Optimization of Cooled Shields in Insulations

J. C. Chato
J. M. Khodadadi
J. Seyed-Yagoobi

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Optimization of Cooled Shields in Insulations

J. C. Chato
J. M. Khodadadi
J. Seyed-Yagoobi
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
Urbana, IL

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NASA
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Ames Research Center
Moffett Field, California 94035
ABSTRACT

A relatively simple method has been developed to optimize the location, temperature, and heat dissipation rate of each cooled shield inside an insulation layer. The method is based on the minimization of the entropy production rate which is proportional to the heat leak across the insulation. The results show that the maximum number of shields to be used in most practical applications is three. However, cooled shields are useful only at low values of the overall, cold wall to hot wall absolute temperature ratio. The performance of the insulation system is relatively insensitive to deviations from the optimum values of temperature and location of the cooling shields.

Design curves are presented for rapid estimates of the locations and temperatures of cooling shields in various types of insulations, and an equation is given for calculating the cooling loads for the shields.
### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area of heat flow, (m^2)</td>
</tr>
<tr>
<td>(C_p)</td>
<td>Specific heat of the boiloff vapor, (kJ/kg\cdot K)</td>
</tr>
<tr>
<td>D</td>
<td>Functional defined by Eq. (14)</td>
</tr>
<tr>
<td>F</td>
<td>Functional defined by Eq. (13)</td>
</tr>
<tr>
<td>(h_{fg})</td>
<td>Latent heat of vaporization of the boiloff liquid, (kJ/kg)</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity, (W/m\cdot K); with subscripts, coefficients in Eq. (1)</td>
</tr>
<tr>
<td>L</td>
<td>Overall thickness of insulation, (m^*)</td>
</tr>
<tr>
<td>(m, n)</td>
<td>Exponents in conductivity function, Eq. (1)</td>
</tr>
<tr>
<td>P</td>
<td>(T_S/T_C), temperature ratio</td>
</tr>
<tr>
<td>q</td>
<td>Heat flow rate, (W)</td>
</tr>
<tr>
<td>R</td>
<td>(T_C/T_H), overall temperature ratio</td>
</tr>
<tr>
<td>s</td>
<td>Dimensionless entropy production rate defined by Eq. (5)</td>
</tr>
<tr>
<td>S</td>
<td>Entropy production rate, (W/K)</td>
</tr>
<tr>
<td>t</td>
<td>Thickness between walls with single shield between, (m^*)</td>
</tr>
<tr>
<td>T</td>
<td>Absolute temperature, (K)</td>
</tr>
<tr>
<td>x</td>
<td>Distance from cold wall, (m^*)</td>
</tr>
<tr>
<td>x'</td>
<td>Distance from cold wall in a multi-shield configuration, (m^*)</td>
</tr>
<tr>
<td>X</td>
<td>(x/t), dimensionless distance*</td>
</tr>
<tr>
<td>X'</td>
<td>(x'/L), dimensionless distance*</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>Defined by Eq. (8)</td>
</tr>
</tbody>
</table>

#### Subscripts

- C | Cold wall
- H | Hot wall
- i | \(i\)-th shield
- \(\text{min}\) | Minimum
- \(\text{opt}\) | Optimum
- S | Shield

\*For systems with single shield \(L = t, x = x', X = X'\)
INTRODUCTION

The search for the ultimate, energy efficient insulation system has led in the past few years to a fascinating rediscovery and application of some fundamental concepts of thermodynamics: specifically, the second law and the use of entropy production rates and availability (or exergy) for design optimization purposes. The classical approach has been to minimize the heat flow between surfaces at different temperatures.

The concept of a single vapor-cooled shield in an insulation has been treated theoretically as far back as 1959 in Scott's classic textbook on cryogenics [1] and designs employing them were described not much later [2]. Paivanas, et al., obtained a patent [3] and later reported on the use of uniformly spaced multiple shields which were cooled by the boil-off from the insulated dewar [4]. Eyssa and Okasha [5] considered only radiative heat exchange between shields and minimized the total refrigeration power required. Hilal, et al., [6,7] used a similar minimization of refrigeration power as the design basis. Related works were reported by Bejan, et al., [8-11].

Recently, Bejan [12] proposed a new point of view, based on the second law of thermodynamics, which considers thermal insulations as dissipators of useful mechanical power (i.e. the availability or exergy) or, alternately, as generators of irreversibility or entropy. Thus, in this method, optimization of an insulation corresponds to minimization of either the entropy production rate or the irreversibility, or the decrease of availability. Various applications of this concept to insulation systems have been documented subsequently [13,14].

Our work grew out of an examination of Cunnington's paper [13] who utilized a numerical technique to find optimum temperatures at given locations for one and two shields for a thermal conductivity function of the form
Although several equations seemed to be incorrectly printed we have found two of the design curves to be essentially correct. Thus, our purpose was

1. To develop a simple optimization technique;
2. To generalize the results to a broader class of insulations; and
3. To develop simple design methods for cooled shields.

The essentials of this report were already published [15].
ANALYSIS

We accept the previously developed concept that to optimize an insulation system is equivalent to minimizing the entropy production rate. In addition, we assume one-dimensional heat flow and that the heat capacity of the boil-off gas is adequate to do the cooling for all shields and does not impose a restriction on the optimization. In contrast to Rejan [9,11] who has developed a constrained optimization based on the heat capacity of the boiloff we employ the argument that in all practical systems the boil-off is generated by cooling of some equipment in addition to the heat leakage across the insulation.

Parallel heat paths, e.g. supports, have not been considered. However, each path can be optimized separately using its own thermal conductivity function. Then a design decision has to be made whether the two structures should be independently cooled at their respective optimum conditions.

We examine the general situation of an insulation where equivalent thermal conductivity, \( k \), can be expressed as a two-term function of the absolute temperature

\[
k = k_1 T^m + k_2 T^n
\]

(1)

where, typically, the first term represents actual conduction with \( m = 1 \) and the second term represents radiation with \( n \geq 3 \). In the following, \( m \) and \( n \) can be any value except -1.

The heat flow across a layer of insulation can be expressed in terms of Fourier's law

\[
q \, dx = Ak \, dT
\]

(2)
Substituting \( k \) from Eq. (1) and integrating across a layer from one end at 1, to the other at 2, yields

\[
q = \frac{A}{x_2 - x_1} \left[ \frac{k_1}{m+1} (T_{2, m+1} - T_{1, m+1}) + \frac{k_2}{n+1} (T_{2, n+1} - T_{1, n+1}) \right].
\]  

(3)

Now consider the insulation with a cooled shield at \( T_S \) located at \( x \) between a hot surface at \( T_H \) and a cold one at \( T_C \), separated by the insulation thickness, \( t \), as shown in Fig. 1a. The entropy production rate for the insulation can be determined from the heat flows and temperatures as follows

\[
\dot{S} = -\frac{q_H}{T_H} + \frac{q_C}{T_C} + \frac{q_S}{T_S}
\]

(4)

where \( q_S = q_H - q_C \).

The heat flow terms can be expressed in the form of Eq. (3) and the resulting expression can be non-dimensionalized using the following terms

\[
s \equiv \frac{St}{Ak_H} \text{ where } k_H = k \text{ at } T_H,
\]

(5)

\[
p \equiv \frac{T_S}{T_C},
\]

(6)

\[
R \equiv \frac{T_C}{T_H},
\]

(7)

\[
\gamma \equiv \frac{k_2(m+1)}{k_1(n+1)} T_H^{n-m},
\]

(8)

and

\[
x \equiv \frac{x}{t},
\]

(9)
The resulting equation is

\[ s(m + 1)(1 + \gamma \frac{n + 1}{m + 1}) \]

\[ = \frac{1}{1 - \gamma \gamma \{(PR)^{m + 1} - (PR)^{m} - 1 + (PR)^{-1}\}} \]

\[ + \gamma \{(PR)^{n+1} - (PR)^{n} - 1 + (PR)^{-1}\} \]

\[ + \frac{1}{\gamma \gamma \{(PR)^{m+1} - (PR)^{m} - 1 + (PR)^{-1}\}} \]

\[ + \gamma \{(PR)^{n+1} - (PR)^{n} - 1 + (PR)^{-1}\} \]

(10)

Since \( R \), the overall temperature ratio, is generally known, \( s \) is a function of \( P \) and \( X \), and its extreme value can be found by differentiating it with respect to each variable separately and setting the results equal to zero. This procedure yields two equations to be solved simultaneously: \( \frac{3s}{3P} = 0 \) and \( \frac{3s}{3X} = 0 \). Because of the regular form of the expressions, one of the final two equations contains only a single unknown as follows:

\[ R^m \frac{F(m,P) + \gamma R^n F(n,P)}{[R^{m-1} D(m,P) + \gamma R^{n-1} D(n,P)]^2} \]

\[ = \frac{F(m,PR) + \gamma F(n,PR)}{[D(m,PR) + \gamma D(n,PR)]^2} \]

(11)

\[ \frac{X}{1-X} = -\frac{R^{m-1} D(m,P) + \gamma R^{n-1} D(n,P)}{D(m,PR) + \gamma D(n,PR)} \]

