

Consolidated laser-induced fluorescence diagnostic systems for the NASA Ames arc jet facilities

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The spectroscopic diagnostic technique of two photon absorption laser-induced fluorescence (LIF) of atomic species for non-intrusive arc jet flow property measurement was first implemented at NASA Ames in the mid-1990s. In 2013-2014, NASA combined the agency's large-scale arc jet test capabilities at NASA Ames. Concurrent with that effort, the agency also sponsored a project to establish two comprehensive LIF diagnostic systems for the Aerodynamic Heating Facility (AHF) and Interaction Heating Facility (IHF) arc jets. The scope of the project enabled further engineering development of the existing IHF LIF system as well as the complete reconstruction of the AHF LIF system. The updated LIF systems are identical in design and capability. They represent the culmination of over 20 years of development experience in transitioning a specialized laboratory research tool into a measurement system for large-scale, high-demand test facilities. This paper will document the latest improvements of the LIF system design and demonstrations of the redeveloped AHF and IHF LIF systems.

I. Introduction

High enthalpy air arc jet facilities have been important tools for the development and validation of thermal protection systems (TPS) for human and robotic space exploration missions. The arc jets at NASA's Ames Research Center offer facility configurations for testing of material samples and subsystems to evaluate thermal and structural performance at flow conditions that simulate the aeroheating environment of atmospheric entry. However, arc jets produce a dissociated gas stream with a chemical composition, temperature, and velocity that differs markedly from the anticipated flight environment. Because critical evaluation of thermal protection material performance depends on transforming test observations into expectations for flight conditions, determining the consequences of

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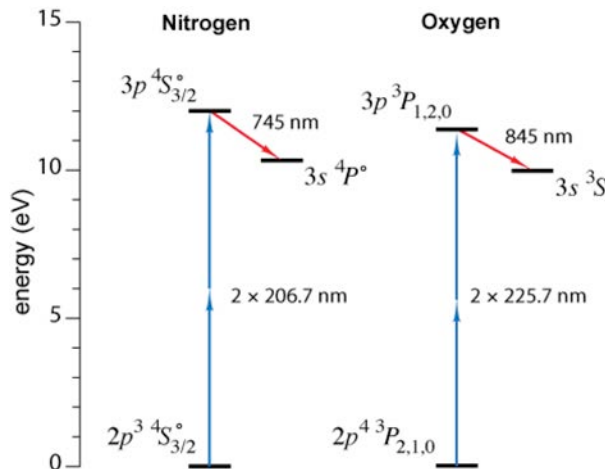


Figure 1. Excitation and emission paths and participating electronic states for two-photon laser-induced fluorescence of atomic nitrogen and oxygen.

of the photon emission yields quantitative information about the probed species. Since no physical object contacts the gas, the technique can be used on gases that are at high temperatures and velocities and in highly reactive environments.

For (air) arc jet flow diagnostics the potential target species are N, O, O₂, and NO. At the enthalpies typical of NASA arc jet testing, atomic N and O are major species in the freestream. Quantitatively measuring atomic N and O spectroscopic properties with LIF provides insight regarding the physical, chemical, and thermodynamic state of the high enthalpy flow environment present in arc jet testing. The data from LIF measurements can be used to derive gas dynamic flow properties, stagnation enthalpy, and the distribution of energy over the constitutive modes: kinetic, thermal, and chemical. These data are of value not only for material response testing but also for validating high fidelity CFD simulation tools used for both the ground test and flight environments.¹

II. Laser-induced fluorescence of atomic species

The LIF processes for atomic oxygen and atomic nitrogen are shown in Fig. 1. An atom simultaneously absorbs two photons from a pulsed, tunable ultraviolet laser, leaving the atom in an unstable excited electronic state. The excited state decays by emitting a single infrared photon, which is the fluorescence signal. The photon absorption and emission wavelengths are characteristic of the species being probed, thus assuring selective identification of the target species and its associated spectroscopic properties. Atomic nitrogen and oxygen absorb photons at approximately 206.7 and 225.7 nm, respectively, and emit at 745 and 845 nm. The exact absorption (and emission) wavelengths, and the distributions of absorption (and emission) around these wavelengths, are measured using laser and spectroscopic instrumentation. These measurements are related to test quantities using various relationships derived from quantum and statistical mechanics, and through calibration against reference environments. Two-photon absorption is a weak process; sensitive signal detection techniques and pulse averaging are employed to measure the fluorescence signal magnitude.

