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APPARENT OPERATING LIMITS OF ARC HEATERS WITH RESPECT TO TOTAL ENTHALPY AND STAGNATION PRESSURE[2]

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REFERENCE: Richter, R., "Apparent Operating Limits of Arc Heaters With Respect to Total Enthalpy and Stagnation Pressure," ASTM/IES/AIAA Space Simulation Conference, 14-16 September 1970.

ABSTRACT: For many years arc heaters have been operated over a wide range of operating conditions. An apparent upper limit with respect to stagnation pressure and total enthalpy was found which could not be exceeded. It is attempted to show that this limit is not imposed by the enthalpy-pressure combination but is caused by the limit in total power input that can be achieved with the non-segmented constricted arc heater. The failure or fast deterioration of arc heater components is found to be primarily due to high arc currents which are employed to heat the gas to maximum temperature. It is concluded that the enthalpy-stagnation limit of nonsegmented constricted arc heaters operating under similar constraints can be exceeded.

KEY WORDS: arc currents, arc heaters, constricted arc, enthalpy, operational limits, stagnation pressure

NOMENCLATURE: C = Constant (Relation (1)); D = Diameter, cm; H = Enthalpy, Btu/lb or joules/kg; I = Current, amps; P = Power, watt; V = Voltage, volt; $\dot{W}$ = Mass flow rate, g/sec.; T = Temperature, ^{o}R; h = Heat transfer coefficient, Btu/sec-^{o}R-ft^2; k = Heat conductivity, Btu-ft/sec-^{o}R-ft^2; p = Pressure, atm; q = Heat load, Btu/ft^2-sec or kW/cm^2; t = Wall thickness, inch; σ = Stress, psi

SUBSCRIPTS: A = arc; a = anode; all = allowable; c = constrictor; c = cathode; c = copper; M = melting; T = total; W = water; o = stagnation.

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Arc heaters have long been employed for chemical processing and reentry simulation because of their capability to raise gases to high temperatures. Presently they are primarily used for testing of heat shield materials for manned and unmanned spacecrafts and missiles under conditions encountered during reentry into the atmosphere of the earth or other planets.

For the simulation of the environment encountered during the reentry phase with respect to heat transfer and fluid dynamics, an arc heater has to heat air at a combination of high enthalpy and stagnation pressure. The approximate operating point of an arc heater for simulating the reentry conditions into the earth atmosphere of a manned spacecraft is 40,000 Btu/lb at a stagnation pressure of 1 atm, while that for simulating the reentry conditions of a missile is about 4,000 Btu/lb at a stagnation pressure of 200 atm. The operating conditions for the manned spacecraft have now been achieved, while attempts are still under way to reach the operating conditions needed for the simulation of the reentry conditions of missiles. The obtainment of the desired conditions is apparently subject to limitations. Figure 1 shows the apparent operating limits of arc heaters with respect to stagnation pressure and total enthalpy as they have been experienced by many investigators. It is therefore of great interest to find the physical limits for reaching, with arc heaters, the desired total enthalpy at a given stagnation pressure as well as to determine the operating parameters that set these limits.

The limit to the achievable enthalpy at a given stagnation pressure appeared primarily to be determined by the structural integrity of the arc heater components. In attempts to raise the total enthalpy at a given operating pressure, failures of the electrodes and/or of the containment walls would occur. Failures of the electrodes would be attributed to exceeding the average local heat load on an electrode surface which is a function of the total arc current, the operating pressure, and the attachment point velocity over the surface. The failure of the containment walls could be attributed to stray arc attachments and/or local over-heating.

During the development of several arc heaters and in the course of a special Air Force supported program, a better understanding of the apparent operating limits for arc heaters has been generated. A substantial amount of experimental data was obtained which permitted some correlations of the most important parameters. But as had been found previously by many other investigators, the number of operating parameters in arc heaters is fairly large and their inter-relation rather complex. The main parameters appear to be:

1. Arc Current
2. Operating Pressure
3. Mass Flow Rate
4. Constrictor Design

   a. Diameter
   b. Length
   c. Wall Thickness
   d. Cooling
5. Electrode Design
   a. Magnetically Forced Arc Movement
   b. Magnetic Field Strength
   c. Gas Induced Arc Movement
   d. Vortex Strength
6. Electrode Separation
7. Gas Properties as Function of Pressure and Temperature
   a. Radiation
   b. Electrical Conductivity
   c. Thermal Conductivity
   d. Viscosity
   e. Absorptivity

The possible number of permutations between these parameters is so large that it would be unrealistic to hope for establishing absolute operating limits of arc heaters by an experimental process of elimination. Some form of analysis has therefore to be developed but whose basic assumptions are well supported by a broad experimental background.

