NASA CONTRACTOR REPORT

Upgrading of NASA-Ames High-Energy Hypersonic Facilities -- a Study

Charles E. Shepard
Wm. C.A. Carlson

Eloret Institute
1178 Maraschino Drive
Sunnyvale CA 94087

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Ames Research Center
Moffett Field, California 94035

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Point of Contact: Thomas E. Polek, 229-4
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16. Abstract

This study reviews facility capabilities of NASA, Ames Research Center to simulate hypersonic flight with particular emphasis on arc heaters. Scaling laws are developed and compared with ARCFLO II calculations and with existing data. The calculations indicate that a 300 MW, 100 atmosphere arc heater is feasible. Recommendations for the arc heater, which will operate at voltages up to 50 kilovolts, and the associated elements needed for a test facility are included.

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INTRODUCTION

There has been renewed interest in hypersonic flight recently, motivated largely by the prospect of advances in SCRAMJET performance. Ames Research Center has a number of existing facilities capable of investigating this regime as well as extensive capabilities in Computational Fluid Dynamics (CFD). It is the purpose of this study to investigate the ability of current and scaled up arc heaters to contribute to this research and to evaluate its relative merits compared to other approaches.

This study shows that it is feasible and economical to improve the arc heater heat-transfer and aerodynamic simulation capabilities to better duplicate hypersonic free flight conditions by increasing the power capabilities which will provide larger test section areas and/or higher simulated Reynolds Number and by increasing the operating pressure. The study is mainly concerned with total enthalpies that correspond to flight Mach numbers of about 10 to 25 (2,000 to 12,500 Btu/lb) and altitude of about 100,000 to 250,000 feet. The lower limit is selected which will provide a level of oxygen dissociation and therefore permit studies in the real gas regime. Lower enthalpies than that are in the perfect gas regime and can be produced satisfactorily by heat storage or conventional tunnels.

SIMULATION APPLICATIONS

The altitude and enthalpy limits selected for this study were largely set by the requirements of two applications, the National AeroSpace Plane (NASP) and the Aeroassisted Orbital Transfer Vehicle (AOTV). The NASP flight regime extends from 100,000 feet altitude and 7000 feet per second velocity to 250,000 feet altitude and 25,000 feet per second velocity, as shown in Fig 1. The AOTV regime extends beyond these requirements in both categories. There are many other applications which are appropriate to Ames that should be considered such as earth return from solar, lunar, or satellite orbit. The analysis, which is given later, shows that the upgraded arc heaters could provide heat-transfer and aerodynamic data over a wide range of flight conditions. Thus, although specific applications are being considered, the upgraded facilities will be versatile with respect to other applications which are of interest.

HYPERSONIC FLIGHT SIMULATION

Several hypersonic simulation studies have been made recently (Ref. 1, 2. 3, 4, and 5). This study is intended to complement the others by providing data on arc heaters. It should be emphasized that, because arc heaters operate continuously at actual flight total enthalpies, they can provide valuable hypersonic flight information. By operating at higher pressure than before, the effect of non-equilibrium introduced during expansion through the nozzle can be reduced. In the case of CFD verification, it should be possible to calculate and verify some aspects of the arc heater generated flow particularly properties of the chemically reacting flow in the nozzle and behind the normal shock.

Table I shows the flight conditions that are to be simulated in the 100,000 to 250,000 foot altitude range that is of primary interest (Ref. 6). An enthalpy range of 1,000 to 12,500 Btu/lb, corresponding to a Mach number range of about 7 to 24, is also included. Reynolds number per foot, density and pressure are shown for each altitude and enthalpy. There is need for experimental facilities that can better simulate this hypersonic flight regime where real gas effects can be very important. A dramatic example is the unexpected performance in the pitching moment for the Space Shuttle (Ref. 7 and 8) possibly caused by non-equilibrium flow behind the bow shock. Deviations from equilibrium are difficult to calculate and are therefore uncertain. Experiments are needed to measure the magnitude of such effects and to verify CFD predictions. In addition to the study of external flows, there are numerous internal flows that need to be studied (for example, propulsion systems such as SCRAMJETS).

FACILITY REQUIREMENTS

Discussion. At a October 22, 1987 briefing before a committee studying requirement for hypersonic flow facilities, H. B. Beach, Jr. Deputy Director for Aeronautics at LRC presented the summary of hypersonic flight simulation requirements shown on Table II. Upon examination it appears that electric arc heaters can make substantial contributions in all of the categories listed. These applications are discussed below in some detail below. Preceding this however is a discussion of some of the effects of arc heater test stream non-equilibrium on flight simulation.

A fundamental problem with any supersonic nozzle simulation is the inability to generate actual flight Mach numbers. The required reservoir pressure is simply too high. Nevertheless, the Mach number of most arc heater test streams is generally high enough (say M > 5) for adequate hypersonic simulation and creates no great problems. However, the non-equilibrium nozzle expansion process is of greater concern. This is an inherent condition which comes about from the fact that when thermal energy is being converted into kinetic energy, the rapid drop in pressure prevents the excited species in the gas from maintaining equilibrium. (This problem is experienced with shock tunnels to a lessor degree since the pressure is usually higher.) The result is a test stream which is hotter and moving slower than if equilibrium had been maintained.

The critical question is the effect of the nozzle induced non-equilibrium on the simulation of flight non-equilibrium phenomena behind a shock. Flow that is generated from a higher reservoir pressure will obviously produce a more realistic simulation of flow behind a normal shock. For that reason higher operating pressures are being proposed as part of the arc heater upgrading. On the other hand, much of the nozzle induced non-equilibrium will disappear behind the normal shock and the arc heater test stream is undoubtedly superior to low enthalpy facilities that are incapable of generating any aspect of the flight non-equilibrium. Nevertheless, there are important effects such as an incorrect shock stand-off distance which should be considered. Another problem is the Reynolds number that may be lower that required for exact simulation. However the size of the models possible, duration of test times and duplication of the proper enthalpy are the strong points of these units. It is the authors opinion that the many arc heater advantages outweigh the problems, especially at the higher pressures that are proposed. It is therefore concluded that arc heaters are useful for hypersonic flight simulation, especially when their results are compared with those of other experimental facilities (ballistic ranges and shock tunnels) and with CFD calculations.

Arc heater performance required for simulating some of the required conditions between 100,000 feet altitude and 250,000 feet altitude are summarized on Tables I and III. Table I shows the flight conditions as a function of altitude and total enthalpy. In addition, the arc heater air flow rate (lb/sec) that is required to duplicate the mass flux density and the power input (megawatts) that is required to match the power density of flight are tabulated for four supersonic nozzles whose exit diameter vary from 12 to 48 inches. The contours that are sketched indicate the approximate nozzle exit diameters that can be used with a gross power input of 300 megawatts. This table shows that power density simulation is limited to small nozzle exit diameters as the altitude is decreased.

Table III shows a similar tabulation for pressure simulation. Small nozzle area ratios are needed for pressure duplication as the flight altitude decreases. The arc heaters ability to satisfy the requirements of Table II are discussed below.

Configuration Aerodynamics. The arc heater is capable of providing nearly proper free stream velocity from a conical nozzle (at low enthalpies about 85 percent of the velocity is achieved while at high enthalpy the level is about 60 percent), and satisfactory test times over the range of altitude and flight velocities shown in Tables I and III. Mass flux and Reynolds number simulations are possible at small nozzle sizes or lower flight velocities as shown in the tables. Surfaces exposed to a stream exiting from a semi-elliptic nozzle can simulate boundary layer build-up accurately.

Aerothermodynamics and heat transfer. Historically arc heaters have been employed to perform thermodynamic testing since they can duplicate heating rates for long test times for most conditions. They do fall short of duplicating the radiative component for conditions such as those of the AOTV. However this component can be added via radiative lamps to supplement that provided by the arc heated stream. If the test gas is made to duplicate the environment of interest, the wave length of the radiation from the arc heated stream will be correct as opposed to the supplemental from radiative sources which will typically not be correct. Existing equipment was operated at 60 MW and relatively low pressure to duplicate the conditions for the Space Shuttle. Scaling up to 300 MW at higher pressures will provide conditions capable of simulating most mission conditions. Larger size test specimens will increase confidence levels in test results such as the investigation of catalytic effects on surfaces of sharp nosed vehicles. The thicker shock layer will increase the time available for the species to reach equilibrium before it reaches the surface of interest. Actively cooled models are apt to have shorter times required to reach thermal equilibrium and will permit shorter testing times than was required for the insulated layer thermal protection scheme. Panel sizes up to approximately 3 feet square could be accommodated.

Combuster engine performance. Arc heaters are capable of providing the approximate velocity, enthalpy, density and test times required for these tests, however the scale available at 300 MW is limited and evaluations would be required to establish whether such scale tests would be meaningful. The improper chemical composition of the free stream due to its non-equilibrium condition is also undesirable. It appears that the amount of hydrogen required for such tests would result in storage volumes and flow amounts leading to safety requirements which would not be compatible with the confined conditions near the existing arc heater complex. This complex contains many utilities such as vacuum, water, high pressure air and an existing nominally 150 MW versatile DC power supply. These utilities would be very expensive to duplicate elsewhere. However it may be possible to utilize the conditions provided by these arc heaters, both 150 MW and 300 MW, to conduct very short duration tests of limited hydrogen flow rates to obtain valuable information pertaining to the validity of proposed concepts.

Inlet nozzles and propulsion airframe integration. The conditions required for these tests are essentially the same as for the section above with the exception that the test may require exposing the system to a free jet whereas the above could be conducted in a direct connection to the arc heater. This requirement will required a larger test stream and consequently greater power or smaller sized test body. If these tests can be done without introduction of excessive hydrogen the above safety problems would be reduced.

Boundary layer transition. Tests in the semi-elliptic nozzle attached to the 60 MW arc heater operating at 10 atmospheres pressure have produced turbulent streams over the test area downstream of the nozzle. Adjusting the pressure should provide a regime where transition to turbulence could be studied. Size and test times should be adequate to perform any investigations required.

Structures and aerothermal loads. Larger arc heater units will provide a test area where larger sections of structures from devices of interest can be inserted for testing. Stagnation pressures can be duplicated over limited areas as indicated in the tables. External means of loading the test articles can be provided to simulate the conditions of a section normally surrounded by other elements. Velocity, enthalpy and test times can be simulated.

CFD Verification. It is possible to calculate and verify some aspects of the arc heater generated flow. In particular, the properties of the nozzle flow and of those behind a normal shock, particularly at the higher pressures, could be compared with CFD calculations.

Hypersonic Simulation Facilities. A list of hypersonic flight simulation facilities would include:

1. Ballistic and launcher free-flight range.
2. Shock tubes.
3. Shock tunnels.
4. Stored energy (e.g., pebble bed) tunnels.
5. Conventional hypersonic tunnels
6. Electric arc jets.

These devices have their strengths and weaknesses. Briefly, the major limitation of each facility type is:

1. Ballistic free-flight ranges are limited to small, strong, models flying at near zero angle of attack and providing very short test times with data obtained by stationary instruments required to be taken from a model in transit, while integrally mounted instruments must be very small and rugged and typically less accurate.

2. Shock tubes Mach numbers are low (less than 10) and testing times are very short.

3. Shock tunnels have a short test time (less than .001 sec) and test streams suffer from being out of chemical equilibrium similar to arc heaters.

4. Stored energy and continuously operating heated tunnels have a low total enthalpy (less than 1,000 Btu/lb) and consequently do not provide streams capable of producing real gas effects.

5. Conventional tunnels have the same limitations at the stored energy tunnels of item 5.

6. Arc heaters operate at relatively low pressure and thereby produce more non-equilibrium nozzle expansion effects than shock tunnels. Also Mach number simulation is poor due to nozzle viscous effects and excess temperature in the free stream.

NOZZLE REQUIREMENTS FOR SIMULATION

Nozzles. Arc heaters, pebble-bed heaters, and shock tunnels rely on supersonic nozzles and therefore share the simulation problems of a supersonic nozzle. Although exact duplication of flight conditions is impractical (e.g., at 100,000 feet, Mach 20 would require a nozzle reservoir pressure of about 300,000 atmospheres), useful simulation can nevertheless be achieved.

The problems with flight simulation via supersonic nozzles are:

1. It is impractical to duplicate flight Mach number and static properties.
2. The flow freezes at a relatively low Mach number (between M = 1 and 3). Further expansion produce an incorrect chemistry and non-equilibrium properties.
3. Nozzle wall boundary layer buildup (and excess temperature in non-equilibrium conditions) limits the Mach number.
4. Nozzle are difficult to design due to a lack of accurate CFD nozzle codes.

The simulation of flight conditions by a "ideal" nozzle (no boundary layer, adiabatic) is tabulated in Table I for the duplication of flight mass flux density. This is the simplest simulation where the arc heater mass flow is equal to the flight rho*u times the test section area. This is equivalent to Reynolds number simulation for a full sized model and an assumed viscosity ratio of unity. Table I shows the required arc jet flow rate for various test section diameters (inches). This table shows that a flow rate of about 84 pounds per seconds is required for a 24 inch diameter nozzle at 100,000 foot altitude, while at 200,000 feet, about 5 pounds per second would supply a 48 inch diameter nozzle.

A similar simulation for the pressure behind a normal shock is shown in Table III. This would be useful in duplicating the Fay-

Riddell convective stagnation point heat transfer where q is proportional to the square root of total pressure. The table shows that it is more difficult to duplicate $p_{t,2}$ than rho*u and that reducing the throat diameter increased the required pressure.

ARC HEATER PERFORMANCE CALCULATIONS

The parameters for the proposed arc heater were produced using codes developed in the course of this study. Since the ARC FLO computer code provides a good estimate of the arc jet operating conditions that are necessary to achieve the required performance, they were used as the main source for developing these codes. The procedure is described in Appendix A. The results of this procedure are tabulated in Table VI. These equations for enthalpy, voltage, constrictor wall heat transfer rate, and efficiency are considered as function of current, pressure, flow rate, and constrictor diameter. The calculations are not exact, since the exponents are probably functions of the operating parameters. Nevertheless, they are useful in determining the major trends and are very helpful as a design tool. The maximum error in enthalpy is 11.3% as shown in Figure 2 where enthalpy from the multiple linear regression curve fit is plotted against the ARC FLO calculated values. Slightly larger maximum errors occurred with voltage (12%) and wall heat transfer rate (20%). Figures 3, 4 and 5 shows the quality of the curve fit for voltage, wall heat rate and efficiency. It is now possible to estimate arc heater performance for any desired set of operating conditions with sufficient accuracy for design purposes.

Scaling laws. In order to examine the form of the equations of Table VI, a few are repeated below in a slightly different form:

Enthalpy: $H = 574 * (I/D^{1.5})^{.489} * P^{-.241} * M^{-.017} * D^{-.0005}$

Voltage: $V = 3018 * I^{.053} * P^{.423} * M^{.29} * D^{.024}$

Wall Heat: $Q = .0631 * I^{1.036} * P^{1.027} * M^{-.35} * D^{-.662}$

Efficiency: $E = 203 * I^{-.462} * P^{-.69} * M^{.74} * D^{-.872}$

Enthalpy. The above formula that groups current and constrictor diameter together, shows that enthalpy is insensitive to air flow rate. If the effect of flow is omitted, the equation can be approximated by the following:

$$H = 525\ (I/D^{1.5})^{.5} * P^{-.25}$$

Figure 6 shows the excellent fit of the scaling law enthalpy to the ARC FLO enthalpy calculations. This law is similar to the Winovich/Balboni scaling law of reference 9 which can be expressed as:

$$H = \text{constant} * (I/D^2)^{.624} * P^{-.311}$$

Both of the above equations show that enthalpy is a function of pressure to a small negative exponent. The value of the exponent in the I/D^n term should be the subject of further study. In the small early constricted arc heaters, that exponent was unity.

The effect of length is not shown in the above scaling law, but is nevertheless a very important result of this study. For uniform flow injection along the constrictor disk that is used at Ames, it was found that enthalpy continued to increase with length until the flow choked. This is very different than for upstream flow injection where the enthalpy reached an asymptotic value at a L/D of about 50. The improvement with length varied but for any given case it was found that enthalpy varied as some power of L/D, typically 0.5 for those cases where the flow was far from choking. The effect for all cases can be seen in Table V where the results of the ARC FLO calculations and the extensions to larger L/D's are given. A simple curve fit of length for the entire set of ARC FLO calculations could not be found.

<u>Voltage</u>. The set of equations for voltage show an insensitivity to both current and constrictor diameter. The low exponent for D was unexpected. For example, Nicolet determined the exponent to be 0.75 in reference 10. The consequence is that the present

equation predicts that arc voltage depends only on the L/D ratio and is otherwise independent of length.

