| | | 17 to 24 | XL | mesh length/mesh width |
| | | 25 to 32 | FR | gas flow rate, lb/sec |
| | | 33 to 40 | T11 | $T_1$, stage inlet gas temperature, $^oR$ |

Card type number 2 may be repeated for a group of stages (NN). The sample problem has a total of 30 stages. The first group contains 6 stages (XIT(1) = 6.0); the second group, 8 stages (XIT(2) = 14.0); the third group, 8 stages (XIT(3) = 22.0); and the fourth group contains 8 stages (XIT(NN) = 30.0).

This program is written in FORTRAN IV and is operational on the IBM 7094-2/7044 direct-coupled system of the Lewis Research Center. A flow chart of the program is shown in figure 11.

Machine running time is approximately 2 minutes per case.

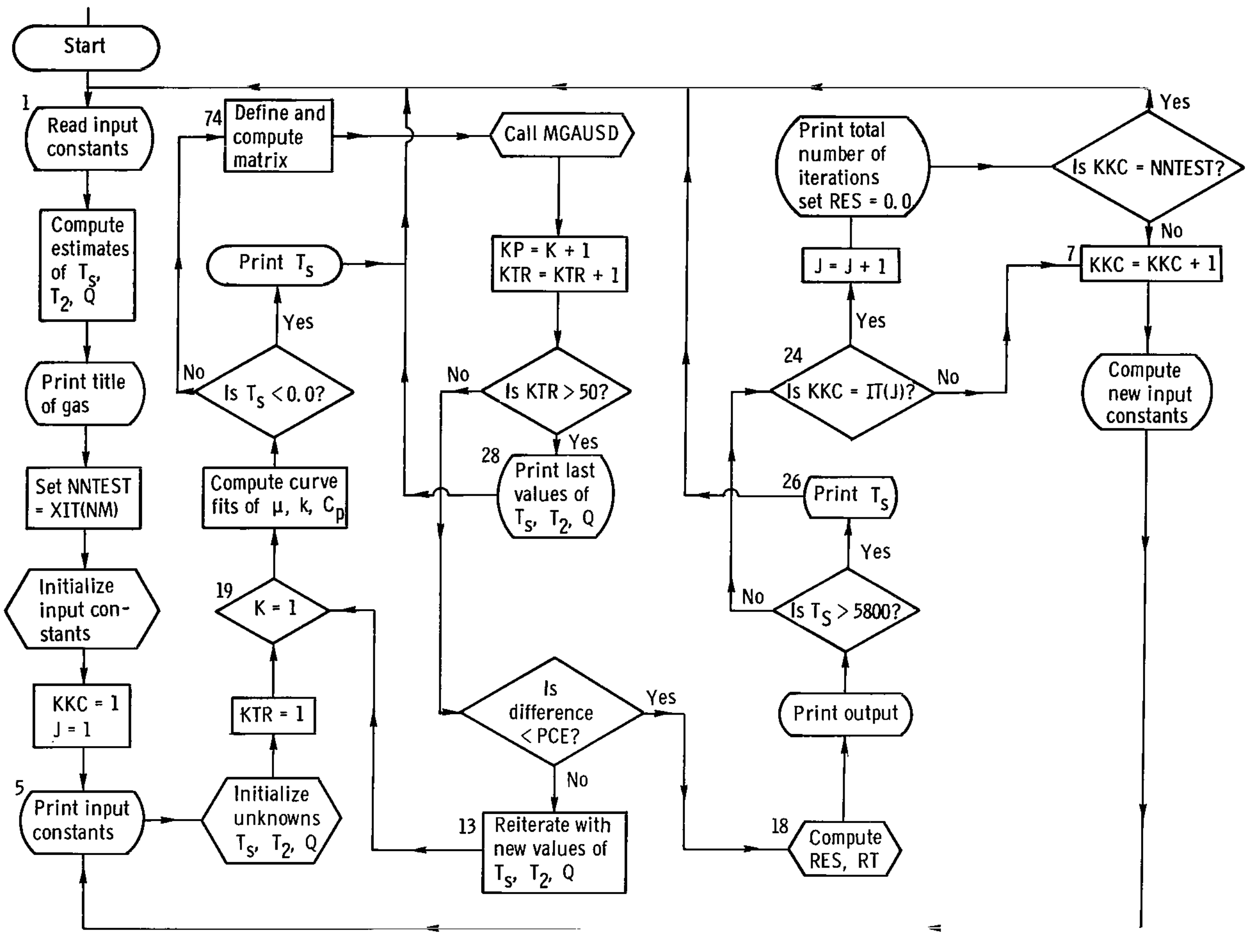



Figure 11. - Flow chart for main program HEWMAN.

