Types and Trend of Arc Heater Facility

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Abstract　The types of operational aerospace arc heater facility is performed. These facility include multi-segment, huels or vortex stabilized, magnetically-stabilized, induction-coupled and magnetplasmdynamic heaters. The main facility is described. The trend of arc heater facility is also introduced in this paper.

Key words　Arc heater, Facility types , Trend

电弧加热设备的类型及趋势

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文　摘　介绍了现有的应用于航天领域的电弧加热设备类型,包括叠片、管弧或涡稳、磁稳、感应以及磁等离子动力加热器。描述了主要的设备,同时对电弧加热设备的发展趋势进行了介绍。

关键词　电弧加热,设备类型,趋势

0　Introduction

High heat flux, surface pressure, and surface shear levels exist on all aeroshell and aerostructure configurations traversing endoatmospheric and transatmospheric flight corridors at Mach numbers greater than 5. These factors combine to challenge even the most robust of ablative and insulative materials designed to protect vehicles operating in that regime. Consequently, systems designers for hypersonic weapons, space access vehicles and reentry vehicles are concerned in several key issues with respect to high-speed aero-heating and the resultant heat transfer that precede thermal protection system (TPS) ablation. These issues are all important concerns to the experimentalist tasked with evaluating thermal protection materials and structural components in ground test facilities[1].

Such simulations typically require a test gas, usually air, heated to temperatures between 3 000 and 18 000°R and supplied continuously for several minutes. Arc heaters provide an efficient heating source for such simulations, having sufficient flexibility in their various configurations to enable aerothermal simulations for a large sector of the hypersonic velocity/pressure altitude flight envelope. Consequently, arc heaters have found widespread use in both military and commercial aerospace applications for development of high-temperature materials and structures for missiles, reentry vehicles, high-speed transports, military/civil space transportation and space access vehicles, scramjet combustors, and hypervelocity ordnance and munitions systems.

The types of arc heaters and main arc heater facility are described. The trend of arc heater facility was also introduced in this paper.

1　Types of arc heater

In order to simulate the hypersonic vehicles' thermal conditions in ground, several types of arc heater were developed[2]. These facility include multi-segment, huels or vortex stabilized, magnetically-stabilized, induction-coupled (ICP) and magnetplasmadynamic (MPD) heaters. Fig. 1 gives these arc heaters pressure-enthalpy envelopes.

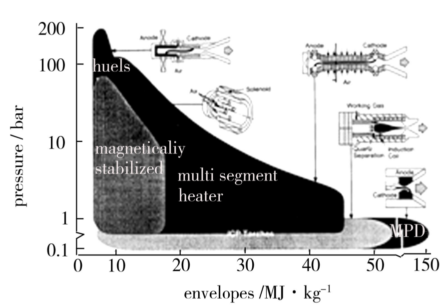

Fig. 1　Pressure-enthalpy envelopes of deferent arc heaters

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Fig. 2 provides a timeline arc heater facility development since 1970's. From Fig. 2 we can see the multi-segment, huels or vortex stabilized and magnetically-stabilized are the main types of arc heater facility. The great power arc heater are developed in NASA ames, NASA JSC, NASA Langley, USF AEDC, Russia Tsniimash and CIRA.

The following sections describe the main arc heater facility and test simulating capability.