Constrictor Wall Heat Rate. This equation is notable in that the wall heat flux varies linearly with both current and pressure.

Efficiency. Efficiency decreases with increasing current, pressure and constrictor diameter and increases with increasing flow rate. Part 2, of Table VI, where sonic flow has been introduced, gives a clearer picture of efficiency. Here efficiency varies with the 1.5 power of the nozzle throat diameter. Thus for high efficiency, the nozzle throat should be as large as possible.

Extended sets of equations. A better set of "independent" variables substitutes nozzle throat diameter for flow rate and is obtained by using the Winovich sonic flow relationship. These equations, given in Table VI Part (2), are used for performance calculations. A third set of equations, Table VI Part (3), include wall heating rate for the purpose of calculating performance at a given Q.

The scaling laws were built into a "spreadsheet" and a number of calculations were made. Table VII shows a typical calculation. After entering the constrictor diameter, arc current , pressure and flow rate a number of quantities are calculated. These include enthalpy, wall heating rate, voltage, gross power, net power, efficiency, and throat diameter. A number of limits have to be considered. They are:

voltage (50 kV max)

constrictor wall heating rate. (6,600 Btu/ft2s=7.5 kW/cm2)

gross power (300 MW max)

Also, the throat diameter must be no larger than the constrictor diameter.

Calculations were made for constrictor diameters of from 6 cm to 16 cm. The results of these calculations were:

(1) highest efficiency was obtained if the nozzle throat diameter was approximately equal to the constrictor diameter.

(2) A relatively small constrictor diameter was required to keep the gross power level below 300 MW.

(3) Extending the constrictor length to 100 diameters raised enthalpy and voltage. At high pressures the voltage was very high and a shorter arc was necessary.

Table VII also includes calculations for a 150 MW, 25 kilovolt arc heater. These calculations shows that the lower voltage of the present power supply severely limit the performance at high pressure. For example as a result of the 25 kV limit, at 100 atmospheres the maximum flow rate is less than one tenth that of the 300 MW heater.

Tables VIII and IX show the maximum performance for the 150 and 300 megawatt arcs. Simulated altitudes are also shown. The results are also given in Figure 7 and 8. The 150 MW arc can operate at about the same pressure and altitude levels as the 300 MW arc, but the mass flow rates are much lower. This results in a lower Reynolds number (or a higher altitude). Figure 8 shows the effect of lower flow rate on the maximum Reynolds number or minimum altitude for the two arc heaters with the 24 or 48 inch exit diameter nozzles.

Effect of cooling on radial profiles. The ARC FLO calculations, that describe the arc heating in great detail, can also show the effect of cooling on radial profiles. This process is discussed in Appendix B. The effect of cooling is a loss in mass-average enthalpy that may be significant at high pressure and high enthalpy. It also causes a profound flattening of the radial enthalpy and mass flux density profiles, as shown in Figures 9 and 10.

Nozzle throat heat transfer rate. This potential limit on arc heater performance is discussed in detail in appendix C. The calculation has been included in the spreadsheet performance calculation of Table VIII. At maximum constrictor wall heat transfer rate the nozzle heat rates are high but can be managed by conventional cooling techniques.

Verification of the scaling equations. The scaling equations are verified by comparing the predictions with experimental values of enthalpy and voltage. (Wall heat rates are usually not available). Figure 11(a) shows the enthalpy comparison for Ames 20 MW arc heater data points plus those 60 MW data points that are tabulated in ref 9. Other data from the Ames 60 MW arc heater could not be compared with the ARC FLO calculations because of the large amount of scatter, possibly due to a faulty air flow meter. In order to verify the predictions at high pressure, the AEDC data of reference 10 was compared with ARC FLO in Figure 11(b). The correlation was surprisingly good, with the AECD enthalpy about 7 per cent higher than ARC FLO.

The voltage verification with Ames 20 and 40 MW arc heaters show much scatter as shown in Figure 12(a). The agreement is fairly good at low voltages (3kV and less), but diverges at higher voltage. Because the AMES data is generally for pressures less than 10 atmosphere the AEDC HEAT arc heater was again used for comparison. In Figure 12(b), the voltage gradients were compared. The AEDC voltage gradient for uniform flow injection was about 25 per cent higher than the ARC FLO for distributed flow injections. In view of the fact that ARC Flo would have predicted higher voltage gradients for the AEDC heaters which use upstream flow injection, the agreement is satisfactory.

Considering all these limitations, the correlation is considered to be meaningful.

RECOMMENDATIONS

Arc Heater. Based on the above, it its recommended that a constricted arc heater be developed for use in the larger facility which would be 8 centimeters (3.15 inch) in constrictor diameter, have length to diameter ratio which could be varied from 50 to 100, operate at 100 atmospheres, and have its wall heating rate limited to about 6600 BTU per foot squared second. According to the scaling laws (discussed previously and described in Appendix A) this unit will operate at 50,000 volts at a current of 6000 amperes. This voltage will be provided by the entire proposed power supply connected in series. The current requirement is also within the capabilities of the power supply and has been achieve previously by the Giant Planet Pilot Facility heater. Improved performance of heater components required is discussed in Appendix D. The most pressing of these is probably a design which will insure division of arc current to multiple electrodes at the higher pressure conditions. The only previous experience at these pressures has been at AEDC where they have not been successful in achieving reliable division. However the electrode configurations they have used have been first generation components and have not included components specifically designed with this problem in mind. Earlier version of the constricted arc jet injected all of the air at the upstream end. Gradually the practice of injecting air along the constrictor tube has been accepted. This mode of air injection results in better stability and is in harmony with the idea of "wall-stabilized" arcs which were the basis of the modern arc jet. The ARC FLO calculations were made for 67 per cent distributed air injection.

From the above discussion, the best configuration is an upgraded version of the present Ames constricted arc jet which is operated on D.C. Major elements of the facility which will require attention include the power supply, vacuum system, water system, NO scrubbing system and the building required to accommodate the units. The suggested schematic diagram of the facility is shown on Fig. 13. The major elements will be discussed below.

<u>Vacuum System</u>. It is suggested that the vacuum requirements for the larger facility be meet by utilizing the existing pumping and storage capacity of the 3.5 foot wind tunnel. This is feasible if an auxiliary pilot arc (to be discussed in appendix D) is used for arc starting purposes. If a single stage steam ejector is placed between the test section and the vacuum spheres a pressure of about 0.015 atmospheres (11 mm Hg) could be maintained while flowing 25 pounds per second for about five

minutes. For higher flow rates of up to 70 pounds per second a run time of about one minute would be available with discharge pressures not exceeding 0.15 atmospheres (114 mm). Steam to drive the ejector would be that available from the present steam plant. The proposal is covered more completely in Appendix E. The shorter test times appear to be satisfactory since improved instrumentation permits rapid gathering of data and the duration required to reach equilibrium in actively cooled thermal protection systems is short.

Cooling Water System. The water system would be comprised of a combination of the currently available storage, heat exchangers and storage combined with approximately 9000 gallons per minute of added pumping capacity and additional storage and heat exchanger capacity to accommodate the run times.

Air Supply. The high pressure air requirements, covered in appendix F, would be meet by accessing the high pressure storage across the street from building N238. Piping and flow control valves and instrumentation will be required at the site.

Power Supply. The power supply proposed is discussed in Appendix G and will consist of two power modules which will provide a supply equal in output to the existing supply. Since the proposed arc heaters will operate at higher voltages, a major problem exists due to the increased spacing required between the DC power busses and to ground. This spacing along with the increase in length of the arc units make the installation incompatible with the existing dimensions of Building N238. It is therefore proposed to install a new building in the area between N238 and the four vacuum spheres which would be designed to provide the required space. If such a course of action is followed it is suggested that spacing be provided for the possible increase of operating voltage to 100 KV by the addition of a third block of 150 MW power to be connected in series again. A building roughly 90 feet wide by 110 feet long is proposed. Such a location would provide ready discharge of the steam ejector stage into the vacuum spheres.

Scrubber. It is proposed to provide NO scrubbing to remove this contaminant by placing a filled scrubbing tower of low capacity directly in the spheres. This would permit relatively long duration operation for the removal process. The water spray could provide the circulation necessary and valving could isolate the sump and spray system from the low pressure of the spheres.

DEVELOPMENT APPROACH

Proposed Arc Jet Configuration. Examination of the problems involved with operating larger arc heaters lead to the conclusion that an increase to 300 MW by doubling the capacity of the existing power supply was the most practical. To operate the existing and the new power supply together would require similar capabilities since operation in series will require the same current while operation in parallel will require the same voltage. Scaling laws obtained from experimental data and from Arcflo calculations have been developed and indicate that higher pressure arcs at power levels of 300 MW are possible although of course development activity will be required. The research objectives which will benefit by increasing the arc heater power to 300 MW include the following:

1. Propulsion: Investigations of body -inlet conditions require relatively large scale models to produce meaningful information. Propulsion efficiency investigations require large scale models to provide meaningful simulation of fuel mixing and combustion processes. Restraints imposed by safety requirements for storage and transporting of the required fuel may be a major impediment to this type of investigation. 2. Larger arc heaters will provide Reynolds numbers closer to those required for simulation of hypersonic vehicles such as the NASP. These Reynolds numbers will still fall short of the required for the model sizes possible in the free stream models.

3. Testing of actively cooled panels for heat protection systems will be permitted at larger scale (approximately 3 foot wide by whatever length is dictated by diminishing

heating rates) and at higher heating rates than are currently possible.

4. Investigations of surface catalicity for sharp nosed models will be improved due to the thicker boundary layer provided and corresponding better confidence level regarding the proper state of the gas at the surface interface.

<u>Development approach.</u> Development of a 300 MW arc heater will require increasing the heater size by a factor of 5 above the 60 MW level where similar air operated arc heaters at ARC have performed. Operation of the Giant Planet arc on hydrogen-helium mixtures will also give meaningful information. To achieve this end a systematic approach should be taken to improve the design of each of the components of the heater and to verify the performance of the new design experimentally. The major components of present arc heaters are all of the first generation design and information gained from their operation should permit improvements in the design in many instances. The approach to implementing the recommendations discussed in Appendix D should be pursued in the following manner.

1. Heater components should be redesigned to improve performance to the maximum level practical.

2. A limited number of these components should be manufactured and assembled into a short arc heater to investigate their performance at high pressure, high voltage gradient, and at current levels indicated by the projected

design. Particular attention should be given to the problem of division of current between multiple electrodes and/or to the capability of a single electrode. It is recommended that a pilot arc be employed for starting, which will permit operation at atmospheric pressure and make the investigation independent of the vacuum system. This will also give information regarding any benefit to be gained in current distribution between multiple electrodes by operating the pilot arc during regular high pressure operation. Investigations should include the effect of performance on varying the distribution of air injection along the arc heater bore, and the increase of argon concentration in the upstream package on current distribution.

3. The operating pressure should be increased as soon as possible in order to gain experience with this type of operation and to learn of the problems that are involved. The existing power supply is more than adequate for a short version (perhaps L/D=25) of the high pressure arc.

4. Additional ARC FLO calculations should be made to check the results of the scaling law performance predictions. Work should start as soon as possible on ARC FLO code modifications to permit evaluation of:

a. The effect of the settling chamber on arc heater performance.

b. The effect of 100 per cent distributed flow injection.

(the present calculations are for 67% distributed flow.)

c. The effect of swirl on performance.

The ARC FLO code should be made available to the Ames personnel who are involved in the arc heater design. Much time and money can be saved by calculating before building. A users' manual should be provided.

OTHER APPROACHES

Alternating current arc heaters. Arc heaters operated directly from an alternating current source were considered. While these units could take advantage of the three phase circuitry, it would require three units ganged together into a common plenum to do so. Also the restart problem at the zero current condition twice each cycle would be a problem which could require a pilot arc for each of the three units. The requirement of a common plenum would also introduce additional losses. Addition of variable reactors would be required to provide a stable arc and to give control of the system. The cost of such a system along with the development required before a reliable unit could be available resulted in the elimination of this approach from consideration.

Direct acceleration. Direct acceleration of the gas by means of MGD interactions seem to be attractive at first inspection.

However these devices must utilize conducting gas and the energy will be preferentially deposited in the slower moving boundary layer largely as ohmic heating. The development required precluded further consideration of this approach.

Combined sources. One attractive approach would be to utilize the stored energy available from the 3.5 ft wind tunnel in conjunction with the energy available from the arc heaters. In this manner one could achieve enthalpies above 2000 BTU per pound (a level where oxygen begins dissociating and that is not achievable by the storage heater alone) at flow rates above 100 pounds per second. This would require extending the arc heater pressure levels to nearly 200 atmospheres to utilize the range of the pebble bed heater.

COST ESTIMATE FOR 150 MW ADDITION -- Millions

Building	$1.
3 Arc heaters @ 1.3	4.
3 Pilot arcs with power supply	1.5
High pressure air piping and control	1.
Steam ejector with steam extension	1.5
Scrubbers	1.5
Isolation valves	1.0
Water system	3.0
Power supply (150 MW)	7.0
Data system extension	1.0
Component development and verification	3.0
Hydrogen system (not included)	

TOTAL	$25.5

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APPENDIX A

ARC FLO CALCULATIONS

The procedure for estimating arc heater performance over a wide range of operating conditions with a relatively few ARC FLO calculations is described in reference 10. The advantage is that a few correlation equations or "scaling laws" can adequately describe the arc heater performance and save hundreds of the involved ARC FLO computations that would otherwise be required. The procedure is as follows:

1. Using previous calculations and experimental results, estimate the range of current (I), pressure (P), flow rate (M), constrictor diameter (D) and length (L) that are appropriate to the applications of interest.
2. Establish a calculation matrix that will cover the above range of operating variables.(18 sets, see Table IV.)
3. With the aid of a data correlation scheme, determine the functional relationship between Enthalpy and the operating variables:

   (a). Assume enthalpy = constant * $I^a * P^b * M^c * D^d$ for a length to diameter ratio (L/D) of 50.

   (b). Take the log of the above equation to get a linear equation: log H=log(constant)+a*log I+b*log M,etc.

(c). Use linear multiple regression for the set of 18 equations to get a least-squares data fit.

(d). Repeat the above process for voltage(V), constrictor wall heating rate (Q), and efficiency (Eff.).

4. The ARC FLO calculations extend to L/D=50. These were extended out to L/D = 100 in order to determine the effect of length on performance. The data correlation was then repeated for L/D=75 and L/D=100. The calculated and extended data are shown in Table V. As a check on the extension procedure, one ARC FLO calculation was made for L/D=100. Agreement was about 3 per cent.

APPENDIX B

COOLING AND PROFILE FLATTENING

Within the constrictor the enthalpy profiles are rather sharply peaked and the centerline value is several times the mass-average. Once the heating stops, the central part cools rapidly and the radial profile becomes much flatter. This is illustrated in Figure 9 where local values of total enthalpy are plotted. At a station which is located about 4.2 diameters downstream, the centerline value has dropped to half of its former enthalpy. The mass average value has decreased about 12.5 per cent over this distance for this example. This flattening effect is very advantageous for most applications where uniform profiles are desired. This effect on the mass-flux profiles is even better. Profiles, similar to those for enthalpy are shown in Figure 10.

There is a danger that the losses in mass-average enthalpy can become excessive, especially at high pressure. The actual "settling chamber" provided by the electrode assembly and the faring between the electrode and the nozzle has a greater diameter than the constrictor and may cause excessive losses. The ARC FLO code should be modified in order to accurately study the effect. Until this is done, the losses and profile flattening can be estimated by using a constrictor length that gives the same residence time for the plasma as the actual plenum would provide.

Appendix C

Nozzle Throat Heat Transfer Rate

At high pressure and high enthalpies and for small values of throat/constrictor diameter, nozzle throat heat rates (from conventional calculations) becomes appreciable and may limit arc heater performance. On the other hand, ARC FLO calculations indicate rather low levels of forced convective heat transfer rate within the constrictor tube. One would expect that, with appropriate corrections for diameter and for a low value of length to diameter ratio at the nozzle entrance, the ARC FLO constrictor wall heat calculations could be extended into the nozzle and would agree reasonably well with the usual forced convection heat transfer calculation. As an example, consider Case #1 of the calculation matrix. At a distance of 50 diameters the ARC FLO convective constrictor wall heat flux was 36 Btu/ft2sec. This might increase to 206 when the above corrections are applied. The McAdams calculated convective heat rate (described below) was 4380 Btu/ft2sec. This puzzling situation should be studied further before designing nozzles for the up-graded arc heaters. Nevertheless, it would be dangerous to rely on the lower ARC FLO projections, and the more conventional calculation will be used for this study and is given below.