## Output

Input and output are printed out for each iteration. Output consists of the following:

| | |
|---|---|
| T2 | outlet gas temperature, $^{\circ}R$ |
| TS | surface temperature, $^{\circ}R$ |
| Q | rate of heat transfer to gas, Btu/sec |
| RT | total resistance |
| IT | mesh number |

## Computer Code Symbols

| | |
|---|---|
| A1 | first equation (B1) |
| A2 | second equation (B2) |
| A3 | third equation (B3) |
| AH | correction factor for Q |
| AK | correction factor for $T_s$ |
| AL | correction factor for $T_2$ |
| AR | $A_f$, total frontal area, in.$^2$ |
| ASF | $A_s/A_f$, total surface area/total frontal area, in.$^2$/in.$^2$ |
| CODE | two letter code for element ($H_2$, He, or $N_2$) |
| CP | specific heat of gas at constant pressure, Btu/(lb)($^{\circ}R$) |
| CPA | current coefficients, $C_p$ curve, at T11 |
| CPAH | coefficients, $C_p$ curve, hydrogen |
| CPAHE | coefficients, $C_p$ curve, helium |
| CPAN | coefficients, $C_p$ curve, nitrogen |
| CPBPH | breaking points, $C_p$ curve, hydrogen |
| CPBPHE | breaking points, $C_p$ curve, helium |
| CPBPN | breaking points, $C_p$ curve, nitrogen |
| CTS | current value of $T_s$ |
| D | d, wire diameter, in. |

| | |
|---|---|
| DCP | derivative of $C_p$ at T11 |
| DE | $D_e$, equivalent diameter, ft |
| DK | derivative of k at CTS |
| DM | derivative of $\mu$ at CTS |
| DRES | reciprocal of electrical resistance at each stage, ohm |
| E | voltage, V |
| FR | W, gas flow rate, lb/sec |
| IT | XIT, mesh number |
| KKC | stage number |
| L | denotes gas used |
| NN | number of stage groups |
| NNTEST | last stage of each case |
| P | $\epsilon$, mesh porosity, percent |
| PCE | percent error |
| Q | rate of heat transfer to gas, Btu/sec |
| QQQ | initialization of Q |
| RES | 1/RT, reciprocal of electrical resistance |
| RHO | $\rho$, resistivity of tungsten, ohm-ft |
| RT | total electrical resistance, ohm |
| TB | $T_b = (T_1 + T_2)/2$, average bulk temperature, $^{o}R$ |
| TS | $T_s$, average surface temperature, $^{o}R$ |
| TS1 | initialization of $T_s$ |
| T11 | initial $T_1$, stage inlet gas temperature, $^{o}R$ |
| T2 | stage outlet gas temperature, $^{o}R$ |
| T21 | initialization of $T_2$ |
| XIT | mesh number |
| XK | $k_s$, thermal conductivity of gas, Btu/(ft)(sec)($^{o}R$) |
| XKA | current coefficients, k curve, at CTS |
| XKAH | coefficients, k curve, hydrogen |

| | |
|---|---|
| XKAHE | coefficients, k curve, helium |
| XKAN | coefficients, k curve, nitrogen |
| XKBPH | break points, k curve, hydrogen |
| XKBPHE | break points, k curve, helium |
| XKBPN | break points, k curve, nitrogen |
| XL | mesh length/mesh width |
| XLA | $S/A_c$, total wire length/total cross-sectional area (for 1 sq in. of mesh) |
| XM | $\mu$ at CTS |
| XMA | current coefficients, $\mu$ curve, at CTS |
| XMAH | coefficients, $\mu$ curve, hydrogen |
| XMAHE | coefficients, $\mu$ curve, helium |
| XMAN | coefficients, $\mu$ curve, nitrogen |
| XMBPH | break points, $\mu$ curve, hydrogen |
| XMBPHE | break points, $\mu$ curve, helium |
| XMBPN | break points, $\mu$ curve, nitrogen |
| XMU | $\mu_s$, absolute viscosity of gas, lb/(sec)(ft) |