(12)

where the following functionals were used:
\[ F(b, B) = R^{b+1} - B^b - 1 + B^{-1} \]  \hspace{1cm} (13)

\[ D(b, B) = (b + 1) B^b - b B^{b-1} - B^{-2} \] \hspace{1cm} (14)

Thus, to find the optimum temperature and location for a shield, Eq. (11) can be solved for \( P \), and then \( X \) can be calculated from Eq. (12). The heat to be removed by the shield, \( q_S = q_H - q_C \), can be found, as before, from Eq. (3). In dimensionless form the equation becomes

\[
\frac{q_S^t}{Ak_H T_H^{(m+1)}(1 + \gamma \frac{n+1}{m+1})} = \frac{1 - (PR)^{m+1} + \gamma[1 - (PR)^{n+1}]}{1 - X}

- \frac{(PR)^{m+1} - R^{m+1} + \gamma[(PR)^{n+1} - R^{n+1}]}{X}. \hspace{1cm} (15)

For multiple shields, \( t_i \) represents the distance between the two surfaces surrounding the \( i \)-th shield on either side, \( T_{H,i} \) and \( T_{C,i} \) are the temperatures of these two surfaces, \( X_i = x_i/t_i \) is the location of the shield relative to \( t_i \), and \( x_i' \) is the location of the shield relative to the cold wall as shown in Fig. 1b. To determine the optimum temperatures and locations for multiple shields, first, we assumed a temperature for the first shield next to the cold wall, then we used Eqs. (11) and (12) to find the temperature and location of the second shield. This process was repeated for the rest of the shields and the hot wall. Thus, each shield was optimized consecutively with respect to the two surfaces on either side. With given values of the overall temperature ratio, \( R \), and of the number of shields, the process requires iterative solution.
To put the results into proper perspective, the entropy production rates can be compared to the thermodynamically minimum rate obtainable through spatially continuous cooling. According to Bejan [12], this rate is

$$S_{\text{min}} = \frac{A}{t} \left[ \int_{T_C}^{T_H} \left( k \right)^{1/2} T^{-1} \, dT \right]^2. \quad (16)$$

This expression was evaluated analytically for the single-term functions of $k$, i.e. for $\gamma = 0$, and numerically otherwise.
RESULTS AND DISCUSSION

The first set of curves, Figs 2 through 9, show the relative entropy production rates for various thermal conductivity functions and for up to four optimally cooled shields as functions of the overall temperature ratio $R = T_C/T_H$. The curves show that the entropy production rate increases with decreasing values of the temperature ratio, $R$, and with increasing values of the exponent, $m$ and $n$. Adding shields, of course, reduces the entropy production rate; but for most of the practical temperature range, say $0.01 < R < 0.4$, only three shields contribute to significant decreases and adding a fourth shield can be considered unnecessary. No shields are useful at high values of $R$; but this "high" range is strongly dependent on the exponent of the temperature. The curves developed with $k = k_1 T^{0.6}$ for one and two shields were very close to those given by Cunnington [13], converted appropriately.

Study of the results of two-term conductivities reveals that the curves fall between those obtained for each of the two terms alone. If $\gamma$ is small the first term, $T^m$, dominates; whereas if $\gamma$ is large (>10), the second term, $T^0$, controls. Thus, general conclusions can be drawn from examining the results of the single-term conductivities.

The second set of curves, Figs. 10 through 31, show the optimum temperature ratios, $T_S/T_H$, and optimum locations, $x'/L$, of cooled shields as functions of the overall temperature ratio, $T_C/T_H$, for various thermal conductivity functions and with different number of cooled shields.

Figures 10 and 11 show the optimum single shield temperature ratios, $PR = T_S/T_H$, and locations, $X = x/L$, for five conductivity functions. Both of these functions generally decrease with decreasing $R$. The other figures in this set show shield temperatures and locations for systems with up to three
shields and for both single-term and two-term conductivities. The results are strongly non-linear. For example, for \( k_1T^3 \) and \( R = 0.01 \), the optimum temperature ratios for three shields are about 0.09, 0.3, and 0.6 and the optimum locations are about 0.05, 0.2, and 0.5. As is to be expected, our unconstrained optimization yields a somewhat better performance per shield than Bejan's [9,11] constrained method.

The sensitivities of the entropy production rates to deviations from the optimum values of PR and X are demonstrated in the last set of curves, Figs. 32 through 35, for single shields. The sensitivity increases with the value of the exponents, m and n, but the curves are relatively flat near the minima. A ±20 percent change from optimum, for example, has negligible effect. Thus, the system is relatively tolerant of deviations from the optimum design conditions.

Calculations with two different conductivities on the two sides of a cooled shield show that using the better insulator on both sides always yields the optimum condition. However, if for some reason two types of insulations have to be used, then the better insulator should be placed on the warm side of the shield.
REFERENCES


Figure 1 Schematic of the Nomenclature for (a) Single and (b) Multiple Shields
Curve Set 1: Figures 2 through 9

The effect of optimally cooled shields on the entropy production rate for various thermal conductivities.
Figure 3

$k = k_1 T^{0.6}$

No. of Shields

$S/S$

$T_{cold}/T_{hot}$
Figure 4

\[ k = k_1 T \]

No. of Shields

\[ \frac{T_{\text{cold}}}{T_{\text{hot}}} \]

\[ 100.0 \]

\[ 10.0 \]

\[ S/S \]
$k = k_1 T + k_2 T^3$  \( \gamma = 0.5 \)

No. of Shields

$T_{\text{cold}} / T_{\text{hot}}$

$S/S$

Figure 7
$k = k_1 T + k_2 T^{3.0}$

$\gamma = 2.0$

**No. of Shields**

- 0
- 1
- 2
- 3
- 4

Figure 8
Figure 9

The graph shows the relationship between $S/S_{\text{min}}$ and $T_{\text{cold}}/T_{\text{hot}}$ for different numbers of shields. The equation $k = k_1 T + k_2 T^{3.0}$ with $\gamma = 5.0$ is used to calculate the values.
Curve Set 2: Figures 10 through 31

Optimal shield temperatures and locations for various thermal conductivity functions with different number of shields.
Figure 10

No. of Shields = 1

\[
\frac{T_{\text{shield}}}{T_{\text{hot}}} \text{ vs. } \frac{T_{\text{cold}}}{T_{\text{hot}}}
\]

- \( k = k_1 \)
- \( k = k_1 T^{0.6} \)
- \( k = k_1 T \)
- \( k = k_1 T^{2.0} \)
- \( k = k_1 T^{3.0} \)
No. of Shields = 1

- \( k = k_1 \)
- \( k = k_1 T^{0.6} \)
- \( k = k_1 T \)
- \( k = k_1 T^{2.0} \)
- \( k = k_1 T^{3.0} \)

Figure 11
\[ k = k_1 T_0^{0.6} \]

No. of Shields = 2

\[ \frac{T_{\text{cold}}}{T_{\text{hot}}} \]
\[ k = k_1 T^{0.6} \]  No. of Shields = 2

\[ \left( \frac{X}{L} \right)_{opt} \]

---

**Figure 13**
$k = k_1 T_0^{0.6}$

No. of Shields = 3

$T_{\text{cold}} / T_{\text{hot}}$ vs. $1 / T_{\text{cold}}$
$k = k_1 T^{0.6}$  
No. of Shields = 3

- SHIELD 1
- SHIELD 2
- SHIELD 3

Figure 15
\[ k = k_1 T \]

No. of Shields = 3

- --- SHIELD 1
- --- SHIELD 2
- --- SHIELD 3

Figure 16
\[ k = k_1 T^{3.0} \]

No. of Shields = 2

\[
\frac{T_{\text{cold}}}{T_{\text{hot}}} \quad \text{SHIELD 1}
\]

\[
\frac{T_{\text{shield}}}{T_{\text{hot}}} \quad \text{SHIELD 2}
\]
\[ k = k_1 T^{3.0} \]

No. of Shields = 2

\[ \frac{[X/L]}{opt} \]

\[ T_{\text{cold}} / T_{\text{hot}} \]

Figure 19
$k = k_1 T^{3.0}$

No. of Shields = 3

- --- SHIELD 1
- -- SHIELD 2
- - SHIELD 3

Figure 20
\[ k = k_1 T^{3.0} \]

No. of Shields = 3

- SHIELD 1
- SHIELD 2
- SHIELD 3

\[ \frac{T_{\text{cold}}}{T_{\text{hot}}} \]

Figure 21
No. of Shields = 1

\[ k = k_1 T + k_2 T^{3.0} \]

\[ \gamma = 0.5 \]

\[ \gamma = 2.0 \]

\[ \gamma = 5.0 \]
\[ k = k_1 T + k_2 T^{3.0} \]
\[ \gamma = 0.5 \]
No. of Shields = 2