The McAdams (ref 12) equation 9-14 recommended for the inlet region of a tube in turbulent flow is:

$$q = H*(.023)*[1 + (D/L)^{.7}]*(Kv)*G*Pr^{-2/3}*Re^{-.2}$$

where: q = noz. heat transfer rate, Btu/ft2sec

H = total enthalpy, Btu/lb

L/D=dimensionless distance along nozzle

G = throat mass flux density, lb/ft2sec

Pr= Prandtl number at film enthalpy, H_f

H_f= H/2

Re= Reynolds number at film enthalpy

Kv= (wall viscosity/film viscosity)$^{.14}$

The $[1 + (D/L)^{.7}]$ term accounts for the increased heating at the inlet of a tube and typically may double the rates. The Prandtl number remains relatively constant at high densities and this term is about 1.3 . The Reynolds number depends on viscosity which is a function of temperature. Because of the .20 exponent, one can use the Sutherland formula which gives viscosity to about 8 per cent at 8,000 °R. The viscosity ratio term reduces heating by about 10 per cent.In addition to the above turbulent forced convection, radiation will also contribute to the nozzle heat load. From Appendix B, the cooling and profiles flattening of the flow leaving the constrictor will reduce radiation heat flux at the nozzle throat considerably. This reduction will depend on the mass average enthalpy, pressure, and the volume between the downstream electrode assembly and the nozzle throat. An accurate radiation calculation using ARC FLO would require a modification of the code. Another method is to use Winovich's radiation formula from reference 9.

Calculations made for the convective heat rates for the maximum arc heater performance points are given in Table VII. A rather crude estimate of the radiation portion of the nozzle throat heat flux has been included. Here it was assumed that the radiation flux density at the nozzle throat has dropped to 50% of its value within the constrictor and that the heat load is further reduced by the nozzle throat to constrictor area ratio. The total nozzle throat heating rate are higher than desired, but well within the state-of-the-art cooling capabilities.

Appendix D

ARC HEATER COMPONENTS

The design of arc heater components currently in use are essentially the same design that was established during the design phase of the 6 cm , nominally 20 MW arc heater about 1970. While these designs have performed admirably over nearly two decades, a number of characteristics have been observed which indicate improvements are possible. In light of the anticipated design of larger units these limitations should be investigated fully.

These larger units will require extending the capabilities of pressure containment, electrode current capacity, current distribution ability, constrictor voltage standoff capabilities, and greater cooling capabilities. In most cases the elements are being operated near their ultimate capability. This condition requires that the design must be made optimum after considering all influencing aspects such as aerodynamic, electrical, thermal and material strength. Since failures on any component can result in cascade failure of adjacent components to rapidly include the entire unit, it is essential that component performance should be experimentally verified and that safe operating limits be established.

Elements which will be impacted by the anticipated arc heater modifications are discussed below.

1. <u>Increased pressure.</u> It is anticipated that operating pressure for advanced arc heaters will be in the range of 100 atmospheres. Current operating pressure for devices in operation at ARC has been nominally 10 atmospheres. However successful tests have been performed at AEDC on arc heaters of a similar design at operating pressures as high as 125 atmospheres. To upgrade current heaters at Ames to this operating level will require increasing the strength and tension on the clamping rods. In addition the seals between all disks, spacers and other elements must be re-evaluated and tested to verify their ability to operate at the elevated pressure. Backup rings and supporting lands may require modification. Increased pressure will slow the arc foot movement on the electrodes making copper erosion more severe. In addition, transfer of the arc to additional electrodes in the upstream package when current is increased will become more difficult. Both of these problems will be discussed in the section on electrodes. Lateral stability must be provided as the unit becomes longer as is anticipated.

2. <u>Constrictor Disks.</u> A tendency to arc between adjacent disks has been observed. The disk should be reduced in thickness as much as possible to reduce the voltage imposed on the gap between disks. Constrictor disks used by AEDC in their high pressure heater are about 15% thinner than the ones used at Ames. At maximum heat transfer rate the surface of the disk in contact with the heated stream operates approaching the melting point of copper. Since the thickness of this surface is made as thin as possible to achieve the highest heat transfer rate possible, the strength of the water cooling passage wall is a limiting element at the high pressure in the arc heater during operation and of the water in the passage upon rapid shutdown conditions.

For maximum strength the shape of a pressure vessel would be circular rather then the rectangular shape currently used. A completely circular section on the inside surface of the constrictor could lead to enhanced heating and turbulence and an elliptical section could be employed as being nearly as effective. The circular section would also eliminate the corners of the inner surface where the electrical potential gradients are the highest. This would help eliminate the problem of arcing between disks at this location, which has been a problem in the past and will be more severe at higher voltages. Another attempt to strengthen the wall could be to provide a rib on the center of the inner face of the water passage which would remain at a low temperature to provide strength both due to the stiffening web and the fact that it is maintained at its high strength low temperature state. As a added advantage it provides a positioning land for inserting the backup wedges which will form the water passage such that the dimension of the water passage more precisely. A disk with such a rib was tested in the early 1970's, with apparently good results but it was not adopted at that time since the need did not exist. The pressure drop along such a disk would be somewhat greater and would need to be compensated for in the water supply pressure.

3. Electrodes. The internal magnetic field copper electrodes in use with current constricted arc has performed well at the conditions at which it has been operated. Erosion rates have been low and life time of the electrodes have been from a few to as much as 40 hours of operating time. The electrode lifetime depends on the severity of the conditions, as one would expect. The electrodes in use are of a single design and size, which again dates to the design of the 20 megawatt arc heater, circa 1970. These electrodes are nominally rated at 1000 amperes each. This limit is due to the heating to the internal coil to the level where nucleate boiling takes place on the surface of the conductor and causes the temperature to began rising at a higher rate. Also the magnetic field at the surface of the electrode is low which causes excess erosion on the surface due

to the slow movement of the arc attachment point. These conditions could be improved by redesign of the electrode to give more turns (the current number is four) and to increase the cross section area of the conductor and the surface cooling. This would permit higher current in the magnetic coil and increase the magnetic field on the arcing surface due both to the increased current and the increased number of turns. These modifications are particularly important to permit maintaining the current and lifetime capabilities at increased pressure.

The increased voltage due to high pressure operation will also necessitate reducing the axial dimension of the electrode to reduce the voltage shorted by the copper surface. When the electrode was used in the 8 cm diameter constrictor, it exhibited a tendency for the arc to preferentially attach to the leeward side of the crest of the electrode beyond the 4 th electrode (progressing in the downstream direction) although this phenomenon had not been observed in the 6 cm application. It is likely this is due to aerodynamic attachment of the flow in this region. Increasing the diameter of the electrode to maintain or increase the 6 cm ratio of electrode diameter to constrictor diameter should relieve the problem. While the current design of electrodes give a relatively low level of contamination, means can be taken to reduce this problem even further to meet the requirements of other applications such as aerodynamic investigation which may involve spectroscopy.

contamination from the upstream electrode could be virtually eliminated by exhausting the gas which inhabits the upstream electrode package through a vent nozzle in the upstream end of the arc heater. In addition if the upstream package could be made to operate in a stagnant argon atmosphere, the erosion rate could be made very low. This could be accomplished by tailoring the upstream constrictor diameter (heating rates in an argon atmosphere are very low) such that the adjacent air could be prevented from migrating into the chamber by a minimal flow of argon to block the passage. Any requirement for cold gas injection in the downstream package which may remain after utilizing the circular section spacer disks should be as well accomplished using air as argon, which is the present practice. Air is the current gas and has a higher electrical breakdown strength than argon.

4. Current initiation and sharing. Past operating experience has shown that the requirements for a good vacuum for arc initiation are quite exacting. Minor difficulties with the vacuum system can result in frustration from inability to strike an arc. Lower power arc heaters with atmospheric pressure starting capabilities in the range of several hundred kilowatts to 6 megawatts have been developed and applied in the steel industry. Such a device with a rating with a rating of several hundred kilowatts could be inserted at the upstream end of the heater and activated to provide ionization for starting the larger

unit. Such a device is available from the Plasma Energy Corp of Rayleigh, NC. Current distribution between the upstream electrodes can also be a problem, particularly at high pressures where the voltage gradient is higher. Experiments at AEDC at pressures of 100 atmospheres and above have not been successful in dividing current between multiple electrodes. This indicates that considerable development will be required to solve the problem. The approach should be to design the electrode for optimum magnetic field distribution to encourage sharing, to reduce the voltage gradient by providing a stagnant argon atmosphere, to reduce the voltage across the electrode by reducing the axial dimension, by making the arcing distance required more nearly equal by diminishing the inner radius on electrodes farther from the constrictor bore, and perhaps by continuing operation of the pilot arc during operation. It should be recognized however that the use of vacuum for starting is a very sensitive detector of leaks in the system, and if this is eliminated diligence must be maintained to insure that a leak does not exist which could lead to catastrophic failure. Improvements could be made both from the erosion and current sharing standpoint, if the upstream electrode package could be made to operate in nearly pure argon while keeping the percentage of total flow low as discussed above. Attention should also be given to investigating a single high current electrode, since present studies indicate that high power heaters will operate at relatively low current.

5. Heat sink operation. Much operating experience can be obtained on new devices by operating them for short times such that the thermal capacity of the components are capable of absorbing the imposed heat while still remaining below the melt, or strength requirements. The time available is of course dependant on the level of heating but in the past times of 0.5 seconds have been commonly achieved. Time to melt is listed as a function of heat transfer rate in Table X for a copper component. This shows that much longer test times are available than in other test facilities such as shock tunnels and free flight tunnels. It may be difficult however to establish equilibrium operating conditions at high pressure, without extinguishing the arc, and still have time to get meaningful data.

6. Failure Detection. Since the arc load is similar to most electrical failures, which also result in arcs, no good method has been employed currently to detect failure modes and to remove the electrical power rapidly. As a result failures typically do considerable damage to the units and can be the cause of major overhauls. Computer technology has progressed considerable since the present power supply was built in the form of programmable controllers. These should be investigated to determine if a scheme could be developed which would provide a current sensor with the value of current which is consistent

with the operating conditions at that time. Shutdown could be achieved by blocking the gate signal to the SCR and consequently be achieved very rapidly compared to the present situation. Minimizing failure damage in this way could be very cost effective.

Appendix E

VACUUM SYSTEM

Examination of the vacuum requirements for the arc heated facility along with the existing vacuum storage capabilities existing, have lead to the conclusion that utilizing these existing capabilities is an attractive course to follow. The four spheres pumped by the 3.5 ft. system have a storage capacity of approximately 1 million standard cubic feet. The pump down pressure is approximately 0.015 atmospheres (11 mm). A single stage steam ejector could be added between the arc heater exit and the spheres to give an additional pumping capability. A direct contact condenser would be needed following the steam ejector stage to condense the steam and to cool the hot gas stream, along with valves for the required isolation. The steam available to drive this ejector from the present steam plant would be sufficient to pump slightly more than three times the capacity of the existing fourth stage or about 25 pounds per second. This would give an available run time of approximately 5 minutes while maintaining a discharge vacuum level of about 0.015 atmospheres. For higher mass flows of approximately 70 pounds per second, the test times would be reduced to about a minute with the discharge vacuum level rising to approximately 0.15 atmospheres at the end of the run. An annular steam ejector would seem to have advantages for this application and should be investigated. These advantages include, eliminating the requirement of placing a nozzle in the core of the hot stream where high heating presents a problem; providing cooling on the surface of the ejector; and providing pumping preferentially at the slower moving boundary layer. Relatively low capacity scrubbers could be place inside the spheres to remove the NO, since these could perform over an extended period of time by cycling the gas through the system by water ejector action pumping. The sump of these scrubbers could be external to the sphere and be valved off during the evacuation cycle.

Appendix F

HIGH PRESSURE GAS SUPPLY

The existing high pressure storage in the newly constructed tank farm across the street from Bldg. N238 is of adequate size and pressure to drive the arc units proposed. Piping to the facilities would be required, but should consist of standard procedures.

Appendix G

POWER SUPPLY

Recent investigations of arc heater operating characteristics have indicated that larger units will almost certainly be built using higher voltage as instead of higher current. In light of this situation, the versatility which was built into the original power supply would seem to be unnecessary and that additional units of compatible size need not be comprised of as many modules with the complexity of numerous set-up switches. For the addition of one additional 150 MW unit (Making a total of 300 MW) two modules of 75 MW each would seem to be adequate versatility. This would give a maximum voltage of 64 KV and a minimum of 16 KV for the full power connections. If a second 150 MW supply were to be added it could be provided in a single module. This would provide 96 KV (all voltages are open circuit voltage) with a minimum of 34 KV for full power connections. One of the major problems of the higher voltage is the large spacing require between DC busses and to ground. This would be a major problem for installations in building N 238. However it may be possible to accomplish the transmission in a reasonable space by providing a sealed duct filled with an atmosphere of sulphur hexafluoride (SF_6) which has a much greater dielectric strength than does air. For the 96 KV case it seems likely that an entirely new installation with the adequate spacing designed into the structure would be the most desirable solution.

The present power contract for the field is adequate for the power level of 300 MW, however the rate of increasing and dropping of power would require an agreement with the utility company. In the absence of such an agreement, a dummy load could be installed to pick up power at an acceptable rate after which it would be transferred to the arc heater unit. Following a run the reverse procedure would be followed. The addition of a second 150 MW unit would require renegotiating with regard to power level as well as the rate of increase and decrease of power. The utility lines serving the Ames substation have the capacity to provide this power, however the contract would require modification. (At the present time, TVA has not imposed any restrictions on the arc heater installations at AEDC.) Power factor correction would continue to be provided by the capacitors at the Unitary substation.

