

## **General Disclaimer**

### **One or more of the Following Statements may affect this Document**

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

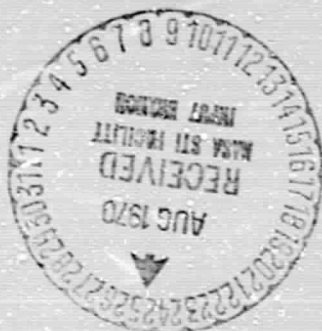
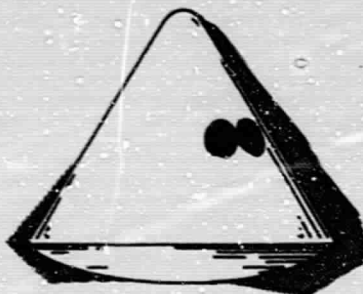
36

Copy No. 10

NASA Project Apollo Working Paper No. 1072

PROJECT APOLLO

VACUUM CHAMBER HEAT TRANSMISSION ANALYSIS



FACILITY FORM 602

N70-35703	
(ACCESSION NUMBER)	
20	(THRU)
(PAGES)	1
TMX 65085	(CODE)
(NASA CR OR TMX OR AD NUMBER)	33
	(CATEGORY)



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
MANNED SPACECRAFT CENTER

Houston, Texas

April 24, 1963

NASA PROJECT APOLLO WORKING PAPER NO. 1072

PROJECT APOLLO

VACUUM CHAMBER HEAT TRANSMISSION ANALYSIS

Prepared by:

Walter W. Guy  
Walter W. Guy  
Environmental Control Systems Branch

Wilbert E. Ellis  
Wilbert E. Ellis  
Environmental Control Systems Branch

Authorized for Distribution:

Maxime A. Faget  
Maxime A. Faget  
Assistant Director for Engineering and Development

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

April 24, 1963

## TABLE OF CONTENTS

<u>Title</u>	<u>Page</u>
ABSTRACT . . . . .	1
OBJECTIVE . . . . .	1
INTRODUCTION . . . . .	1
PROBLEM DEFINITION . . . . .	2
DISCUSSION AND RESULTS . . . . .	4
CONCLUSION . . . . .	5



## LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Heat transmission equations . . . . .	6
2	Heat transfer error in chamber simulation of space . .	7
3	Composition of chamber heat flux . . . . .	8
4	Heat transfer for equilibrium condition . . . . .	9
5	Equilibrium temperature conditions . . . . .	10
6	Simulation temperature error . . . . .	11
7	Simulation error in heat transmission ( $T_v = 720^\circ R$ ). . .	12
8	Simulation error in heat transmission ( $T_v = 540^\circ R$ ). . .	13
9	Simulation error in heat transmission ( $T_v = 360^\circ R$ ). . .	14
10	Simulation error in heat transmission ( $T_v = 180^\circ R$ ) . .	15
11	Simulation error in heat transmission ( $T_v = 180^\circ R$ , $T_{cw} = 8^\circ R$ ) . . . . .	16
12	Maximum heat transfer error for vehicle temperatures of $180^\circ R$ , $320^\circ R$ , $540^\circ R$ , $720^\circ R$ . . . . .	17

## VACUUM CHAMBER HEAT TRANSMISSION ANALYSIS

### ABSTRACT

An analytical investigation into the effect of the test chamber pressure level on the accuracy of deep space heat transfer simulation, using as parameters the test subject's emissivity and surface temperature, reveals that with the exception of extremely low temperature conditions, a test chamber pressure of approximately  $10^{-5}$  mmHg provides the best thermal simulation.

### OBJECTIVE

The accurate simulation of a deep space environment is mandatory for valid vehicle and component thermal evaluation and heat transfer research. Since radiation in deep space is the only mode of external thermal transfer, other means of heat transmission (conduction and convection) introduce errors in thermally simulating a deep space environment. These errors are not the only source of erroneous data. Using a nitrogen cold wall to approximate the near absolute zero of space also introduces inconsistencies in the simulation. The purpose of this paper is to present the results of an analytical investigation into the effect of the test chamber pressure level on the accuracy of deep space heat transfer simulation.

### INTRODUCTION

In an environmental control chamber with Apollo test capability, the following were assumed:

- a.  $\frac{\text{Diameter (vehicle)}}{\text{Diameter (chamber)}} = .5$
- b. Nitrogen cold-walls:  $140^{\circ}\text{R}$
- c. Emissivity, E, of cold walls = .9
- d. Operating pressure range =  $10^{-3}$  mmHg through  $10^{-5}$  mmHg

In such a chamber, at atmospheric pressure, the greatest portion of heat transfer would be through gas conduction and free convection. As the pressure is reduced to the operating range,  $10^{-3}$  mmHg, the gas acts more as separate molecules rather than gas masses. Although this change does not affect the mode of thermal transmission in conduction, free convection (which is the transfer of heat propagated by the buoyant movement of a fluid due to a change in density within a fluid because of its close proximity with a body of a different temperature) is practically nonexistent at this reduced pressure. The low-density, low-pressure condition affects conduction heat transfer in magnitude (without altering the mode) because of the small number of molecules available as conductors, but has almost no effect on radiation heat transfer. The Equations of Thermal Transmission - Stephan Boltzman radiation and Knudsen gas conduction equations - are stated and defined in figure 1. The Stephan Boltzman equation shown is applicable for radiation between concentric cylinders and was used throughout this analysis. Neither the total pressure nor surrounding air affect the validity of the Stephan Boltzman radiation equation. The Knudsen equation, however, is accurate only in the region of "free molecule" conduction. This low conduction region is established at various pressure levels for different gases and separation distances of the heat transfer surfaces. Gas conduction in the pressure range above the free molecular zone is considerably greater than that indicated by Knudsen's equation. No attempt was made to define the point at which the region of "free molecule" conduction was established, since the simulator geometry, test object geometry, and exact composition of residual gases are points of conjecture. Therefore, for this analysis the Knudsen equation will be assumed valid at pressures of  $10^{-3}$  mmHg and below. Any deviation encountered because of this assumption will result in "lower-than-actual" values for gas conduction computed at the upper portion of the  $10^{-3}$  to  $10^{-5}$  mmHg range.

#### PROBLEM DEFINITION

The importance of gas conduction in a vacuum chamber can be illustrated with a practical example. To determine a temperature profile for a launch vehicle during the cool-off period after aerodynamic exit heating, a chamber such as the one described above would be needed. If the chamber were evacuated to  $10^{-3}$  mmHg and the vehicle surface heated, the heat rejected could be accurately determined by temperature monitoring ( $Q = WC_p \Delta T$ ). To assume that this heat rejection was by radiation, (as will be the case in deep space) would be incorrect. In fact, for an aluminum skin vehicle with a nominal emissivity of .05 and an effective temperature in the 700°R range, the error would be approximately



48 percent, as seen in figure 2. This error could be reduced to about 8 percent by a decade reduction in pressure, and to almost 0.2 percent at  $10^{-5}$  mmHg. Thus, it can be seen that gas conduction heat transfer can appreciably affect test results.

Figure 3 is included to represent the composition of the total heat flux to the chamber wall from an object at various temperatures. The first curve is gas conduction; the second is radiation; and the last is the total heat flux to the cold wall (that is, a summation of the conduction and radiation).