III. Arc jet flow property measurement with two-photon laser-induced fluorescence

LIF techniques have been applied in arc jet measurements for chemistry studies since the early 1990s in various environments, including hydrogen,⁴ nitrogen-methane,⁵ and air.⁶⁻¹⁴ A development effort that began at Ames in the early 1990s pioneered the application of N-atom LIF in large-scale arc jet facilities, starting with the 20 MW Aerodynamic Heating Facility (AHF).⁷ A comprehensive experimental capability for quantitative N-atom and O-atom LIF is now considered state of the art for arc jet diagnostics. Two such systems were developed and used at NASA in the late 2000s – one for the 60 MW Interaction Heating Facility (IHF) at NASA Ames,¹² and another for the 10 MW Test Position 2 (TP-2) facility at NASA Johnson Space Center.¹⁴ Both of these new systems leveraged previous experience from the Ames AHF LIF system. The new systems further expanded performance and efficiency by introducing a calibration source engineered for use in the arc jet facilities, advanced instrumentation, and custom data acquisition and instrument control software.

these differences is one of the principal challenges in establishing ground-to-flight traceability for cases where gas-surface chemistry is a significant influence on material thermal response. Detailed chemical and physical measurements of arc jet flow parameters could help reduce these uncertainties by establishing a set of boundary conditions upon which the simulations would be anchored.¹⁻³

Laser-induced fluorescence (LIF) spectroscopy is a spatially resolved, selective, and nonintrusive means to probe concentrations and energetics of individual atomic and molecular species. The technique is used extensively in laboratory chemical physics applications, especially in applications where conventional contact probes are ineffective or would perturb the measured environment. In a LIF measurement of a flowing gas, a laser pulse excites specific electronic states in the target atom or molecule; within a few tens of nanoseconds, the excited state relaxes by emitting a photon. Spectroscopic analysis

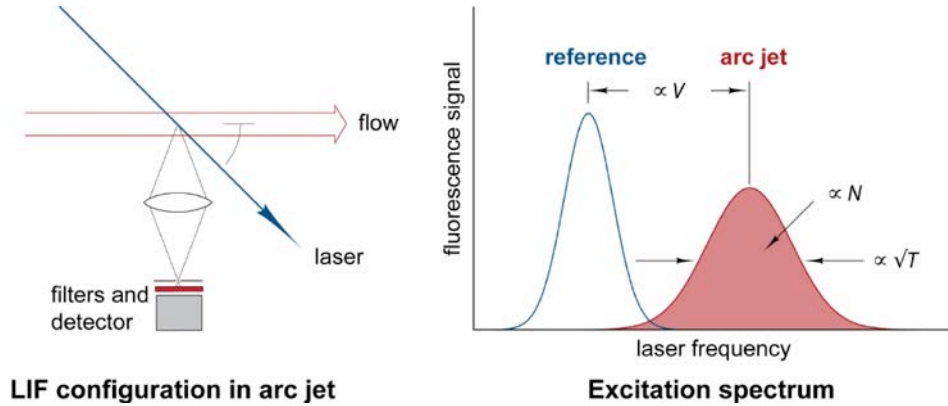


Figure 2. Simultaneous property measurement in the arc jet free stream from the laser-induced fluorescence excitation spectrum. Velocity is obtained from the frequency shift of the absorption feature. Temperature is obtained from the Doppler broadening of the excitation lineshape. The ground state density is obtained from the integral of the excitation lineshape.