# PROGRAM LISTING

```
                                                     - HEWMAN -          0003
                                              HEATED WIRE MESH ANALYSIS    0004
$IBFTC HEWMAN                                                         HEWM0000
C                                                                     HEWM0001
C     ANALYTICAL INVESTIGATION OF ELECTRICALLY HEATED WIRE MESH FOR FLOWHEWM0002
C     ING GAS HEATERS                                                 HEWM0003
C                                                                     HEWM0004
      DIMENSION A(20,21),ANS(20),D(35),ASF(35),DE(35),A1(2),A2(2),A3(2),HEWM0005
     1T2(2),TS(2),Q(2),RHO(2),TB(2),P(35),TTS(35),TT2(35),QQQ(35),DRES(3HEWM0006
     25),QIN(35),XLA(35),E(35),XIT(35),IT(35),TITLE(6),TEST(3),CPBPH(3),HEWM0007
     3CPAH(3,5),XKBPH(4),XKAH(4,5),XMBPH(2),XMAH(2,5),CPBPHE(1),CPAHE(1,HEWM0008
     45),XKBPHE(5),XKAHE(5,5),XMBPHE(5),XMAHE(5,5),CPBPN(3),CPAN(3,5),XKHEWM0009
     5BPN(3),XKAN(3,5),XMBPN(2),XMAN(2,5),CPA(5),XKA(5),XMA(5),QG(2)    HEWM0010
      DOUBLE PRECISION A,ANS                                          HEWM0011
      DATA TITLE/6HHYDROG,3HEN ,6HHELIUM,3H    ,6HNITROG,3HEN /       HEWM0012
      DATA TEST/2HH2,2HHE,2HN2/                                       HEWM0013
C                                                                     HEWM0014
C     CURVE FIT COEFFICIENTS                                          HEWM0015
C                                                                     HEWM0016
      DATA(CPBPH(I),(CPAH(I,J),J=1,5),I=1,3)/1600.,.60895594E-13,-.17668HEWM0017
     1624E-09,.19863776E-06,-.58512098E-04,.34488570E+01,3400.,.66711351HEWM0018
     2E-14,-.96354453E-10,.47186254E-06,-.68641899E-03,.37794389E+01,999HEWM0019
     39.,.33788127E-14,-.54401793E-10,.29369051E-06,-.40627483E-03,.3680HEWM0020
     43507E+01/                                                       HEWM0021
      DATA(XKBPH(I),(XKAH(I,J),J=1,5),I=1,4)/3240.,-.44762447E-18,.45602HEWM0022
     1272E-14,-.14757960E-10,.49758692E-07,.67895535E-05,4200.,-.2244840HEWM0023
     24E-17,.19534089E-13,-.14034318E-10,-.20252412E-06,.50636788E-03,50HEWM0024
     300.,.13421374E-17,-.79444732E-14,-.15509958E-10,.21192557E-06,-.28HEWM0025
     44865473E-03,9999.,.31153528E-18,.14254711E-14,-.79974343E-11,-.5965HEWM0026
     559474E-07,.35433426E-03/                                        HEWM0027
      DATA(XMBPH(I),(XMAH(I,J),J=1,5),I=1,2)/3240.,-.41257712E-19,.46966HEWM0028
     11670E-15,-.21505826E-11,.91476697E-08,.16277624E-05,9999.,.16330742HEWM0029
     22E-19,-.23379722E-15,.12630465E-11,.13345724E-08,.86894117E-05/  HEWM0030
      DATA(CPBPHE(I),(CPAHE(I,J),J=1,5),I=1,1)/9999.,0.0,0.0,0.0,0.0,1.2HEWM0031
     1148/                                                            HEWM0032
      DATA(XKBPHE(I),(XKAHE(I,J),J=1,5),I=1,5)/1080.,-.77890956E-17,.277HEWM0033
     1180897E-13,-.42174067E-10,.56632175E-07,.35187003E-05,1980.,-.10875HEWM0034
     22264E-18,.14469528E-14,-.75917067E-11,.35675647E-07,.85407794E-05,3HEWM0035
     33060.,.22115952E-18,-.20091672E-14,.54316253E-11,.14383910E-07,.213HEWM0036
     4499514E-04,4320.,.99375672E-18,-.14409781E-13,.77161781E-10,-.16520HEWM0037
     55692E-06,.18686650E-03,9999.,.10734377E-18,-.18710445E-14,.11455015HEWM0038
     66E-10,-.14133485E-07,.58283775E-04/                             HEWM0039
      DATA(XMBPHE(I),(XMAHE(I,J),J=1,5),I=1,5)/1080.,-.43709039E-17,.154HEWM0040
     1162508E-13,-.23183404E-10,.30621850E-07,.18674307E-05,1980.,-.49656HEWM0041
     22867E-18,.34463889E-14,-.10082049E-10,.25066486E-07,.24508796E-05,3HEWM0042
     33060.,.96140067E-19,-.80792886E-15,.17373264E-11,.99491831E-08,.996HEWM0043
     4406022E-05,4320.,.69156058E-19,-.97000761E-15,.46564625E-11,-.37171HEWM0044
     55825E-09,.21218701E-04,9999.,.45480686E-19,-.90894728E-15,.65060669HEWM0045
```

```
     6E-11,-.12201804E-07,.41129947E-04/
      DATA(CPBPN(I),(CPAN(I,J),J=1,5),I=1,3)/1200.,-.32947199E-13,.11359
     1297E-09,-.11757656E-06,.51070120E-04,.24025236,2600.,-.38860908E-1
     24,.27320397E-10,-.76523934E-07,.12770844E-03,.17811544,9999.,.3465
     39852E-15,-.52774543E-11,.27527779E-07,-.49201293E-04,.31484032/
      DATA(XKBPN(I),(XKAN(I,J),J=1,5),I=1,3)/1900.,-.42173368E-18,.22349