Figure 4 plots these total heat flux curves for a chamber at  $10^{-3}$ ,  $10^{-4}$ , and  $10^{-5}$  mmHg in addition to the heat flux that would be radiated to outer space from a body at these same temperatures. This information can be utilized to determine simulation-temperature errors by cross plotting the data of a particular problem.

For example, if the test object were a typical manned spacecraft and a realistic deep space equilibrium temperature was desired, the aforementioned chamber would again be needed. It is assumed that the spacecraft is divided into zones of different thermal-conduction characteristics and that the overall-coefficients of heat transmission lie within the band  $U=.0316$  through  $.191$  BTU/HRT<sup>2</sup>°F. These two boundary values will be used for illustration purposes. By using a nominal interior temperature of 75°F, outer skin emissivity of 0.75, and allowing the outer vehicle skin temperature to vary, a heat conduction curve for each of the  $U$  values can be plotted ( $Q=UA\Delta T$ ). The intersection of these two curves with the total heat flux curves for  $10^{-3}$ ,  $10^{-4}$ , and  $10^{-5}$  mmHg and the outer space radiation curve will determine vehicle equilibrium temperatures.

Vehicle equilibrium temperatures at the three operating pressures are shown for each  $U$  value on figure 5. It can be seen that the temperatures vary more than 18°F for either overall-coefficient of heat transmission.

The temperature-difference ( $\Delta T_v$ ) error encountered in the simulator over the actual deep space condition is shown in figure 6. This figure indicates that for the  $U$  values considered there is a chamber pressure that results in zero  $\Delta T_v$  error. (That is, the simulated temperature is the actual deep space equilibrium temperature.) Could this combination of pressure and temperature be duplicated, perfect simulation would be achieved. However, this is probably of more academic interest than

practical value, since great difficulty is encountered in accurately obtaining and maintaining a precise chamber pressure.

These two examples are not meant to be indicative of every type of problem that will be encountered. Rather than try to find representative problems to cover the range of test conditions, a better understanding can be achieved by not treating specific problems but pursuing a more general line of analysis.

## DISCUSSION AND RESULTS

The duplication of the thermal characteristics of a deep space environment is the object of a chamber test run; the accuracy of the simulation is the measure of success. The deviation from perfect simulation is the difference in heat transfer under deep space conditions and heat transfer in the chamber. This error may be positive or negative depending on test conditions. The three (3) parameters that affect this error most are the test vehicle emissivity, and temperature, and the chamber absolute pressure. By plotting the simulation error against chamber pressure at a fixed vehicle temperature for various emissivity values, a more complete picture is given. The pressure was confined to the  $10^{-3}$  to  $10^{-5}$  mmHg range while the emissivity was allowed to vary from 0.05 to 0.95 for each graph. Separate graphs were drawn for vehicle skin temperatures of 720°R (figure 7), 540°R (figure 8), 360°R (figure 9), and 180°R (figure 10).

Figures 7, 8, and 9 indicate a reasonable accuracy is maintained for all emissivities at  $10^{-5}$  mmHg; but with decreasing temperatures, progressively more error is encountered at  $10^{-3}$  mmHg.

This generalization is false when applied to the 180°R test vehicle in figure 10. The error is considerable at either  $10^{-3}$  or  $10^{-5}$  mmHg. This can be explained by realizing the nitrogen cold wall temperature is only 140°R; thus introducing a large error in radiation at the lower vehicle temperature. If work is to be done in this low temperature region, reasonable accuracy can be outlined by using an 8°R helium cold wall and decreasing the chamber pressure a decade to  $10^{-6}$  mmHg as shown in figure 11.

Figure 12 is included to give a general picture of the maximum error in deep space heat transmission simulation encountered at any vehicle temperature. At  $10^{-5}$  mmHg, this maximum error (for test vehicle emissivities ranging from 0.05 to 0.95 and temperatures ranging from 360°R to 720°R) is approximately 6 percent. At the higher pressure,



$10^{-3}$  mmHg, (for same ranges of emissivity and temperature) the maximum error is in excess of 80 percent. In the low vehicle temperature range,  $180^{\circ}\text{R}$ , the maximum error for the emissivity range of 0.05 to 0.95 is greater than 50 percent for pressures  $10^{-3}$  through  $10^{-5}$  mmHg. This error can be reduced to about 6 percent by using an  $8^{\circ}\text{R}$  helium cold wall and reducing the chamber pressure to  $10^{-6}$  mmHg. It should be noted that the helium cold wall does not reduce the error at  $10^{-3}$  mmHg.

#### CONCLUSION

A conclusion stating a definite course of action is impossible with the multitude of variable parameters; but a general statement can be made. With the exception of extremely low temperature work, a test chamber pressure of  $10^{-5}$  mmHg gives the best thermal simulation accuracy for all parameters considered.

$$Q_{\text{RADIATED}} = \sigma \left( \frac{\epsilon_1 \epsilon_2}{\epsilon_2 + \frac{A_1}{A_2} (1 - \epsilon_2) \epsilon_1} \right) (T_1^4 - T_2^4) \text{ BTU/HR-FT}^2$$

Q = HEAT FLUX

$\sigma$  = STEFAN-BOLTZMANN CONSTANT

$\epsilon_1$  = VEHICLE EMISSIVITY

$\epsilon_2$  = COLD WALL EMISSIVITY

$A_1$  = VEHICLE LATERAL AREA

$A_2$  = COLD WALL LATERAL AREA

$T_1$  = VEHICLE TEMPERATURE

$T_2$  = COLD WALL TEMPERATURE

$$*Q_{\text{CONDUCTED}} = \frac{1}{2} \left( \frac{\alpha_1 \alpha_2}{\alpha_2 + \frac{D_1}{D_2} (1 - \alpha_2) \alpha_1} \right) \frac{\gamma + 1}{\gamma - 1} \sqrt{\frac{R_M}{2\pi}} \sqrt{\frac{P}{T_M}} (T_1 - T_2) \text{ BTU/HR-FT}^2$$

Q = HEAT FLUX

$\alpha_1$  = VEHICLE ACCOMMODATION COEFFICIENT

$\alpha_2$  = COLD WALL ACCOMMODATION COEFFICIENT

$D_1$  = VEHICLE DIAMETER

$D_2$  = COLD WALL DIAMETER

$\gamma = C_P/C_V$

$R_M$  = UNIVERSAL GAS CONSTANT

P = PRESSURE OF RESIDUAL GAS

T = ABSOLUTE TEMPERATURE OF RESIDUAL GAS

M = MOLECULAR WEIGHT OF THE RESIDUAL GAS

$T_1$  = VEHICLE TEMPERATURE

$T_2$  = COLD WALL TEMPERATURE

\* KNUDSEN EQUATION - Page 145 in "Cryogenic Engineering" by R. Scott.