**Figure 24**
$k = k_1 T + k_2 T^{3.0}$  $\gamma = 0.5$  No. of Shields = 2

$[x/L]_{opt}$

$T_{cold}/T_{hot}$

Figure 25
\[ k = k_1 T + k_2 T^{3.0} \]
\[ \gamma = 0.5 \]
\[ \text{No. of Shields} = 3 \]

\[ [X/L]_{opt} \]

\[ T_{cold}/T_{hot} \]

Figure 27
$k = k_1 T + k_2 T^{3.0}$  \( \gamma = 2.0 \)

No. of Shields = 2

---

**Figure 28**
$k = k_1 T + k_2 T^{3.0}$  \( \gamma = 2.0 \)  No. of Shields = 2

- --- SHIELD 1
- --- SHIELD 2

$[x' / L]_{opt}$

$T_{cold} / T_{hot}$

Figure 29
\[ k = k_1 T + k_2 T^{3.0} \quad \gamma = 2.0 \]

No. of Shields = 3

- \text{SHIELD 1}
- \text{SHIELD 2}
- \text{SHIELD 3}

Figure 30
Curve Set 3: Figures 32 through 35

System sensitivity to deviations from the optimum shield temperatures and locations for two overall temperature ratios with one cooled shield
Figure 32

\[ \frac{T_{\text{cold}}}{T_{\text{hot}}} = 0.006 \]

- \( k = k_1 \)
- \( k = k_1 T \)
- \( k = k_1 T^{3.0} \)
Figure 33

\[ T_{\text{cold}} / T_{\text{hot}} = 0.006 \]

- \( k = k_1 \)
- \( k = k_1 T \)
- \( k = k_1 T^{3.0} \)
$T_{\text{cold}} / T_{\text{hot}} = 0.060$

$k = k_i T$

$S / S$

$x / L$

Figure 35
APPENDIX

COMPUTER PROGRAMS
SEPARS and SHIELD

These two programs are essentially identical, but SEPARS is written in
PASCAL whereas SHIELD is in BASIC.

To allow for consecutive calculations of different systems, the program
always recycles to the starting point. Consequently, the first input
requested is either a 1, if a calculation is to be performed, or a 0, if no
more work is to be done.

Next the program requests input of the insulation's characteristics,
specifically, the two exponents of the temperatures in the two-term
conductivity function, the maximum number of cooled shields (<10) to evaluate,
the value of $\gamma$, and the temperature ratio of the first shield to the cold
wall, $P(1) = \frac{T_{S1}}{T_C}$. The program calculates and presents the characteristics
of all optimal systems of cooled shields from one shield to the maximum number
specified in the input.

The flow chart and a program sample follows.
TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0. READ PFC

IS PFC = 1?

NO

YES

ENTER INSULATION CHARACTERISTICS, NUMBER OF SHIELDS AND P(1)

I = 1

C

IM1 = I - 1
IM2 = I - 2

SOLVE R(i) ITERATIVELY

CALCULATE S(i), X(i)

IS I > 1?

NO

YES

L2(i) = (1.0 - X(i-1)) / X(i)

ONE SHIELD ARRANGEMENT
ASSIGN L3(1), TCH(1), TSH(1), L4(1) AND XPL(1)

TWO SHIELDS ARRANGEMENT
ASSIGN L4(2) AND TCH(2)

THREE SHIELDS ARRANGEMENT
ASSIGN L4(3) AND TCH(3)

FOUR OR MORE SHIELDS ARRANGEMENT
ASSIGN B AND L4(1)

J = 2
ASSIGN L3(i+1) AND E(i+1) J = 1
CALCULATE Q(J), SISH(J)

OUTPUT THE HEAT REMOVAL RATE AND ENTROPY PRODUCTION RATE AT EACH SHIELD ALONG WITH OPTIMUM LOCATION AND OPTIMUM TEMPERATURE FOR THE SHIELDS' ARRANGEMENT

J = J + 1

IS J > 1 ?

YES

CALCULATE QHOT, QCOLD AND SCOLD
CALCULATE STOTAL[I]
CALCULATE SMIN[I], STOTMIN[I], SMAI[I], SMAIN[I]

IS I > NS ?

NO

YES

P[I+1] = 1.0 / P1

2
OUTPUT TCH(I), QCOLD, QHOT, SCOLD, SMIN(I), SMAX(I), STOTAL(I), SMAXIN(I) AND SOTMIN(I)

I = I + 1

IS I > NS?

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0. READ PFC

IS PFC = 1?

END SEPARS
**PROGRAM SHIELDSINPUT,OUTPUT.JX.**

```
THIS PASCAL PROGRAM WAS DEVELOPED TO OPTIMIZE THE LOCATION, TEMPERATURE AND HEAT DISSIPATION RATE OF EACH COOLED SHIELD INSIDE AN INSULATION LAYER. THE THERMAL CONDUCTIVITY OF THE INSULATION HAS THE GENERAL FORM:

K = K1(T*M) + K2(T*M)

THE METHOD IS BASED ON THE MINIMIZATION OF THE ENTROPY PRODUCTION RATE WHICH IS PROPORTIONAL TO THE HEAT LEAK ACROSS THE INSULATION.

THE SHELF OF ARRAYS DETERMINES THE MAXIMUM NUMBER OF SHIELDS.

THE SIZE OF ARRAY1 IS EQUAL TO N*(I-1).

(*) THE SIZE OF ARRAY2 IS EQUAL TO N*I.

(* *) LET THICK1: REPRESENT THE SPACING BETWEEN I-TH SHIELD / LOCAL COLD TEMPERATURE RATIO.

(*) BETWEEN (I-1)-TH & I-TH SHIELDS.

(* *) ---) BETWEEN (I-1)-TH & I-TH SHIELDS.

**TYPE**

ARRAY1=ARRAY; 1: OF REAL.

ARRAY2=ARRAY; 11: OF REAL.

(* THE SIZE OF ARRAYS DETERMINES THE MAXIMUM NUMBER OF SHIELDS *)

(* THE SIZE OF ARRAY2 IS EQUAL TO N*I *)

# **ARRAY**

12: ARRAYS.

13: ARRAYS.

14: ARRAYS.

15: ARRAYS.

16: ARRAYS.

17: ARRAYS.

18: ARRAYS.

19: ARRAYS.

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74: ARRAYS.
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**J C CHATO & J M KHODADAD**

**DEPT OF MECHANICAL & INDUSTRIAL ENGRC**

**UNIV OF ILLINOIS AT URBANA-CHAMPAIGN**

**1106 W GREEN STREET**

**URBANA, IL 61801**

**JULY 1983**

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**ORIGINAL PAGE 58 OF POOR QUALITY**

```
PROCEDURE INPUTH. (* INPUT OF DATA HEADING *)
BEGIN
  WRITEN.
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
END.

PROCEDURE PFCH. (* PFCH *)
BEGIN
  WRITEN.
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
  WRITEN:
END.

PROCEDURE SINGLESPACE.
BEGIN
  WRITEN.
  WRITEN.
  WRITEN.
  WRITEN.
END.

FUNCTION PWR(II,E) REAL.
BEGIN
  VAR
    A REAL.
  BEGIN
    A = E**II.
  END.

FUNCTION D(E,II,E) REAL.
BEGIN
  D = (E-0.9)*(PWR(II,E))**E/(PWR(II,E))**E - (0.9*SQR(II))
END.
```
FUNCTION F(E,E:REAL):REAL.
BEGIN (* FUNCTIONAL F *)
  F = (FWR(E*(E+1.0)) - FW(E,E) - E + (1.0/E))
END. (* FUNCTIONAL F *)

FUNCTION SIMPSON(TCH,R:REAL):REAL.
TYPE
  ARR = ARRAY[1:10] OF REAL.
VAR
  C,T
  DELTAR
  N
  K,L
BEGIN (* COMPUTE MINIMUM ENTROPY PRODUCTION RATE USING SIMPSON'S NUMERICAL INTEGRATION SCHEME *)
  DELTAR = TCH/(TCH+100.0).
  FOR I = 1 TO 10 DO
  BEGIN
    TCI = TCH*(DELTAR*(I-1)).
    TCL = 0.5*(TCH*(TCI)+TCL). \ $^{0.5}/(CCL)$
  END.
  H = F(I)+F(I+1).
  FOR K = 1 TO 10 DO
  BEGIN
    IF X = (K DIV 2)*2 THEN
      H = H + 4*D*T(K)
    ELSE
      H = H + 2*D*T(K)
  END.
  SIMPSON = 2*(GR*(DELTAR/3*(PH)))-(2*C+TCH+TCH/MP).
END. (* COMPUTE MINIMUM ENTROPY PRODUCTION RATE USING SIMPSON'S NUMERICAL INTEGRATION SCHEME *)

(* MAIN PROGRAM BODY *)

(* THIS BLOCK IS USED TO INPUT THE INSULATION THERMAL CONDUCTIVITY. NUMBER *)
(* OF SHIELDS AND 1ST. SHIELD / COLD WALL TEMPERATURE RATIO *)

BEGIN
  INPUT
  READ(N.E.P.GAMA.PH).
  SIMPLE
  IF GAMA = 0 THEN
  END.
  ELSE
  END.

BEGIN
  WRITE(' THERMAL CONDUCTIVITY OF THE INSULATION IS X = E1*T**.M.3.1')
  END.

BEGIN
  WRITE(' THERMAL CONDUCTIVITY OF THE INSULATION IS X = E1*T**.M.3.1')
  END.

BEGIN
  WRITE(' THERMAL CONDUCTIVITY OF THE INSULATION IS X = E1*T**.M.3.1')
  END.

BEGIN
  INPUT
  READ(N.E.P.GAMA.PH).
  SIMPLE
  IF GAMA = 0 THEN
  END.
  ELSE
  END.

BEGIN
  WRITE(' THERMAL CONDUCTIVITY OF THE INSULATION IS X = E1*T**.M.3.1')
  END.

BEGIN
  WRITE(' THERMAL CONDUCTIVITY OF THE INSULATION IS X = E1*T**.M.3.1')
  END.

BEGIN
  INPUT
  READ(N.E.P.GAMA.PH).
  SIMPLE
  IF GAMA = 0 THEN
  END.
  ELSE
  END.
(* THIS BLOCK CALCULATES B[I] ITERATIVELY *)