     1799E-14,-.44977566E-11,.90421007E-08,.35708245E-06,3800.,.48366958
     2E-19,-.55485031E-15,.20306218E-11,.16420137E-08,.38586614E-05,9999
     3.,-.58176164E-19,.10634372E-14,-.73856933E-11,.26436289E-07,-.2095
     49671E-04/
      DATA(XMBPN(I),(XMAN(I,J),J=1,5),I=1,2)/1800.,-.96213327E-18,.52937
     1485E-14,-.12553952E-10,.25208125E-07,.11203481E-05,9999.,-.1637768
     23E-19,.29989957E-15,-.23507248E-11,.15825006E-07,.41787548E-05/
C
C     READ INPUT
C
    1 READ (5,107) CODE,NN
      READ (5,100) (D(I),E(I),ASF(I),DE(I),P(I),XLA(I),XIT(I),I=1,NN)
      READ (5,100) PCE,AR,XL,FR,T11
C
C     PRINT TITLE
C
      L=0
      DO 8 I=1,6,2
      L=L+1
      IF(CODE.NE.TEST(L)) GO TO 8
      II=I+1
      WRITE (6,101) (TITLE(J),J=I,II)
      III=II/2
    8 CONTINUE
C
C     STARTING VALUES FOR NEWTON-RAPHSON
C
      TSG=1500.
      T1G=T11
      IIII=1
   97 RHOG=5.2E-6*(TSG*1.0E-3)**1.185
      QG(1)=(E(1)**2*.948E-3)/(RHOG*XLA(1)*XL)
      GO TO (90,91,92),III
   90 CPG=3.47
      GO TO 93
   91 CPG=1.248
      GO TO 93
   92 CPG=.248
   93 T2G=(QG(1)+CPG*T1G*FR)/(FR*CPG)
      TBG=(T1G+T2G)/2.0
      CTS=TSG
      GO TO 94
   95 XG1=(FR*144.0*DE(1))/(P(1)*AR*XM)
      XG2=(AR*ASF(1)*.364)/(144.0*DE(1))
```

```
      QG(2)=XG2*XK*(TSG-TBG)*XG1**.542
      IF(QG(2).GT.QG(1)) GO TO 96
      TSG=TSG+100.
      IF(TSG.LT.5800.) GO TO 97
      TSG=1500.
      T2G=600.
      QG(2)=1.0
   96 TSIN=TSG
      T2IN=T2G
      IIII=0
      DO 98 I=1,NN
      QIN(I)=QG(2)
   98 CONTINUE
      NNTEST=XIT(NN)
      RES=0.0
      T21=T2IN
      TS1=TSIN
      DO 3 I=1,NN
      QQQ(I)=QIN(I)
    3 CONTINUE
      KKC=1
      J=1
C
C     PRINT INPUT FOR EACH STAGE
C
    5 WRITE (6,102) KKC
      WRITE (6,106)
      WRITE (6,103)
      WRITE (6,104) D(J),E(J),ASF(J),DE(J),XL,P(J),AR
      WRITE (6,109)
      WRITE (6,104) FR,PCE,T11,XLA(J),T21,TS1,QQQ(J)
      WRITE (6,108)
      T1=T11
      T2(1) = T21
      TS(1) = TS1
      Q(1)= QQQ(J)
      KTR=1
   19 K=1
C
C     PROPERTIES OF ELEMENTS COMPUTED
C
      GO TO (40,41,42),III
   40 DO 43 I1=1,3
      IF(T1.GT.CPBPH(I1))GO TO 43
      DO 44 J1=1,5
      CPA(J1)=CPAH(I1,J1)
   44 CONTINUE
      GO TO 49
   43 CONTINUE
      WRITE (6,114) T1
```

```
      GO TO 1
   41 DO 45 J1=1,5
      IF(T1.GT.CPBPHE(1)) GO TO 48
      CPA(J1)=CPAHE(1,J1)
   45 CONTINUE
      GO TO 49
   48 WRITE(6,115)T1
      GO TO 1
   42 DO 46 I1=1,3
      IF(T1.GT.CPBPN(I1))GO TO 46
      DO 47 J1=1,5
      CPA(J1)=CPAN(I1,J1)
   47 CONTINUE
      GO TO 49
   46 CONTINUE
      WRITE (6,116) T1
   49 CP=0.0
      DO 50 II=1,5
      CP=CP*T1+CPA(II)
   50 CONTINUE
      CTS = TS(K)
   94 GO TO (51,52,53),III
   51 DO 55 I1=1,4
      IF(CTS.GT.XKBPH(I1)) GO TO 55
      DO 56 J1=1,5
      XKA(J1)=XKAH(I1,J1)
   56 CONTINUE
      GO TO 59
   55 CONTINUE
      WRITE(6,117) CTS
      GO TO 1
   52 DO 57 I1=1,5
      IF(CTS.GT.XKBPHE(I1)) GO TO 57
      DO 58 J1=1,5
      XKA(JI)=XKAHE(I1,J1)
   58 CONTINUE
      GO TO 59
   57 CONTINUE
      WRITE (6,118) CTS
      GO TO 1
   53 DO 60 I1=1,3
      IF(CTS.GT.XKBPN(I1)) GO TO 60
      DO 61 J1=1,5
      XKA(J1)=XKAN(I1,J1)
   61 CONTINUE
      GO TO 59
   60 CONTINUE
      WRITE(6,119) CTS
      GO TO 1
   59 XK=0.0
```

```
      DK=0.0                                                            HEWM0196
      DO 62 II=1,5                                                      HEWM0197
      XK=XK*CTS+XKA(II)                                                 HEWM0198
      IF(II.EQ.5) GO TO 62                                              HEWM0199
      DK=DK*CTS+XKA(II)*FLOAT(5-II)                                     HEWM0200
   62 CONTINUE                                                          HEWM0201
      GO TO (63,64,65),III                                              HEWM0202
   63 DO 66 I1=1,2                                                      HEWM0203
      IF(CTS.GT.XMBPH(I1)) GO TO 66                                     HEWM0204
      DO 67 J1=1,5                                                      HEWM0205
      XMA(J1)=XMAH(I1,J1)                                               HEWM0206
   67 CONTINUE                                                          HEWM0207