Alt feet x1000	Enthalpy Btu/lb	Velocity ft/sec	Mach No.	Pressure atm. x10^-6	Density lb/ft2s x10^-6	Re/ ft x10^n exp	Rho*U #/f2s	Re sim. Nozzle Exit Diameter, inches 12	24	36	48	Power Density MW/f2s	Flight Power Density, MW. Nozzle Exit Diameters, inch 12	24	36	48
100	1,000	7,074	7.1	11,500	1,068	.76+6	7.56	5.9	23.7	53	95	8	6	25	56	100
100	2,000	10,000	10.1	11,500	1,068	1.15+6	10.68	8.4	33.6	75	134	23	18	71	159	283
100	4,000	14,142	14.3	11,500	1,068	1.62+6	15.10	11.9	47.4	107	190	64	50	200	450	800
100	7,000	18,720	18.9	11,500	1,068	2.15+6	19.99	15.7	62.8	141	251	148	116	463	1,043	1,854
100	10,000	22,370	22.6	11,500	1,068	2.57+6	23.89	18.8	75.1	169	300	252	198	791	1,780	3,164
100	12,500	25,000	25.2	11,500	1,068	2.87+6	26.70	21.0	83.9	189	336	352	276	1,105	2,487	4,421
120	1,000	7,074	6.9	4,540	415	2.81+5	2.94	2.3	9.2	21	37	3	2	10	22	39
120	2,000	10,000	9.8	4,540	415	3.98+5	4.15	3.3	13.0	29	52	9	7	27	62	110
120	4,000	14,142	13.9	4,540	415	5.63+5	5.87	4.6	18.4	41	74	25	19	78	175	311
120	7,000	18,720	18.3	4,540	415	7.45+5	7.77	6.1	24.4	55	98	57	45	180	405	720
120	10,000	22,370	21.9	4,540	415	8.90+5	9.28	7.3	29.2	66	117	98	77	307	692	1,230
120	12,500	22,370	21.9	4,540	415	8.90+5	9.28	7.3	29.2	66	117	122	96	384	865	1,537
140	1,000	7,074	6.7	1,988	170	1.09+5	1.20	.94	3.78	8	15	1.3	1.0	4.0	9	16
140	2,000	10,000	9.5	1,988	170	1.54+5	1.70	1.33	5.34	12	21	3.6	2.8	11.3	25	45
140	4,000	14,142	13.4	1,988	170	2.18+5	2.40	1.89	7.55	17	30	10.1	8.0	31.8	72	127
140	7,000	18,720	17.7	1,988	170	2.89+5	3.18	2.50	9.99	22	40	23.5	18.4	73.7	186	295
140	10,000	22,370	21.2	1,988	170	3.45+5	3.80	2.99	11.94	27	48	40.1	31.5	125.9	283	504
140	12,500	25,000	23.7	1,988	170	3.86+5	4.25	3.34	13.35	30	53	56.0	44.0	175.8	396	703
160	1,000	7,074	6.5	918	75	4.62+4	.53	.42	1.66	4	7	.6	.4	1.7	4	7
160	2,000	10,000	9.2	918	75	6.52+4	.75	.59	2.35	5	9	1.6	1.2	4.9	11	20
160	4,000	14,142	13.1	918	75	9.23+4	1.06	.83	3.32	7	13	4.5	3.5	14.0	31	56
160	7,000	18,720	17.3	918	75	12.21+4	1.40	1.10	4.39	10	18	10.3	8.1	32.4	73	130
160	10,000	22,370	20.7	918	75	14.59+4	1.67	1.31	5.25	12	21	17.6	13.8	55.3	124	221
160	12,500	25,000	23.1	918	75	16.31+4	1.87	1.47	5.87	13	23	24.6	19.3	77.3	174	309
180	1,000	7,074	6.3	429	36	2.24+4	.252	.20	.79	1.78	3.16	.27	.21	.8	1.9	3.3
180	2,000	10,000	8.9	429	36	3.16+4	.356	.28	1.12	2.52	4.47	.75	.59	2.4	5.3	9.4
180	4,000	14,142	12.5	429	36	4.47+4	.503	.40	1.58	3.56	6.33	2.12	1.67	6.7	15.0	26.7
180	7,000	18,720	16.6	429	36	5.92+4	.666	.52	2.09	4.71	8.37	4.92	3.86	15.4	34.8	61.8
180	10,000	22,370	19.8	429	36	7.07+4	.796	.63	2.50	5.63	10.01	8.39	6.59	26.4	59.3	105.5
180	12,500	25,000	22.1	429	36	7.90+4	.890	.70	2.80	6.29	11.18	11.73	9.21	36.8	82.9	147.4
200	1,000	7,074	6.8	195	17	1.10+4	.120	.09	.38	.85	1.51	.13	.10	.40	.9	1.6
200	2,000	10,000	9.5	195	17	1.56+4	.170	.13	.53	1.20	2.13	.36	.28	1.12	2.5	4.5
200	4,000	14,142	13.5	195	17	2.20+4	.240	.19	.75	1.70	3.01	1.01	.79	3.18	7.1	12.7
200	7,000	18,720	17.9	195	17	2.92+4	.317	.25	1.00	2.24	3.99	2.34	1.84	7.36	16.6	29.4
200	10,000	22,370	21.3	195	17	3.49+4	.379	.30	1.19	2.68	4.77	4.00	3.14	12.56	28.3	50.3
200	12,500	25,000	23.9	195	17	3.90+4	.424	.33	1.33	3.00	5.33	5.59	4.39	17.55	39.5	70.2
250	1,000	7,074	7.7	20	2	1.83+3	.016	.013	.05	.11	.20	.017	.013	.053	.12	.21
250	2,000	10,000	10.9	20	2	2.58+3	.023	.018	.07	.16	.28	.048	.037	.150	.34	.60
250	4,000	14,142	15.4	20	2	3.65+3	.032	.025	.10	.23	.40	.135	.106	.423	.95	1.69
250	7,000	18,720	20.3	20	2	4.83+3	.042	.033	.13	.30	.53	.312	.245	.981	2.21	3.92
250	10,000	22,370	24.3	20	2	5.78+3	.051	.040	.16	.36	.64	.533	.419	1.674	3.77	6.70
250	12,500	25,000	27.2	20	2	6.45+3	.056	.044	.18	.40	.71	.744	.585	2.339	5.26	9.35

Table I. Hypersonic Flight Conditions and Mass Flux Density (Reynolds Number) Simulation.

FACILITY REQUIREMENTS/CHARACTERISTICS TO MEET RESEARCH REQUIREMENTS

Research Requirement	Facility Requirements (Not Exhaustive)							
	V or Mach	Rho or Gamma	RE, L	Size	Enthal or Temp	Pres	Flow Qual	Test Time
Configuration Aerodynamics	■	■	■					■
Aerothermodynamics/ Heat Transfer	■		■		■			
Inlets/Nozzles; Prop/Airframe Integ	■		■	■	■			■
Boundary Layer Transition	■		■		■		■	
Combuster/ Engine/Perf	■			■	■	■		■
Structures/Aerothermal Loads	■			■	■	■		■
CFD Calib/Verif	■	■	■	■	■	■	■	■

TABLE II

Alt feet x1000	Enthalpy Btu/lb	FlightV ft/sec	Mach No.	Reynolds No./ft x10^exp	Pressure atm x10^ exp.	for Flight static duplication. (atmospheres) A/A* 50	A/A* 100	A/A* 200	A/A* 400	Pt,2 atm	pressure behind normal shock. (atmospheres) A/A* 50	A/A* 100	A/A* 200	A/A* 400
100	1,000	7,074	7.1	.76 6	1.15-2	5.8	13.7	32.6	77	.76	13	30	63	127
100	2,000	10,000	10.1	1.15 6	1.15-2	7.8	18.6	44.4	106	1.51	25	59	126	252
100	4,000	14,142	14.3	1.62 6	1.15-2	10.7	25.4	60.4	144	3.02	50	117	252	503
100	7,000	18,720	18.9	2.15 6	1.15-2	13.7	32.6	77.6	185	5.29	88	206	441	881
100	10,000	22,370	22.6	2.57 6	1.15-2	16.1	38.2	91.0	216	7.55	126	294	629	1,258
100	12,500	25,000	25.2	2.87 6	1.15-2	17.8	42.2	100.5	239	9.43	157	367	786	1,571
120	1,000	7,074	6.9	2.81 5	4.54-3	2.6	6.2	14.7	34.9	.28	5	11	24	47
120	2,000	10,000	9.8	3.98 5	4.54-3	3.5	8.4	20.0	47.6	.56	9	22	47	94
120	4,000	14,142	13.9	5.63 5	4.54-3	4.8	11.5	27.3	64.9	1.12	19	44	94	187
120	7,000	18,720	18.3	7.45 5	4.54-3	6.2	14.7	35.0	83.3	1.97	33	77	164	328
120	10,000	22,370	21.9	8.90 5	4.54-3	7.3	17.3	41.0	97.6	2.81	47	109	234	468
120	12,500	25,000	24.5	9.94 5	4.54-3	8.0	19.1	45.3	107.8	3.51	58	136	292	584
140	1,000	7,074	6.7	1.09 5	1.99-3	1.28	3.04	7.24	17.23	.12	2	5	10	19
140	2,000	10,000	9.5	1.54 5	1.99-3	1.74	4.15	9.87	23.47	.23	4	9	19	38
140	4,000	14,142	13.4	2.18 5	1.99-3	2.38	5.65	13.44	31.98	.46	8	18	38	77
140	7,000	18,720	17.7	2.89 5	1.99-3	3.05	7.25	17.26	41.05	.81	13	31	67	134
140	10,000	22,370	21.2	3.45 5	1.99-3	3.58	8.51	20.23	48.13	1.15	19	45	96	192
140	12,500	25,000	23.7	3.86 5	1.99-3	3.95	9.40	22.35	53.16	1.44	24	56	120	239
160	1,000	7,074	6.5	4.62 4	9.18-4	.66	1.57	3.74	8.89	.051	.8	2.0	4.2	8.5
160	2,000	10,000	9.2	6.52 4	9.18-4	.90	2.14	5.09	12.11	.101	1.7	3.9	8.4	16.9
160	4,000	14,142	13.1	9.23 4	9.18-4	1.23	2.92	6.94	16.50	.202	3.4	7.9	16.9	33.7
160	7,000	18,720	17.3	12.21 4	9.18-4	1.57	3.74	8.90	21.18	.354	5.9	13.8	29.5	59.0
160	10,000	22,370	20.7	14.59 4	9.18-4	1.84	4.39	10.44	24.83	.505	8.4	19.7	42.1	84.2
160	12,500	25,000	23.1	16.31 4	9.18-4	2.04	4.85	11.53	27.43	.631	10.5	24.5	52.6	105.2
180	1,000	7,074	6.3	2.24 4	4.29-4	.34	.82	1.95	4.64	.022	.36	.85	1.82	3.65
180	2,000	10,000	8.9	3.16 4	4.29-4	.47	1.12	2.65	6.32	.044	.73	1.69	3.63	7.26
180	4,000	14,142	12.5	4.47 4	4.29-4	.64	1.52	3.62	8.60	.087	1.45	3.38	7.24	14.48
180	7,000	18,720	16.6	5.92 4	4.29-4	.82	1.95	4.64	11.04	.152	2.53	5.91	12.67	25.34
180	10,000	22,370	19.8	7.07 4	4.29-4	.96	2.29	5.44	12.95	.217	3.62	8.44	18.09	36.18
180	12,500	25,000	22.1	7.90 4	4.29-4	1.06	2.53	6.01	14.30	.271	4.52	10.54	22.59	45.17
200	1,000	7,074	6.8	1.10 4	1.95-4	.18	.42	.99	2.36	.012	.19	.45	.96	1.93
200	2,000	10,000	9.5	1.56 4	1.95-4	.24	.57	1.35	3.22	.023	.38	.89	1.92	3.83
200	4,000	14,142	13.5	2.20 4	1.95-4	.33	.78	1.84	4.39	.046	.77	1.79	3.83	7.65
200	7,000	18,720	17.9	2.92 4	1.95-4	.42	1.00	2.37	5.63	.080	1.34	3.13	6.70	13.39
200	10,000	22,370	21.3	3.49 4	1.95-4	.49	1.17	2.78	6.60	.115	1.91	4.46	9.56	19.12
200	12,500	25,000	23.9	3.90 4	1.95-4	.54	1.29	3.07	7.29	.143	2.39	5.57	11.94	23.88
250	1,000	7,074	7.7	1.83 3	2.00-5	.025	.059	.141	.336	.0015	.026	.060	.13	.26
250	2,000	10,000	10.9	2.58 3	2.00-5	.034	.081	.192	.457	.0031	.051	.119	.25	.51
250	4,000	14,142	15.4	3.65 3	2.00-5	.046	.110	.262	.623	.0061	.102	.237	.51	1.02
250	7,000	18,720	20.3	4.83 3	2.00-5	.059	.141	.336	.800	.0107	.178	.415	.89	1.78
250	10,000	22,370	24.3	5.78 3	2.00-5	.070	.166	.394	.938	.0152	.254	.592	1.27	2.54
250	12,500	25,000	27.2	6.45 3	2.00-5	.077	.183	.436	1.036	.0190	.317	.740	1.59	3.17

Table III Hypersonic Flight Conditions and Pressure Simulation.

Case No.	Cons.Dia inches	Current amperes	Flow Rate lb/sec	Pressure atmospheres
1	3.15	2000	10	50
2	3.15	4000	5	30
3	3.15	5380	2.85	12.75
4	3.15	4000	30	100
5	4.724	4000	50	100
6	4.724	6000	10	50
7	4.724	8000	5	10
8	4.724	6000	20	50
9	6.3	8000	100	100
10	4.724	10000	50	50
11	4.724	19000	10	30
12	4.724	25000	2	10
13	6.3	12000	50	100
14	6.3	20000	40	50
15	6.3	25000	15	30
16	6.3	35000	3	10
17	4.724	6000	14.4	50
18	3.15	4000	30	75

Table IV. ARC FLO Calculation Matrix.

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Case	Dia. in.	Current amp	Flow lb/sec	Pres. atm	WallHeat Btu/ft2s	H Btu/lb	Volts kV	Efficiency
1	3.15	2000	10	50	1900	4044	24.65	.864
2	3.15	4000	5	30	3570	6147	16.35	.495
3	3.15	5380	2.85	12.75	2160	8866	8.98	.553
4	3.15	4000	30	100	5300	4560	39.87	.899
5	4.724	4000	50	100	3520	3508	52.8	.877
6	4.724	6000	10	50	4275	4384	25.23	.305
7	4.724	8000	5	10	1530	8433	9.31	.597
8	4.724	6000	20	50	3800	4449	28.15	.552
9	6.3	8000	100	100	4780	3765	60.61	.818
10	4.724	10000	50	50	3690	5577	36.37	.804
11	4.724	19000	10	30	10800	9232	18.1	.283
12	4.724	25000	2	10	5610	15812	7.07	.189
13	6.3	12000	50	100	7970	4935	44.15	.49
14	6.3	20000	40	50	9290	7027	31.65	.469
15	6.3	25000	15	30	10700	8665	23.16	.236
16	6.3	35000	3	10	5920	13896	8.96	.14
17	4.724	6000	14.4	50	3880	4290	26.21	.414
18	3.15	4000	30	75	3620	4618	37.95	.948

Part (a). ARC FLO Calculations for L/D = 50.

1	3.15	2000	10	50	1900	4956	38.97	.864
2	3.15	4000	5	30	3570	7386	24	.495
3	3.15	5380	2.85	12.75	2160	10531	13.01	.553
4	3.15	4000	30	100	5300	5704	63.47	.899
5	4.724	4000	50	100	3520	4160	81.04	.877
6	4.724	6000	10	50	4275	5651	36.98	.305
7	4.724	8000	5	10	1530	9886	13.6	.597
8	4.724	6000	20	50	3800	5508	42.23	.552
9	6.3	8000	100	100	4780	4547	94.66	.818
10	4.724	10000	50	50	3690	6872	56.26	.804
11	4.724	19000	10	30	10800	10522	26.45	.283
12	4.724	25000	2	10	5610	17053	10.08	.189
13	6.3	12000	50	100	7970	6036	65.83	.49
14	6.3	20000	40	50	9290	8320	46.69	.469
15	6.3	25000	15	30	10700	9808	33.9	.236
16	6.3	35000	3	10	5920	14699	12.96	.14
17	4.724	6000	14.4	50	3880	5179	36.98	.414

Part (b). Extension to L/D= 75.

1	3.15	2000	10	50	1900	5735	53.93	.864
2	3.15	4000	5	30	3570	8414	31.52	.495
3	3.15	5380	2.85	12.75	2160	11908	16.93	.553
4	3.15	4000	30	100	5300	6685	87.97	.899
5	4.724	4000	50	100	3520	4689	109.71	.877
6	4.724	6000	10	50	4275	5829	48.51	.305
7	4.724	8000	5	10	1530	11560	17.8	.597
8	4.724	6000	20	50	3800	6409	56.3	.552
9	6.3	8000	100	100	4780	5192	132.5	.818
10	4.724	10000	50	50	3690	7969	76.77	.804
11	4.724	19000	10	30	10800	11533	34.65	.283
12	4.724	25000	2	10	5610	17960	12.99	.189
13	6.3	12000	50	100	7970	6578	88.44	.49
14	6.3	20000	40	50	9290	9395	61.63	.469
15	6.3	25000	15	30	10700	10583	44.48	.236
16	6.3	35000	3	10	5920	15698	16.82	.14
17	4.724	6000	14.4	50	3880	5829	48.51	.414

Part (c). Extension to L/D = 100.

Table V. Results of ARC FLO Calculations

Results of ARC FLO calculation correlation.

Part 1. Constants for equations of enthalpy (H), Voltage (V), Constrictor Wall Heat Flux (Q), and Efficiency (Eff.).

L/D	Y =	constant	*I^a	*P^b	*M^c	*D^d
50	H =	574	.489	-.241	-.017	-.734
75	H =	884	.468	-.255	.022	-.827
100	H =	1475	.436	-.304	.063	-.871
50	V =	9.53	-.053	.449	.241	-.847
75	V =	14.20	-.0616	.438	.269	-.890
100	V =	18.53	-.0678	.431	.291	-.923
50	Q =	.0631	1.036	1.027	-.350	-.662
75	Q =	.0698	1.036	1.027	-.350	-.662
100	Q =	.0754	1.036	1.027	-.350	-.662
50	Eff.=	203	-.462	-.690	.740	-.872
75	Eff.=	164	-.462	-.690	.740	-.872
100	Eff.=	139	-.462	-.690	.740	-.872

Part 2. M (Air Flow rate) is replaced by D*(noz.throat dia).

L/D	Y =	constant	*I^a	*P^b	*(D*)^c	*D^d
50	H =	605	.490	-.261	-.016	-.748
75	H =	849	.463	-.232	.060	-.829
100	H =	1286	.425	-.236	.136	-.857
50	V =	5.70	-.099	.715	.478	-.774
75	V =	7.73	-.111	.731	.525	-.789
100	V =	9.18	-.116	.750	.560	-.821
50	Q =	.132	1.104	.641	-.703	-.765
75	Q =	.137	1.121	.662	-.648	-.895
100	Q =	.156	1.116	.662	-.640	-.906
50	Eff.=	21.80	-.575	.127	1.487	-.710
75	Eff.=	29.34	-.586	.126	1.512	-.720
100	Eff.=	21.79	-.575	.127	1.487	-.710

Part 3. I (current) is replaced by Q (wall heat rate).