```
REP
S1 = F[R(I), M] * G[N, P(I)] + B[N, P(I)]
B[N, P(I)] = G = 0
G = B
IF B < 0 THEN GOTO 100
IF B = 0 THEN GOTO 200
IF ABS(G) < 0.008 THEN GOTO 200
DO = RO
100 B[I] = B[I]*CC
IF B[I] = 0 9HCC THEN B[I] = B[I]+CC
CC = CC + 1
END
100 COUNT = COUNT + 1
UNTIL (G[I] = 0) OR (ABS(G[I]) < 0.008)
```

(* IN THIS BLOCK VARIABLES ARE ASSIGNED FOR DIFFERENT SHIELD CONFIGURATIONS *)

```
IF I = 1 THEN
BEC:
L[I] = (0 - E[I] - 1)/E[I]
ELSE IF I = 2 THEN
BEGIN
B = 0
L[I] = 0
FOR J = 2 TO I DO BEGIN
L[I] = L[I] + L[I-1]/L[I-1]
END
BEGIN
B = B[I]
L[I] = L[I] + B
END
END
```

```
BEGIN
L[I] = L[I] + L[I-1] + 1.0
L[I] = L[I] + L[I-1]
FOR J = 2 TO I DO BEGIN
L[I] = L[I] + L[I-1]/L[I-1]
END
BEGIN
L[I] = L[I] + L[I-1]/L[I-1]
BEGIN
L[I] = L[I] + L[I-1]/L[I-1]
BEGIN
L[I] = L[I] + L[I-1]/L[I-1]
BEGIN
L[I] = L[I] + L[I-1]/L[I-1]
BEGIN
END
END
END
END
```
BEGIN
  LI3(1) = 1.0;
  TCH(1) = 81.0;
  TSH(1) = TCH(1) + Mp(1);
  LE(1) = 0.0;
  TEP(1) = E(1);
END.

TS(1+1) = 0.
TJ(1) = TCH(1),

SINGLESPACE.

WRITE:' NUMBER OF SHIELDS = ',I2).
WRITE:' NUMBER OF ITERATIONS = ',COUNT1).
SINGLESPACE.

WRITE:' HEAT REMOVAL RATE  ENTHALPY PRODUCTION RATE  OPTIMUM LOCATION  OPTIMUM TEMPERATURE  ').

SINGLESPACE.

IF (I1) THEN
  FOR J = 1 TO I DO TJ(J) = TSH(J-1),
  LI(J-1) = 61.1.

(* IN THIS BLOCK DIMENSIONLESS HEAT REMOVAL AND ENTHALPY PRODUCTION RATES *)
(* ARE CALCULATED FOR EACH SHIELD *)

FOR J = 1 TO I DO
  BEGIN
    zi = (PWR(TSH(1+1), MP1) - PWR(TSH(J+1), MP1) + L3(J,1) + Mp(1) - PWR(TCH(J), MP1) + PWR(TCH(1), MP1) + L3(1,1) + Mp(1))
    zi = (PWR(TSH(J+1), MP1) - PWR(TSH(J+1), MP1) + L3(J,1) + Mp(1) - PWR(TCH(J), MP1) + PWR(TCH(1), MP1) + L3(1,1) + Mp(1))
    SISH(J) = zi / TSH(J),
    WRITE(' SHIELD ', J, ' SISH(J) 9.5 ', ' 9.SISH(J) 9.5 ', ' 9.TSH(J) 9.5),
  END.

(* FINALLY OTHER QUANTITIES OF INTEREST ARE CALCULATED IN THIS BLOCK *)

SINGLESPACE.

QHOT = Q(COLD) - Q(COLD) - QHOT,
QCOLD = QHOT - PWR(TCH(J), MP1) - PWR(TCH(1), MP1) + GAMA - PWR(TSH(J), MP1) + GAMA - PWR(TCH(1), MP1) + L3(1,1) + Mp(1),
QCOLD = QCOLD / TCH(J),
STOTAL1 = QCOLD - QHOT,
FOR J = 1 TO I DO STOTALIII = STOTALIII + SISH(J),
SKINII = QCOLD + QCOLD / TCH(1),
SKINII = QCOLD / TCH(1),
STOTKINII = QCOLD / TCH(1),
SMAII = (COLD) - PWR(TCH(J), MP1) - PWR(TCH(1), MP1) + GAMA - PWR(TSH(J), MP1) + GAMA - PWR(TCH(1), MP1) + L3(1,1) + Mp(1),
SMAII = SMAII / SISH(1),

IF I1S THEN PI(1) = 0/R1.
SINGLESPACE.

WRITE:' COLD WALL / HOT WALL TEMPERATURE RATIO  9.TCH(1) 14.4),
WRITE:' HEAT OUT AT COLD WALL  9.QHOT 14.4),
WRITE:' HEAT IN AT HOT WALL  9.QCOLD 14.4),
WRITE:' ENTHALPY PRODUCTION RATE AT COLD WALL  9.QHOT 14.4),
WRITE:' ENTHALPY PRODUCTION RATE AT HOT WALL  9.QCOLD 14.4),
WRITE:' MINIMUM ENTHALPY PRODUCTION RATE  9.SMAII 14.4),
WRITE:' MAXIMUM ENTHALPY PRODUCTION RATE  9.SMAII 14.4),
WRITE:' TOTAL ENTHALPY PROD RATE WITH ' J.3 ' SHIELDS  9.SMAII 14.4),
WRITE:' MAXIMUM / MINIMUM ENTHALPY PRODUCTION RATIO  9.SMAII 14.4),
WRITE:' TOTAL / MINIMUM ENTHALPY PRODUCTION RATIO  9.SMAII 14.4),

SINGLESPACE.
SINGLESPACE.
SINGLESPACE.

END.
PFCH.
READM.
READ(PFCH).
END.
TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0.

ENTER ----- M N NS GAM A P[1] <-----

WHERE: M ----- 1ST. POWER IN THE THERMAL CONDUCTIVITY EQUATION
N ----- 2ND. POWER IN THE THERMAL CONDUCTIVITY EQUATION
NS ----- NUMBER OF SHIELDS
GAMA -- =0 IF USING ONE TERM THERMAL CONDUCTIVITY EQUATION
>0 IF USING TWO TERM THERMAL CONDUCTIVITY EQUATION
P[1] -- 1ST. SHIELD / COLD WALL TEMPERATURE RATIO, ALWAYS > 1

? 1.0 3.0 1 2.5 15.0

THERMAL CONDUCTIVITY OF THE INSULATION IS K = K1*T**1.0 + K2*T**3.0

[K2*(N+1)]/[K1*(N+1)]*THOT**(N-M) = 2.50

NUMBER OF SHIELDS = 1
NUMBER OF ITERATIONS = 35

<table>
<thead>
<tr>
<th>HEAT REMOVAL RATE</th>
<th>ENTROPY PRODUCTION RATE</th>
<th>OPTIMUM LOCATION</th>
<th>OPTIMUM TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHIELD 1</td>
<td>0.43837</td>
<td>1.85659</td>
<td>0.36744</td>
</tr>
</tbody>
</table>

COLD WALL / HOT WALL TEMPERATURE RATIO = 0.015741
HEAT OUT AT COLD WALL = 0.014350
HEAT IN AT HOT WALL = 0.452719
ENTROPY PRODUCTION RATE AT COLD WALL = 0.911631
ENTROPY PRODUCTION RATE AT HOT WALL = -0.452719
MINIMUM ENTROPY PRODUCTION RATE = 1.000503
MAXIMUM ENTROPY PRODUCTION RATE = 18.236148
TOTAL ENTROPY PROD. RATE WITH 1 SHIELDS = 2.315503
MAXIMUM / MINIMUM ENTROPY PRODUCTION RATIO = 18.226962
TOTAL / MINIMUM ENTROPY PRODUCTION RATIO = 2.314340

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0.

? 1

ENTER ----- M N NS GAM A P[1] <-----

WHERE: M ----- 1ST. POWER IN THE THERMAL CONDUCTIVITY EQUATION
N ----- 2ND. POWER IN THE THERMAL CONDUCTIVITY EQUATION
NS ----- NUMBER OF SHIELDS
GAMA -- =0 IF USING ONE TERM THERMAL CONDUCTIVITY EQUATION
>0 IF USING TWO TERM THERMAL CONDUCTIVITY EQUATION
P[1] -- 1ST. SHIELD / COLD WALL TEMPERATURE RATIO, ALWAYS > 1

? 1.0 0.90 2 0.0 25.0

THERMAL CONDUCTIVITY OF THE INSULATION IS K = K1*T**1.0

NUMBER OF SHIELDS = 1
NUMBER OF ITERATIONS = 23
### Heat Removal Rate vs. Entropy Production Rate

<table>
<thead>
<tr>
<th>Shield</th>
<th>Heat Removal Rate</th>
<th>Entropy Production Rate</th>
<th>Optimum Location</th>
<th>Optimum Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shield 1</td>
<td>0.75466</td>
<td>7.03151</td>
<td>0.35870</td>
<td>0.10732</td>
</tr>
<tr>
<td>Shield 2</td>
<td>0.88411</td>
<td>4.70678</td>
<td>0.48690</td>
<td>0.18786</td>
</tr>
</tbody>
</table>

- **Cold Wall / Hot Wall Temperature Ratio**
  - Shield 1: 0.004293
  - Shield 2: 0.000806

- **Heat Out at Cold Wall**
  - Shield 1: 0.016030
  - Shield 2: 0.001162

- **Heat In at Hot Wall**
  - Shield 1: 0.770687
  - Shield 2: 0.940073

- **Entropy Production Rate at Cold Wall**
  - Shield 1: 3.734070
  - Shield 2: -0.940073

- **Entropy Production Rate at Hot Wall**
  - Shield 1: 3.504633
  - Shield 2: 3.920388

- **Minimum Entropy Production Rate**
  - Shield 1: -0.770687
  - Shield 2: 157.970919

- **Maximum Entropy Production Rate**
  - Shield 1: 115.966533
  - Shield 2: 7.920388

- **Total Entropy Prod. Rate with 1 Shields**
  - Shield 1: 9.994891
  - Shield 2: 157.970919

