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I, **Brendan Paxton**, hereby submit this original work as part of the requirements for the degree of Master of Science in Aerospace Engineering.

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Student's name: **Brendan Paxton**

This work and its defense approved by:

Committee chair: San-Mou Jeng, Ph.D.

Committee member: Jongguen Lee, Ph.D.

Committee member: Samir Tambe, Ph.D.

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Systems Design and Experimental Evaluation of a High-Altitude Relight Test Facility

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Brendan Paxton

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Committee Chair: Prof. San-Mou Jeng

Abstract

Novel advances in gas turbine engine combustor technology, led by endeavors into fuel efficiency and demanding environmental regulations, have been fraught with performance and safety concerns. While the majority of low emissions gas turbine engine combustor technology has been necessary for power generation applications, the push for ultra-low NO_x combustion in aircraft jet engines has been ever present. Recent state-of-the-art combustor designs notably tackle historic emissions challenges by operating at fuel-lean conditions, which are characterized by an increase in the amount of air flow sent to the primary combustion zone. While beneficial in reducing NO_x emissions, the fuel-lean mechanisms that characterize these combustor designs rely heavily upon high-energy and high-velocity air flows to sufficiently mix and atomize fuel droplets, ultimately leading to flame stability concerns during low-power operation. When operating at high-altitude conditions, these issues are further exacerbated by the presence of low ambient air pressures and temperatures, which can lead to engine flame-out situations and hamper engine relight attempts.

To aid academic and industrial research ventures into improving the high-altitude lean blow-out and relight performance of modern gas turbine engine combustor technologies, the High-Altitude Relight Test Facility (HARTF) was designed and constructed at the University of Cincinnati (UC) Combustion and Fire Research Laboratory (CFRL). Following its construction, an experimental evaluation of its abilities to facilitate optically-accessible ignition, combustion, and spray testing for gas turbine engine combustor hardware at simulated high-altitude conditions was performed. In its evaluation, performance limit references were established through testing of the HARTF vacuum and cryogenic air-chilling capabilities. These tests were conducted with regard to end-user control—the creation and the maintenance of a realistic high-altitude environment simulation. To evaluate future testing

applications, as well as to understand the abilities of the HARTF to accommodate different sizes and configurations of industrial gas turbine engine combustor hardware, ignition testing was conducted at challenging high-altitude windmilling conditions with a linearly-arranged five-swirler array, replicating the implementation of a multi-cup combustor sector.

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List of Symbols and Abbreviations

Symbols

a, b, d, f, g	parameters used in non-linear regression analysis
A	orifice bore diameter
A_{eff}	effective flow area
c	specific heat capacity
C_D	orifice discharge coefficient
C_V	valve flow coefficient
k	ratio of specific heats
m	mass
$\dot{m}$	mass flow rate
P	total pressure
ΔP	total pressure drop
ρ	gas density
R^2	coefficient of determination
T	total temperature
Φ	fuel-air equivalence ratio

Abbreviations

3-D	three-dimensional
AC	alternating current

ACFM	actual cubic feet per minute
ANSI	American National Standards Institute
C-D	converging-diverging
CFRL	University of Cincinnati Combustion and Fire Research Laboratory
CTRZ	center toroidal recirculation zone
DAQ	data acquisition
DC	direct current
FN	pressure-swirl atomizer flow number
HARTF	High-Altitude Relight Test Facility
HVAC	heating, ventilating, and air conditioning
KO	water knock-out or separation
I/O	input/output
LDI	lean direct injection
LDV	laser Doppler velocimetry
LIN	liquid nitrogen gas
LOX	liquid oxygen gas
LPP	lean-premixed pre-vaporized
LRVP	liquid ring vacuum pump
N ₂	nitrogen gas
NI	National Instruments
NO _x	oxides of nitrogen
NPS	nominal pipe size
O ₂	oxygen gas
ODT	outer tube diameter

PDPA	phase Doppler particle analysis
RQL	rich-burn, quick-quench, lean-burn
ODT	outer tube diameter
SCFM	standard cubic feet per minute
TTL	transistor-transistor logic
UC	University of Cincinnati