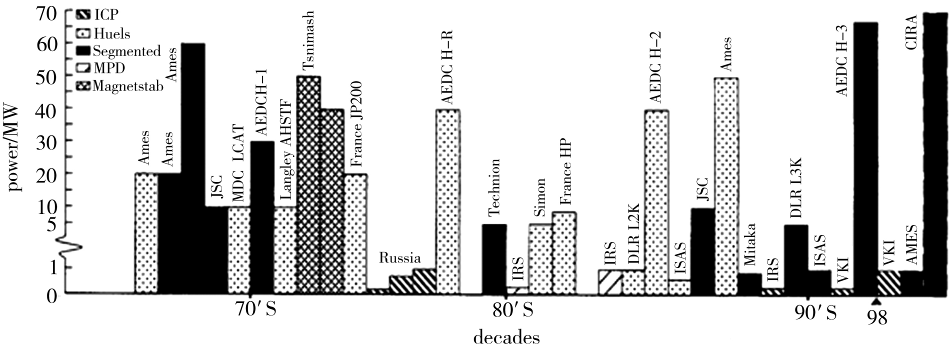


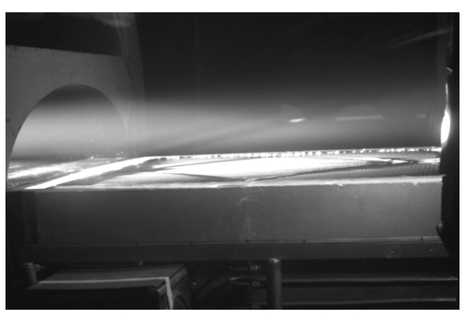
Fig. 2 Time history of arc heater facility development

1.1 NASA ames arc heater facility

The ames arc heater facility has a rich heritage of over 40 years in TPS development for every NASA Space Transportation and Planetary program, including Apollo, Space Shuttle, Viking, Pioneer-Venus, Galileo, Mars Pathfinder, Stardust, X-33, X-34, SHARP-B1 and B2, X-37 and MER-A and B. With this early TPS history came a long heritage in the development of arc jets. These facilities are used to simulate the exit and entry heating that occurs for locations on the body where the flow is brought to rest (stagnation point or nose cap, wing leading edges and on other TPS areas of the space craft). Exposures have been run from a few minutes to over an hour, from one exposure to multiple exposures of the same sample in order to understand the TPS materials' response to a hot gas flow environment representative of real hyperthermal environments. The ames arc heater facility is a key enabler of the three major areas of interest to TPS development: selection, validation, and qualification.

The ames arc heater facility photo is provided in Fig. 3 and summary of the facility is given in Tab. 1[3-6].

laboratory buildings



60 MW IHF

20 MW AHF

Fig. 3 Ames arc heater facility

Tab. 1 Summary of NASA ames arc heater facility

Facilityname	Simulated testing features
Aerodynamic Heating Facility (AHF)	• Air or Nitrogen gases • 20-MW Ames-designed constrictor arc heater or 12 MW Huels arc heater. • Nozzles from 3 to 36" exit diameter (76 to 914 mm) • Samples sizes up to 8" diameter (203 mm) or 26×26" (660 by 660 mm) wedge • Pressures from 0.005 to 0.125 atm (with Huels heater in excess of 5 atm) • Heat fluxes from less than 1 on a wedge to over 300 W/cm^2 on a 4" dia. semisphere 5-arm fully programmable model insertion system

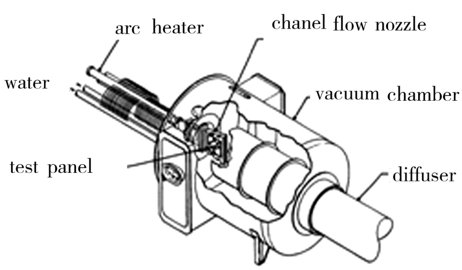
continue Tab. 1

Interaction Heating Facility(IHF)	• 60-MW Ames-designed constrictor arc heater • Nozzle exit sizes from 152 mm to > 1 m (6" to 41") • Stagnation, free jet wedge, or flat panel with semielliptic nozzle • Stagnation pressures from 0.01 to over 1 atm • Heat fluxes from 5 to >6000 kW/m^2 • Enthalpies from 7 to 47 MJ/kg • Power supply capable of delivering 75 MW for 30 minutes or 150 MW for a 15 second
Panel Test Facility (PTF)	• 20-MW Ames-designed constrictor arc heater • Semielliptic nozzle • Test samples up to 355 by 355 mm • -4 deg to +8 deg inclinations of the surface of the test sample • Run durations up to 30 minutes possible • Cold wall (fully catalytic) heat flux from 6 to 340 kW/m^2 • Surface pressures from 66 to 4700 Pa
Turbulent Flow Duct (2×9)	• Air or nitrogen gases • Linde (Huels) free-length arc heater (12-MW) • Test samples of 203 mm high by 508 mm long (8" by 20") • Surface pressures from 0.02 to 0.15 atm • Cold wall heat fluxes from 20 to 700 kW/m^2 • Enthalpy range from 3 to 9 MJ/kg
Developmental Arc Jet Facility (DAF)	• Multiple gases or gas mixtures (N_2, O_2, Air, CO_2, Ar, H_2, He, CH_4) for simulations of a wide range of planetary entry profiles • 3-MW Aerotherm™ segmented arc heater • Stagnation or free wedge configurations • Multiple model insertion system, up to 10 positions available

1.2 NASA JSC ARMSEF

NASA Johnson Space Center's (JSC) arc heater facility named Atmospheric Reentry Materials and Structures Facility (ARMSEF) has been used primarily to develop, evaluate and certify every type of TPS used on the Apollo Command Module and the Space Shuttle Orbiter vehicle.