L/D	Y =	constant	*Q^a	*P^b	*(D*)^c	*D^d
50	H =	1858	.407	-.541	.286	-.356
75	H =	2365	.379	-.501	.315	-.403
100	H =	3140	.350	-.484	.367	-.463
50	V =	24.84	-.22	.654	.478	-.921
75	V =	5.90	-.086	.795	.466	-.908
100	V =	6.95	-.094	.817	.498	-.932
50	Eff.=	10.99	-.509	.471	1.132	-1.144
75	Eff.=	8.514	-.489	.468	1.185	-1.244
100	Eff.=	6.89	-.482	.464	1.171	-1.228

Table VI. ARC FLO calculation correlations.

L/D=	50	50	75	75	100	100	100
Pressure, atm	125	100	70	50	30	20	10
Flow, lb/sec	50.0	50.0	30.0	20.0	10.0	6.7	2.8
Current, amperes	4600	5700	6000	7600	9200	12000	17500
Const.Dia, in	3.150	3.150	3.150	3.150	3.150	3.150	3.150
ConLength, in	158	158	236	236	315	315	315
Calculated results:							
MassAve H, Btu/lb :	4467	5235	7320	8830	11938	14785	20343
Ave.Wall Heat Rate	6663	6616	6398	6668	6622	6615	6554
Voltage, kilovolts	51.60	46.15	47.92	36.54	29.25	21.46	11.98
Gross Power, MW	237.4	263.1	287.5	277.7	269.1	257.6	209.6
Net Power, MW	211.9	248.3	208.4	167.6	113.3	94.0	53.1
Efficiency, percent	.89	.94	.72	.60	.42	.36	.25
Throat dia., inches	2.71	3.13	3.10	3.11	3.01	3.15	3.04
RhoV, lb/ft2sec	1245	935	573	380	202	124	55
Film Temp, deg.K	3685	4040	4927	5478	6502	7331	8739
Viscosity, lb/ftsec	58.92	61.87	68.70	72.62	79.39	84.48	92.48
Reynolds # x10^6	5.54	3.97	2.19	1.37	.67	.38	.15
HeatXfer Coef.	2.31	1.85	1.28	.93	.57	.39	.21
NozThroat ConvHeat	10310	9704	9365	8222	6834	5788	4209
NozThroatRad.Heat	2473	3269	3096	3244	3026	3307	3053
Total Noz.HeatRate	12783	12974	12461	11466	9860	9096	7262

Part (a) 300 Megawatt Heater. Maximum voltage = 50 kilovolts.

L/D=	50	50	50	50	75	100	100
Pressure, atm	125	100	70	50	30	20	10
Flow, lb/sec	2.2	4.0	12.0	11.0	6.0	3.3	1.5
Current, amperes	1350	2000	3750	5100	6400	7900	12000
Const.Dia, in	2.362	2.362	2.362	2.362	2.362	2.362	2.362
ConLength, in	118	118	118	118	177	236	236
Calculated results:							
MassAve H, Btu/lb :	3194	4045	7305	9174	12681	15154	21344
Ave.Wall Heat Rate	6702	6547	6556	6579	6578	6623	6632
Voltage, kilovolts	24.96	25.40	24.90	20.60	18.95	17.64	10.07
Gross Power, MW	33.7	50.8	93.4	105.0	121.3	139.3	120.9
Net Power, MW	6.8	15.4	83.2	95.7	72.2	48.0	30.4
Efficiency, percent	.20	.30	.89	.91	.60	.34	.25
Throat dia., inches	.54	.84	1.96	2.32	2.36	2.23	2.27
RhoV, lb/ft2sec	1422	1036	573	374	197	123	54
Film Temp, deg.K	2980	3431	4921	5612	6755	7446	9008
Viscosity, lb/ftsec	52.58	56.72	68.66	73.54	80.98	85.16	93.94
Reynolds # x10^6	5.32	3.59	1.64	1.00	.48	.28	.11
HeatXfer Coef.	2.66	2.09	1.36	.98	.60	.41	.22
NozThroat ConvHeat	8491	8472	9905	8963	7573	6245	4621
NozThroatRad.Heat	174	416	2255	3179	3286	2965	3055
Total Noz.HeatRate	8665	8888	12160	12141	10858	9210	7676

Part(b). 150 MW arc heater. Maximum voltage = 25 kilovolts.

Table VII. Maximum arc heater performance based on voltage, gross powerance. and constrictor wall and nozzle throat heat transfer rates.

D inch	D/L	P atm	M lb/s	I amp	H Btu/lb	V kV	Q Btu/f2s	Eff. %	Gross Pwr,MW	D* in.	Sim.Vel f/s1000
2.36	50	125	2.2	1350	3195	25	6700	20	25	.79	8.2
2.36	50	100	4	2000	4045	25	6550	30	43	.98	10.0
2.36	50	70	12	3750	7305	25	6560	89	93	1.96	13.7
2.36	50	50	11	5100	9170	21	6580	91	105	2.32	16.0
2.36	75	30	6	6400	12680	19	6800	60	121	2.36	17.9
2.36	100	20	3.3	7900	15150	18	6620	34	139	2.23	19.9
2.36	100	10	1.5	12000	21340	10	6630	25	121	2.27	24.5

For 12 in nozzle.			For 24 in nozzle.			For 36 in nozzle.			For 48 in nozzle.		
Rho*U lb/f2s	Rho lb/f3 x.001	Alt. fx1000	Rho*U lb/f2s	Rho lb/f3 x.001	Alt. fx1000	Rho*U lb/f2s	Rho lb/f3 x.001	Alt. ftx1000	Rho*U lb/f2s	Rho lb/f3 x.001	Alt. ftx1000
2.80	.34	124	.70	.085	157	.31	.038	179	.18	.021	194
5.09	.51	115	1.27	.127	147	.57	.057	167	.32	.032	183
15.28	1.12	99	3.82	.279	129	1.70	.124	147	.95	.070	162
14.01	.88	104	3.50	.219	134	1.56	.097	154	.88	.055	168
7.64	.43	119	1.91	.107	151	.85	.047	173	.48	.027	187
4.20	.21	135	1.05	.053	169	.47	.023	193	.26	.013	206
1.91	.08	156	.48	.019	197	.21	.009	218	.12	.005	230

Table VIII. Tabulated 6 cm arc heater performance and simulated altitude.

D	D/L	P	M	I	H	V	Q	Eff.	Gross	D*	Sim.Vel
inch		atm	lb/s	amp	Btu/lb	kV	Btu/f2s	%	Pwr,MW	in.	Kilof/s
3.15	50	125	50	4600	4470	51	6660	92	237	2.71	15.2
3.15	50	100	50	5700	5240	46	6620	93	263	3.13	16.9
3.15	75	70	30	6000	7320	48	6400	72	288	3.10	17.3
3.15	75	50	20	7600	8830	36	6670	59	278	3.11	19.5
3.15	100	30	10	9200	11900	29	6620	40	269	3.01	21.4
3.15	100	20	6.7	12000	14800	21	6620	34	258	3.15	24.5
3.15	100	10	2.8	19000	21100	12	6560	25	210	3.06	30.8

For 12 in nozzle.			For 24 in nozzle.			For 36 in nozzle.			For 48 in nozzle.		
Rho*U	Rho	Alt.	Rho*U	Rho	Alt.	Rho*U	Rho	Alt.	Rho*U	Rho	Alt.
lb/f2s	lb/f3	fx1000	lb/f2s	lb/f3	fx1000	lb/f2s	lb/f3	ftx1000	lb/f2s	lb/f3	ftx1000
	x.001			x.001			x.001			x.001	
63.66	4.20	71	15.92	1.049	100	7.07	.466	117	3.98	.262	130
63.66	3.77	73	15.92	.943	102	7.07	.419	119	3.98	.236	132
38.20	2.21	86	9.55	.551	115	4.24	.245	132	2.39	.138	146
25.46	1.31	97	6.37	.327	127	2.83	.145	146	1.59	.082	160
12.73	.59	116	3.18	.148	147	1.41	.066	167	.80	.037	183
8.53	.35	125	2.13	.087	160	.95	.039	181	.53	.022	197
3.57	.12	151	.89	.029	187	.40	.013	209	.22	.007	224

Table IX. Tabulated 8 cm arc heater performance and simulated altitude.

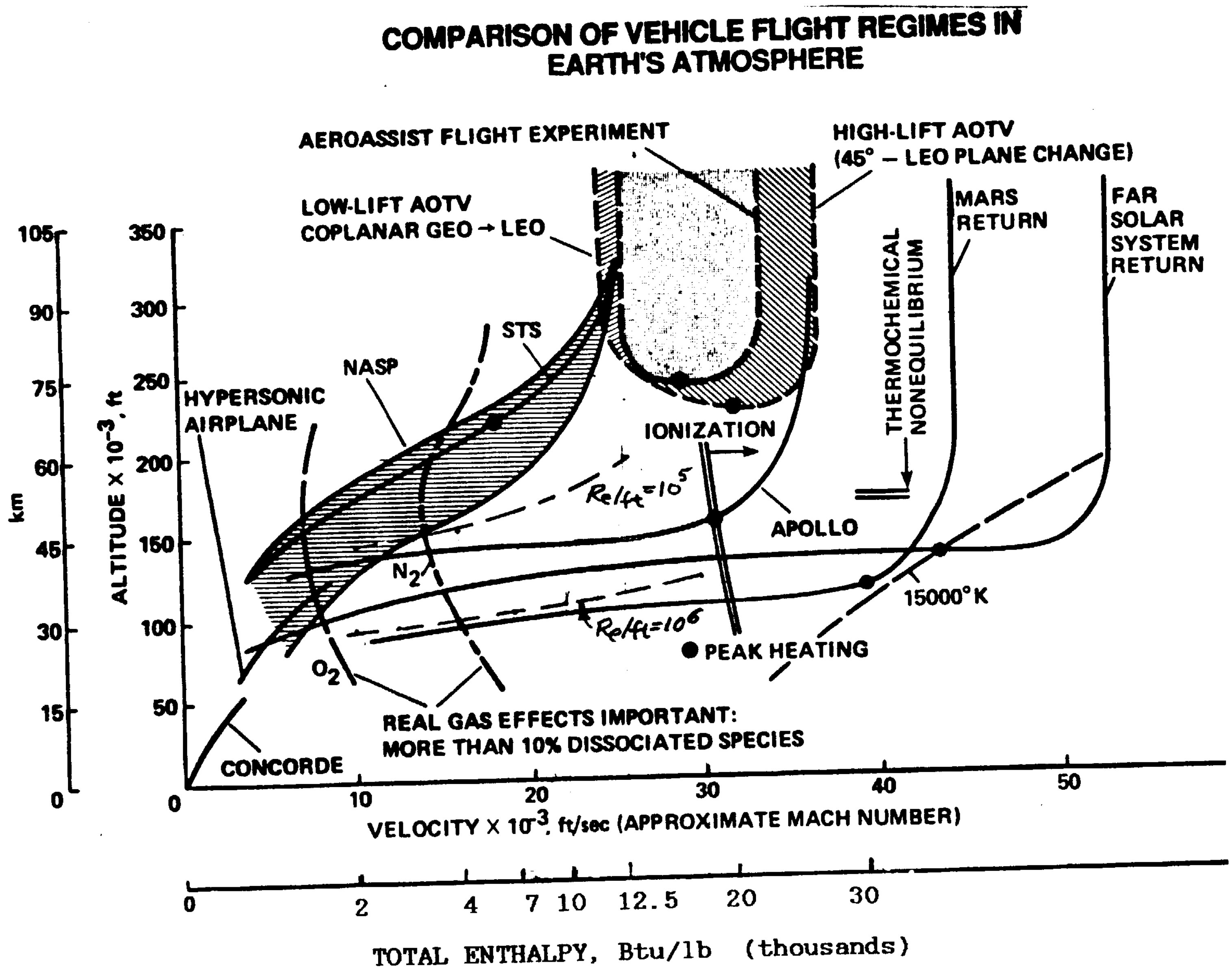

Figure 1. Hypersonic Flight Regime.

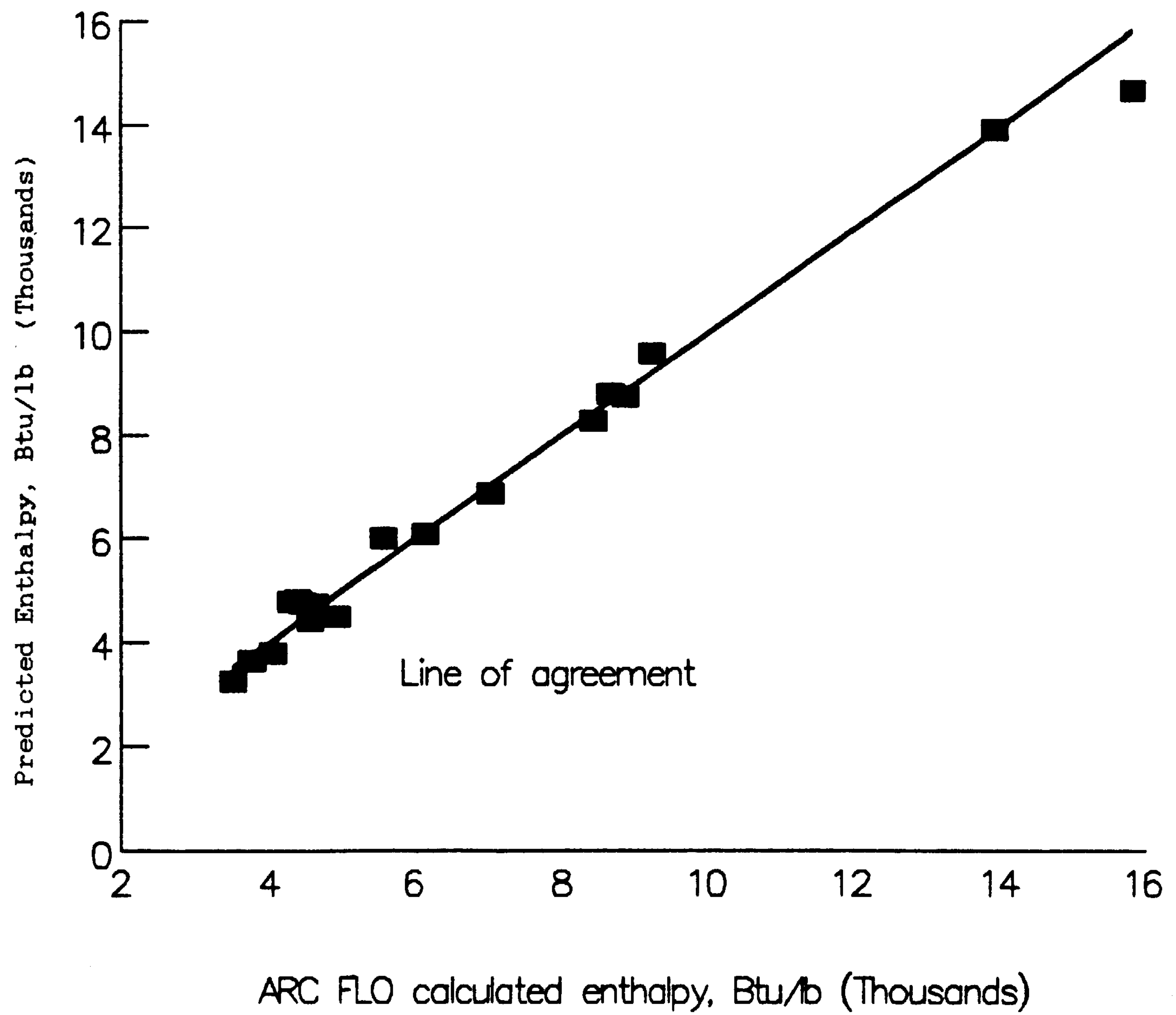

Figure 2. Curve Fit of Enthalpy Correlation Equation.