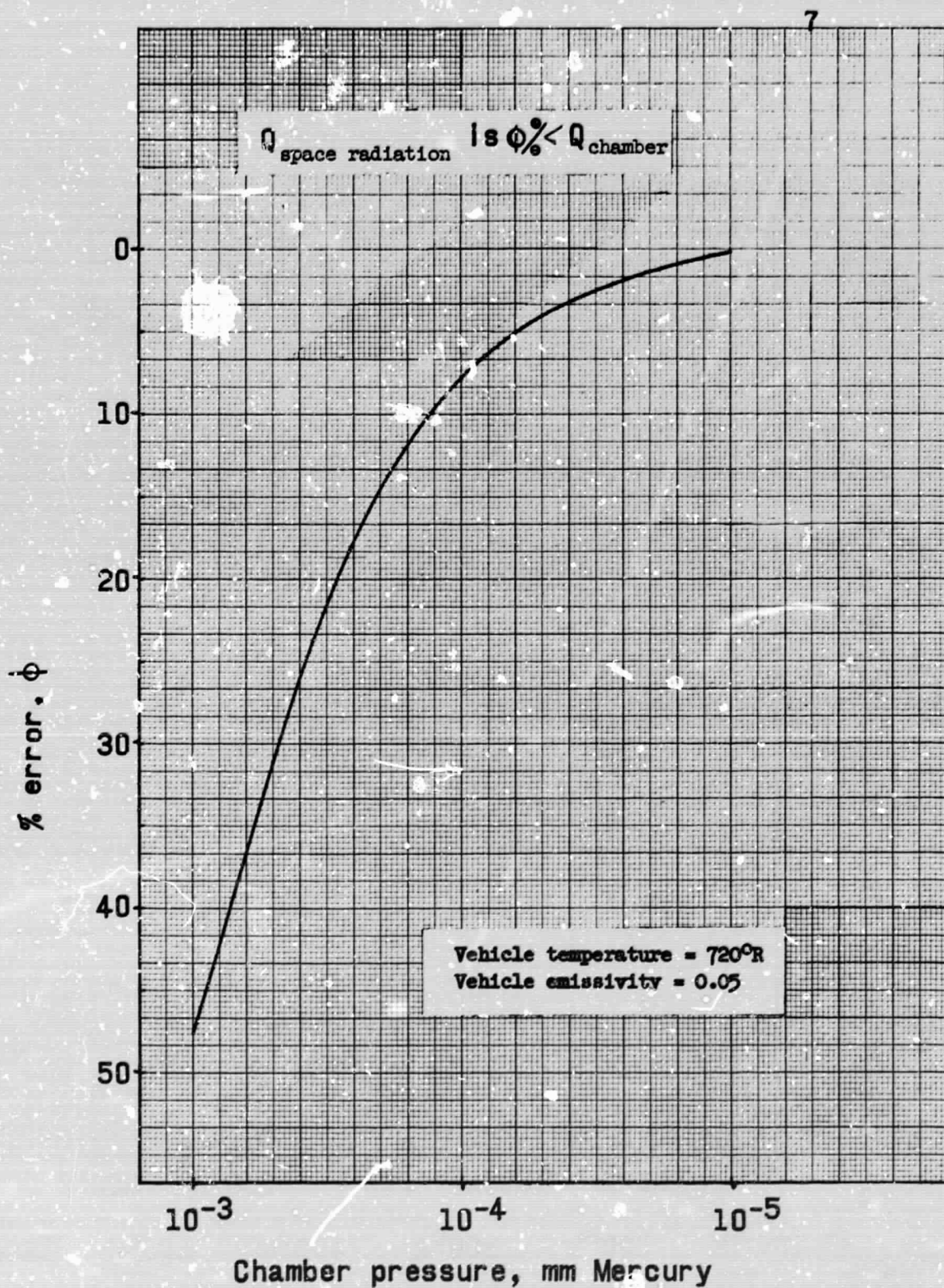


Figure 2.- Heat transfer error in chamber simulation of space.



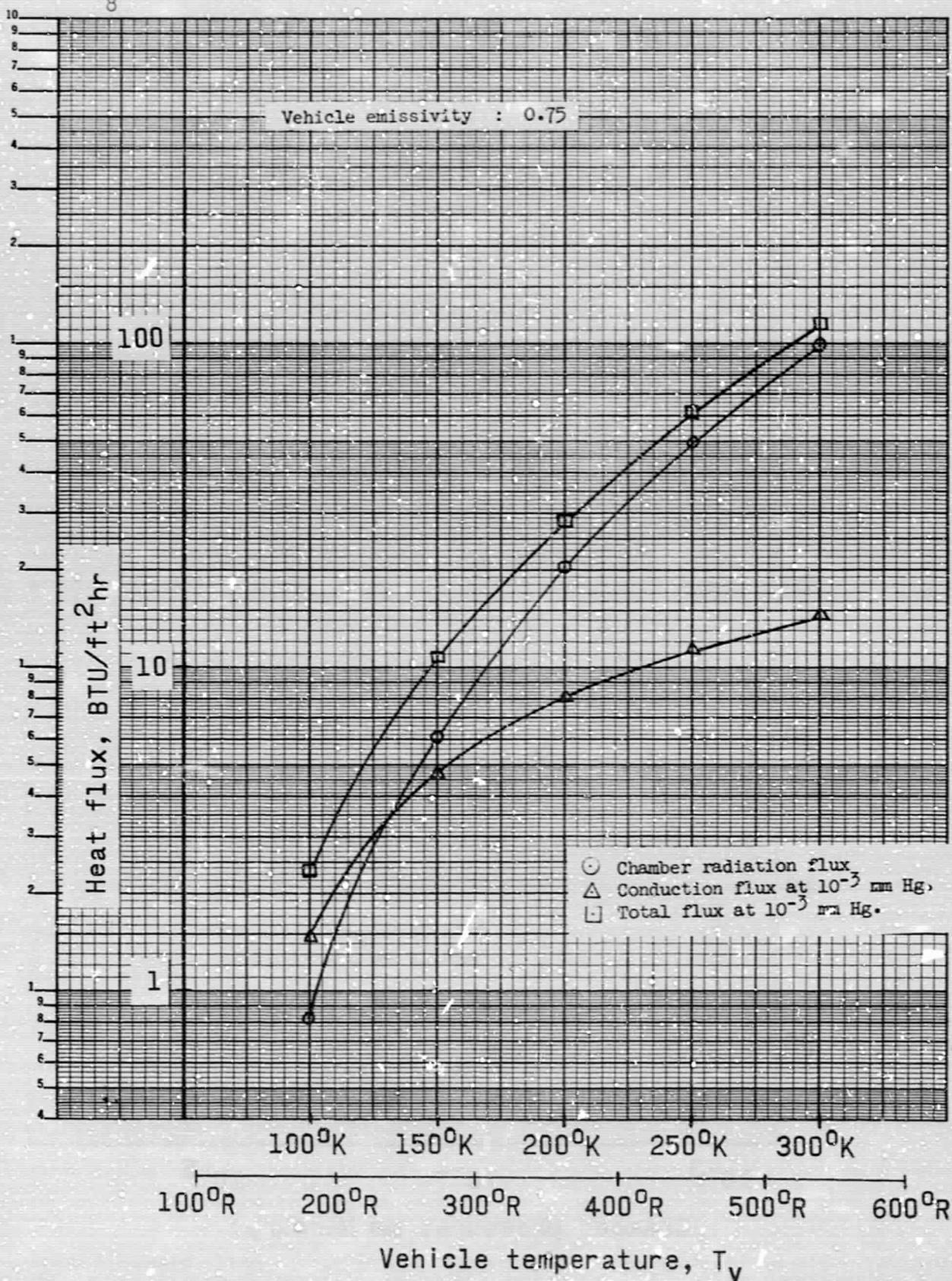


Figure 3.- Composition of chamber heat flux.