Figure 2 summarizes the relevant principles of flow property measurement with LIF. A collimated laser beam from a pulsed, tunable UV laser source is directed into the arc jet facility where it crosses the flow axis at a non-normal angle. A compact telescope images the emitted fluorescence from a small (sub-mm³) volume at the intersection of the flow centerline and the laser beam. The intensity of the fluorescence collected from this volume is measured on a photodetector. The magnitude of the fluorescence signal and its temporal decay are recorded as the laser wavelength is stepped over the absorption feature. The resulting excitation line shape is curve-fit to a theoretical line shape function to determine the peak absorption wavelength, line broadening (or Doppler line width), and integrated signal magnitude.

Quantitative LIF, though straightforward in principle, requires validation of the signal interpretation methodology in order to obtain flow properties in calibrated engineering units. Multiple offline measurements are essential to validate that interpretation and determine the necessary calibration factors. Previous publications have described the process by which arc jet flow properties (velocity, static temperature, and atomic species densities) are determined with LIF.⁷⁻¹⁴

IV. LIF system redevelopment at NASA Ames

The guiding principle for rigorous implementation of a quantitative LIF spectroscopy capability is to ensure that measured values conform to the theoretical relationships or behavioral assumptions applied in analysis – in other words, to validate the LIF system as complete instrument. This principle was re-examined after accumulating experience with the baseline IHF LIF system since its completion in 2008. The overall LIF system architecture was designed to operate such that the fidelity of the system response (the LIF signal) to its theoretical model could be assessed over a broad range of influence parameters. Once conformance to theory has been demonstrated, the measured flow properties can be further applied and analyzed, with justification, in the context of arc jet nonequilibrium aerothermodynamics.

A LIF system for large-scale arc jet flow diagnostics is comprised of a laser laboratory, an optical apparatus incorporated into the arc jet test chamber, and a data acquisition system for recording LIF and laser pulse energy measurements in the laboratory and test chamber. The LIF laser laboratory houses the pulsed, tunable UV laser source, a microwave-driven flow reactor calibration source, an optical configuration for LIF calibration and ancillary parameter measurements, supporting test instrumentation, and the primary data acquisition/instrument control computer. The flow reactor generates low pressure, quantifiable absolute densities of atomic N and O for calibration of the arc jet LIF measurements. The optical apparatus for arc jet LIF measurements delivers a beam from the laser laboratory to the probe volume and collects and detects the emitted fluorescence from the probe volume. The IHF LIF system, which was the subject of References 12 and 13, became the baseline LIF system design prior to the present work.

In order to meet NASA's Multi-Purpose Crew Vehicle (MPCV) Orion TPS program objectives, the agency commissioned a project to establish two fully operational LIF diagnostic systems with identical capabilities for the Ames AHF and IHF arc jets. The baseline IHF LIF system was updated with several critical improvements. The

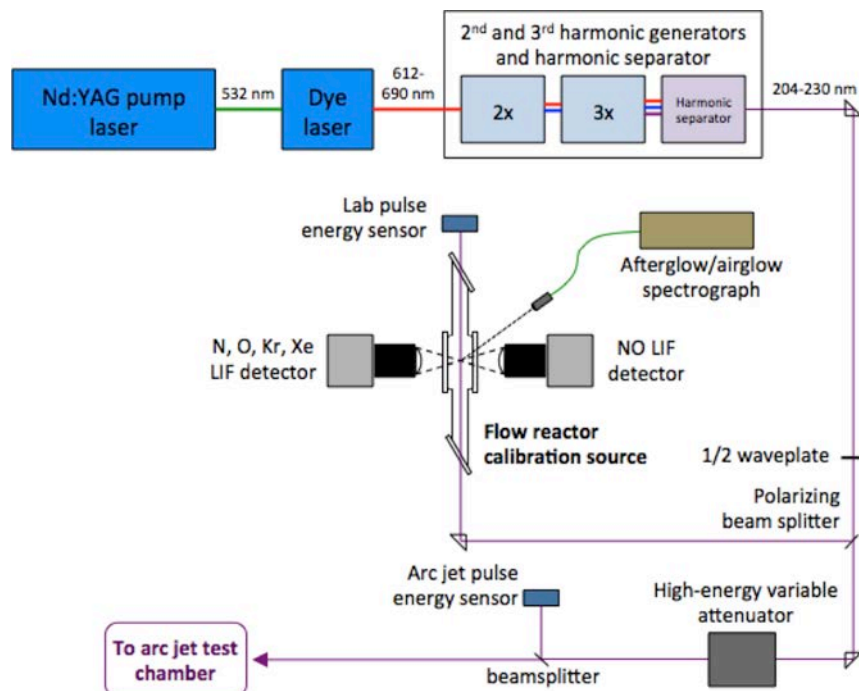


Figure 3. LIF laboratory schematic.