The JSC ARMSEF was first described in detail in Reference [6], and a brief overview is provided below. There are two test positions. Test position one (TP1) is the channel nozzle arc-jet which is used to study flat surface heat transfer at zero angle of attack. Test position two (TP2) is the conical nozzle arc-jet which is used to study heat transfer to various blunted bodies (e. g., wedges, spheres) and small flat plates at the angles of attack between 0 and 45 degrees. Each test position includes a 10 MW arc heater and a 12-ft dia. test vacuum chamber with a diffuser. A solid-state power supply, water cooling system, boiler, 4-stage steam ejector system, vacuum pumping system, test gas supply system, control room, and data room are common and can serve either test position. The JSC arc heater sketch and facility photo is provided in Fig. 4 and summary of the facility is given in Tab. 2[7-8].



Arc heater sketch

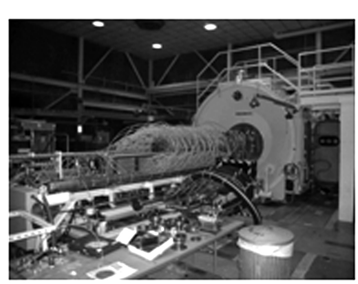


Photo of TP2

Fig. 4 JSC arc heater facility

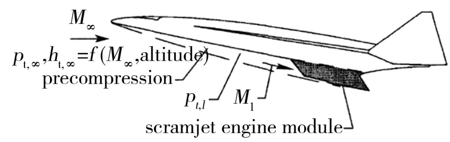
Tab. 2 Summary of JSC arc heater facility

facility type	test position	nozzle throat size /2.54 cm	nozzle exit size /2.54 cm	simulated ability
multi-segment arc heater	TP1	2.0×2.0	8×10	facility power, up to 10 MW
		2.0×2.0	12×12	enthalpies up to 13000 Btu/lb
	TP2	2.0×2.0	24×24	model surface pressures up to 120 PSF
		2.25 diam.	5 to 40 diam.	model surface temperatures up to 3100°F

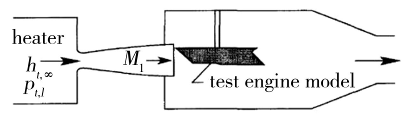
1.3 NASA Langley arc heater facility

The Langley Research Center arc heater facility named Arc-Heated Scramjet Test Facility (AHSTF) generates high energy air flows for testing airframe-integrated subscale scramjet engine modules for hypersonic vehicles. Fig. 1 shows a typical hypersonic vehicle in flight and also shows the corresponding ground facility simulation for the scramjet engine. The AHSTF uses arc-heated air to duplicate true flight stagnation enthalpy conditions for a flight Mach number range of 4.7 to 8.[9-12] The heated test gas is expanded through a nozzle to a Mach number M_1, providing a free-jet simulating condition behind the oblique forebody shock of a hypersonic vehicle flying at various angles of attack.

Fig. 5 shows the simulation sketch of the AHSTF in terms of flight altitude and Mach number. Tests can be conducted at stagnation enthalpies and pressures corresponding to the flight Mach number range and altitudes indicated by the shaded region. Also shown in Fig. 6, the lower axis is the free stream stagnation temperature range corresponding to the test Mach number range. These temperatures ranging from approximately 1 100 to 2 800 K, are produced in the stagnation region upstream from the facility nozzle expansion. Fig. 7 shows the sketch and photo of the AHSTF. Tab. 3 gives the summary of the AHSTF.