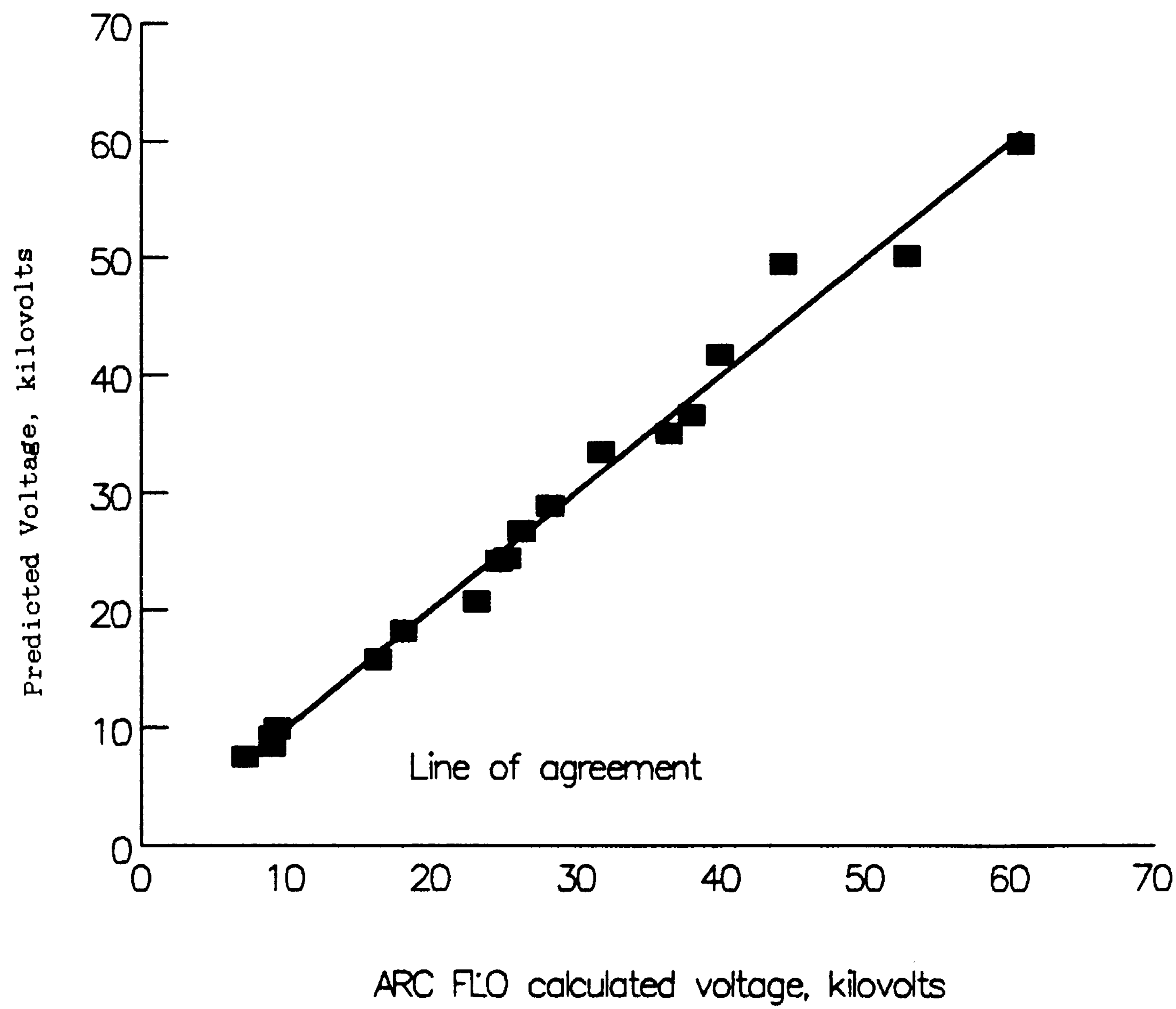

Figure 3. Curve Fit of Voltage Correlation Data.

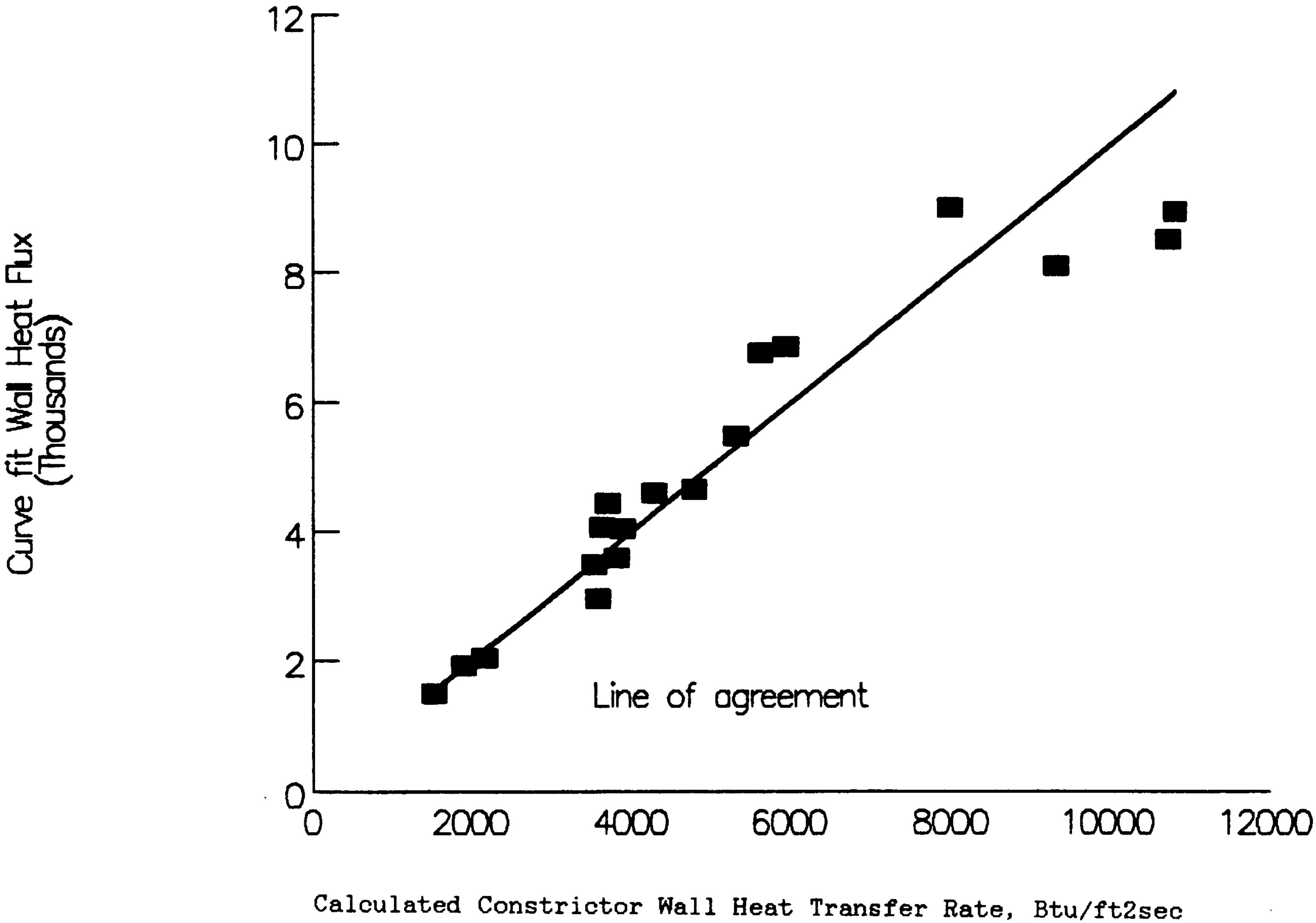

Figure 4. Curve fit of Wall Heat Rate Correlation Data.

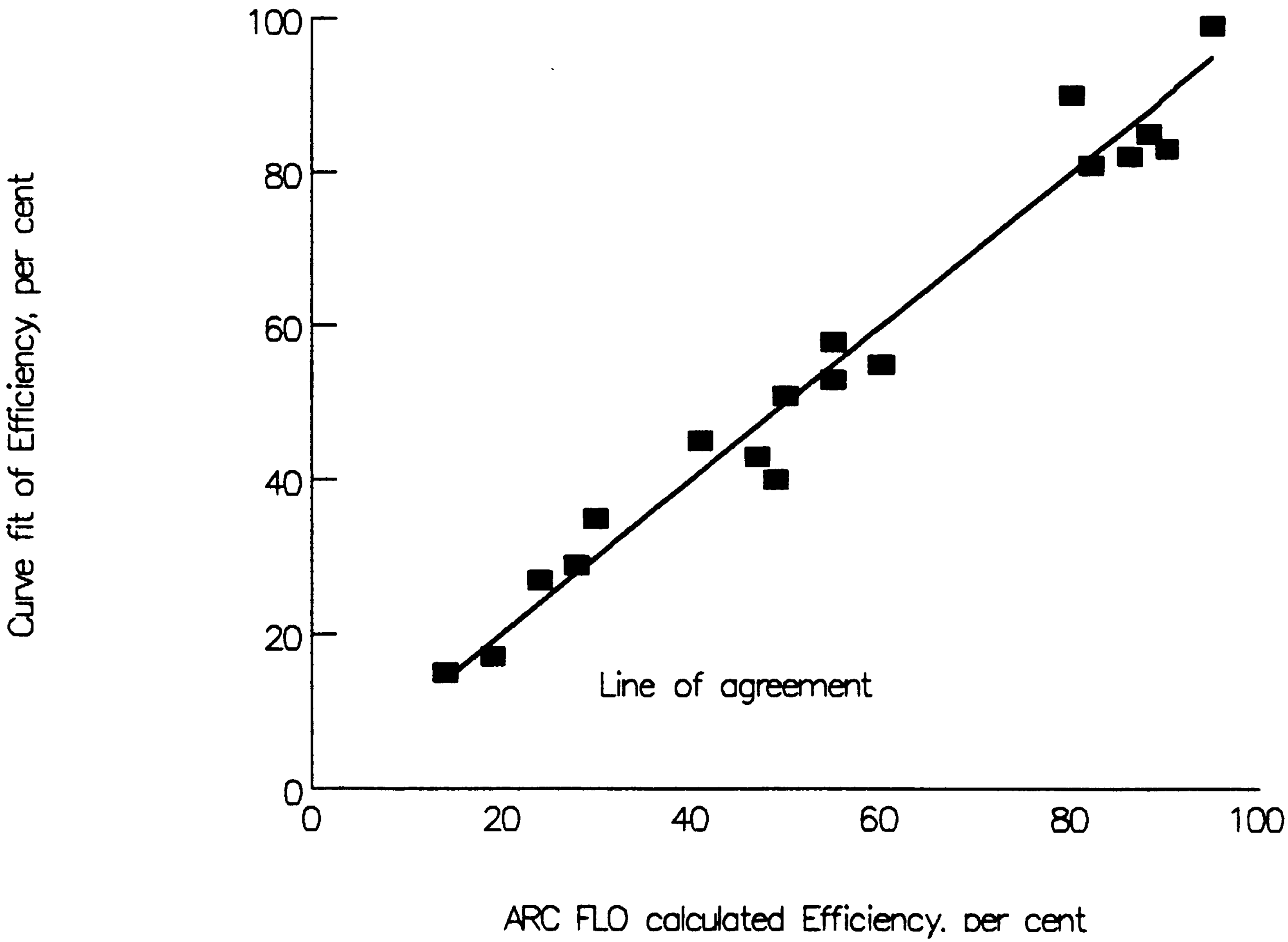

Figure 5. Curve Fit of Efficiency Correlation Data.

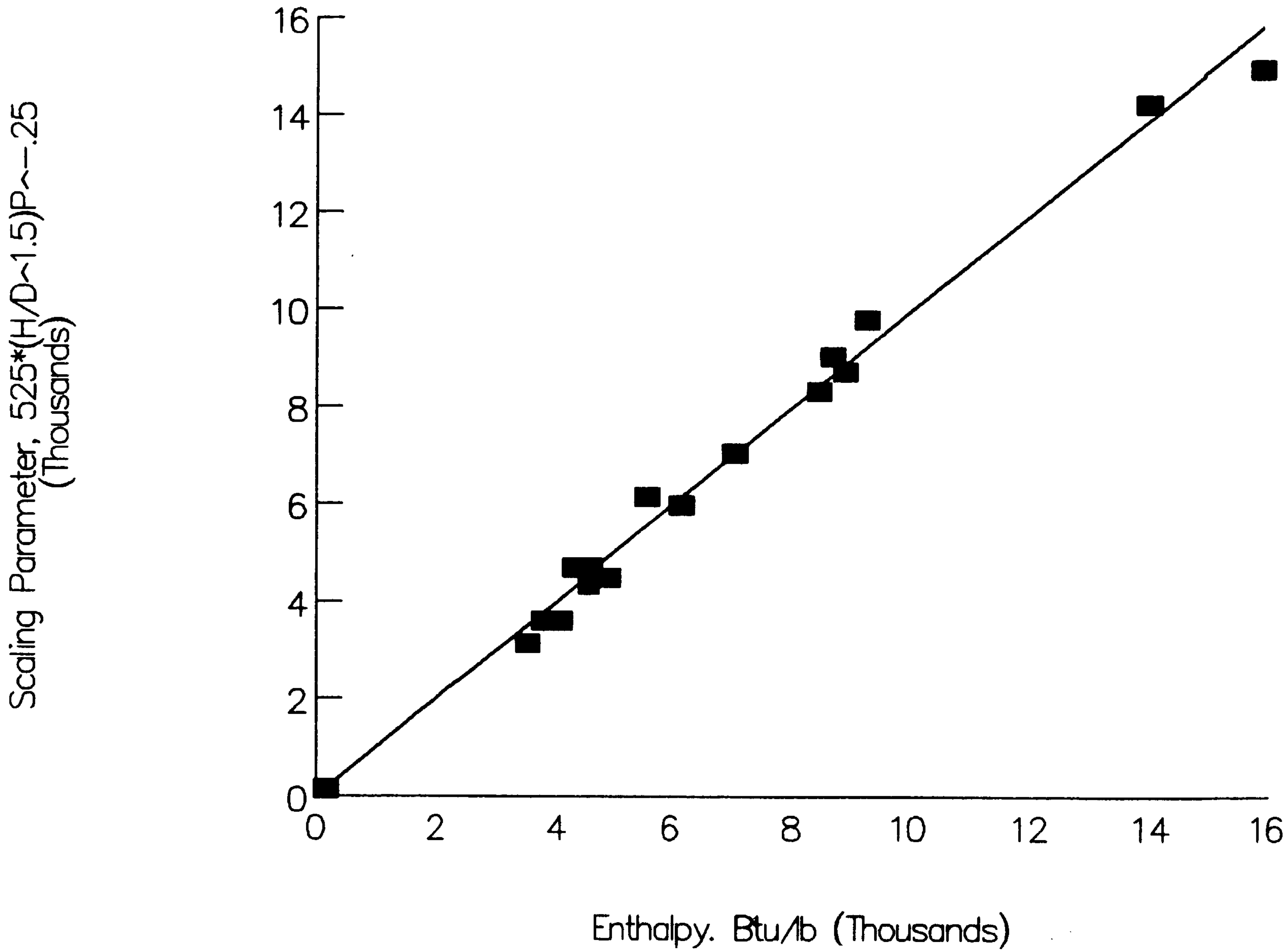

Figure 6. Correlation of Simplified Enthalpy Scaling Law

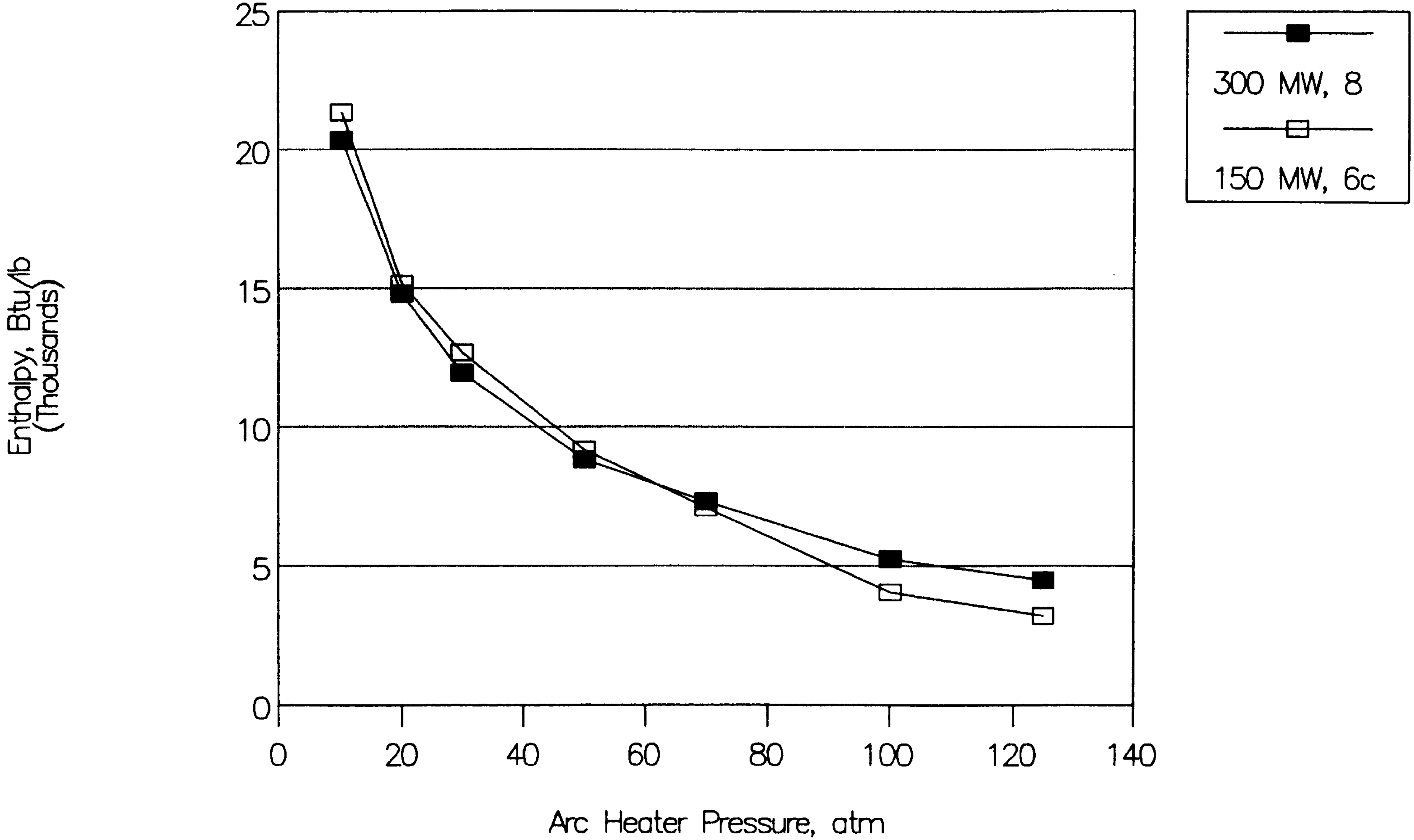

Figure 7. Performance Curves for the 300 and 150 Megawatt Arc Heaters.