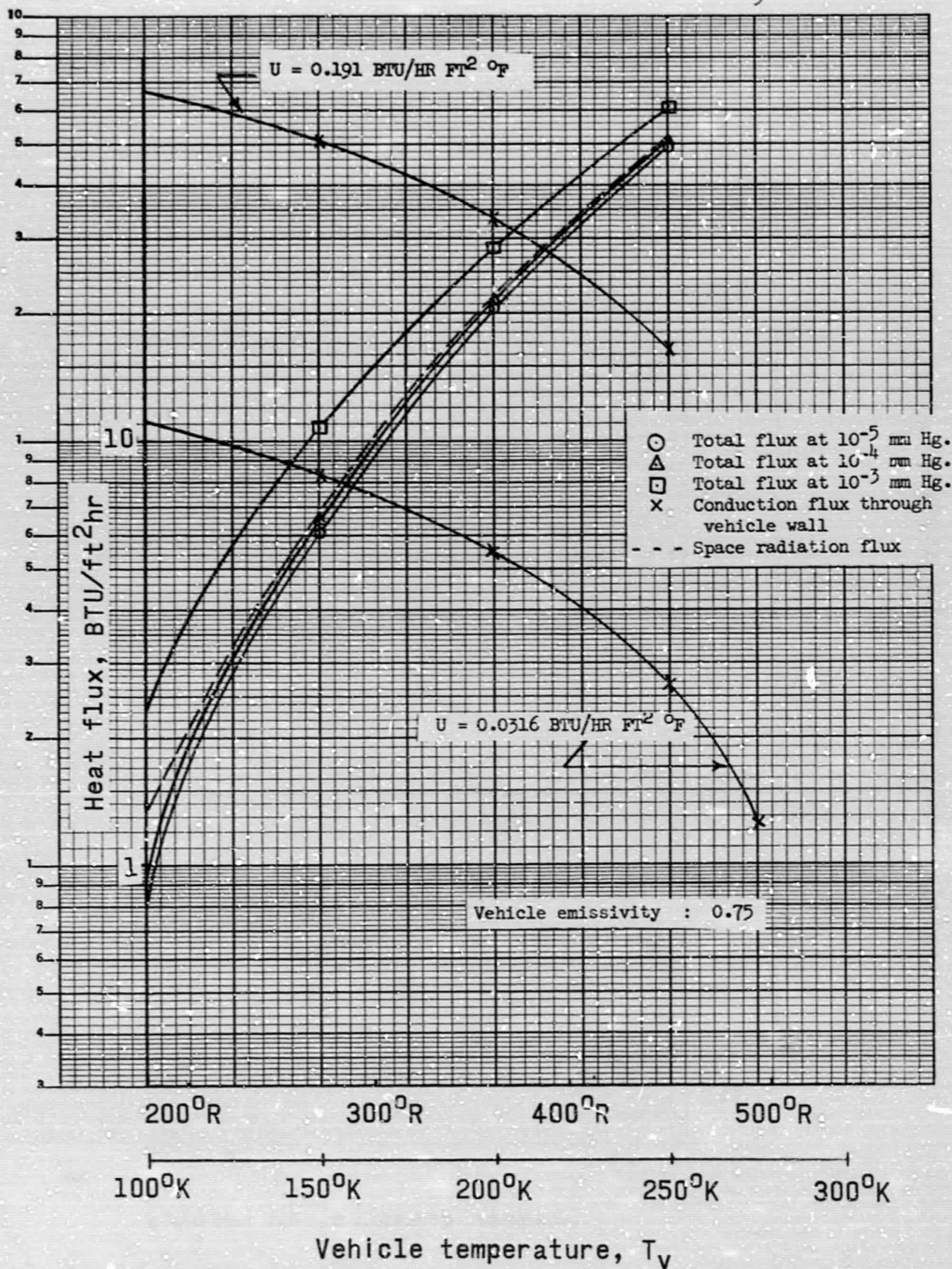


Figure 4.- Heat transfer for equilibrium condition.



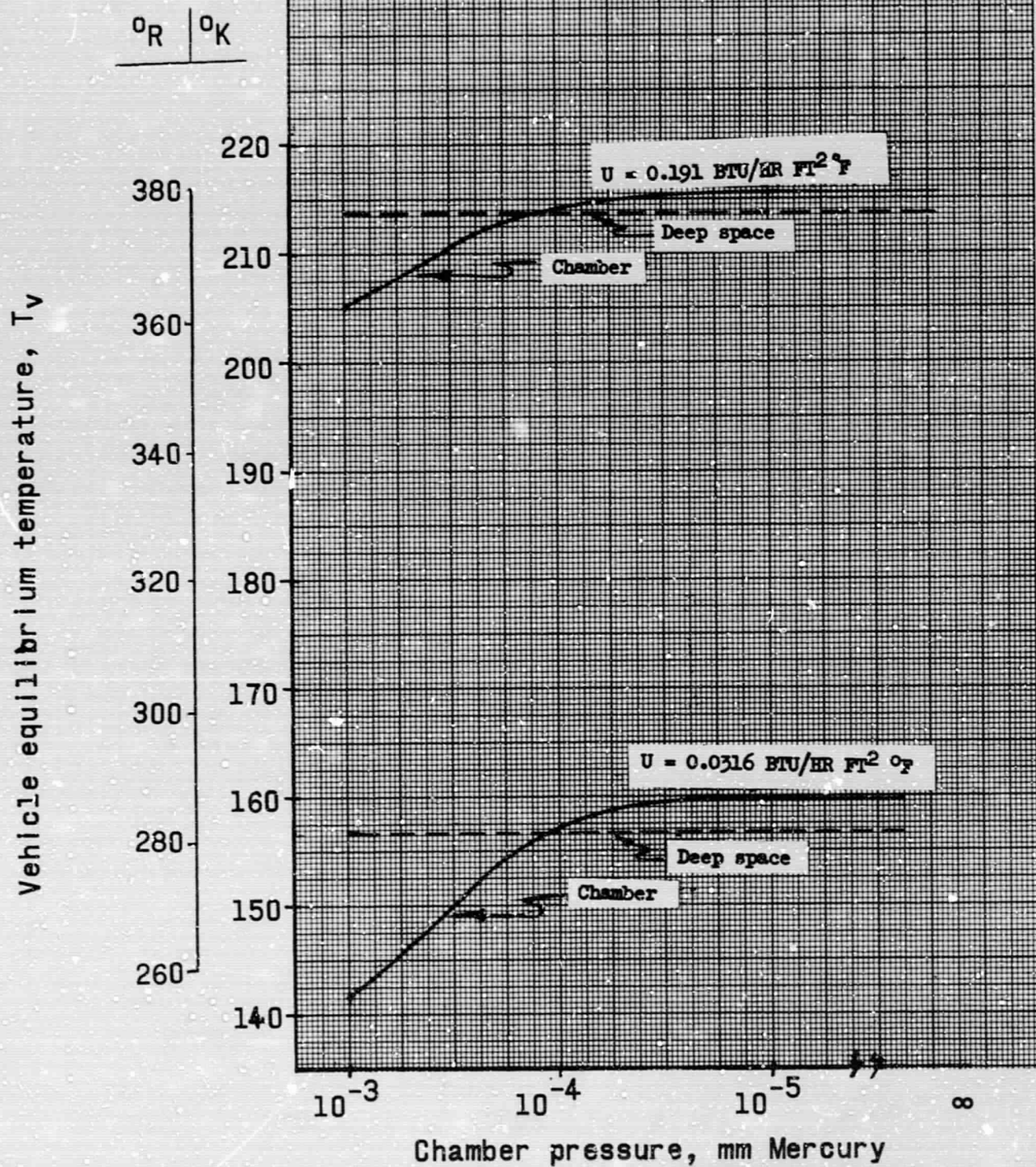


Figure 5.- Equilibrium temperature conditions.