      GO TO 69                                                          HEWM0208
   66 CONTINUE                                                          HEWM0209
      WRITE(6,120) CTS                                                  HEWM0210
      GO TO 1                                                           HEWM0211
   64 DO 68 I1=1,5                                                      HEWM0212
      IF(CTS.GT.XMBPHE(I1)) GO TO 68                                    HEWM0213
      DO 70 J1=1,5                                                      HEWM0214
      XMA(J1)=XMAHE(I1,J1)                                              HEWM0215
   70 CONTINUE                                                          HEWM0216
      GO TO 69                                                          HEWM0217
   68 CONTINUE                                                          HEWM0218
      WRITE(6,121) CTS                                                  HEWM0219
      GO TO 1                                                           HEWM0220
   65 DO 71 I1=1,2                                                      HEWM0221
      IF(CTS.GT.XMBPN(I1)) GO TO 71                                     HEWM0222
      DO 72 J1=1,5                                                      HEWM0223
      XMA(J1)=XMAN(I1,J1)                                               HEWM0224
   72 CONTINUE                                                          HEWM0225
      GO TO 69                                                          HEWM0226
   71 CONTINUE                                                          HEWM0227
      WRITE(6,122) CTS                                                  HEWM0228
      GO TO 1                                                           HEWM0229
   69 XM=0.0                                                            HEWM0230
      DM=0.0                                                            HEWM0231
      DO 73 II=1,5                                                      HEWM0232
      XM=XM*CTS+XMA(II)                                                 HEWM0233
      IF(II.EQ.5) GO TO 73                                              HEWM0234
      DM=DM*CTS+XMA(II)*FLOAT(5-II)                                     HEWM0235
   73 CONTINUE                                                          HEWM0236
      IF(IIII.EQ.1) GO TO 95                                            HEWM0237
      IF(TS(K).GT.0.0) GO TO 74                                         HEWM0238
      WRITE(6,123) TS(K)                                                HEWM0239
      GO TO 1                                                           HEWM0240
C                                                                       HEWM0241
C     SET UP MATRIX OF COEFFICIENTS                                     HEWM0242
C                                                                       HEWM0243
   74 RHO(K) = 5.2E-6*(TS(K)/1000.0)**1.185                             HEWM0244
      A1(K)=((E(J)**2*.948E-3)/(RHO(K)*XLA(J)*XL))-Q(K)                 HEWM0245
```

```
      A2(K) = FR*CP*(T2(K)-T1)-Q(K)                                      HEWM0246
      TB(K) = (T1+T2(K))/2.0                                             HEWM0247
      XCON1=(FR*144.*DE(J))/(P(J)*AR*XM)                                 HEWM0248
      XCON2=(AR*ASF(J)*.364)/(144.*DE(J))                                HEWM0249
      A3(K)=(XCON2*XK*(TS(K)-TB(K))*XCON1**.542)-Q(K)                    HEWM0250
      DA=XCON2*(XK+DK*(TS(K)-TB(K)))                                     HEWM0251
      DB=(.542/(XCON1**.458))*((-XCON1*DM)/XM)                           HEWM0252
      DO 30 II=1,3                                                       HEWM0253
      DO 30 M=1,4                                                        HEWM0254
      A(II,M)=0.0D0                                                      HEWM0255
   30 CONTINUE                                                           HEWM0256
      A(1,1) = -1.0                                                      HEWM0257
      A(2,1) = -1.0                                                      HEWM0258
      A(3,1) = -1.0                                                      HEWM0259
      A(1,2) = (-1.185*E(J)**2*.948E-3*(1.0/TS(K)**2.185)*1000.0**1.185)HEWM0260