- **Total / Minimum Entropy Production Ratio**
  - Shield 1: 9.994891
  - Shield 2: 2.851908

- **Number of Shields** = 2
- **Number of Iterations** = 36

### Total / Minimum Entropy Production Ratio
- Total: 2.019751
- Minimum: 3.089491

**To perform computation, enter 1. Otherwise, enter 0.**

0.175 CPU seconds, 124158 CM used.
PROGRAM SHIELD

10 REM THIS IS A "BASIC" PROGRAM TO CALCULATE OPTIMUM TEMPERATURES.
20 REM LOCATIONS, AND COOLING LOADS FOR Cooled SHIELDS IN A CRYOGENIC
30 REM INSULATION SYSTEM WhOSE THERMAL ConductIVITY Following THE RELATION
40 REM \ E=(T-H)+E*T'H
50 REM MODIFIED IN LATE NOV. 1982.
60 REM
70 REM DEFINITION OF SYMBOLS USED
80 REM
90 REM COLD-SIDE WALL TEMPERATURE TO
100 REM WARM-SIDE WALL TEMPERATURE T9
110 REM SHIELD POSITION RATIO \( \xi_1 \)
120 REM OVERALL THICKNESS OF INSULATION \( L \)
130 REM 1-TH COLD-WARM TEMPERATURE RAT10G \( B_1 \)
140 REM OVERALL SPACING RATIO \( L/L_1 \)
150 REM \( \xi \) = DISTANCE FROM COLD WALL TO \( L_1 \)
160 REM LOCAL SPACING \( R \)
170 REM OVERALL SPACING \( R/L_1 \)
180 REM LOCAL SPACING RATIO \( R/L_1 \)
190 REM COLD-SIDE VAIL TEMPETATURE \( T_9 \)
200 REM WARM-SIDE WALL TEMPETATURE \( T_1 \)
210 REM COLD-WARM TEMPERATURE DIFFERENCES \( \xi_1 \)
220 REM DISTANCE FROM COLD WALL TO \( L_1 \)
230 REM THERMAL SPACING BETWEEN SHIELDS AT \( \xi_1 \) AND \( 1-1 \)
240 REM THERMAL LOCAL TEMPETATURE \( T \)
250 REM LOCAL DIMENSIONLESS ENTROPY PRODUCTION RATE \( S_1 \)
260 REM \( \xi_1 \) = DIMENSIONLESS HEAT REMOVAL RATE \( Q \)
270 REM \( \xi \) = TOTAL DIMENSIONLESS ENTROPY PRODUCTION RATE \( S \)
280 REM OVERALL ENTROPY PRODUCTION RATE WITHOUT SHIELDS \( S_0 \)
290 REM \( \xi_1 \) = OVERALL ENTROPY PRODUCTION RATE \( \xi_1 S_1 \)
300 REM \( \xi \) = DISTANCE FROM COLD WALL \( L_1 \)
310 REM \( \xi_1 \) = OVERALL SPACING \( \xi_1 R \)
320 REM \( \xi_1 \) = OVERALL SPACING \( \xi_1 R \)
330 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
340 REM \( \xi_1 \) = LOCAL SPACING \( \xi_1 R \)
350 REM \( \xi_1 \) = THERMAL LOCAL SPACING \( \xi_1 R \)
360 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
370 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
380 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
390 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
400 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
410 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
420 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
430 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
440 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
450 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
460 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
470 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
480 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
490 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
500 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
510 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
520 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
530 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
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560 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
570 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
580 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
590 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
600 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
610 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
620 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
630 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
640 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
650 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
660 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
670 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
680 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
690 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
700 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
710 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
720 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
730 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
740 REM \( \xi_1 \) = THERMAL SPACING \( \xi_1 R \)
ORIGINAL PAGE 13
OF POOR QUALITY
FOR K=2 TO 180
150 IF K=13 THEN 01207
151 01205 H=H+M(X)
152 01206 GO TO 01200
153 01207 H=H+M(Y)
154 01208 NEXT K
155 01210 S(I)=(D(I)/3+H(I))/{1+G0#M(I)/H(I)}
156 01220 S(I)=S2(I)/S0(I)
157 01230 S(I)=S(I)-S0(I)-R(I)*M(I)-(1/R(I)-1)/M(I)+(1/G0#M(I)/H(I)}
158 01240 S(I)=S(I)/S0(I)
159 01250 IF I=n THEN 01270
160 01260 P(I)=10
161 01270 PRINT
162 01280 PRINT P(I), R(I), H(I), H(I), H(I)
163 01290 PRINT L(I), L(I), L(I)
164 01300 PRINT COLD WALL/NOT WALL TEMPERATURE RATIO, TO/TO=.88(I)
166 01320 PRINT HEAT OUT AT COLD WALL=.OR. HEAT IN AT WARM WALL=.OR.
167 01340 PRINT ENTROPY PRODUCTION RATE AT COLD WAIL=.88
168 01360 PRINT ENTROPY PRODUCTION RATE AT WARM WAIL=.88
169 01380 PRINT MINIMUM ENTROPY PRODUCTION RATE. S8=..S8(I)
170 01400 PRINT MAXIMUM ENTROPY PRODUCTION RATE. S9=..S9(I)
171 01420 PRINT MAXIMUM ENTROPY PRODUCTION RATIO. S8=S8/50 AND S9=S9/50
172 01440 NEXT I
174 01460 END
NEWRAF

This program solves the original, complete, constrained optimization equations developed in Ref. [9] without the simplifying assumption suggested there which eliminated the dimensionless parameter, $h_f g/C_p T_H$. Only single-term thermal conductivity functions were considered in this analysis.

This program also recycles to the starting point. Consequently, the first input is either a 1, if a calculation is to be performed, or a 0, if no more work is to be done.

Next the program requests input of the insulation's characteristics, specifically, the exponent of temperature in the thermal conductivity function, the number of cooled shields, the dimensionless parameter $h_f g/C_p T_H$ for the boiloff from the insulated container, and $R = T_C/T_H$.

The output specifies the optimal characteristics of the given number of shields with the constraint that the cooling capacity is limited to the boil-off of the liquid due only to the heat leak through the insulation itself.