The first attempts in that direction have been made by a new analysis of the arc heating process in arc heaters. This analysis still requires some additional refinements and extensions, though it already permits the evaluation and design of constricted arc heaters over an operating regime in which absorption of radiation has no major influence. The author has primarily worked with constricted arc heaters. However, many of the results that will be discussed are applicable to all arc devices, radiation sources included.

Many attempts have been made to analyse the heating process in arc heaters, primarily of constricted arc heaters (Refs. 1,2,3, and 4). These analyses did not predict too well the experimentally obtained results of the author. The author feels that the main reason for the discrepancies between analytical predictions and test data is the inconsistency between the model underlying the analyses and the actual processes taking place in the constrictor. Many investigators, for instance, have based their analysis on the laminar flow through a smooth tube (Refs. 1 and 4). This condition is rarely encountered in a segmented constrictor which has been the type of arc heater investigated by the author. Furthermore, most analyses assumed the flow as well as the arc to develop in a continuous process along the constrictor (Ref. 1). The results of these analyses predict the heat transfer to the constrictor wall to be primarily determined by the local total enthalpy of the gas

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The numbers in parentheses refer to the list of references appended to this paper.

which increases along the constrictor. This, however, was not borne out by our test data and therefore a different analytical approach appeared to be indicated.

The author approached the analysis of the very complicated arc heating process by synthesizing the various physical processes which apparently take place in the constrictor of an arc heater. These processes are individually analyzed and then combined by demanding an overall energy balance as well as stipulating an arc operation with minimum entropy rise. The complete analysis will be presented at a later date in a separate paper.

The main difficulty in applying the synthesized analysis to test data and/or the design of arc heaters lies in the inavailability of fully substantiated material properties for the various gases. The author employed primarily the thermal conductivity, radiation, electrical conductivity, and viscosity data of Ref. 5. With these material properties for nitrogen, fairly good agreement between test data and calculated heat transfer rates and electric fields were obtained over a very wide range of operating conditions, i.e., from less than 1 atm to 97 atm. The analysis was also applied to data reported in the literature. A good agreement with measured arc diameters of an arc operating in a cross flow was found (Ref. 6). The largest variations between test data and calculated values was about 20 percent. This discrepancy is quite acceptable considering not only the uncertainties associated with the measurement of absolute local heat transfer rates and electric fields in arc heaters but also the uncertainty in the materials properties used.

Two types of constricted arc heater designs have to be distinguished. In one type of design the electric arc operates with what the author will call a "natural" arc length, while in the other type of design the arc length is determined by the distance between the two electrodes. These two types of heaters are illustrated in Figure 2. Many variations for each type of heater are possible, though the basic design must be considered unalterable. It is also possible that in both types of arc heaters the polarity of the two electrodes might have an influence but it will become clear from the future discussions that such influence must be minor and can be included into the overall picture of arc heater operation.

In the first type of arc heaters which is shown schematically in Figure 2a, the natural arc length appears to be a function of all major operating parameters, i.e., mass flow rate, operating pressure, arc current, and gas, as well as the arc heater component configuration and the magnetic field strength, if a magnetic field is employed for the control of the arc. When correlating a substantial number of experimental

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data of non-segmented constricted arc heaters (Refs. 7 and 8), an interesting relation between the major parameters appears to be applicable. This relation could be best expressed by

$$V_T = \frac{C \times \dot{W}^m}{I_A^n \times p_o^{\ell} \times D_c^X} \tag{1}$$

The exponents of the parameters were found to be

$m = 0.835 \qquad n = 0.267$
$\ell = 0.129 \qquad x = 1.34$

and the constant for air, $C = 1617$.

Naturally this relation cannot be justified in the strictest sense of an analysis as it is well known that the total voltage is the sum of several individual voltage drops, all of which are dependent on the operating parameters in a different way, i.e.,

$$V_T = V_a + V_c + V_A \tag{2}$$

In most cases the arc voltage is very much larger than the sum of the electrode voltages. This is especially true for high power, high pressure arc heaters.