most significant experiment configuration change from the baseline IHF system involved the arc jet LIF collection optics. However, the major part of the project was to rebuild the AHF LIF system to the same specifications as the updated IHF system. Both activities proceeded concurrently, and both systems are now in service.

The other improvements to the baseline system design addressed capability and performance gaps and fulfilled requirements for comprehensive validation. A schematic of the laser laboratory is shown in Fig. 3. Most elements of the current laboratory configuration are the same as the baseline IHF system.¹² The improvements and the motivations for implementing them are described in the following subsections.

A. Data acquisition and instrument control software

The custom-developed software that operates the LIF system instrumentation was completely rewritten to permit several data acquisition modes in addition to excitation laser scans (wavelength sweeps), which was the only mode available with the baseline LIF system. LIF signal and pulse energy measurements can now be acquired while independently sweeping several experimental configuration parameters, including calibration source pressure, gas flow rates and incident pulse energy. The additional data acquisition modes enable comprehensive and efficient means to collect multivariate data for validation of the governing model of two-photon LIF. The new capability for flow rate and pressure sweeps in the microwave-driven flow reactor also enables methodical characterization of the NO titration process used to establish the absolute atomic N and O densities.⁹⁻¹⁴

B. Laboratory and arc jet pulse energy control and measurement

Quantitative LIF signal analysis requires normalization by the incident pulse energy. According to theory, the two-photon LIF fluorescence magnitude scales quadratically with pulse energy. However, that relationship does not hold if other loss mechanisms not accounted for in the theory are present, such as ionization by absorption of a third photon from the laser. Operating the instrument in a manner that departs from theory will carry forward a normalization error, resulting in biased estimates of species densities.

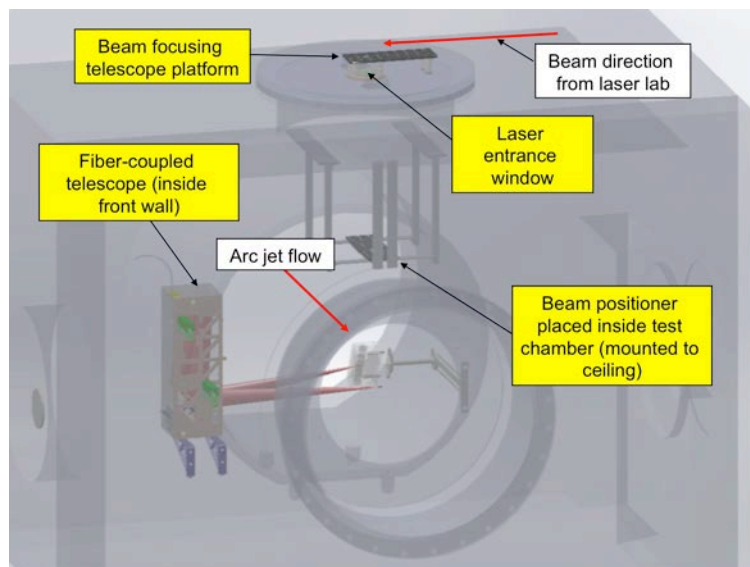
The laser beam path now incorporates the means to independently vary and quantify the incident pulse energies in both the flow reactor and arc jet test chamber. This provides the ability to characterize the nonquadratic response of the two-photon LIF signal to the incident pulse energy by quantifying the nonlinear scaling.