     2/(5.2E-6*XLA(J)*XL)                                                HEWM0261
      A(2,2) = 0.0                                                       HEWM0262
      A(3,2) = XCON2*XK*(TS(K)-TB(K))*DB+XCON1**.542*DA                  HEWM0263
      A(1,3) = 0.0                                                       HEWM0264
      A(2,3) = FR*CP                                                     HEWM0265
      A(3,3) = -.5*XCON2*XK*XCON1**.542                                  HEWM0266
      A(1,4) = -A1(K)                                                    HEWM0267
      A(2,4) = -A2(K)                                                    HEWM0268
      A(3,4) = -A3(K)                                                    HEWM0269
      CALL MGAUSD(A,3,ANS)                                               HEWM0270
      AH=ANS(1)                                                          HEWM0271
      AK = ANS(2)                                                        HEWM0272
      AL = ANS(3)                                                        HEWM0273
      KP=K+1                                                             HEWM0274
      Q(KP)=Q(K)+AH                                                      HEWM0275
      TS(KP)=TS(K)+AK                                                    HEWM0276
      T2(KP)=T2(K)+AL                                                    HEWM0277
      TESTQ=ABS((Q(1)-Q(2))/Q(2))                                        HEWM0278
      TESTTS=ABS((TS(1)-TS(2))/TS(2))                                    HEWM0279
      TESTT2=ABS((T2(1)-T2(2))/T2(2))                                    HEWM0280
      KTR=KTR+1                                                          HEWM0281
      IF(KTR.GT.50) GO TO 28                                             HEWM0282
      IF(TESTQ-PCE) 14,13,13                                             HEWM0283
   14 IF(TESTTS-PCE) 16,13,13                                            HEWM0284
   16 IF(TESTT2-PCE) 18,13,13                                            HEWM0285
   13 Q(1)=Q(2)                                                          HEWM0286
      TS(1)=TS(2)                                                        HEWM0287
      T2(1)=T2(2)                                                        HEWM0288
      GO TO 19                                                           HEWM0289
   18 TTS(J)=TS(2)                                                       HEWM0290
      TT2(J)=T2(2)                                                       HEWM0291
      QQQ(J)=Q(2)                                                        HEWM0292
      RHO(2)=5.2E-6*(TS(2)/1000.0)**1.185                                HEWM0293
      DRES(J)=1.0/(XLA(J)*RHO(2)*XL)                                     HEWM0294
      RES=RES+DRES(J)                                                    HEWM0295
```

```
      RT=1.0/RES
C
C     PRINT OUTPUT FOR EACH STAGE
C
      WRITE (6,105)
      WRITE (6,104) T2(2),TS(2),Q(2),RT
      IF(TTS(J).LE.5800.0) GO TO 24
   26 WRITE(6,111)
      GO TO 1
   24 IT(J)=XIT(J)
      IF(KKC.NE.IT(J)) GO TO 7
      WRITE(6,112) IT(J)
      WRITE(6,126)
      RES=0.0
      IF(IT(J).EQ.NNTEST) GO TO 1
    7 KKC=KKC+1
      TS1=TTS(J)
      T21=TT2(J)+(TT2(J)-T1)
      T11=TT2(J)
      IF(KKC.GT.IT(J))  J=J+1
      GO TO 5
   28 WRITE (6,113)
      WRITE(6,124) TS(1),TS(2),T2(1),T2(2),Q(1),Q(2)
      WRITE(6,125) TESTTS,TESTT2,TESTQ
      GO TO 1
C
C     FORMAT STATEMENTS
C
  100 FORMAT(7E8.5)
  101 FORMAT(84H1ANALYTICAL INVESTIGATION OF ELECTRICALLY HEATED WIRE ME
     1SH FOR FLOWING GAS HEATERS, ,A6,A3,10HPROPERTIES)
  102 FORMAT(6H0STAGE,I3)
  103 FORMAT(1H0,7X,1HD,15X,1HE,13X,4H ASF,13X,2HDE,14X,2HXL,14X,2H P,14
     1X,2HAR)
  104 FORMAT(8E16.8)
  105 FORMAT(1H0,7X,2HT2,14X,2HTS,14X,2H Q,14X,2HRT)
  106 FORMAT (6H0INPUT)
  107 FORMAT(A2,I2)
  108 FORMAT (7H0OUTPUT)
  109 FORMAT(1H0,6X,2HFR,13X,3HPCE,13X,3HT11,13X,3HXLA,12X,8HT2 GUESS,7X
     1,8HTS GUESS,9X,7HQ GUESS)
  111 FORMAT(55H0TEMPERATURE EXCEEDS 5800 DEGREES RANKINE                )
  112 FORMAT(6H0XIT =,I3)
  113 FORMAT(55H0ITERATIONS EXCEED 50                                    )
  114 FORMAT(13H0ARGUMENT T1=,E16.8,45H EXCEEDS LIMIT OF T VS. CP CURVE
     1FOR HYDROGEN)