Subscripts

0	location directly upstream of orifice plate
3	location directly upstream of fuel-air swirlers
4	location directly downstream of fuel-air swirlers
C	corrected
D	discharge
HP	high pressure condition
LP	low pressure condition
V	valve

Chapter 1: Introduction

1.1 Motivation

Novel advances in gas turbine engine combustor technology, led by endeavors into fuel efficiency and demanding environmental regulations, have been fraught with performance and safety concerns. While the majority of low emissions gas turbine engine combustor technology has been necessary for power generation applications, the push for ultra-low NO_x combustion in aircraft jet engines has been ever present. Recent state-of-the-art combustor designs notably tackle historic emissions challenges by operating at fuel-lean conditions, which are characterized by an increase in the amount of air flow sent to the primary combustion zone. While beneficial in reducing NO_x emissions, the fuel-lean mechanisms that characterize these combustor designs rely heavily upon high-energy and high-velocity air flows to sufficiently mix and atomize fuel droplets, ultimately leading to flame stability concerns during low-power operation. When operating at high-altitude conditions, these issues are further exacerbated by the presence of low ambient air pressures and temperatures, which can lead to engine flame-out situations and hamper engine relight attempts.

To aid academic and industrial research ventures into improving the high-altitude lean blow-out and relight performance of modern gas turbine engine combustor technologies, the High-Altitude Relight Test Facility (HARTF) was designed and constructed at the University of Cincinnati (UC) Combustion and Fire Research Laboratory (CFRL). Following its construction, an experimental evaluation of its abilities to facilitate optically-accessible ignition, combustion, and spray testing for gas turbine engine combustor hardware at simulated high-altitude conditions was performed. In its evaluation, performance limit references were established through testing of the HARTF vacuum and cryogenic

air-chilling capabilities. These tests were conducted with regard to end-user control—the creation and the maintenance of a realistic high-altitude environment simulation. To evaluate future testing applications, as well as to understand the abilities of the HARTF to accommodate different sizes and configurations of industrial gas turbine engine combustor hardware, ignition testing was conducted at challenging high-altitude windmilling conditions with a linearly-arranged five-swirler array, replicating the implementation of a multi-cup combustor sector..

1.2 Background

When designing a test facility to support the research and development of current and next-generation gas turbine engine combustor designs, it is necessary to understand the fundamental mechanisms that dictate gas turbine engine performance and to recognize the circumstances pushing the development of combustor designs that would inherently suffer with respect to flame stability and high-altitude relight performance—areas in which historical aircraft jet engine combustor designs have long thrived.

1.2.1 Gas Turbine Combustion

The aeronautical gas turbine engine, in its basic form, utilizes three primary components to perform an irreversible energy transformation to generate thrust, the propulsive force typically required to sustain flight. These three components include the compressor, the combustor, and the turbine. During operation, the compressor consumes fresh air from the surrounding environment and pressurizes it, irreversibly transforming its kinetic energy into pressure potential energy and thermal energy through friction and turbulence. In the combustor, fuel is injected into the pressurized air stream exiting the compressor and the resulting fuel-air mixture is ignited, transforming the chemical potential energy of the injected fuel into thermal energy. The highly-energetic combustion gases

exiting the combustor then enter the turbine, where they are allowed to expand and leave the engine, transforming their high thermal and pressure potential energies into kinetic energy—kinetic energy in the motion of the turbine and compressor linked by the engine shaft, and kinetic energy in the thrust.

With this brief overview of the aeronautical gas turbine engine principles of operation, it can be seen that the combustor alone serves as the primary energy-addition mechanism within the engine. The performance of the combustor is critical in driving the operation of the turbine and compressor components, and its primary performance measure is based entirely upon its abilities to add thermal energy to the engine flow. Simply put, the operation of a gas turbine engine requires the combustor to ignite and sustain the combustion of its injected fuel-air mixtures²¹.