(a) Hypersonic vehicle in flight



(b) Simulation in ground facility

Fig. 5 Ground test simulation of flight for scramjet engine testing

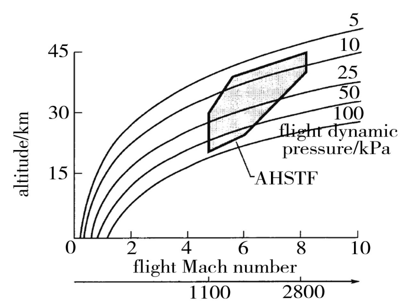
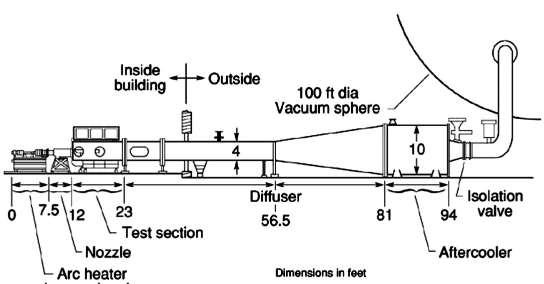


Fig. 6 Simulation capability of AHSTF



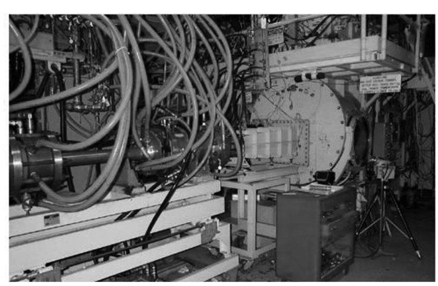


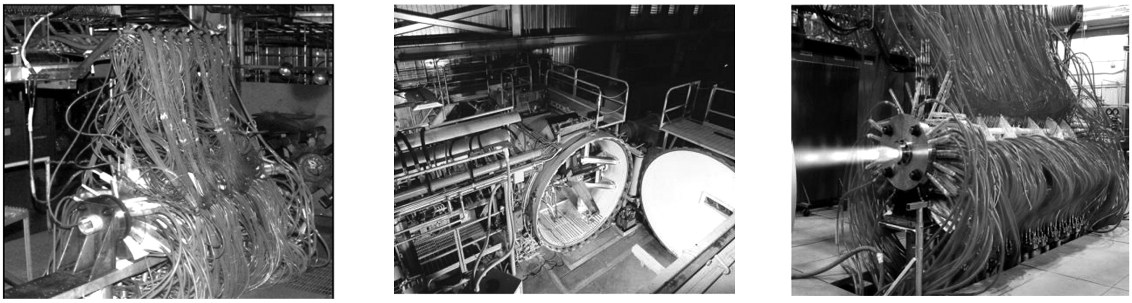
Fig. 7 Sketch and photo of AHSTF

Tab. 3 Summary of AHSTF arc heater facility

facility type	simulated flight Mach No.	nozzle exit Mach No.	nozzle exit size/2.54cm	facility power/MW	max run time/ s
linde(N=3) arc heater	4.7 to 5.5	4.7	11.17×11.17	Up to 13	30-60
	6.0 to 8.0	6.0	10.89×10.89		

1.4 AEDC arc heater facility

The USA DoD arc-heated test facilities at AEDC include two high-pressure segmented arc heaters, High Enthalpy Ablation Test (HEAT)-H_1 and H_3, and one Huels arc (H_2). Both types use a high-voltage, d-c electric arc discharge to heat air to total temperatures up to 13 000°R. High-pressure test flows are achieved by confining the electrical arc discharge to a water-cooled plenum section capable of withstanding high chamber pressures (above 100 atm). The combination of high-enthalpy test gas and high plenum pressure makes it possible to attain stagnation and wedge surface heat fluxes representative of flight at speeds in excess of Mach 20 at high dynamic pressures simulating low-altitude flight where turbulent boundary layers are the general rule at hypersonic speeds. Fig. 8 shows the photo of AEDC arc heater facility[13-15]. Tab. 4 gives the summary of capability.