The flow chart and a program sample follows.
BEGIN NEWRAF

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0. READ PFC.

IS PFC = 1 ?

NO

A

YES

B

ENTER INSULATION CHARACTERISTICS, NUMBER OF SHIELDS, HFG / (CP * THOT) AND TCH

ASSIGN TSHG[1]'S WHICH ARE THE INITIAL GUESSES FOR TSH[1]'S

COUNT = 0
EPS = 1.0E-10

D

COUNT = COUNT + 1

BASED ON TSHG[1]'S AND OTHER DATA

SOLVE THE SYSTEM OF EQUATIONS FOR THE TSH[1]'S USING THE TRIDIAGONAL MATRIX SOLVER

I = 1


I = I + 1

IS I > NS ?

NO

YES


IS DIFFMAI > EPS ?

NO

C

YES
TSH(i) = TSH(i-1)

I = I + 1

IF I > NS THEN
   YES
   D
   C
   ASSIGN IR(i)'s
   SOLVE FOR XPL(i)'s
   I = 1
   CALCULATE Q(i), SISH(i)
   OUTPUT THE HEAT REMOVAL RATE AND ENTROPY PRODUCTION RATE AT EACH SHIELD ALONG WITH OPTIMUM LOCATION AND OPTIMUM TEMPERATURE FOR THE SHIELDS' ARRANGEMENT
   I = I + 1
   IF I > NS THEN
      YES
      CALCUATE QHOT, QCOLD, SCOLD, STOTAL, SMIN, STOTMIN, SMAI AND SMAXIN
      OUTPUT TCH, QCOLD, QHOT, SCOLD, SMIN, SMAI, STOTAL, SMAXIN AND STOTMIN
   TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0. READ PFC
   IF PFC = 1 THEN
      YES
      B
      NO
      A
   END NEWRAF

The Pascal program was developed to optimize the location, temperature and heat dissipation rate of each cooled shield inside an insulation layer. The thermal conductivity of the insulation has the general form of:

\[ K = K_0 e^{-\lambda x} \]

where \( K_0 \) is the initial conductivity, \( \lambda \) is the decay constant, and \( x \) is the distance from the cold wall.

The program utilizes the Newton-Raphson iteration to determine the solution. The main steps include:

1. Initialization of variables, including the size of arrays.
2. Determination of the number of shields.
3. Calculation of the heat transfer rates between shields and the cold wall.
4. Iterative solution for the shield temperatures.
5. Calculation of entropy production rates.

The code snippet provided includes declarations for array sizes and variables, along with the main loop for the iteration process.
PROCEDURE INPUT. (* INPUT OF DATA HEADING *)
BEGIN
WRITELEN.
WRITELEN.
WRITELEN.
WRITELEN.
WRITELEN.
WRITELEN.
WRITELEN.
WRITELEN.
WRITELEN.
WRITELEN.
WRITELEN.
WRITELEN.
WRITELEN.
END. (* INPUT OF DATA HEADING *)

PROCEDURE PVTCH. (* PVTCH *)
BEGIN
WRITELEN.
IF PERFORM COMPUTATION. ENTER 1. OTHERWISE. ENTER 0. ;
WRITELEN.
END. (* PVTCH *)

PROCEDURE SINGLESPACE.
BEGIN
WRITELEN. (* SINGLE SPACE IN OUTPUT *)
END. (* SINGLE SPACE IN OUTPUT *)

FUNCTION PW(EII. E REAL) REAL.
VAR
A REAL.
BEGIN
A = E**E.
PW = EXP(A).
END. (* COMPUTE E**E *)

FUNCTION MAXOFI(W2) REAL.
BEGIN
(* DETERMINES THE LARGEST OF THE TWO GIVEN NUMBERS *)
IF W2 > W2 THEN
W2 = W2
ELSE
W2 = W2
END. (* DETERMINES THE LARGEST OF THE TWO GIVEN NUMBERS *)
FUNCTION MINOF1(NO1,NO2) REAL
BEGIN  (* DETERMINES THE SMALLEST OF THE TWO GIVEN NUMBERS *)
  IF NO1(=NO1 THEN
    MINOF1=NO1
    ELSE
      MINOF1=NO2
    END.
  END.  (* DETERMINES THE SMALLEST OF THE TWO GIVEN NUMBERS *)

BEGIN
  FICH.
  READK.
  READSPEC.
  WHILE FEG=1 DO
  BEGIN
    (*) THIS BLOCK IS USED TO INPUT THE INSULATION THERMAL CONDUCTIVITY, NUMBER (*)
    (*) OF SHIELDS, NFC/(CP*TTHOT) AND COLD WALL / HOT WALL TEMPERATURE RATIO (*)

    INPUT
    READK.
    READ M作为 BETA TCH.
    SINGLESPACE.
    WRITECH
      THERMAL CONDUCTIVITY OF THE INSULATION IS K = E1*F**2. M 3.1,
    SINGLESPACE
    WRITECH
      NFC / (CP*TTHOT) = "BETA". S. 5.
    SINGLESPACE.
    HF. =H-: 0.
    MM. =H-: 0.
    (*) INITIAL GUESSED VALUES FOR TSCHILLS ARE ENTERED *)
    DELTATC = ( R-TCH) / (ME-: E).
    FOR J = 1 TO MS DO TSCHI+ = J*DELTATC*TCH.
    (*) VARIABLE USED TO CHECK CONVERGENCE CRITERION IS SET AND THE ITERATIVE PROCEDURE *)
    (*) OF NEWTON-RAPHSON METHOD IS STARTED *)

    EIS = 01.10.
    COUNT =0
    ITEIRN =0.
    REPEAT.
    COUNT = COUNT +1.
    FOR I = 1 TO MS DO
      BEGIN
        =TSCHI+.
        IF MS =1 THEN
          IF 1 =1 THEN
            BEGIN
              =TSCHI+.
              GIP = TSCHI+.
            END.
          ELSE
            BEGIN
              =TSCHI+.
              GIP = TSCHI+.
            END.
          ELSE
            BEGIN
              =TCH.
              GIP = TSCHI+.
            END.
        END.
      END.
  END.
ORIGINAL PAGE IS OF POOR QUALITY

GIP = 1.0
END.

(* ELEMENTS OF THE TRIAGONAL MATRIX ARE COMPUTED *)

AII = FWR(GI.PH), FWR(GI.M)+FWR(GI.PH) *(TCH-BETA).
BI1 = FWR(GI.PH)+FWR(GI.M)* (TCH-BETA-GI.PH) *(K-1).
CII = FWR(GI.PH) * (TCH-GI.PH).

(* THE TRIAGONAL MATRIX SOLVER IS SHOWN IN THIS BLOCK *)

(* SEE WATSON, J. R. A HANDBOOK OF NUMERICAL MATRICES *)

(* INVERSION AND SOLUTION OF LINEAR EQUATIONS, SECTION *)

(* I. 7. PP. 34-35. JOHN WILEY & SONS, INC., NY. 1948 *)

IF X1 = 0 THEN GOTO 106.
BOLD = O1FBC/BC1.
COLD = B1FBC/BC1.
WORKIN = O1FBC/BC1.
DMAX = B1FBC/BC1.
DMIN = B1FBC/BC1.
GOLD = B1FBC/BC1.
WORKIN = B1FBC/BC1.
WORKIN = B1FBC/BC1.
END.

(* NEWLY CALCULATED VALUES OF TSH(i)S ARE COMPUTED *)

FOR I = 1 TO NS DO
BEGIN
TSMIN = GOLD.
IF X1 = 0 THEN GOTO 106.
IF X1 = 0 THEN GOTO 106.
IF X1 = 0 THEN GOTO 106.
FOR I = 1 TO NS DO
BEGIN
END.

(* CONVERGENCE IS CHECKED. IF THE CRITERION IS SATISFIED, THE ITERATION IS *)

(* TERMINATED. OTHERWISE THE NEWLY CALCULATED TSH(i)S ARE USED AS NEW *)

(* GUESSES FOR ANOTHER ROUND OF ITERATION *)

DIFFMAX = EPS.
FOR I = 1 TO NS DO
BEGIN
DIFF = ABS(TSH(i) - TSH(i-1)).
DIFFMAX = MAXDIFF(DIFF, DIFFMAX).
END.
IF DIFFMAX > EPS THEN
ITERIN = I.
ELSE
FOR I = 1 TO NS DO
TSNI = TSH(i-1).
UNTIL ITERIN.

(* IN THIS BLOCK QUANTITIES USED IN DETERMINING THE SHIELDS' SPACINGS ARE COMPUTED *)

FOR I = 1 TO NS DO
BEGIN
T = TSH(i).
IF NS + 1 THEN
IF I THEN
IF I THEN
TIP = TSH(i-1).
ELSE
ELSE
 ELSE

TIMI = TCH
ELSE
    TIMI = TCH.
    ORI = (MP1*PWR(TI,M)*((TI-TIMI))/((PWR(TI,M)-PWR(TIMI,M))
END.
DEN = 1.
FOR J = 1 TO NS DO DEN = DEN*INNS-1+1)=1.0.
NSP = NSP-1.

(*) FINALLY, SPACINGS BETWEEN SHIELDS AND OTHER QUANTITIES OF INTEREST ARE CALCULATED *)