The basic combustor design principles have remained largely unchanged throughout the history of gas turbine engines. For example, in its geometry, the combustor must not allow the air entering from the compressor to lose its high pressure. To prevent pressure loss, the air exiting the compressor must experience a reduction in its velocity, requiring an air diffuser at the combustor inlet, illustrated in Fig. 1.2-1(b), compared to an impractical straight duct design in Fig. 1.2-1(a). Additionally, in the combustion process, the flame must be anchored and sustained to allow for reliable operation. To accomplish this, a type of shield must be provided to protect the flame region from the high-velocity flows that would otherwise lead to flame instabilities and flame blow-out, as well as to induce vortices, or pockets of recirculation. A simple baffle can be implemented, seen in Fig. 1.2-1(c), but additional design changes are necessary to further enhance the flow circulation and flame anchoring abilities of the combustor. In Fig. 1.2-1(d), a reversed air flow injection method is shown²¹.

Expanding upon these simple gas turbine engine combustor design elements, many enhancements are introduced to improve the performance and the efficiency of the combustion processes, which are both physical and chemical in nature^{21,39}. Research approaches have looked into changing the principal fuel-air mixing and fuel injection mechanisms, modifying the different geometries of the combustor, and even introducing new means of interfacing between combustor hardware.

Figure 1.2-1: Development of gas turbine engine combustor design elements²¹

Historically, in the case of flame anchoring, fuel-air mixers or fuel-air swirlers have long been implemented to impart a tangential-radial “swirling” motion on the axial air flow entering the combustor²¹. Confinement of this swirling motion can generate a low pressure region along the swirl axis, which remains mostly evacuated as centrifugal forces carry the majority of the fuel-air mixture away. As shearing forces along the confinement walls reduce this swirling motion, some of the slowed gases are attracted back to the low pressure region along a pressure gradient. The resulting recirculation brings high-temperature combustion gases from downstream to the near field, aiding in the ignition of new reactants and flame anchoring. The region characterized by this recirculation is known as the

central toroidal recirculation zone (CTRZ). The size and strength of the CTRZ induced by different fuel-air swirlers and combustor geometries is the subject of many different research topics¹⁶.

Aside from the fuel-air swirler design and combustor geometry, the fuel injection mechanism must be prepared to adequately atomize the liquid fuel spray. Atomization, or the separation of liquid volumes into fine droplets, is performed to maximize the total fuel surface area so that it will mix more homogeneously with air. Ideally, atomization should produce fuel droplets with the sizes of singular atoms, or as small as possible, nearly transforming the liquid fuel into a gas. Two main types of fuel atomizers are predominantly implemented in current gas turbine engine combustor designs, the pressure-swirl atomizer and the airblast atomizer²¹.

The pressure-swirl atomizer injects high-pressure fuel tangentially at an upstream location within a small cylindrical chamber. The fuel surges and swirls within the chamber before exiting an orifice and injecting into the fuel-air swirler. Pressure-swirl atomizers require high fuel pressures and are unable to function efficiently at all gas turbine engine operating conditions. If fine atomization is desired at low fuel flow rates, the swirl chamber and orifice must be sized appropriately, which tends to inhibit high fuel flow rates without pressurizing the fuel to inordinate pressures. To counteract these issues, dual-orifice pressure-swirl atomizers are often implemented, which utilize two swirling chambers and two orifices. The central pilot orifice is utilized at low flow rates and a ring-like main orifice that surrounds the pilot is utilized for high flow rates²¹.

The airblast atomizer functions with an entirely different concept. In its design, the airblast atomizer utilizes high-velocity swirling air flows to blast liquid fuels into fine droplets. Very low fuel pressures are implemented either to perform a cross-flow fuel injection into this high-velocity swirling air stream

or to create a film of liquid that breaks up as it travels along a pre-filming surface and ejects from the surface edge. This method of atomization is notably poor for start-up conditions, where the air pressure available for droplet atomization is low, but is favored for its fuel distribution characteristics, where the air flow dominates the pattern of the fuel spray injection^{6,14,19,21,34}.

Current production gas turbine engine combustor technology combines these design components—the geometry, the fuel-air swirlers, and the fuel atomizers—to create a low-pressure primary zone with near stoichiometric burning characteristics. The result is reliable combustion performance with high temperatures. NO_x formation, however, prevails at high-temperature combustion, and cooler temperatures lead to the formation of CO as its oxidation to CO_2 becomes inhibited³⁰. Due to these factors and the regulations pushing for reductions in NO_x emissions, the goals of current and future gas turbine engine combustor concepts weigh heavily upon maintaining combustion temperatures within a tight range for all engine operating conditions^{17,21,30}.