C. Flow reactor titration point monitoring

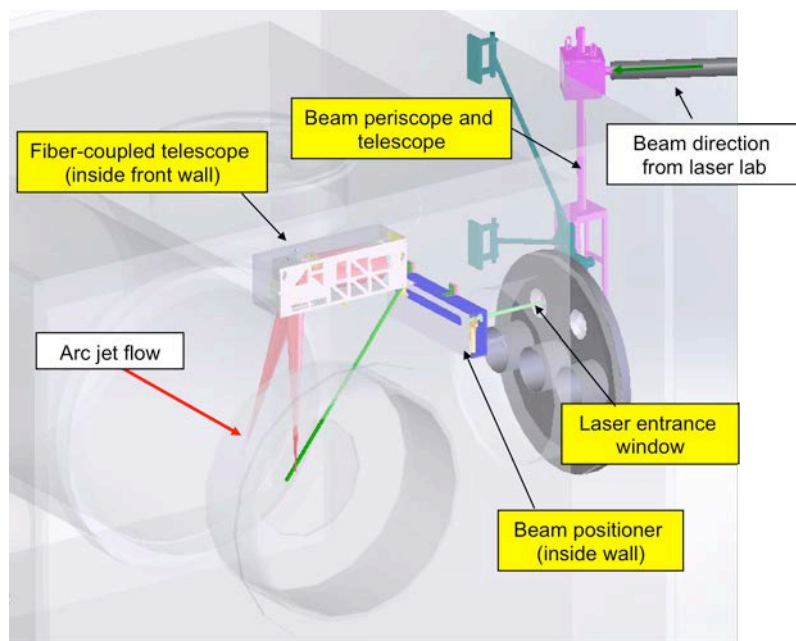
The primary laboratory reference for calibration of arc jet species density and temperature is a flow reactor. It is a gas flow apparatus that provides a stable, quantifiable source of atomic N through low-power microwave dissociation of flowing N₂. The absolute atomic N density in the flow stream of the reactor is determined through titration with NO.⁹⁻¹⁴ The admission of a calibrated flow rate of NO into the partially dissociated N₂ stream initiates the fast exchange reaction $N + NO \rightarrow N_2 + O$. At the titration end point, the flux of admitted NO consumes all free N atoms in the mixing volume, leaving no NO remaining. Or, equivalently, the N flux exactly matches the NO flux admitted into the mixing volume and establishes the means to compute the atomic N density that exists without the NO flow introduced into the stream. The uncertainties of the absolute atomic N and O density measurements in the arc jet

facility are directly proportional to the uncertainty in the atomic N (and O) density in the flow reactor calibration source. That uncertainty, in turn, is influenced by the accuracy with which the NO flow rate at the titration point can be discerned.

The most convenient available means to determine the titration point is to monitor the extinction of the N LIF signal while sweeping the flow rate of NO admitted to the mixing volume – the NO flow rate at which the N LIF signal just disappears indicates the titration point, where all available N has been consumed by reaction with NO, has been reached. To improve accuracy in determining the NO flow rate at the titration point, two additional monitoring means were implemented. The first observes the disappearance then emergence past the titration point of surplus NO with NO LIF excited by the laser, while the second identifies the disappearance of the N₂ first positive (*A-X*) late afterglow emission ($\text{N}(^4S) + \text{N}(^4S) \rightarrow \text{N}_2^* \rightarrow \text{N}_2 + h\nu$), followed by emergence past the titration point of the $\text{NO} + \text{O}(^3P) \rightarrow \text{NO}_2^* \rightarrow \text{NO}_2 + h\nu$ airglow emission.



a)



b)

Fig. 4. Arc jet test chamber optical installations. a) AHF facility. b) IHF facility.

To realize the NO LIF monitor, a second detector with UV sensitivity and a bandpass filter appropriate for discriminating NO *A-X* and *B-X* LIF emission was installed on the opposite side of the flow reactor observation window.

The afterglow/airglow emission monitor was implemented with a spectrograph, high-gain CCD array, and fiber optic collimator as the receiver. The receiver views the observation region within the same plane as the incident laser beam. The three approaches are independent and employed simultaneously to both confirm the anticipated results of the above reactions and yield three estimates for the NO flow rate that depletes the available atomic nitrogen. This capability will be demonstrated in the full paper.