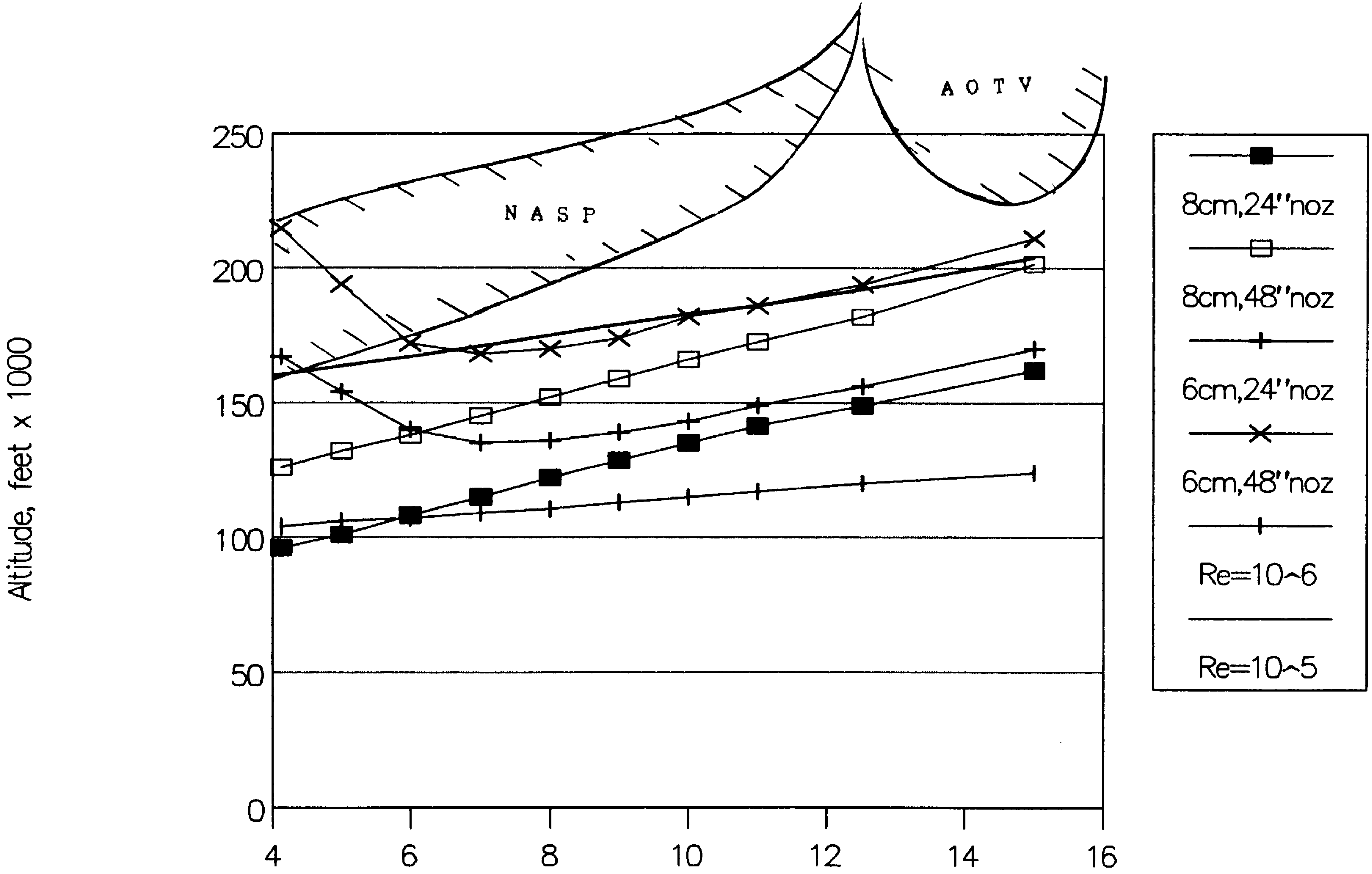

Figure 8. Mass Flux Density Simulation with the 300 MW and 150 MW Arc Heaters

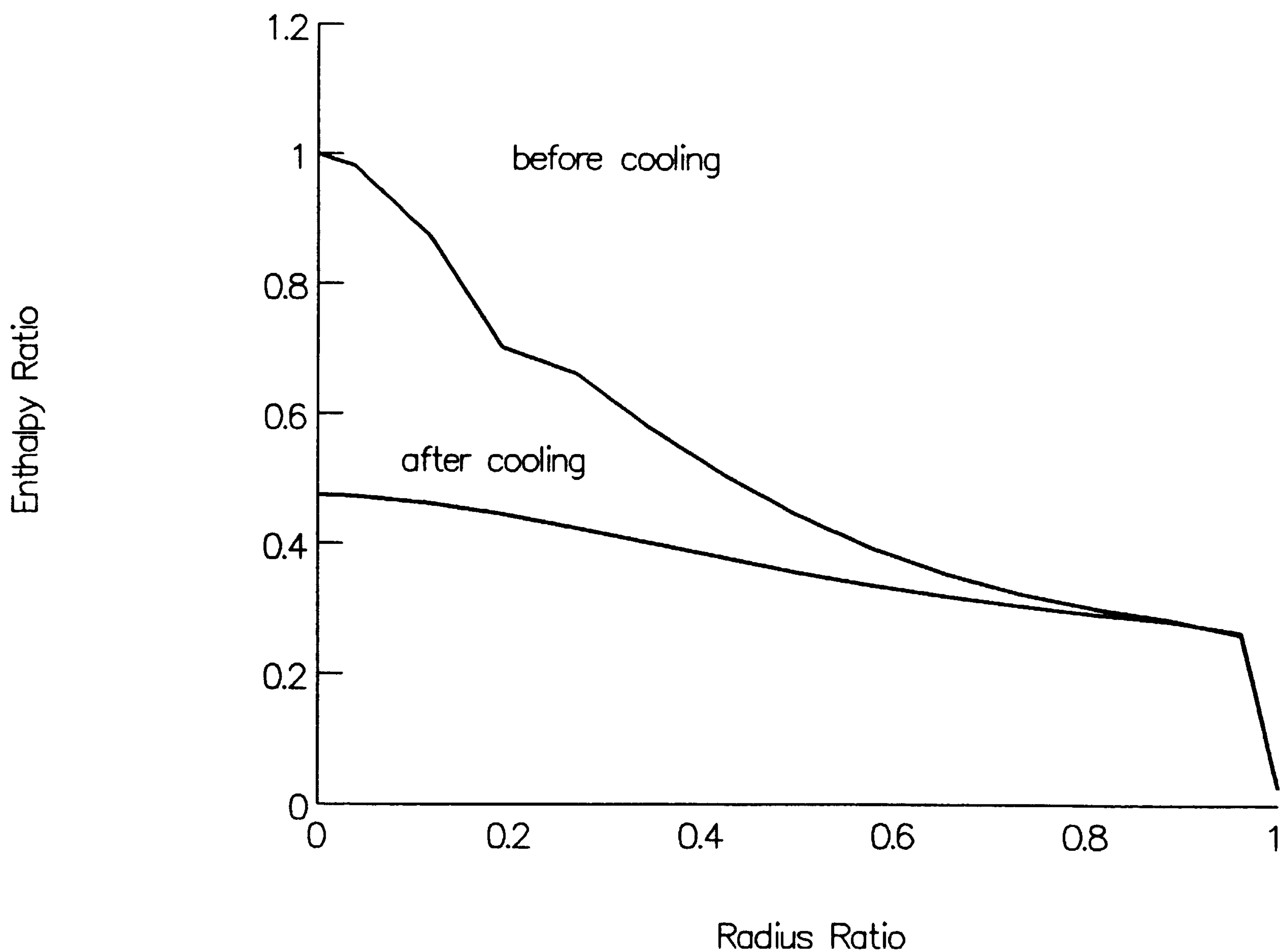

Figure 9. Typical Effect of Cooling on the Radial Enthalpy Profile.

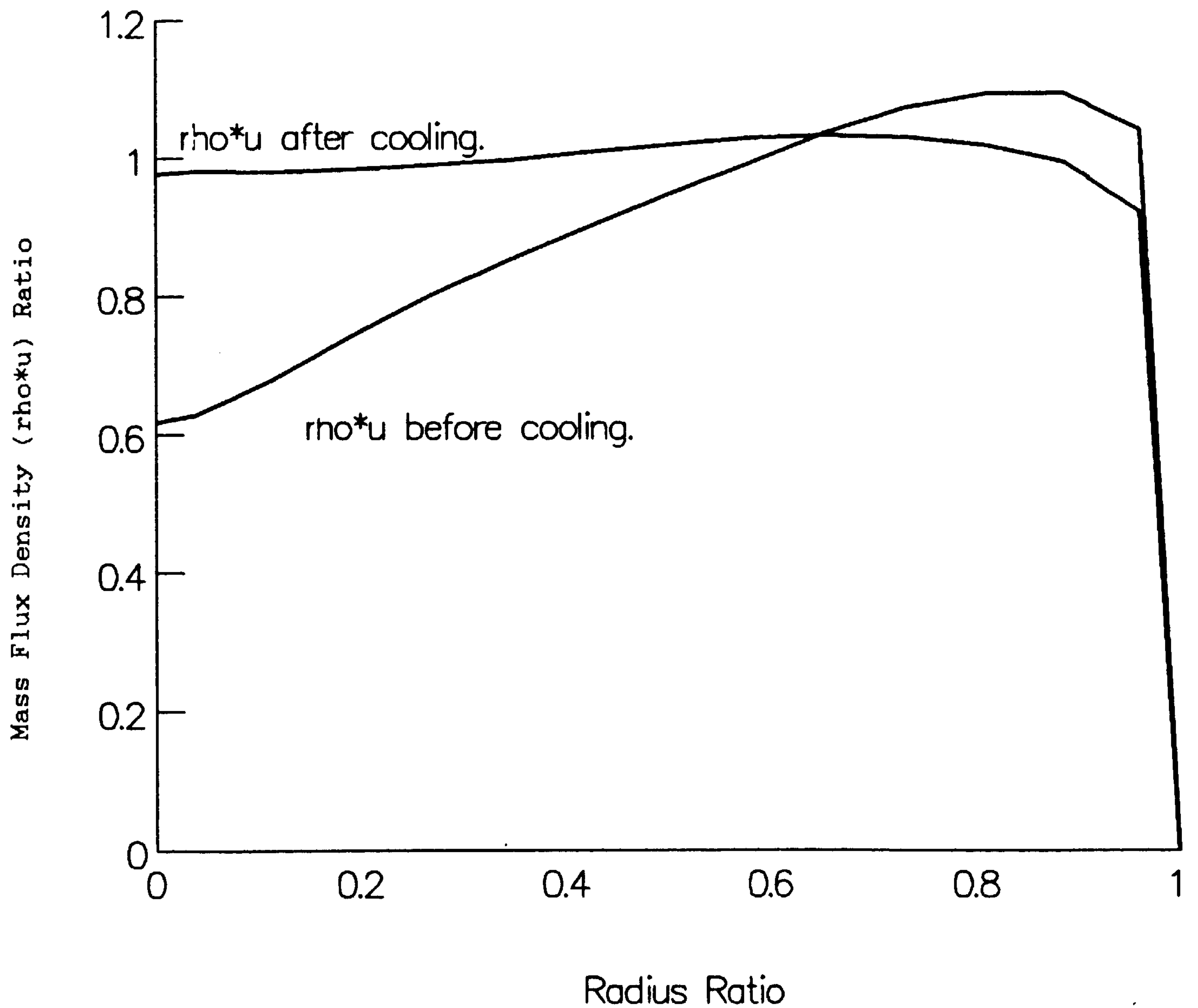

Figure 10 Typical Effect of Cooling on the Radial Mass Flux Density Profile

ARCFLO Enthalpy prediction verification

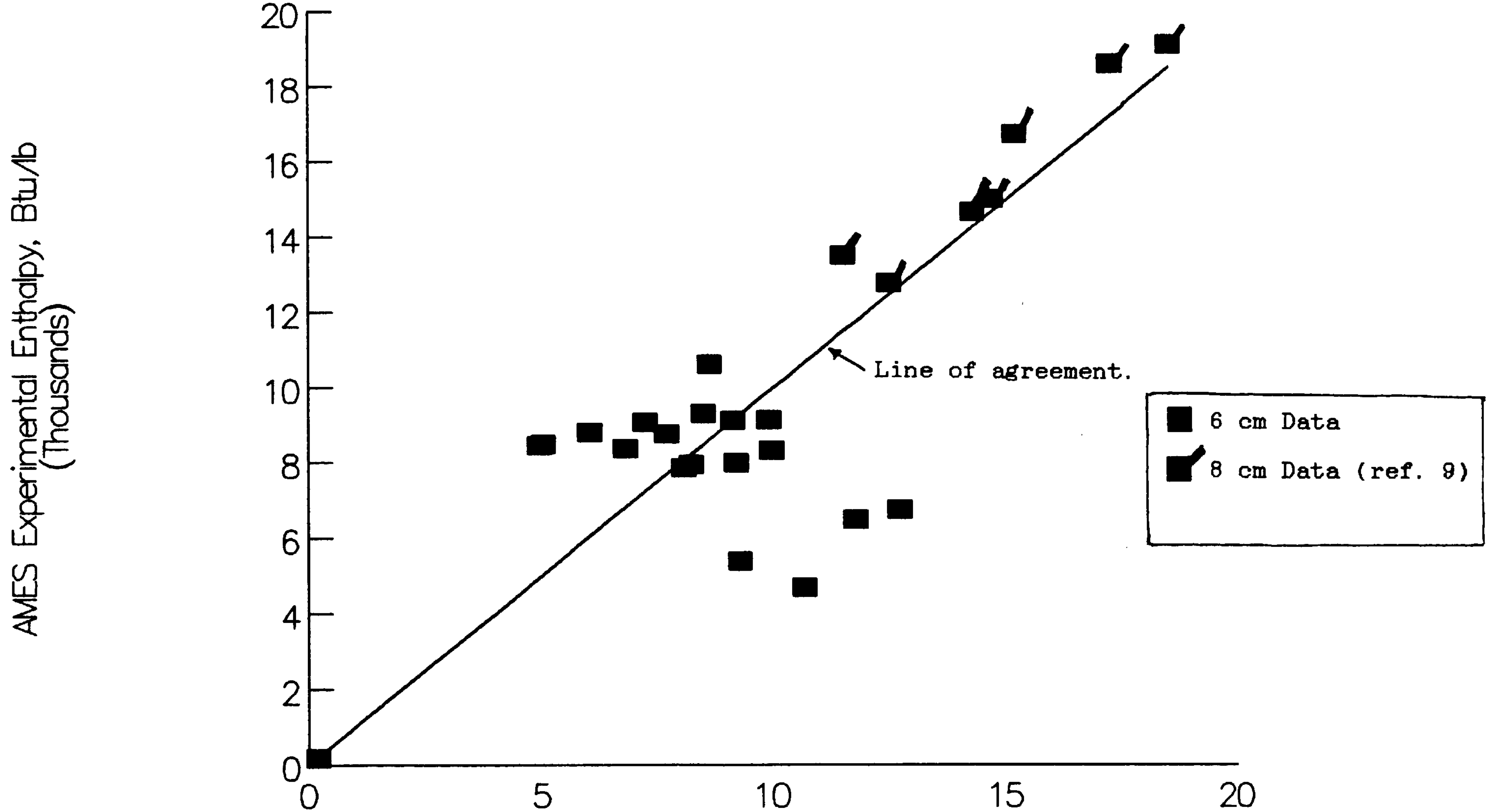

Fig. 11(a). ARCFLO Enthalpy, Btu/lb. (Thousands)