H_1 H_2 H_3

Fig. 8 Photo of AEDC arc heater facility

Tab. 4 Summary of AEDC arc heater facility

facility name	facility type	max. run time/min	nozzle Mach No.	nozzle exit diam/cm	stagnation pressure/atm	stagnation enthalpy /MJ·kg^{-1}	mass flow rate/kg·s^{-1}	facility power / MW
HEAT H_1	atm exhaust, free jet	1 - 2	1.8 to 3.5	2.0 to 7.5	Up to 80	1.40 - 20.0	0.2 to 3.6	Up to 30
HEAT H_2	subatm exhaust	3 - 30	3.4 to 8.3	13.0 to 107	Up to 10	2.75 - 15.0	1.0 to 4.5	Up to 42
HEAT H_3	atm exhaust, free jet	1 - 2	1.8 to 3.5	3.0 to 12.7	Up to 80	1.40 - 20.0	1.4 to 8.0	Up to 70

1.5 CIRA scirocco facility

The scirocco facility in CIRA (Italian Center for Aersopace Research) is one of the more powerful arc tunnel facility in the world. Its energy source is an arc-jet created in a column, filled with compressed air and generated by 70 MW of electrical power. Scirocco is an arc-jet facility constituted by an arc heater segmented into 580 discs with a bore diameter of 0.11 m and a length of 5.5 m. At the extremities of this tube there are 9+9 discs (cathode and anode) and in the middle a confined electrical discharge is generated. An injection of compressed air up to 3.5 kg/s with pressure up to 17 bar is realized into the arc column. This air can reach a temperature up to 10 000 K due to the discharge generated by the electrical energy up to the impressive number of 70 MW (direct current up to 9 000 ampere and voltage up to 3 kV). The heated compressed air accelerated through a convergent-divergent conical nozzle with a throat diameter of 0.075 m and an exit diameter of 1.950 m. This jet impacts the test model under test and the maximum running time is of 30 min (typical reentry time)[16-18]. Fig. 9 shows the photo and simulation capability cures of CIRA scirocco arc heater facility. Tab. 5 gives the summary of the capability.

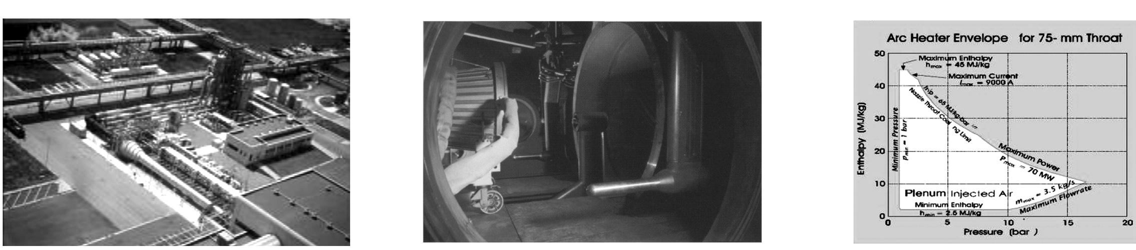


Fig. 9 Photo and simulation capability cures of CIRA scirocco arc heater facility

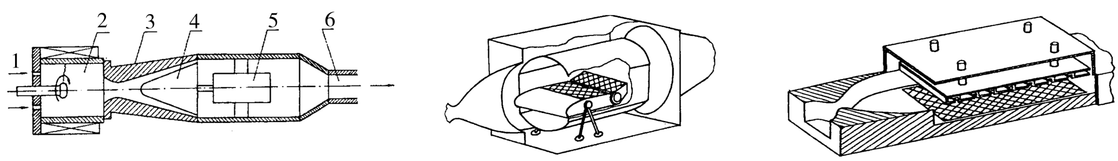
Tab. 5　Summary of CIRA scirocco arc heater facility capability

facility type	nozzle throat size/mm	nozzle exit size /mm	facility power /MW	simulated ability
multi-segment arc heater	75	900	up to 70	enthalpies, 2.5 to 45 MJ/kg
		1150		mass flow rate, 0.1 to 3.5 kg/s
		1350		running time, up to 30 min, total pressure, 1 to 17 bar
		1950		model size, up to 800 mm in diameter

1.6　Russia TSNIIMASH arc heater facility

Although research on these types of heaters was abandoned in favor of heels or segmented in the USA and Italy, magnetically-stabilized arc heater facilities were extensively developed for large scale testing at TSNIIMASH in the former soviet union. These facilities were strongly utilized in the development of carbon-carbon thermal protection systems for buran and other soviet spacecraft. Several test techniques were used with these facilities including shroud, wedge and plate methods[19].