Three significant gas turbine engine combustor concepts have been designed to try and achieve these emissions goals: the rich-burn quick-quench lean-burn (RQL), lean-premixed pre-vaporized (LPP), and lean direct injection (LDI) combustors^{17,30}.

The RQL combustor, proposed in 1980 for land-based gas turbine engines²⁴, burns rich in the primary zone with fuel-air equivalence ratios of 1.8 or higher to reduce temperatures and oxygen concentrations, which in turn inhibits NO_x formation^{2,21,33}. In the secondary zone, air is injected to quickly quench, or complete the oxidation processes, and to reduce the combustor exhaust temperatures with a lean burn—equivalence ratios of 0.6, for example^{21,30,33}. The secondary air injection must be precise, rapid, and adequate in its mixing with the primary zone combustion

processes to operate effectively^{2,5}. The difficulties with optimizing the mixing zone air injection so that the quenching mechanism rapidly passes from rich to lean conditions without lingering near stoichiometric, have been the subjects of its ongoing development in aeronautical applications^{5,21,30}.

The RQL combustor inherently burns rich, obtaining reliable flame anchoring characteristics that aid in ignition and lean blow-out^{2,5,21,30,33}. The LPP and LDI concepts, however, burn lean^{11,17,18,36,37}.

The LPP combustor concept is designed to inject a sufficiently-mixed fuel-air mixture directly into the combustion zone at fuel-air equivalence ratios near 0.6, resulting in low temperatures that inhibit NO_x formation^{11,17,18,21,30}. This method requires a mixing duct upstream of the primary combustion zone where fuel and air mixes with substantial residence times³⁰. The lean combustion of the LPP threatens flame stability for low-power engine operation and starting, where high pressures are not available to aid in the mixing mechanisms required to produce a premixed fuel-air injection^{17,30}.

The LDI concept is designed to send large amounts of air through the combustion dome into the primary combustion zone—air which would otherwise be used for dilution and cooling jets in a secondary combustion zone and at the combustor exit^{23,30,36,37}. Typically, many small fuel-air swirler assemblies are implemented to replace what would be a singular fuel-air swirler assembly to increase local mixing and eliminate high-temperature pockets that would lead to NO_x formation. Fuel spray is sometimes injected directly into the mixing air streams of neighboring fuel-air swirlers, where mixing is strongly dictated by large amounts of air that are sent through the fuel air swirlers. Due to heavy reliance on these high air mass flows in the primary combustion zone, the resulting lean operation, and the complex multi-swirler air mixing interactions, flame stability is of great concern^{36,37}.

1.2.2 High-Altitude Relight

High-altitude relight is the process of re-igniting or restarting a gas turbine engine at high altitudes after a flame-out event, where the flames in the combustor are extinguished. Flame-out events can occur for many reasons—flame instability, air flow disturbances due to debris or liquid ingestion, or inadequate fuel injection—and may occur once per 100,000 commercial flights¹². Heavy rain, hail, and volcanic ash have notably been catastrophic for gas turbines at altitude¹². However, as discussed earlier, historic gas turbine engine designs have been inherently robust with respect to flame stability in the primary combustion zone³⁰. The designs of the new LPP and LDI gas turbine engine combustor concepts will introduce new challenges for high-altitude operation that precede these external variable considerations. To adequately understand the mechanisms that govern high-altitude relight performance, standard operating conditions during high-altitude flight must first be discussed.

The high-altitude regime can be considered anywhere from 10,000 to 40,000 ft above sea level depending on the different subsonic aircraft and their flight paths over the Earth. Average cruise altitudes for modern subsonic commercial aircraft typically range from 35,000 to 38,000 ft³⁰ and regulatory requirements for high-altitude relight typically state a maximum altitude requirement of around 30,000 ft²⁸ for high-altitude relight capability. High-altitude relight capability is mandatory for aeronautical gas turbine engines, regulated by Federal Aviation Regulation Section 25.903³² and European Aviation Safety Agency Certification Specification CS-E 910³¹.