X(1) = 0/DEN.
XPL(I) = X(I).
I=TOTAL = 1.
FOR J = 2 TO NSP DO BEGIN
CON = 1-1+I-1.
IF (NSP1 THEN XPL(J) = XPL(I-1)*X(I).
I=TOTAL = I=TOTAL +1.
END.
IFABS(I=TOTAL-1) < 1.0E-5) THEN GOTO 100.
ORI = (MP1*PWR(TSHK1,MP1)-PWR(TCH,MP1))/((II(I)+MP1).
ORI = NSP1 = 0.0-PWR(TSHK1,MP1))/((II(I)+MP1).
FOR J = 1 TO NS DO ORI = (PWR(TSHK1,MP1)-PWR(TSHK1-1,MP1))/((II(I)+MP1).
SINGLESPACE.
WRITEN: NUMBER OF SHIELDS = .NS 1.
WRITEN: NUMBER OF ITERATIONS = (COUNT 1).
SINGLESPACE.
WRITEN: HEAT REMOVAL RATIO
WRITEN: ENTROPY PRODUCTION RATE
WRITEN: OPTIMUM LOCATION
WRITEN: OPTIMUM TEMPERATURE.
SINGLESPACE.
FOR J = 1 TO NS DO BEGIN
ORI = ORI-1.
SIN = ORI-1.
WRITEN: SHIELD .1.1 
WRITEN: S.0(1): 5.1. 1.1.SHIK1: 9.5. 
WRITEN: T. IPL(I) : 9.5. 
WRITEN: S.TSHK1: 9.5.
END.
SINGLESPACE.
WRITEN: COLD WALL / HOT WALL TEMPERATURE RATIO
WRITEN: HEAT OUT AT COLD WALL
WRITEN: HEAT IN AT HOT WALL
WRITEN: ENTROPY PRODUCTION RATE AT COLD WALL
WRITEN: ENTROPY PRODUCTION RATE AT HOT WALL
WRITEN: MAXIMUM ENTROPY PRODUCTION RATE
WRITEN: TOTAL ENTROPY PRODUCTION RATE
WRITEN: MAXIMUM / MINIMUM ENTROPY PRODUCTION RATIO
WRITEN: TOTAL / MINIMUM ENTROPY PRODUCTION RATIO

100 SINGLESPACE.
IF (DIW = 0) OR (BI(1) = 0) THEN
BEGIN
WRITEN: ---) CHECK THE ASSEMBLY OF COEFFICIENTS TO BE USED IN TRIDIAGONAL MATRIX
WRITEN: ---) CHECK THE TRIDIAGONAL MATRIX SOLVER
END.
SINGLESPACE.
WRITEN: ---) ETOTAL IS NOT EQUAL TO 1.0
WRITEN: ---) CONVERGENCE OF ARE NOT CORRECT
END.
SINGLESPACE.
SINGLESPACE.
00 FETCH.
01 HEADLN.
02 HEAD1(FCC)
03 EN D
04 ENC
05 /EDP.
TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0.

? 1

ENTER ----- M NS BETA TCH -----

WHERE: M ----- POWER IN THE THERMAL CONDUCTIVITY EQUATION
NS ----- NUMBER OF SHIELDS
BETA --- MFG / (CP*THOT)
MFG --- HEAT OF VAPORIZATION [J/KG]
CP --- SPECIFIC HEAT AT CONSTANT PRESSURE [J/KG K]
THOT --- HOT WALL TEMPERATURE [K]
TCH --- COLD WALL / HOT WALL TEMPERATURE RATIO, ALWAYS = 1

? 1.0

THERMAL CONDUCTIVITY OF THE INSULATION IS K = K1*T#1.0
MFG / (CP*THOT) = 0.01450

NUMBER OF SHIELDS = 3
NUMBER OF ITERATIONS = 9

<table>
<thead>
<tr>
<th>SHIELD</th>
<th>HEAT REMOVAL RATE</th>
<th>ENTROPY PRODUCTION RATE</th>
<th>OPTIMUM LOCATION</th>
<th>OPTIMUM TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.10438</td>
<td>1.56143</td>
<td>0.09719</td>
<td>0.06685</td>
</tr>
<tr>
<td>2</td>
<td>0.25983</td>
<td>1.12595</td>
<td>0.28870</td>
<td>0.23076</td>
</tr>
<tr>
<td>3</td>
<td>0.47781</td>
<td>0.89782</td>
<td>0.58568</td>
<td>0.53219</td>
</tr>
</tbody>
</table>

COLD WALL / HOT WALL TEMPERATURE RATIO = 0.001000
HEAT OUT AT COLD WALL = 0.022985
HEAT IN AT HOT WALL = 0.864998
ENTROPY PRODUCTION RATE AT COLD WALL = 22.984544
ENTROPY PRODUCTION RATE AT HOT WALL = -0.864998
MINIMUM ENTROPY PRODUCTION RATE = 3.751018
MAXIMUM ENTROPY PRODUCTION RATE = 499.499501
TOTAL ENTROPY PROD. RATE WITH 3 SHIELDS = 25.704743
MAXIMUM / MINIMUM ENTROPY PRODUCTION RATIO = 133.163725
TOTAL / MINIMUM ENTROPY PRODUCTION RATIO = 6.652738

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0.

? 1

ENTER ----- M NS BETA TCH -----

WHERE: M ----- POWER IN THE THERMAL CONDUCTIVITY EQUATION
NS ----- NUMBER OF SHIELDS
BETA --- MFG / (CP*THOT)
MFG --- HEAT OF VAPORIZATION [J/KG]
CP --- SPECIFIC HEAT AT CONSTANT PRESSURE [J/KG K]
THOT --- HOT WALL TEMPERATURE [K]
TCH --- COLD WALL / HOT WALL TEMPERATURE RATIO, ALWAYS = 1

? 1.0

1.0 2 0.0154 0.000806
THERMAL CONDUCTIVITY OF THE INSULATION IS \( K = K_1 = 1.0 \)

\( \frac{MFG}{(CP*THOT)} = 0.01540 \)

NUMBER OF SHIELDS = 2
NUMBER OF ITERATIONS = 8

<table>
<thead>
<tr>
<th>HEAT REMOVAL RATE</th>
<th>ENTROPY PRODUCTION RATE</th>
<th>OPTIMUM LOCATION</th>
<th>OPTIMUM TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHIELD 1</td>
<td>0.19732</td>
<td>1.97595</td>
<td>0.16252</td>
</tr>
<tr>
<td>SHIELD 2</td>
<td>0.59037</td>
<td>1.48999</td>
<td>0.48495</td>
</tr>
</tbody>
</table>

COLD WALL / HOT WALL TEMPERATURE RATIO = 0.000806
HEAT OUT AT COLD WALL = 0.030677
HEAT IN AT HOT WALL = 0.818366
ENTROPY PRODUCTION RATE AT COLD WALL = 38.061092
ENTROPY PRODUCTION RATE AT HOT WALL = -0.818366
MINIMUM ENTROPY PRODUCTION RATE = 3.776103
MAXIMUM ENTROPY PRODUCTION RATE = 619.846992
TOTAL ENTROPY PROD. RATE WITH 2 SHIELDS = 40.708665
MAXIMUM / MINIMUM ENTROPY PRODUCTION RATIO = 164.149921
TOTAL / MINIMUM ENTROPY PRODUCTION RATIO = 10.780603

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0.

? 0

0.072 CP SECS, 114718 CM USED.

/BYE:

3KMUFTC COSTS: 255,028 SRUS AT $0.0059 = $1.50
DESINS

This program optimizes the characteristics of a single cooled shield with different insulations on the two sides. Only one-term thermal conductivity functions are considered.

This program also recycles to the starting point; thus the first input is 1, if a calculation is to be performed, or 0 if no more work is to be done.

Next inputs are the characteristics of the two insulations, specifically, the exponents of temperature in the thermal conductivity functions on the hot and cold sides of the shield, a coefficient ratio ALFA (defined in the program), the shield to cold wall temperature ratio, \( P = T_S/T_C \), and the hot wall temperature, \( T_H \).

The output specifies the optimal characteristics of the cooled shield as well as other, related information.

The flow diagram and a program sample follows.
BEGIN DESINS

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0. READ PFC.

IS PFC = 1 ?

NO

A

YES

B

ENTER THE TWO INSULATIONS' CHARACTERISTICS, P AND HOT WALL TEMPERATURE

SOLVE TCH ITERATIVELY

CALCULATE X1 AND X

CALCULATE QHOT, QCOLD, SCOLD, STOTAL, SISH, SMIN1, SMIN2, SMAX1 AND SMAX2

OUTPUT TCH, TSH, QCOLD, QHOT, SCOLD, SISH, SMIN1, SMIN2, STOTAL, SMAX1 AND SMAX2

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0. READ PFC

IS PFC = 1 ?

YES

B

NO

A

END DESINS
PROGRAM DIFFCOND(INPUT,OUTPUT,SEM); 

(* THIS PASCAL PROGRAM WAS DEVELOPED TO OPTIMIZE THE *) 
(* LOCATION, TEMPERATURE AND HEAT DISSIPATION RATE *) 
(* FOR A COOLED SHIELD IN A CRYOGENIC INSULATION *) 
(* SYSTEM WHOSE THERMAL CONDUCTIVITY HAS THE FORM *) 