Fig. 10 gives the sketch of test techniques and the Tab. 6 describes the capabilities of the facility.



shroud　　wedge　　plate

Fig. 10　Sketch of test techniques in TSNIIMASH arc heatr facility

Tab. 6　Summary of TSNIIMASH arc heater facility capability

facility	model shape	model size/mm	mach number	pitot pressure /atm	total temperature /K	heat flow rate /kW·m^{-2}	electric power /MW
TT-1	cylinder	D<50	5.8	0.14-0.16	1800-3500	500-1500	5.2
	wedge	200×300	-6	0.15-0.20	2500-4800	40-400	7.3
	cone(shroud)	D=90	<1	10	4000	4000	7.0
	plate	500×150	2.5	4-12	<4000	100-1000	8.5
U-15T-2	cylinder	D<60	2.5	25	4000-5000	30000	35
	cone(shroud)	D=170	<1	14	3500	5000	20
TT-2 (plasmatron)	cylinder	10-30	2	3	7000	15000	1.4
	-"-	10-30	4	0.3	6000	10500	0.70
U-15T-1	wedge	600×1000	6	0.15	3500	100-200	35.5

2　Trend of arc heater facility

From described above, one can see the arc heater has the unique role to reproduce thermal environments simulating flight from Mach 5 to 20 for the long exposure periods required to test thermo-structural performance and survivability of materials and components at high total temperatures. The unique role filled by arc facilities is shown graphically on a total temperature-duration map in Fig. 11. Only the arc heater facility can run in long-duration to simulate the rigorous thermal environments. The development trend of arc heater facility can conclude two facts: one is to develop high pressure arc heater facility and the other is to develop mid-pressure arc heater facility. Both developments are based on the Multi-segment arc heater[20-22].

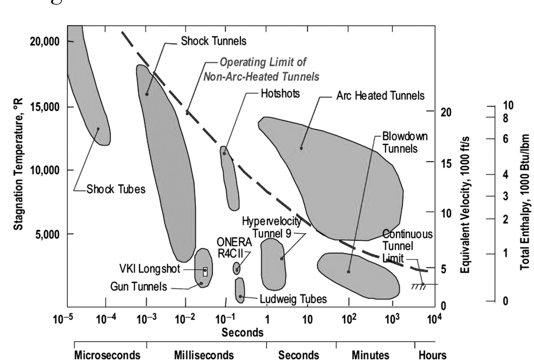


Fig. 11　Unique role of arc heater facility

2.1　Need of mid-pressure arc heater facility

The USA, USAF, USN, and NASA reentry vehicles have a need for a ground-test capability to develop and sustain thermal protection systems and for hypersonic materials. These vehicles include Air Force Space Command (AFSPC) force application systems such as the ICBM fleet, the Maneuvering Reentry Vehicle (MaRV) and the future Common Aero Vehicle (CAV), the USN's SLBM Trident systems, the US Army's Advanced Hypersonic Weapon (AHW) system, and the Missile Defense Agency's (MDA) hypersonic interceptor systems, such as THAAD, GBI, and Navy Aegis, as well as NASA vehicles such as the Orion/Crew Exploration Vehicle (CEV) Lunar/Mars return missions and the Mars Science Laboratory (MSL) planetary entry system. While an adequate capability exists for the high-altitude winged vehicle and low-altitude ballistic reentry portions of the flight envelope (although conditions still fall short of flight conditions for many vehicles), the only facility that covers a portion of the flight envelope of capsule and gliding vehicles such as MaRV and AHW is the DoD H_2 facility. This facility can only cover the lower velocity portion of this envelope; therefore, the most critical portion of the flight profile at which max heating occurs cannot be simulated. Better simulation of the mid-altitude flight regimes will enable the program offices to optimize the number of required flight tests. In this regime a facility operating at moderate pressures of 10 to 70 atm and an enthalpy range of 600 to 8 000 BTU/lbm is required. This mid-pressure facility will be required to operate for time periods of 10 to 30 min for two reasons: (1) vehicles operate in this region for long periods of time and (2) testing multiple configurations during ground testing greatly reduces the test cost and provides a comparative analysis with reference materials [2]. Several government programs are interested in this domain. The altitude-velocity map (Fig. 12) shows a representation of the current operating envelopes of several arc heater facilities along with data points of interest to other DoD programs and NASA.