V. LIF installations in the AHF and IHF arc jet facilities

The optical configurations for the LIF systems in the two facilities had similar requirements: enable single point LIF measurements on the flow centerline at prescribed locations from approximately 10 cm to 50 cm downstream of the nozzle exit. The optical configurations of the laser beam delivery system differ chiefly because of the relative locations of the laser laboratories from facility test chambers (Fig. 4). The beam for the AHF system enters from above while the beam for the IHF system enters from the side. Each beam delivery apparatus includes a collimating telescope outside of the entrance window and a two-element beam steering mirror

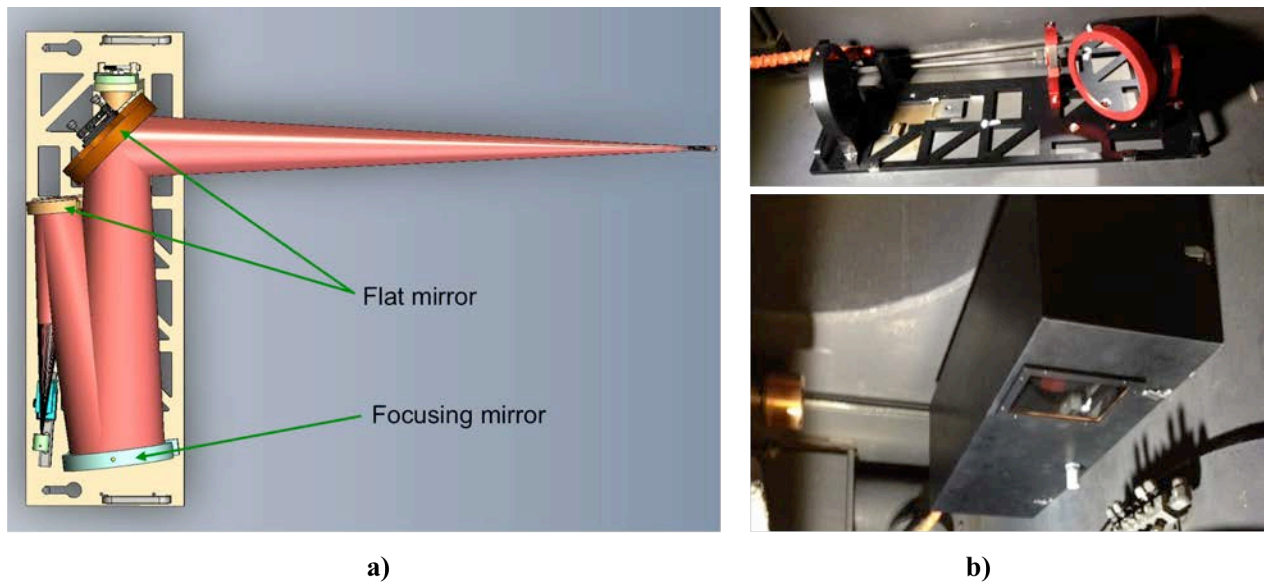


Fig. 5. LIF collection telescope a) Optical configuration. b) Installed in the IHF test chamber with and without protective cover.

system inside the test chamber to direct the beam into the flow at a non-normal angle.

The introduction of a new model support system in the IHF test chamber compelled a redesign of the LIF collection optics. An entirely different approach was implemented with an all-reflective telescope that coupled the imaged LIF emission into a fiber optic bundle. The armored and thermally insulated bundle passes through a facility port on an adjacent side wall of the test chamber. The fiber bundle output was reimaged onto an integrated detector system placed next to the facility. The telescope was designed to be used in both the IHF and AHF test chambers.

The telescope is a three-mirror folded Herschelian design (Fig. 5a)). The first flat mirror turns the imaged light by 90° to the primary focusing mirror. A second flat mirror directs the focused light on to the face of the fiber bundle. When mounted to the nozzle wall of the arc jet test chamber, rotation of the first mirror enables selection of the imaged point along a line coincident with the nozzle axis. An anodized cover with an entrance window protects the telescope when installed in the facility. The $f/\#$ of the telescope is approximately 10 with a demagnification of approximately 2. Figure 5b) shows the telescope installed in the IHF test chamber.