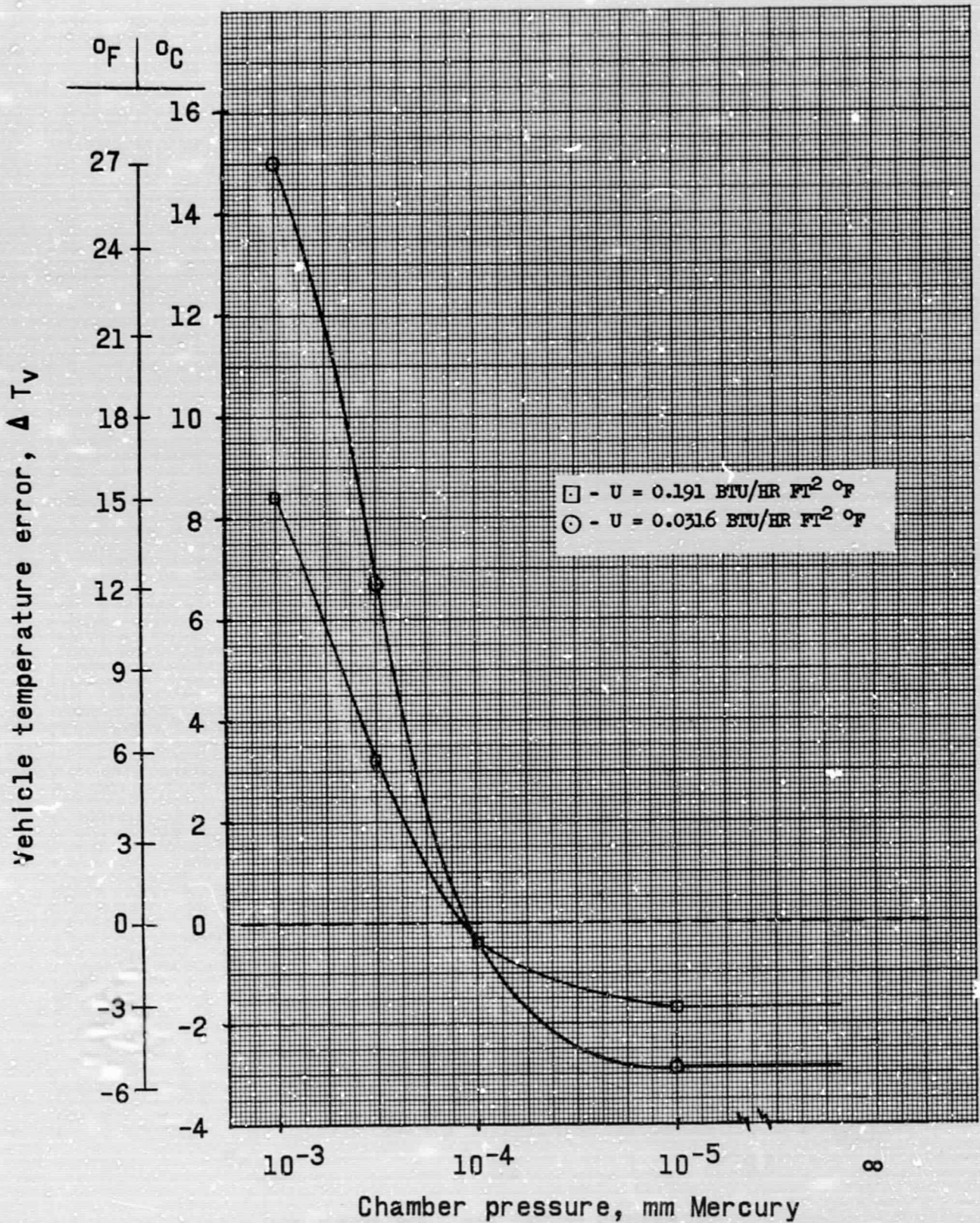


Figure 6.- Simulation temperature error.