But, nevertheless, the relation as it stands conveys the interesting effects of the most important parameters on the total voltage. The total voltage-arc current characteristic shows a negative slope with a power of approximately 0.267. This slope prevails at current levels at which investigators of stationary arcs have observed arc operation with a positive slope. The negative slope of nonsegmented arc heaters has therefore to be attributed to a shortening of the arc length with increasing arc current. This deduction is further substantiated by the positive voltage current characteristics of arc heaters which do not permit the arc to shorten itself (Refs. 9 and 10). If the total voltage is divided by the electric field which was found to be also a function of the major operating parameters, the effect of the major operating parameters on the arc length would be expressed.

When multiplying the total voltage by the arc current, relation (1) leads to a relation between the major operating parameters and total input power

$$P_T = V_T I_A \tag{3}$$

The numbers in parentheses refer to the list of references appended to this paper.

$$P_T = \frac{C \dot{W}^m I_A^{1-n}}{p_o^{\ell} D_c^x} \tag{4}$$

From this relation it is seen that the total input power, P_T, is primarily a function of the arc current, the main flow rate, the operating pressure, and the constrictor diameter. The mass flow rate and the constrictor diameter have a strong influence in contrast to the relatively weak influence of the operating pressure. The medium influence of the arc current on the total power input was always quite obvious by the negative slope of the voltage-current characteristic of such heaters. But the most important aspect of this relation is the influence of the mass flow rate, $\dot{W}$, on the total power input. The relation points out quite clearly that if a current limit exists, then there exists also an enthalpy limit. Because the mass averaged total enthalpy is a fraction of the total input power divided by the mass flow rate, the faction being the efficiency, η,

$$H_T = \eta \frac{V_T I_A}{\dot{W}} \tag{5}$$

or

$$H_T = \frac{\eta\, C\, I_A^{1-n}}{D_c^x\, p_o^{\ell}\, \dot{W}^{1-m}} \tag{6}$$

The efficiency was found to be a strong function of the arc current. If we set as a first approximation

$$\eta \sim I^{-z}$$

where the value for z is found to vary between 0.12 and 0.35, the enthalpy, H_T, is given by

$$H_T = \frac{C'\, I^{1-n-z}}{D_c^x\, p_o^{\ell}\, \dot{W}^{1-m}} \tag{7}$$

The exponent 1-n-z is very much less than 1. For that reason we find that for a given arc heater configuration a limit to the achievable total enthalpy at a given pressure exists regardless of arc current.

The important results of this exercise are the following:

1. The arc heater does not have an operating limit that is determined by the total enthalpy of the gas. Quite the opposite, the enthalpy limit is determined by the arc heater.

2. An enthalpy limit is established by the total electric power input for a given gas flow rate and arc heater configuration, as indicated by the strong influence of the constrictor diameter and the mass flow rate on the total voltage.

Relation (7) seems to indicate that the total enthalpy at a given pressure could be increased by decreasing the constrictor diameter, D_c. This is indeed possible. But, when decreasing the constrictor diameter, a new limit is being approached.

When a segmented constricted arc heater was operated over a wide range of operating conditions, heat transfer rates to the constrictor wall could be measured under various operating conditions. In Figure 3 the heat loads on a constrictor when operating with a stagnation pressure of around 1 atm are shown (Ref. 9) while in Figure 4 heat transfer rates for a second constrictor operating at stagnation pressures ranging from 38 atm to 51 atm are shown (Ref. 10). It can be seen in both figures that the heat transfer rates are almost constant over the entire length of the constrictor. This result seems to indicate that the heat loads under the conditions under which the heaters were operated are predominantly a function of the arc current. Some arc devices were tested under conditions and with constrictor configurations for which this was not at all the case (Ref. 9). Under some conditions it could be clearly shown that the measured heat transfer rates were the sum of two heat transfer processes; one as shown in Figures 3 and 4 was almost constant along the constrictor, the other was directly proportional to the local mass averaged total enthalpy. But those were cases which the author does not consider applicable to the present discussion. In Figure 5, calculated heat loads for various arc currents and constrictor diameters are shown. Experimental correlations between local heat transfer rates and constrictor diameters are not available as it was not possible to build a representative number of segmented constrictors of different diameters. Since good agreement was found between measured and calculated heat transfer rates, the use of analytical values can be justified. These correlations show that the heat load increases quite rapidly with decreasing constrictor diameter and that, therefore, a limit exists to how small a constrictor diameter can be made.