(* K = K1*(T**M) ON THE HOT SIDE *) 
(* K = K2*(T**N) ON THE COLD SIDE *) 
(* THE METHOD IS BASED ON THE MINIMIZATION OF THE *) 
(* ENTROPY PRODUCTION RATE WHICH IS PROPORTIONAL TO *) 
(* THE HEAT LEAK ACROSS THE INSULATION *) 
(* THE NETHOD IS BASED ON THE MINIMIZATION OF THE *) 
(* TOTAL DIMENSIONLESS ENTROPY PRODUCTION RATE *) 
(* DIMENSIONLESS ENTROPY PRODUCTION RATE AT SHIELD *) 
(* COLD WALL / HOT WALL TEMPERATURE RATIO, ALWAYS < 1 *) 
(* SHIELD / HOT WALL TEMPERATURE RATIO, ALWAYS < 1 *) 
(* DISTANCE FROM COLD WALL / THICKNESS RATIO *) 
(* T / (1.8-2) *) 

(* DUMMY VARIABLE *) 
(* NUMBER OF ITERATIONS NEEDED TO DETERMINE TCH *) 
(* DUMMY VARIABLE *) 
(* DIMENSIONLESS ENTROPY PRODUCTION RATE AT SHIELD *) 
(* COLD WALL / HOT WALL TEMPERATURE RATIO, ALWAYS < 1 *) 
(* SHIELD / HOT WALL TEMPERATURE RATIO, ALWAYS < 1 *) 
(* DISTANCE FROM COLD WALL / THICKNESS RATIO *) 
(* T / (1.8-2) *) 

VAR 

P REAL (* SHIELD / COLD WALL TEMPERATURE RATIO, ALWAYS 1 *) 
SH REAL (* MAXIMUM ENTROPY PRODUCTION RATE BASED ON K1*T**M *) 
SM REAL (* MAXIMUM ENTROPY PRODUCTION RATE BASED ON K1*T**N *) 
SN REAL (* MINIMUM ENTROPY PRODUCTION RATE BASED ON K1*T**M *) 
SM REAL (* MINIMUM ENTROPY PRODUCTION RATE BASED ON K1*T**N *) 
SREAL (* TOTAL DIMENSIONLESS ENTROPY PRODUCTION RATE *) 
S LREAL (* DIMENSIONLESS ENTROPY PRODUCTION RATE AT SHIELD *) 
CM REAL (* COLD WALL / HOT WALL TEMPERATURE RATIO, ALWAYS < 1 *) 
SH REAL (* SHIELD / HOT WALL TEMPERATURE RATIO, ALWAYS < 1 *) 
I REAL (* DISTANCE FROM COLD WALL / THICKNESS RATIO *) 
XI REAL (* T / (1.8-2) *) 

CC REAL (* DUMMY VARIABLE *) 
COUNT INTEGER (* NUMBER OF ITERATIONS NEEDED TO DETERMINE TCH *) 
DD REAL (* DUMMY VARIABLE *) 
ALFA REAL (* (K1*(N+1))/K1*(N+1) *) 
GI REAL (* DUMMY VARIABLES *) 
IND INTEGER (* INDEX TO TERMINATE THE SEARCH FOR TCH *) 
NM REAL (* POWER OF THE THERMAL CONDUCTIVITY ON HOT SIDE *) 
MF REAL (* POWER OF THE THERMAL CONDUCTIVITY ON COLD SIDE *) 
N REAL (* EQUALS N+1 *) 
NP REAL (* EQUALS N+1 *) 
PI INTEGER (* PROGRAM FLOW CONTROLLER *) 
OLD REAL (* HEAT OUT AT COLD WALL *) 
OLD REAL (* HEAT IN AT HOT WALL *) 
SC REAL (* ENTROPY PRODUCTION RATE AT COLD WALL *) 
SEM TEXT (* OUTPUT FILE TO BE USED IF DESIRED *) 
THOT REAL (* HOT WALL TEMPERATURE (1) *) 

J C. CHATO & J. M. KHODADADI 
DEPT. OF MECHANICAL & INDUSTRIAL ENG. 
UNIV. OF ILLINOIS AT URBANA-CHAMPAIGN 
1314 W. GREEN STREET 
URBANA, IL 61801 
JULY 1983
PROCEDURE INPUT:
BEGIN
    ENTER M M ALFA P THOT
    WHERE M = POWER OF THE THERMAL CONDUCTIVITY EQUATION ON THE HOT SIDE.
    ALFA = (EXP(R-1))/(EXP(R+1))
    P = SHIELD / COLD WALL TEMPERATURE RATIO, ALWAYS > 1
    THOT = HOT WALL TEMPERATURE
END.

PROCEDURE PFC.
BEGIN
    WRITE
    TO PERFORM COMPTUATION, ENTER 1 OTHERWISE, ENTER 0
END.

PROCEDURE SINGLESPACE.
BEGIN
    WRITE
    SINGLE SPACE IN OUTPUT
END.

FUNCTION PWR.II.E REAL, REAL.
VAR A REAL.
BEGIN
    A = EXP.II.E
    PWR = EXP.A
    END

FUNCTION DII.II.REAL, REAL.
BEGIN
    D = FUNCTION D
    C = (EXP.E) * PWR.II.E * (E+1/(3-SQR.E))
    END

FUNCTION F.E.II.REAL.
BEGIN
    F = FUNCTION E
    END

BEGIN
    TXTCM
    READM.
    READ.PFC.
    WHILE PFC = DO
BEGIN
    INPUT
    READM.
    READM.M,ALFA,P,THOT
    SINGLESPACE
    WRITE
    THERMAL CONDUCTIVITY OF THE INSULATION ON THE HOT SIDE IS $ K = EXP.E \times ALFA $.
    WRITE
    THERMAL CONDUCTIVITY OF THE INSULATION ON THE COLD SIDE IS $ K = EXP.E \times THOT $.
    WRITE
    THOT = HOT WALL TEMPERATURE

(* THIS BLOCK CALCULATES TCH ITERATIVELY *)

**REPEAT**

TCH = TCH - CC

**IF** TCH < 0 **THEN**

BEGIN

END

**IF** TCH > 0 **THEN**

BEGIN

TCH = TCH + CC

END

**IF** ABS(TCH) < 0.00001 **OR** TCH < 0.00001 **THEN**

BEGIN

CC = (1.0 - TCH)

END

CC = (1.0 - TCH)

**IF** ABS(CC) > 0.0001 **THEN**

BEGIN

CC = 0.0001

END

ORIGINAL PAGE IS OF POOR QUALITY
TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0.

1

ENTER ---> M N ALFA P THOT <----

WHERE:
M ----- POWER OF THE THERMAL CONDUCTIVITY EQUATION ON THE HOT SIDE
N ----- POWER OF THE THERMAL CONDUCTIVITY EQUATION ON THE COLD SIDE
ALFA -- [K2*(M+1)]/[K1*(N+1)]
P ----- SHIELD / COLD WALL TEMPERATURE RATIO, ALWAYS = 1
THOT -- HOT WALL TEMPERATURE [K]

1 0 0.0 20.0 4.5 300.0

THERMAL CONDUCTIVITY OF THE INSULATION ON THE HOT SIDE IS K = K1*(T**1.0).
THERMAL CONDUCTIVITY OF THE INSULATION ON THE COLD SIDE IS K = K2*(T**0.0).

[K2*(M+1)]/[K1*(N+1)] = 20.00
HOT WALL TEMPERATURE = 300.00 [K]

NUMBER OF ITERATIONS = 36
COLD WALL / HOT WALL TEMPERATURE RATIO = 0.001666
SHIELD / HOT WALL TEMPERATURE RATIO = 0.007497
SHIELD LOCATION = 0.390755
HEAT OUT AT SHIELD = 0.820144
HEAT OUT AT COLD WALL = 0.820441
HEAT IN AT HOT WALL = 0.820441
ENTROPY PRODUCTION RATE AT COLD WALL = 0.298568
ENTROPY PRODUCTION RATE AT HOT WALL = -0.820441
ENTROPY PRODUCTION RATE AT SHIELD = 109.396253
MINIMUM ENTROPY PRODUCTION RATE BASED ON K1*T**M = 3.680131
MINIMUM ENTROPY PRODUCTION RATE BASED ON K2*T**N = 40.925828
TOTAL ENTROPY PRODUCTION RATE = 178.307751
ENTROPY PROD. W/O SHIELD BASED ON K1*T**M = 299.619216
ENTROPY PROD. W/O SHIELD BASED ON K2*T**N = 598.241762

TO PERFORM COMPUTATION, ENTER 1. OTHERWISE, ENTER 0.

0

0.044 CP SECS, 10233B CM USED.
A relatively simple method has been developed to optimize the location, temperature, and heat dissipation rate of each cooled shield inside an insulation layer. The method is based on the minimization of the entropy production rate which is proportional to the heat leak across the insulation. The results show that the maximum number of shields to be used in most practical applications is three. However, cooled shields are useful only at low values of the overall, cold wall to hot wall absolute temperature ratio. The performance of the insulation system is relatively insensitive to deviations from the optimum values of the temperature and location of the cooling shields.

Design curves are presented for rapid estimates of the locations and temperatures of cooling shields in various types of insulations, and an equation is given for calculating the cooling loads for the shields.