  115 FORMAT(13H0ARGUMENT T1=,E16.8,45H EXCEEDS LIMIT OF T VS. CP CURVE
     1FOR HELIUM  )
  116 FORMAT(13H0ARGUMENT T1=,E16.8,45H EXCEEDS LIMIT OF T VS. CP CURVE
     1FOR NITROGEN)
```

```
  117 FORMAT(13H0ARGUMENT TS=,E16.8,45H EXCEEDS LIMIT OF T VS. K CURVE FHEWM0346
     1OR HYDROGEN )                                                      HEWM0347
  118 FORMAT(13H0ARGUMENT TS=,E16.8,45H EXCEEDS LIMIT OF T VS. K CURVE FHEWM0348
     1OR HELIUM   )                                                      HEWM0349
  119 FORMAT(13H0ARGUMENT TS=,E16.8,45H EXCEEDS LIMIT OF T VS. K CURVE FHEWM0350
     1OR NITROGEN )                                                      HEWM0351
  120 FORMAT(13H0ARGUMENT TS=,E16.8,45H EXCEEDS LIMIT OF T VS. MU CURVE HEWM0352
     1FOR HYDROGEN)                                                      HEWM0353
  121 FORMAT(13H0ARGUMENT TS=,E16.8,45H EXCEEDS LIMIT OF T VS. MU CURVE HEWM0354
     1FOR HELIUM  )                                                      HEWM0355
  122 FORMAT(13H0ARGUMENT TS=,E16.8,45H EXCEEDS LIMIT OF T VS. MU CURVE HEWM0356
     1FOR NITROGEN)                                                      HEWM0357
  123 FORMAT(36H0PROGRAM CANNOT PROCEED         TS =,E16.8)              HEWM0358
  124 FORMAT(8H0TS(1) =,E14.6,8H TS(2) =,E14.6,8H T2(1) =,E14.6,8H T2(2)HEWM0359
     1 =,E14.6,7H Q(1) =,E14.6,7H Q(2) =,E14.6)                          HEWM0360
  125 FORMAT(9H0TESTTS =,E14.6,9H TESTT2 =,E14.6,8H TESTQ =,E14.6)       HEWM0361
  126 FORMAT(1HL)                                                        HEWM0362
      END                                                                HEWM0363
$IBFTC MGAUS                                                             MGAU0000
      SUBROUTINE MGAUSD(A,N,ANS)                                         MGAU0001
C     THIS SUBROUTINE SOLVES FROM 2-6                                    MGAU0002
C     SIMULTANEOUS LINEAR EQUATIONS                                      MGAU0003
      DIMENSION A(20,21),ANS(20)                                         MGAU0004
      DOUBLE PRECISION  A      , ANS                                     MGAU0005
      DO 1 I=1,N                                                         MGAU0006
    1 ANS(I)=0.0D0                                                       MGAU0007
      DO 10 I=1,N                                                        MGAU0008
      DO 9 J=I,N                                                         MGAU0009
      A(I,J+1)=A(I,J+1)/A(I,I)                                           MGAU0010
      IF(I-N) 9,20,9                                                     MGAU0011
    9 CONTINUE                                                           MGAU0012
      K=I+1                                                              MGAU0013
      DO 8 II=K,N                                                        MGAU0014
      DO 8 JJ=I,N                                                        MGAU0015
    8 A(II,JJ+1)=-A(II,I)*A(I,JJ+1)+A(II,JJ+1)                           MGAU0016
   10 CONTINUE                                                           MGAU0017
   20 ANS(N)=A(I,J+1)                                                    MGAU0018
      IF(N-1)31,30,31                                                    MGAU0019
   30 RETURN                                                             MGAU0020
   31 J=N-1                                                              MGAU0021
      II=J                                                               MGAU0022
      DO 11 I=1,II                                                       MGAU0023
      K=J+1                                                              MGAU0024
      DO 12 M=1,I                                                        MGAU0025
      ANS(J)=ANS(K)*A(J,K)+ANS(J)                                        MGAU0026
   12 K=K+1                                                              MGAU0027
      ANS(J)=A(J,K)-ANS(J)                                               MGAU0028
   11 J=J-1                                                              MGAU0029
      RETURN                                                             MGAU0030
      END                                                                MGAU0031
```