This limit to the permissible heat load cannot be a simple one. It is determined by the operating pressure as well as the yield strength at elevated temperature of the material of which the constrictor is built. For any given heat load the wall thickness of a container under pressure has two limits, one limit is set by the maximum allowable temperature of the material; the other limit by the tensile or compressive strength of the material as a function of the effective temperature. If

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the allowable temperature is the melting temperature, T_m, then the maximum wall thickness as a function of heat load is given by

$$t = k \left\{ \frac{T_m + T_w}{\dot{q}} - \frac{1}{h} \right\} \tag{8}$$

For simplicity, a thin wall tube is being considered. When the same assumption is applied to the stress consideration, the relation between pressure and wall thickness is given by

$$t = \frac{\Delta p \ D_c}{2 \ \sigma_{all}} \tag{9}$$

Elimination of the wall thickness t between relations 8 and 9 produces the following limit

$$\dot{q}_{all} = k \ (T_m + T_w) \ / \ \left\{ \frac{\Delta p \ D_c}{2 \ \sigma_{all}} + \frac{k}{h} \right\} \tag{10}$$

This relation has been plotted for copper into Figure 5. The combined results show clearly the constraint on the size of the constrictor diameter.

SUMMARY

The preceeding discussion has attempted to explain the observed stagnation pressure - total enthalpy limit of nonsegmented constricted arc heaters by the rather complex relations between the major operating parameters and the physical dimensions of the arc device. When expanding the experimentally determined relation between total voltage, constrictor diameter, arc current, mass flow rate and stagnation pressure it is realized that the apparent enthalpy limit that was found experimentally with such heaters is effectively a design limit. The destruction of heater components is not at all caused by the stagnation pressure-total enthalpy combination. The destruction or excessive deterioration of components has to be attributed to the high arc current which is employed in an unsuccessful attempt to overcome the basic limit on the total power input imposed by the heater design. The stagnation pressure - total enthalpy limit has been exceeded by the use of a segmented constrictor which makes the arc length independent of the stagnation pressure, the mass flow rate, and the constrictor diameter. Arc heaters with segmented constrictors are subject to new limits whose dependence on the major parameters are not included in this discussion.

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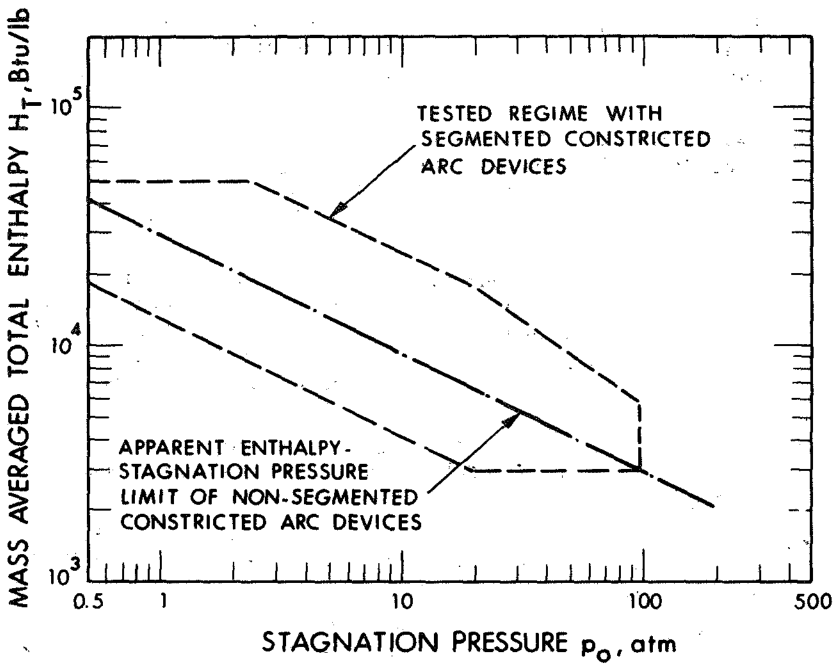
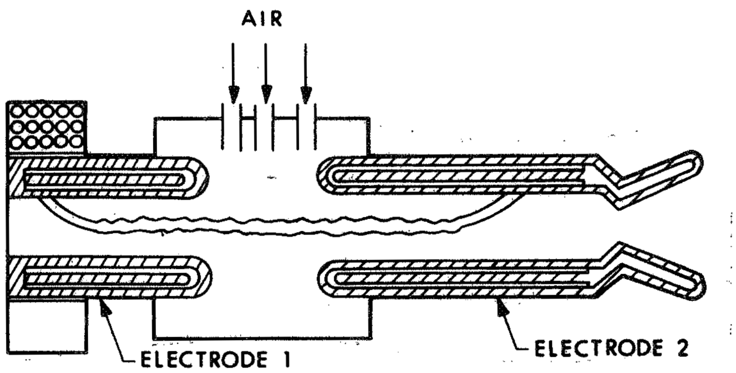
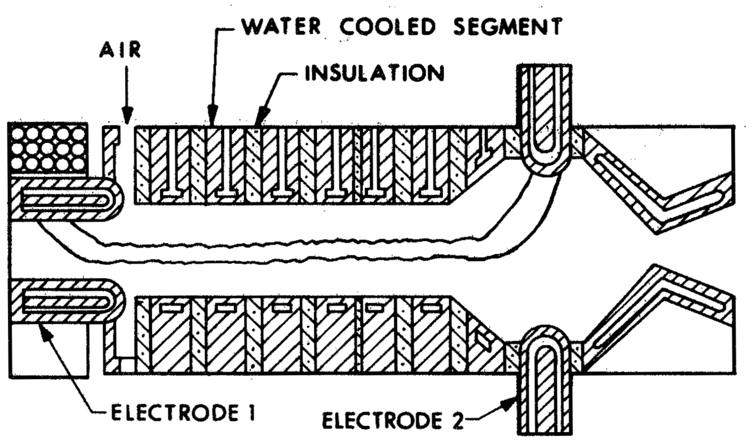