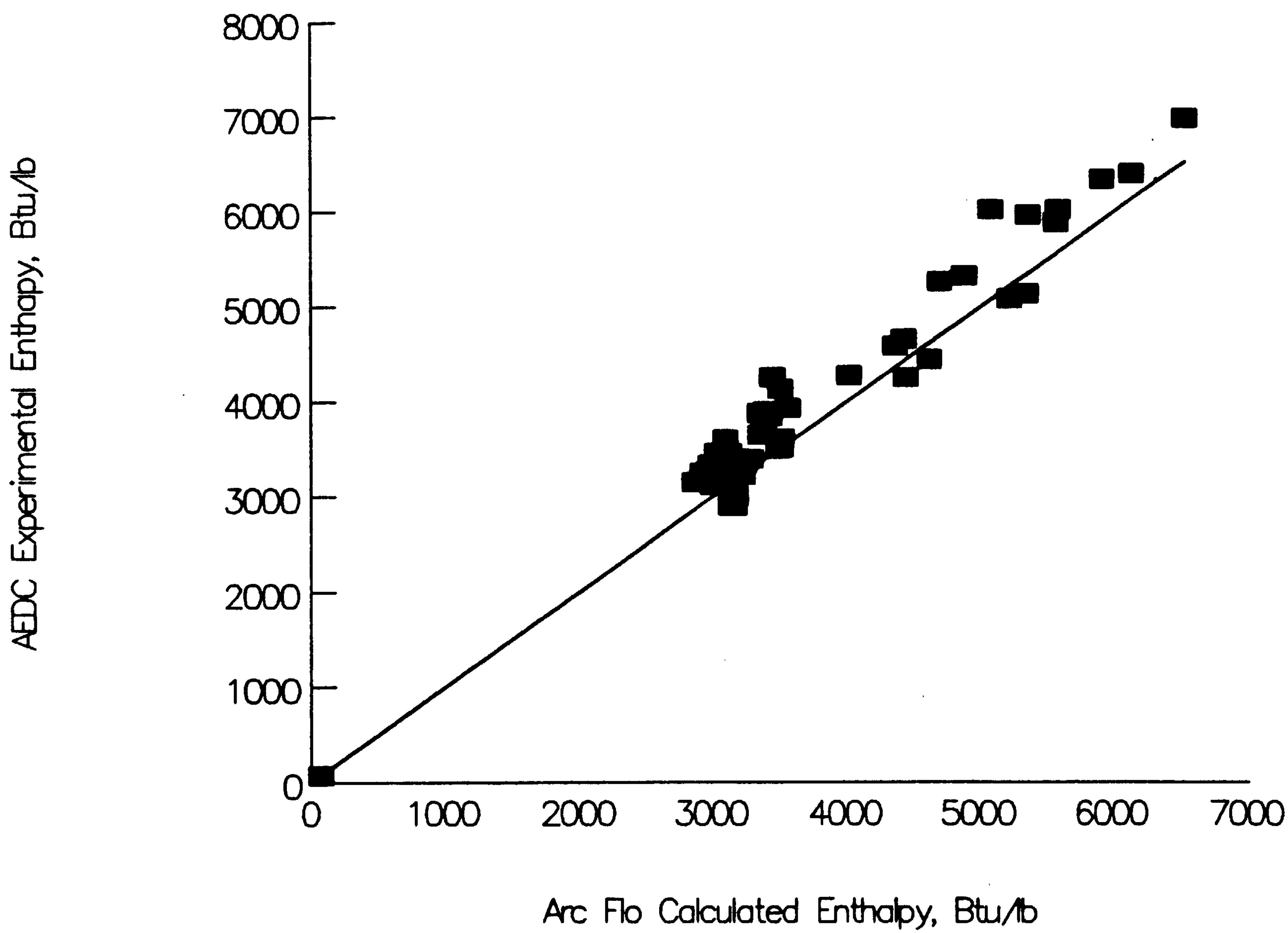

Figure 11(b) Verification of ARC FLO Enthalpy Predictions by AEDC Experimental Data.

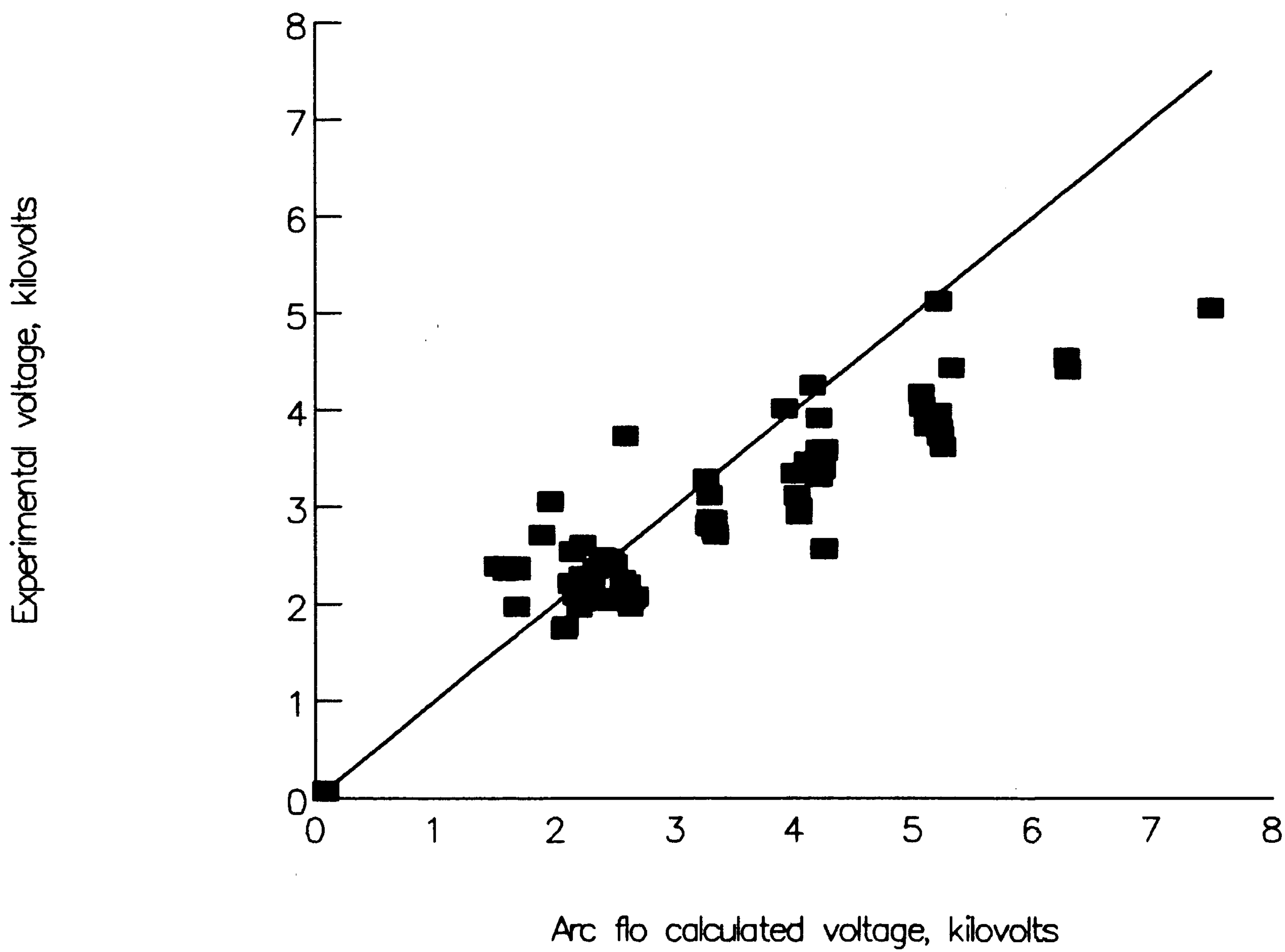

Figure 12(a) Verification of ARC FLO Voltage Predictions by Ames Experimental Data

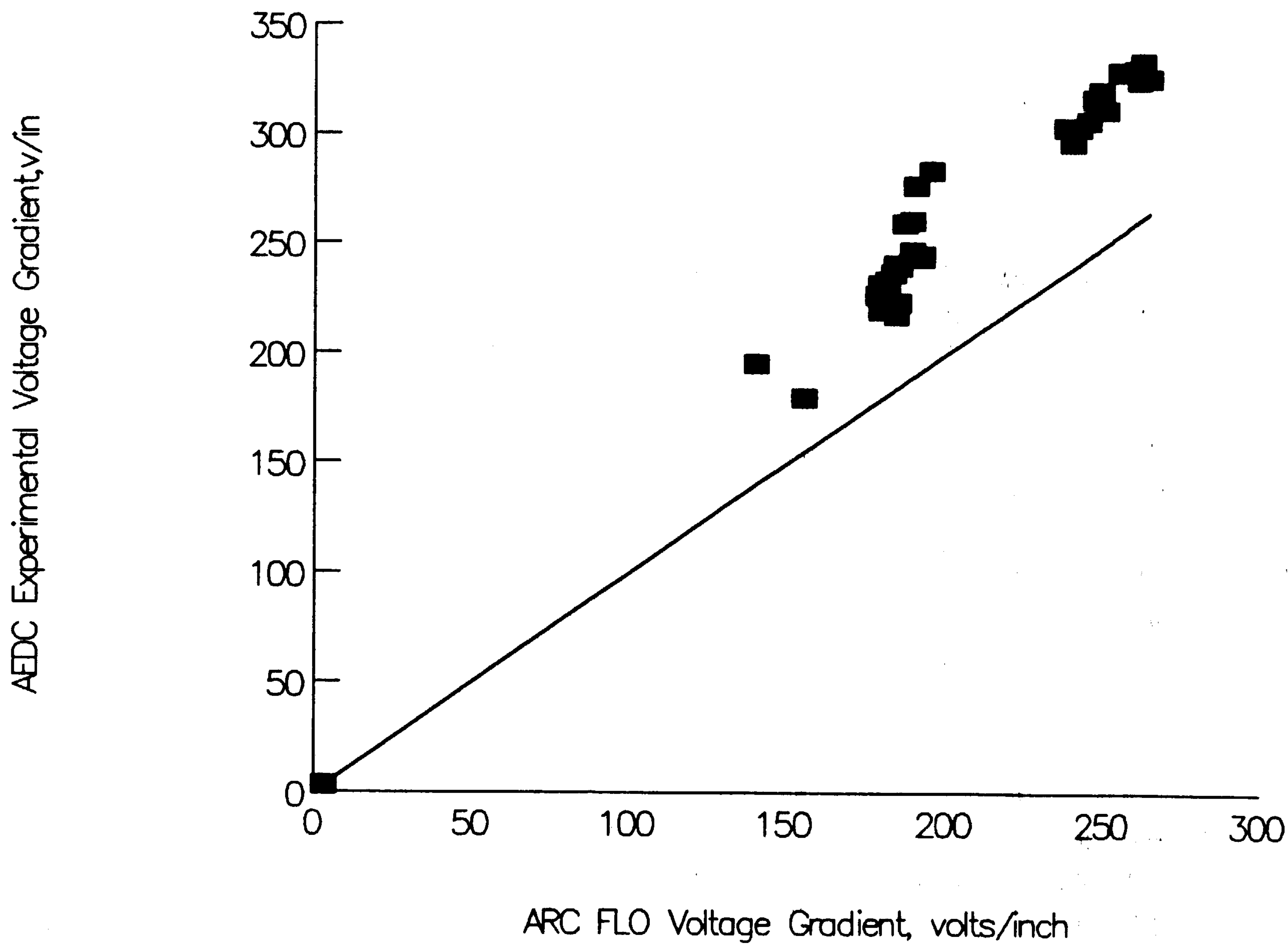

Figure 12(b) Verification of ARC FLO Voltage Predictions by AEDC Experimental Data

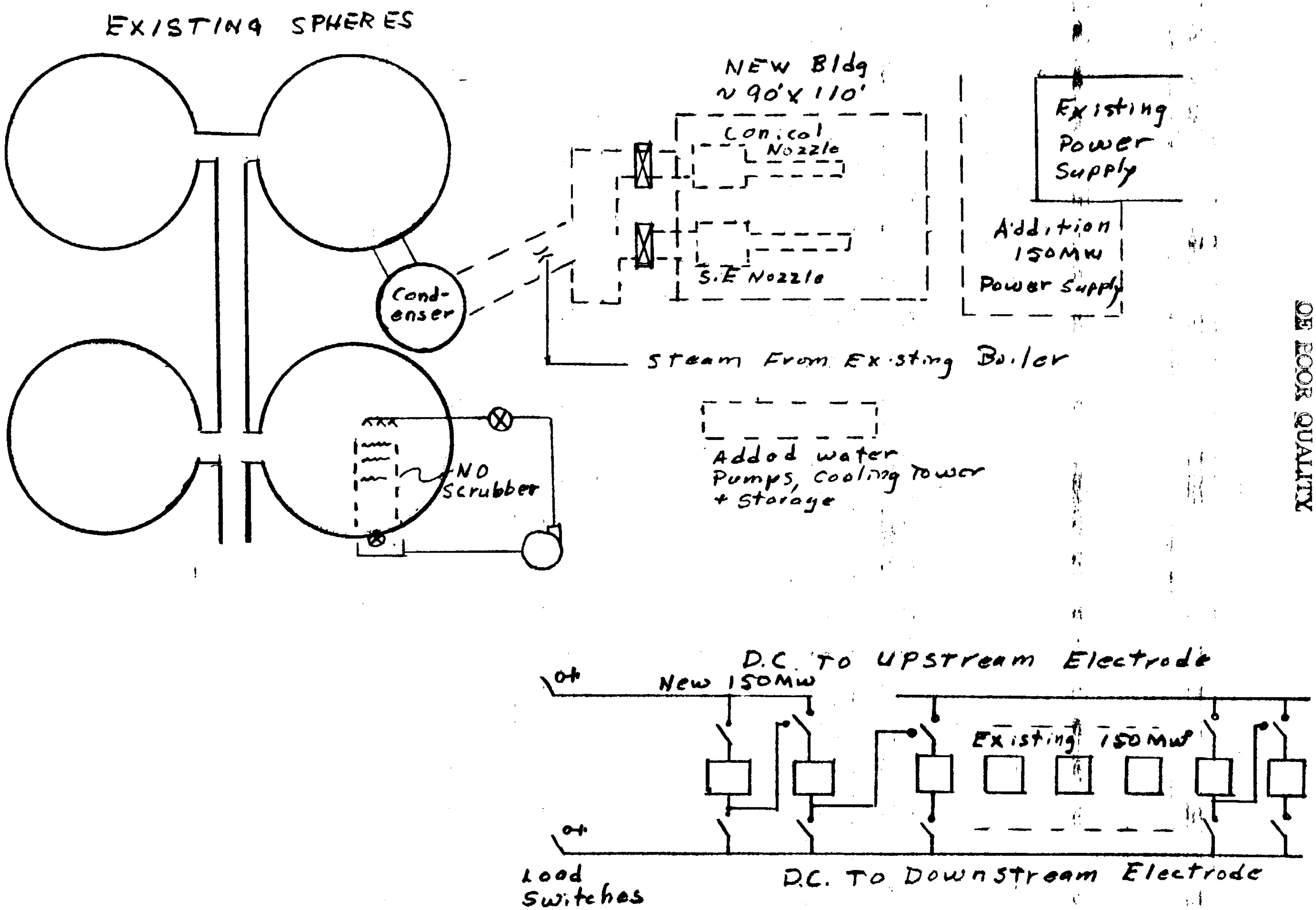

FIG. 13 - FACILITY SCHEMATIC