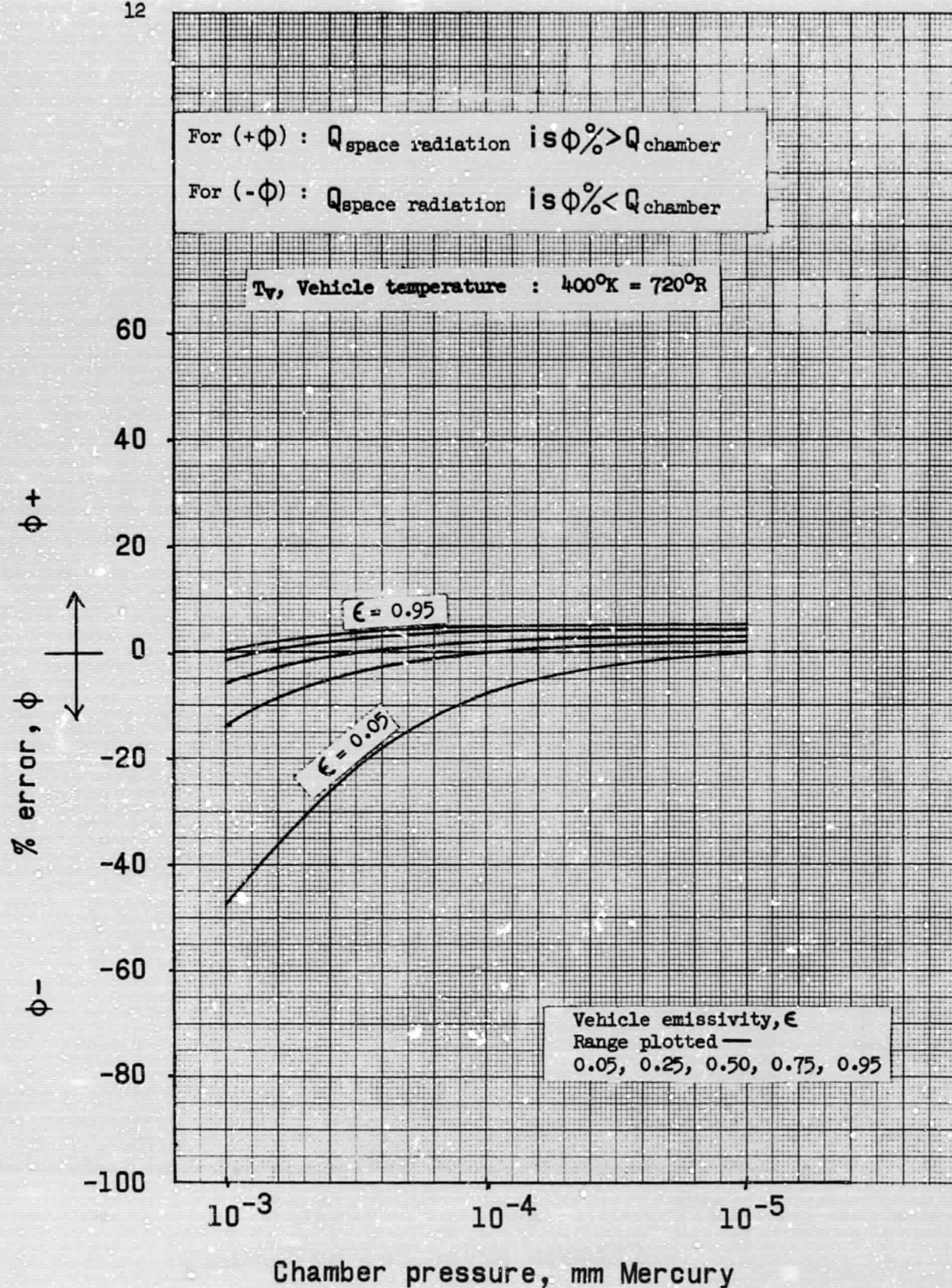


Figure 7.- Simulation error in heat transmission ( $T_V = 720^\circ\text{R}$ )

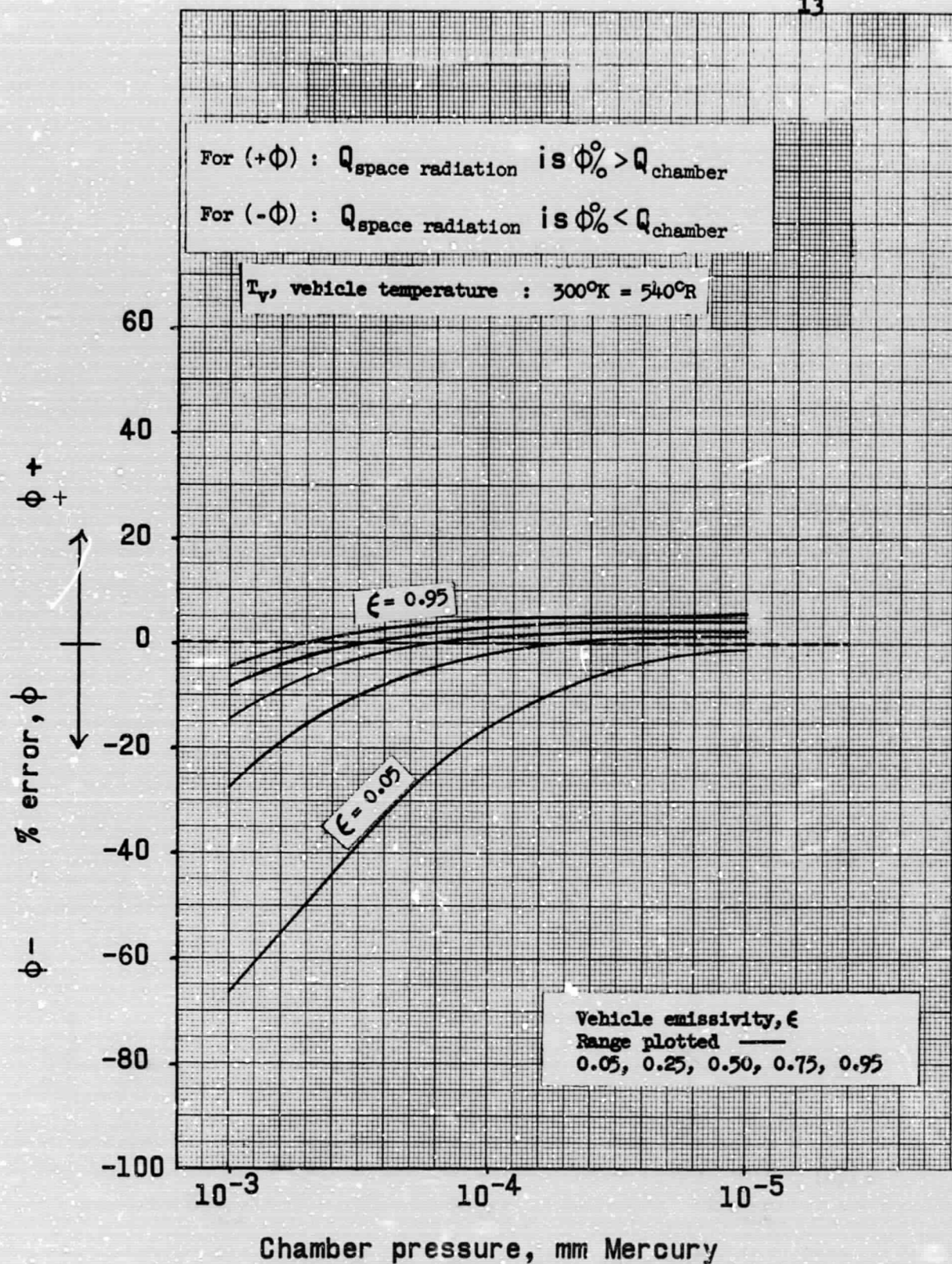


Figure 8.- Simulation error in heat transmission ( $T_v = 540^\circ\text{R}$ ).



For  $(+\Phi)$  :  $Q_{\text{space radiation}}$  is  $\Phi^{\circ} > Q_{\text{chamber}}$

For  $(-\Phi)$  :  $Q_{\text{space radiation}}$  is  $\Phi^{\circ} < Q_{\text{chamber}}$