Fig. 1--Experimentally established operating regimes of constricted arc heaters.



a. NONSEGMENTED CONSTRICTED ARC HEATER CONFIGURATION



b. SEGMENTED CONSTRICTED ARC HEATER CONFIGURATION

Fig. 2--Two basic types of constricted arc heater configurations.

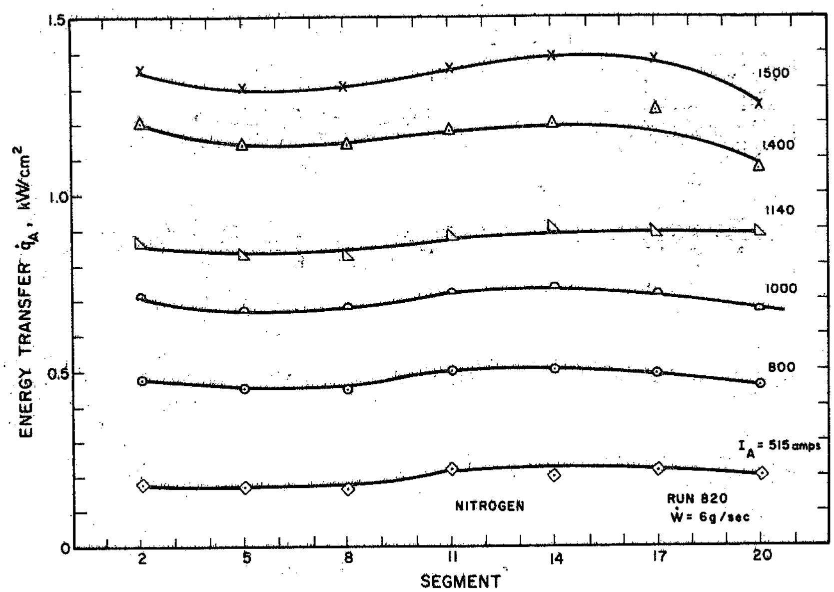


Fig. 3--Measured heat transfer rates along the constrictor of a low pressure arc heater ($\approx$ 1 atm).