At these high altitudes, there are significant reductions in air temperature, air pressure, and air density, natural to the atmosphere of the Earth. According to U.S. Standard Atmosphere 1976, at 30,000 ft altitude, the air temperature is -47.8°F, compared to 59°F at sea level. The air pressure is 4.37 psia,

less than 30% of the 14.7 psia air pressure at sea level, and the air density is 8.91×10^{-4} slugs/ft³, or 37% of the 23.8×10^{-4} slugs/ft³ air density sea level air density. With these values, it can be seen that the high-altitude environment is harsh, providing less thermal energy, less pressure potential energy, and less air mass per volume to aid in the combustion processes within the gas turbine engine²⁶.

Following a flame-out event at high altitude, the gas turbine engine shaft begins to decelerate, slowing the rotational motion of the compressor and turbine blades. Accordingly, the air passages cool after the flames are extinguished and are cooled further by the corresponding reductions in compression performance. Ram pressure resulting from the forward momentum of the aircraft induces a windmilling characteristic on the compressor, which maintains some rotational motion. However, the air velocities at the compressor inlet mostly diminish by the time the air reaches the combustor. To make predictions of combustor inlet conditions following flame-out, Read et al. utilize equations for temperature determination using the in-flight Mach number and assume half of the engine inlet dynamic head is lost in the compressor, to find values of 17.3°F and 5.8 psia, for the combustor inlet temperature and pressure, respectively, following a flame-out event at an altitude of 30,000 ft³⁰.

The consequences of these conditions include poor liquid fuel atomization performance, especially when implementing airblast fuel atomizers^{6,14,19,30,34}. Large droplet sizes are unavoidable due to the reductions in air momentum, which suffers from losses in air density, available air mass per volume, and air velocity³⁰. Droplet atomization is further inhibited by the increase in fuel viscosity that results from the cooling of the engine, whose heat is utilized during normal operation to warm the fuel as it flows from the cold fuel storage tanks to the fuel atomizers^{8,20}. Furthermore, the air temperature reductions inhibit the evaporation rates of the cooled fuel droplets, which are found to yield lower vapor pressures due to their reduced temperatures³⁰.

Figure 1.2-2: Spark energy required for kerosene-air ignition at various conditions²⁷

Earlier, it was discussed that droplet atomization is critical in providing reliable combustion and ignition performance. Research has shown that flame speed drops significantly with larger droplet sizes, inhibiting the flame kernel generation and propagation necessary to relight the combustor²¹. Flame kernel propagation has also been found to require higher amounts of ignition energy than flame kernel generation²². Additionally, the minimum ignition energy to ignite droplets in a heterogeneous mixture has been found to vary according to the droplet size raised to the fourth power^{4,30}. It has been found that, when implementing a pressure-swirl atomizer, for a constant ignition energy, a 50% increase in the fuel-air equivalence ratio is required to ignite a fuel-air mixture whose inlet air speed is reduced by 50%, due to less air velocity available to assist in atomization, shown below in Fig. 1.2-2(a)²⁷. It has also been found that for a constant air velocity, reductions in atomization performance cannot be overcome with higher ignition energy, shown in Fig. 1.2-2(b)²⁷. This is to show that high-

altitude relight is incredibly difficult when compared to the standard gas turbine engine operating conditions, where the pressure potential energy and thermal energy increases significantly as it passes through the compressor. Some physical and chemical limitations cannot be overcome.

The catastrophic consequences of the high-altitude flame-out event—negatively impacting combustor inlet air momentum, injected fuel droplet atomization quality, injected fuel droplet evaporation rates, flame speeds, flame kernel propagation rates, and the minimum required ignition energy—are only compounded when considering the LPP and LDI combustor concept designs. The fuel-lean operation of these combustors relies heavily upon the combustor inlet air to perform the fine fuel-air mixing mechanisms required for their low-temperature combustion processes, compared to the robust RQL combustor concept and traditional gas turbine engine combustors that rely on high-pressure fuel injection for fuel-rich and for stoichiometric combustion in the primary combustion zone, respectively^{2,5,17,21,30,24,33}.

The complexity of the compounding factors contributing to high-altitude relight performance make this issue highly complicated for numerical simulation and modeling^{13,35}, thus a test facility for experimentally evaluating combustor designs is necessary to provide comprehensive testing capabilities to simulate high-altitude operation following flame-out events.