$T_v$ , vehicle temperature :  $200^{\circ}\text{K} = 360^{\circ}\text{R}$

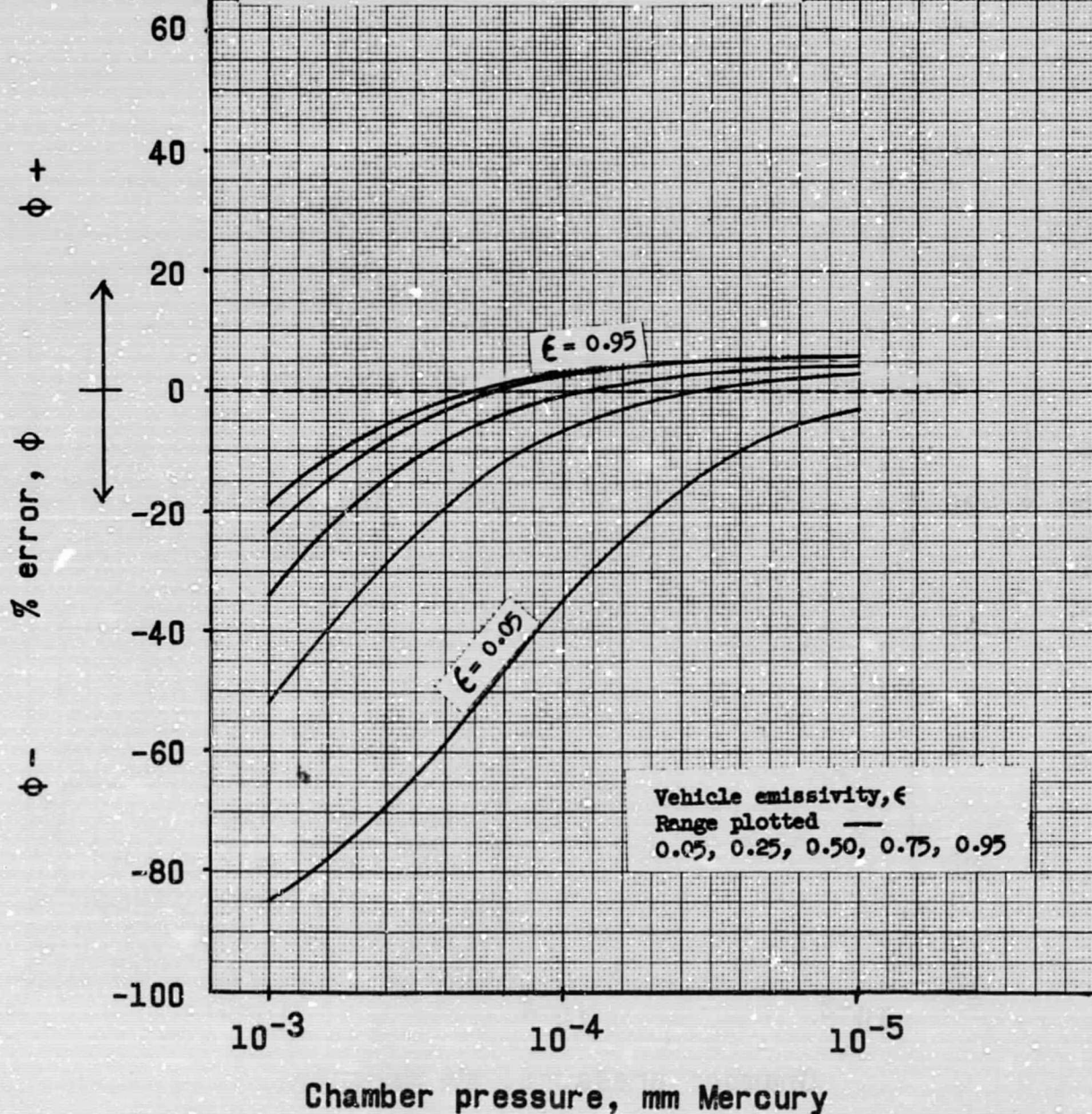


Figure 9.- Simulation error in heat transmission ( $T_v = 360^{\circ}\text{R}$ ).



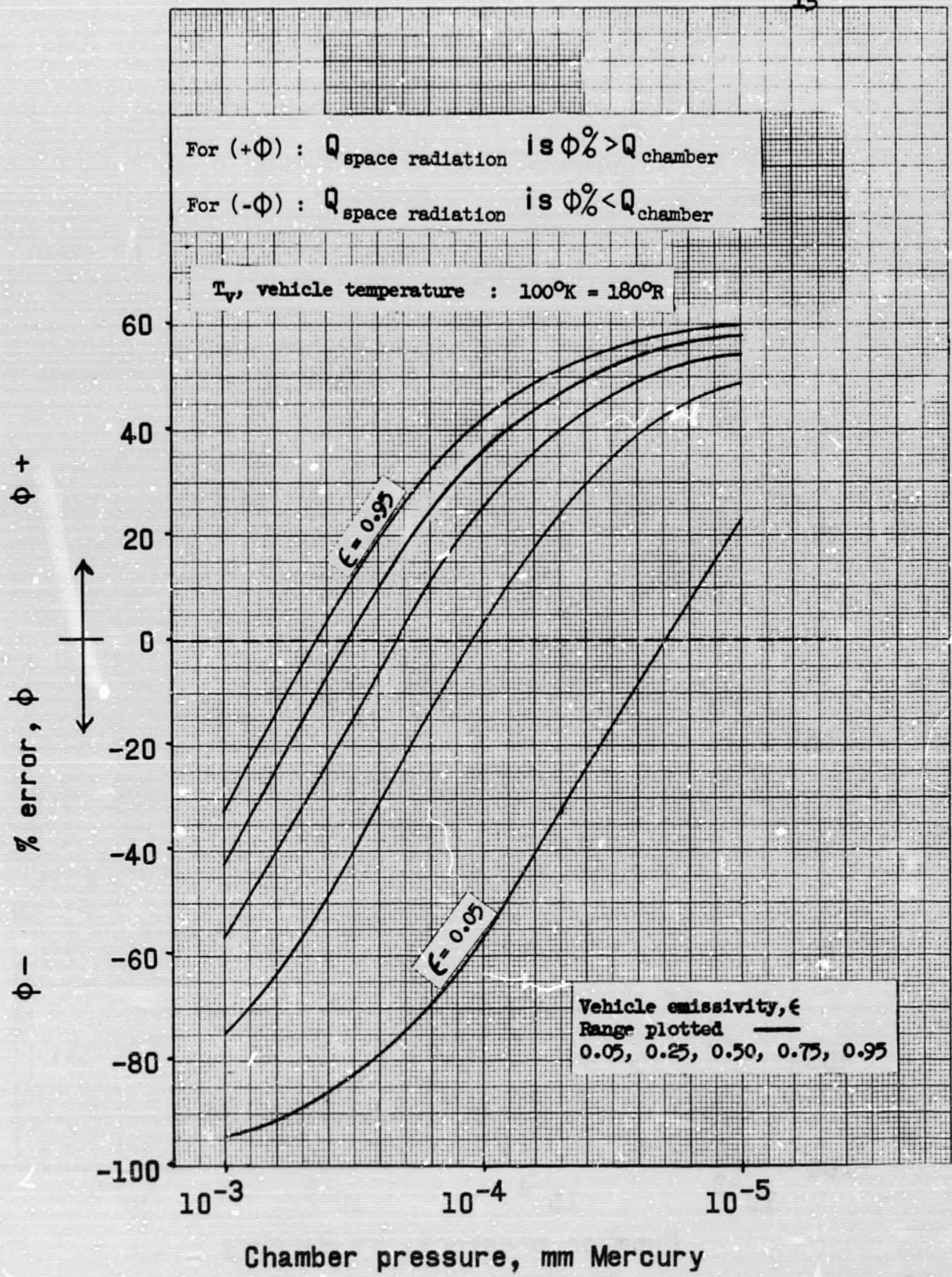


Figure 10.- Simulation error in heat transmission ( $T_v = 180^\circ\text{R}$ ).