VI. Summary

The origins of two photon LIF spectroscopy were chemical physics and combustion research laboratories supporting comparatively small-scale test chambers or flow systems. Transitioning this powerful diagnostic technique from the laboratory to a large-scale, extreme environment arc jet test facility was successfully demonstrated over two decades ago in the Ames AHF arc jet. The two state-of-the-art LIF systems now supporting both workhorse Ames arc jet facilities are the culmination of many years of development experience and incremental innovation. The conference paper will present results from LIF system validation analyses and arc jet test results from both test facilities.

References

- ¹Grinstead, J.H., Stewart, D.A., and Smith, C.A., "High enthalpy test methodologies for thermal protection systems development at NASA Ames Research Center", AIAA paper 2005-3326, May 2005.
- ²Scott, C.D., "Survey of measurements of flow properties in arcjets," *Journal of Thermophysics and Heat Transfer*, Vol. 7, pp. 9-24, 1993.
- ³Sharma, S.P., Park, C.C., Scott, C.D., Arepalli, S., and Taunk, J., "Arc Jet Characterization", AIAA Paper No. 1996-0612, Jan. 1996.
- ⁴Liebeskind, J.G., Hanson, R.K., and Cappelli, M.A., "Laser-induced fluorescence diagnostic for temperature and velocity measurements in a hydrogen arcjet plume," *Applied Optics*, Vol. 32, pp. 6117-6127, (1993).
- ⁵Raiche, G.A., and Jeffries, J.B., "Laser-induced fluorescence temperature measurements in a dc arcjet used for diamond deposition," *Applied Optics*, Vol. 32, 4629-4635, 1993.
- ⁶Arepalli, S., Yuen, E.H., and Scott, C.D., "Application of Laser Induced Fluorescence for Flow Diagnostics in Arc Jets", AIAA Paper No. 1990-1763, June 1990.

⁷Bamford, D.J., O’Keefe, A., Babikian, D.S., Stewart, D.A., and Strawa, A.W., “Characterization of arc-jet flows using laser-induced fluorescence” *Journal of Thermophysics and Heat Transfer*, Vol. 9, pp. 26-33, 1995.

⁸Fletcher, D.G., “Nonintrusive diagnostic strategies for arcjet stream characterization”, *Measurement techniques for high enthalpy and plasma flows*, NATO Research and Technology Organization proceedings RTO-EN-8, 3B-1–3B-37, Neuilly-Sur-Seine Cedex, France, 2000.

⁹Fletcher, D.G., “Arcjet flow properties determined from laser-induced fluorescence of atomic nitrogen”, *Applied Optics*. Vol. 38, pp. 1850-1858, 1999.

¹⁰Fletcher, D.G., Bamford, D.J., “Arcjet flow characterization using laser-induced fluorescence of atomic species”, AIAA Paper No. 98-2458, June 1998.

¹¹Grinstead, J.H., Driver, D.M., and Raiche, G.A., “Radial profiles of arcjet flow properties measured with laser-induced fluorescence of atomic nitrogen”, AIAA Paper No. 2003-400, Jan. 2003.

¹²Grinstead, J.H., Harris, C.L., Yeung, D., Scott, G.P., Porter, B.J., Graube, P., and Greenberg, R.B., “Next-generation laser-induced fluorescence diagnostic systems for NASA arc jet facilities”, AIAA Paper No. 2009-1521, Jan. 2009.

¹³Grinstead, J.H., Porter, B.J., Carballo, J.E., “Flow Property Measurements Using Laser-Induced Fluorescence in the NASA Ames Interaction Heating Facility Arc Jet,” AIAA Paper 2011-1091, Jan. 2011.

¹⁴Scott, C., Suess, L., Milhoan, J., Oelke, L., Godfrey, D., Larin, M., Grinstead, J., and Del Papa, S., “Enthalpy Distributions of Arc Jet Flow Based on Measured Laser Induced Fluorescence, and Heat Flux and Stagnation Pressure Distributions,” AIAA Paper No. 2011-3778, June 2011.