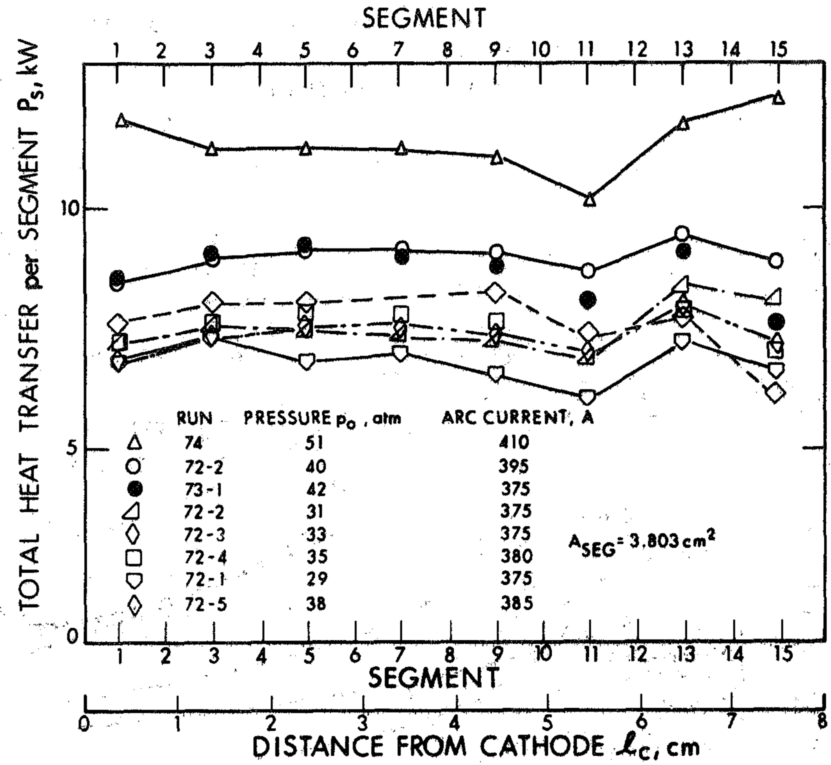


Fig. 4--Heat transfer rates along the constrictor of a high pressure arc heater.

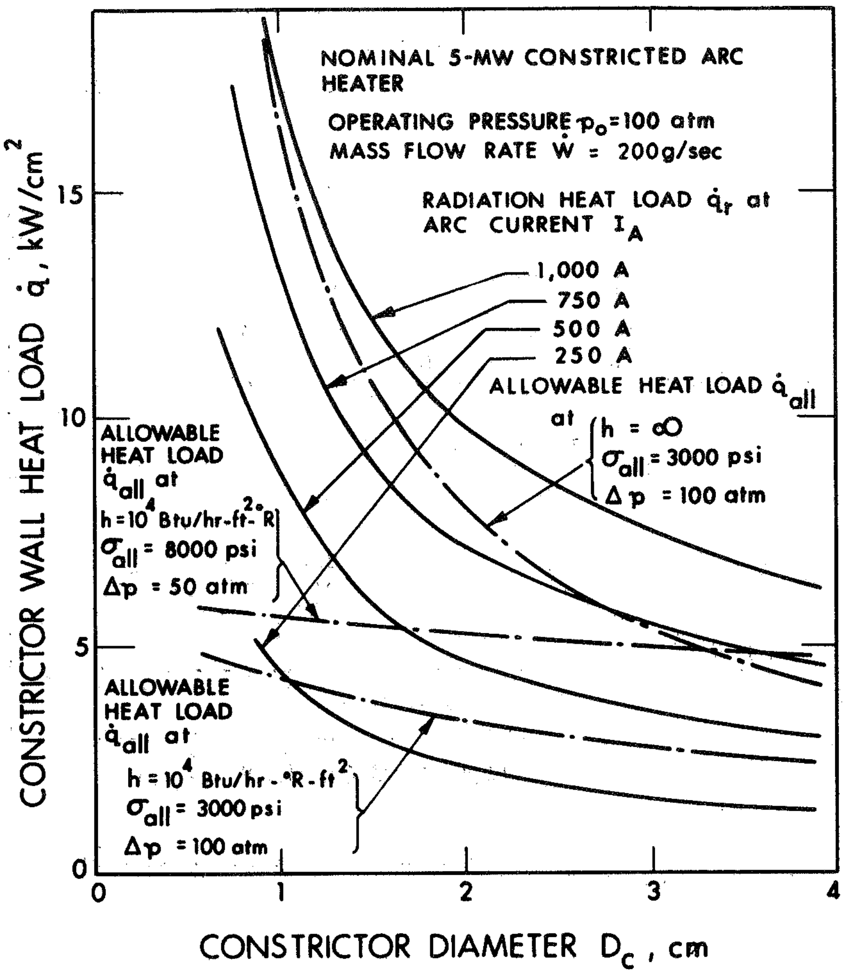


Fig. 5--The effect of constrictor diameter on the maximum heat load and the allowable heat load.