ANALYTICAL INVESTIGATION OF ELECTRICALLY HEATED WIRE MESH FOR FLOWING GAS HEATERS, NITROGEN PROPERTIES

STAGE 1

INPUT

| D | E | ASF | CE | XL | P | AR |
|---|---|---|---|---|---|---|
| C.3CCC00C0E-C1 | C.1757CCC0E C2 | C.552C0C00E 01 | 0.59400000E-02 | 0.10625000E C1 | C.7C4CCCCCE 00 | C.42500000E 01 |

| FR | PCE | T11 | XLA | T2 GUESS | TS GUESS | Q GUESS |
|---|---|---|---|---|---|---|
| C.65CCCCCCE C0 | C.1CCCCC00E-C1 | C.5CCCC0C0E 03 | 0.27400000E 03 | 0.77715221E C3 | C.34CCCCCCE 04 | 0.48352277E 02 |

OUTPUT

| T2 | TS | Q | RT |
|---|---|---|---|
| 0.77879018E C3 | C.3377C085E C4 | C.47809145E 02 | 0.64031472E-02 |

STAGE 2

INPUT

| D | E | ASF | CE | XL | P | AR |
|---|---|---|---|---|---|---|
| C.3CCC0000E-C1 | 0.1757CCCCE C2 | 0.552C0C00E C1 | 0.59400000E-02 | 0.10625000E C1 | 0.7C4C0CC0E 00 | C.42500000E 01 |

| FR | PCE | T11 | XLA | T2 GUESS | TS GUESS | Q GUESS |
|---|---|---|---|---|---|---|
| C.65CC00CCE CC | C.1CCCCCC0E-C1 | C.77879018E 03 | 0.27400000E 03 | 0.10575804E C4 | C.3377CC85E C4 | C.47809145E 02 |

OUTPUT

| T2 | TS | Q | RT |
|---|---|---|---|
| 0.10441955E C4 | 0.34557519E C4 | C.45828684E 02 | 0.32692872E-02 |

# REFERENCES


1. Siegel, Byron L.; Maag, William L.; Slaby, Jack G.; and Mattson, William F.: Heat-Transfer and Pressure Drop Correlations for Hydrogen and Nitrogen Flowing Through Tungsten Wire Mesh at Temperatures to 5200° R. NASA TN D-2924, 1965.
2. Maag, William L.; and Mattson, William F.: Forced-Convection Heat-Transfer Correlations for Gases Flowing Through Wire Matrices at Surface Temperatures to 5500° R. NASA TN D-3956, 1967.
3. Eshbach, Ovid W., ed.: Handbook of Engineering Fundamental. Second ed., John Wiley and Sons, Inc., 1952, Sec. 2-57.
4. Grier, Norman T.: Calculation of Transport Properties and Heat-Transfer Parameters of Dissociating Hydrogen. NASA TN D-1406, 1962.
5. Svehla, Roger A.: Estimated Viscosities and Thermal Conductivities of Gases at High Temperatures. NASA TR R-132, 1962.
6. Weast, Robert C., ed.: Handbook of Chemistry and Physics. 37th ed., Chemical Rubber Publishing Co., 1955, p. 2360.
7. Scarborough, James B.: Numerical Mathematical Analysis. Third ed., The Johns Hopkins Press, 1955.
8. Knudsen, James G.; and Katz, Donald L.: Fluid Dynamics and Heat Transfer. McGraw-Hill Book Co., Inc., 1958.
9. Siegel, Byron L.: Design and Operation of a High-Temperature Tungsten-Mesh Gas Heater. NASA TM X-1466, 1967.

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