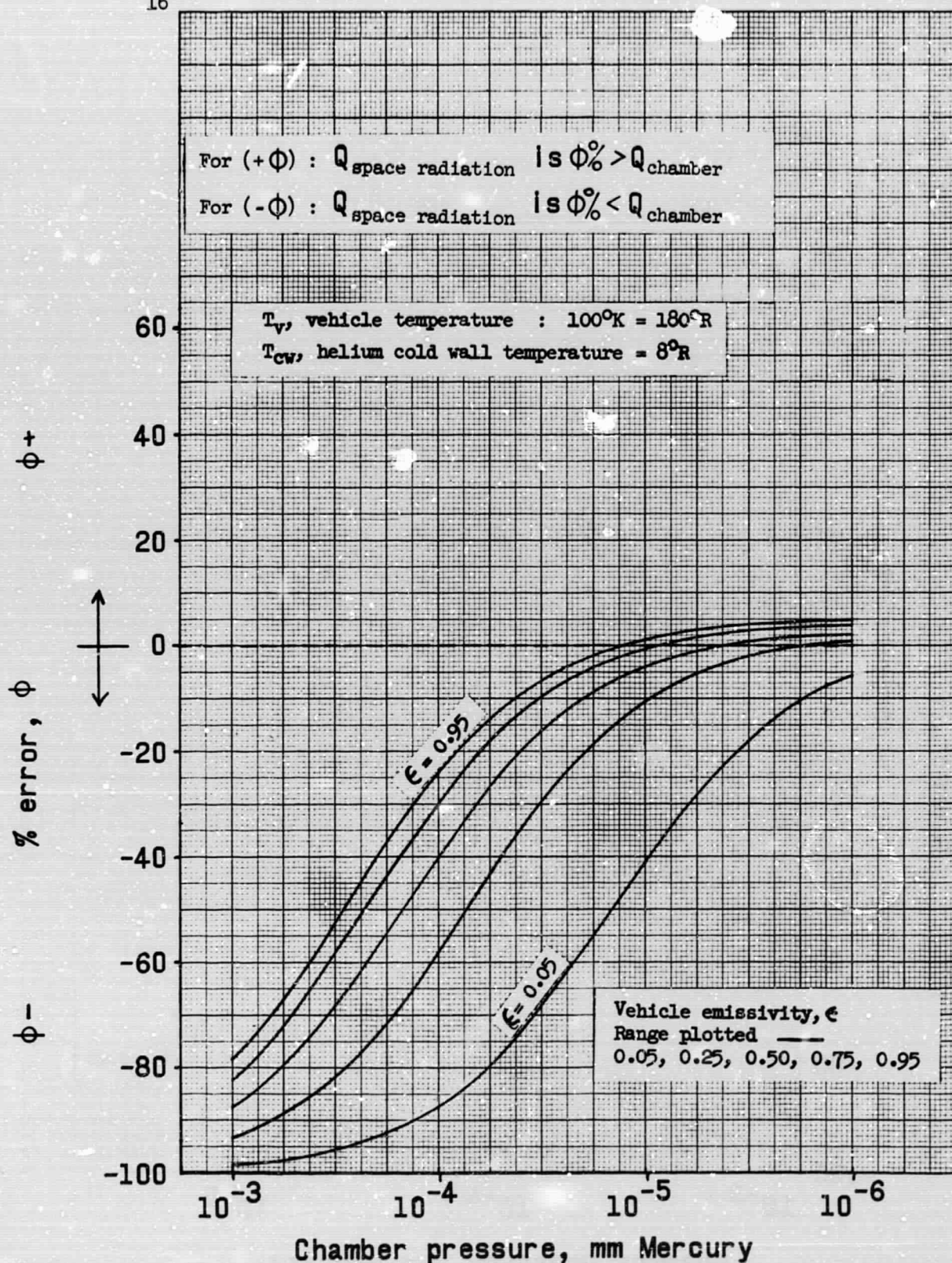


Figure 11.- Simulation error in heat transmission  
 $(T_v = 180^\circ\text{R}, T_{wc} = 8^\circ\text{R})$ .



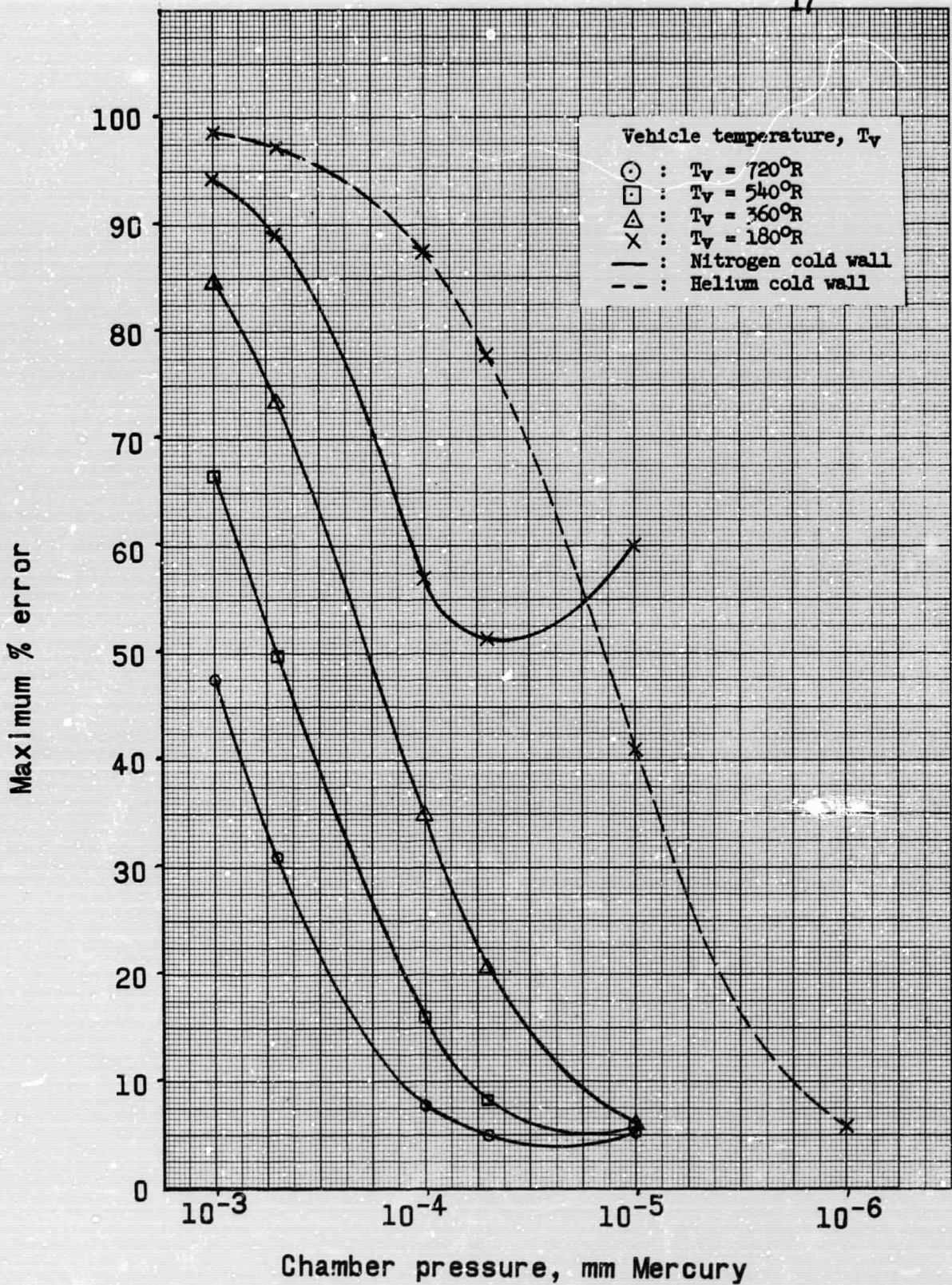


Figure 12.- Maximum heat transfer error for vehicle temperatures of  $180^{\circ}\text{R}$ ,  $320^{\circ}\text{R}$ ,  $540^{\circ}\text{R}$ ,  $720^{\circ}\text{R}$ .