As one can see, a large capability gaps exists between the high-pressure (low altitude) and low-pressure (high altitude) region of the flight envelope. There are test points of interest to various flight vehicle types. These are: (1) Intermediate-range hypersonic glide missile. (2) Mach 10 hypersonic cruise tactical missile. (3) MaRV glide and lunar reentry. (4) Maneuvering reentry pullout and glide. (5) Mid-endo MaRV glide and orbital reentry. (6) MaRV terminal dive and interceptor fly-out.

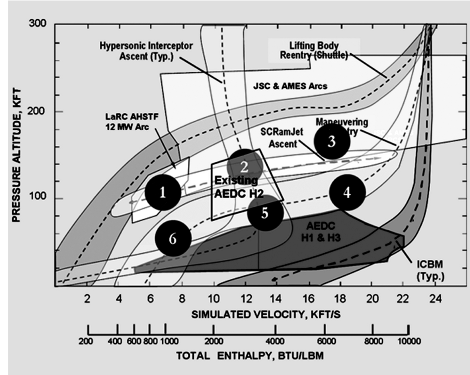


Fig. 12 USA National mission operating points and existing ground simulation capability

2.2 Development of mid-pressure arc heater facility

In order to meet the need of mid-pressure arc facility, AEDC propose to integrate a segmented arc heater into the H_2 Huels heater. The major changes are a new thyristor-based power supply, improved cooling-water capacity, construction of the necessary air and water manifolds in the H_2 bay, and a modular-based cart system to switch out the existing H_2 Huels arc heater with the segmented heater. Other proposed upgrades include the addition of air and water manifolds and stilling chambers because a segmented arc heater requires more air and water than a huels, along with additional instrumentation such as voltage towers, flowmeters and thermocouples. The FY09 technology program has already produced some promising results. Electrode wear rates were reduced by 90 and 99% for the anode and cathode respectively, through various improvements in electrode design. All of these improvements culminated in a 9 min run time for the H_3 arc heater and a 16 min run time on a single anode. Fig. 13 provides the proposed new facility with huels and segmented heaters. Fig. 14 provides the relative wear rates for electrodes.

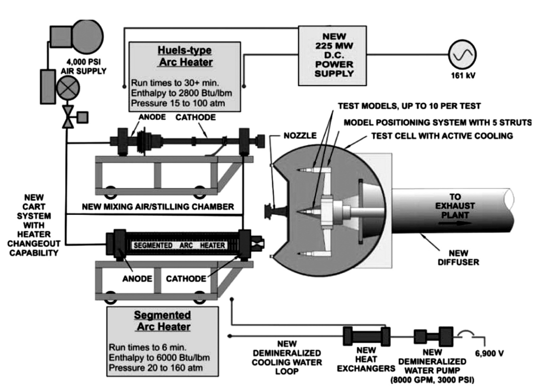


Fig. 13 Proposed new facility with huels and segmented heaters

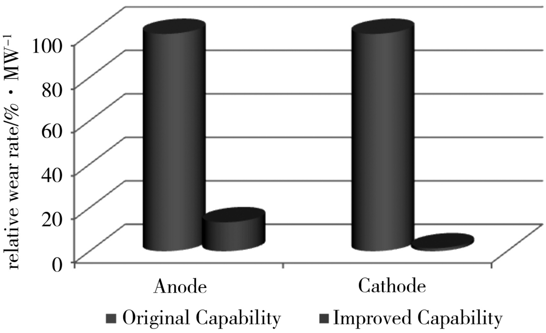


Fig. 14 Relative wear rates for electrodes

2.3 Need of high pressure arc heater facility

Arc heaters have been and remain very important components in the reentry materials development process. Arc heaters are the only facilities capable of producing a high-enthalpy, high-shear flow for realistic flight exposure periods from several seconds to minutes. Existing high-pressure arc facilities, however, fall short of duplicating flight conditions. This is illustrated in Fig. 14, where the capability of the existing facilities to simulate flight conditions is shown by plotting a variety of critical parameters both for H_3 operating with a 120 atm chamber pressure and for a reentry vehicle under a typical mission scenario. As can be seen, values of critical parameters in arc heaters are only often 50% or less of flight values. While arc heaters provide the best capability that currently exists, there clearly is room for improvement. Also shown in Fig. 15 are the projected test conditions for an arc heater operating with a chamber pressure of 200 atm.

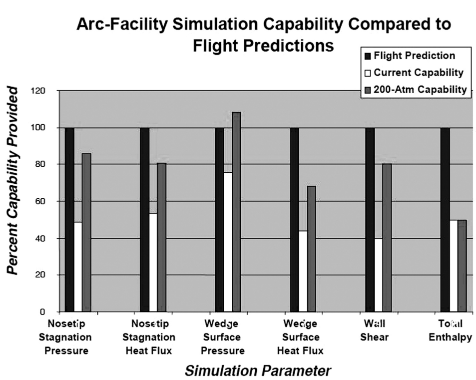


Fig. 15 Comparison between flight conditions and H_3 arc heater test conditions

As expected, increasing the chamber pressure significantly increases the stagnation pressure for nose tip testing and surface pressure for the testing of heat-shield materials on a wedge. Because heat flux into a material scales as the square root of stagnation, pressure as shown by the Fay-Riddell equation[6] the nose tip and wedge heat flux also increases despite facility enthalpy remaining unchanged. Wall shear also increases with increasing stagnation pressure, resulting in shear values of about 80% of flight conditions. (Note that the total enthalpy remains unchanged, since increasing enthalpy would require increasing current.) Clearly, increasing heater chamber pressure will lead to an improved test capability. Likewise, an improved ground-test capability will support better material screening, support development of improved material models, and reduce flight-test risks.

2.4 Development of high pressure arc heater facility

The current schedule and projected heater capability are shown in Fig. 16. The development involves: (1) the design of a heater segment that can contain the required high heater pressures while providing sufficient electrical isolation and sufficient cooling; (2) the determination of a heater configuration, including air distribution, electrode region design, heater electrical ballasting, and other issues needed to maintain arc stability and prevent arc attachment to the heater wall; and (3) the development of a heater nozzle system design that will prevent throat burnout.

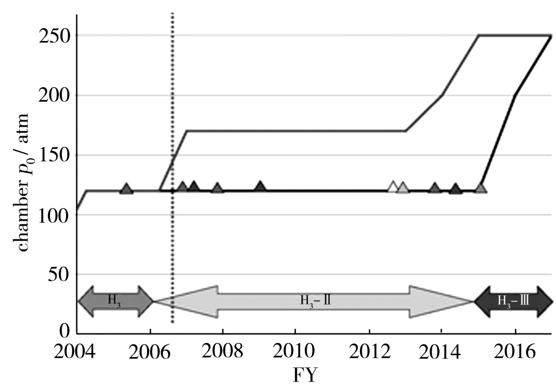


Fig. 16 Current schedule and projected heater capability

In FY 2006, 21 runs of the H_3-II facility have been completed (Fig. 17), culminating in a 6 s run at a chamber pressure of more than 196 atm. This represents a significant step forward in demonstrating the viability of high pressure heater operation. A summary graph showing run time versus chamber pressure for the runs completed thus far in FY06 is given in Fig. 17. As can be seen, several short, 6 s runs have been accomplished in the 120 to 200 atm range, medium, 15 s runs have been accomplished at 130 and 140 atm, and a long, about 30 s run at 115 atm was accomplished.

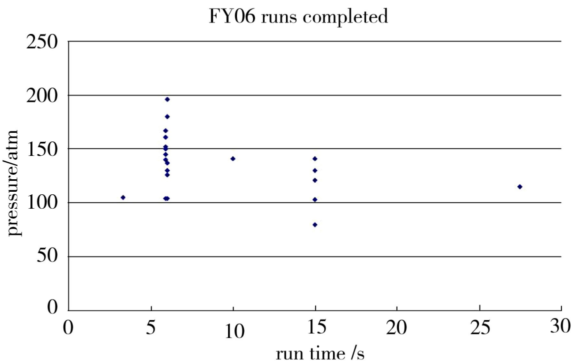


Fig. 17 Run time and chamber pressure summary for FY06 development runs

3 Conclusion

These facilities include multi-segment, huels or vortex stabilized, magnetically-stabilized, induction-coupled and magnetplasmdynamic heaters. The main facility was described. The development trend of arc heater facility includes mid-pressure and high pressure arc heater facility. The technology program involves electrode wear, the determination of a heater configuration and the development of a heater nozzle system design that will prevent throat burnout.

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