1.3 Location

The HARTF was designed and constructed at the UC CFRL. At the beginning of the project in early 2013, a single building, Building A, existed for the purpose of performing vertical and horizontal combustion and spray testing on gas turbine engine combustor hardware—configured with singular hardware or with multi-hardware configurations. LDI combustor hardware, for example, had been

previously implemented for combustion and spray testing at the test rigs occupying the Building A space at the CFRL. During the beginning of the HARTF design phase, the test facility was designed to become an additional mobile testbed that would exist in Building A. However, CFRL expansion plans at the end of 2013 and in early 2014 led the facility to occupy its own test cell. With a new, permanent location, the facility was required to be redesigned.

On the grounds of the CFRL are an arrangement of high-pressure air compressors, high-pressure Jet-A fuel pumps, de-ionized water pumps, and even a high-pressure natural gas supply. These provisions became critical for the development of the HARTF, which would ultimately rely on most of these resources.

1.4 Approach

The HARTF design approach began with establishing the desired capabilities of the facility, namely the minimum pressure, minimum temperature, and maximum air mass flow rate that would potentially exist in an adapted gas turbine engine combustor sector undergoing high-altitude relight testing. Once these goals were understood and established, different industrial hardware options were researched and selected to achieve the capabilities desired. The HARTF systems design was then conceptualized to adequately implement these hardware components into a feasible configuration while also enabling user-friendly operation. To realize these systems concepts, plumbing systems and support structures were first designed, followed by a selection of suitable control and measurement devices. Software interfacing was then utilized to coordinate methods of operation. Upon completion and approval of the HARTF design, the facility was constructed at the CFRL between the months of May 2014 and July 2015. Experimental evaluations of the completed facility followed thereafter to understand how it met its design goals and to understand the different characteristics of its operation.

Chapter 2: Facility Design

2.1 Flow Scaling

For all intents and purposes, the primary design goal of the HARTF was to simulate windmilling conditions at altitudes between 30,000 ft and 35,000 ft for different combustor hardware configurations. Relating these altitudes to the U.S. Standard Atmosphere 1976 atmospheric model, the desired atmospheric pressures were found to range from 3.47 psia to 4.37 psia²⁶. The desired atmospheric temperatures were found to range from -65.6°F to -47.8°F²⁶. Flow scaling was performed to find the maximum air mass flow rate that would be required at these atmospheric conditions when adapting typical industrial gas turbine combustor hardware to the facility. Essentially—the HARTF was required not only to be able to create the conditions that would simulate a high-altitude environment, it was required to do so while pulling certain rates of air mass flow.

To perform flow scaling for the facility, a specific industrial and proprietary fuel-air swirler was chosen to represent the largest flow area that might be adapted in a single swirl cup configuration at the HARTF. Common test conditions encountered at other CFRL test facilities were consulted to push the flow scaling procedure in a realistic direction. The CFRL allowed for research into its comprehensive history of spray diagnostics and combustion testing for industrial gas turbine engine combustor hardware, and a specific high-pressure condition was ultimately chosen for the flow scaling procedure—an air mass flow rate of 1 lb/sec through a single fuel-air swirler, with upstream conditions of 90 psia pressure and 400°F temperature. These conditions were utilized to calculate the corrected, or “non-dimensional,” mass flow rate, as referenced in Eq. 2.1-1 below, where the units of $\dot{m}$ air mass flow, T total temperature, and P total pressure are pounds per second, degrees Rankine,

and pounds per square inch absolute, respectively. To relate the chosen flow conditions for high pressure (HP) combustion testing to the low pressure (LP) conditions that would be tested at the HARTF, the corrected mass flow rate was equated between the two, as shown in Eq. 2.1-2 and rearranged in Eq. 2.1-3. The LP temperature and pressure conditions were selected within their aforementioned ranges to be -50°F and 4.0 psia, respectively.

$$\dot{m}_C = \dot{m} \frac{\sqrt{T}}{P} \quad (2.1-1)$$

$$\dot{m}_{LP} \frac{\sqrt{T_{LP}}}{P_{LP}} = \dot{m}_{HP} \frac{\sqrt{T_{HP}}}{P_{HP}} \quad (2.1-2)$$

$$\dot{m}_{LP} = \dot{m}_{HP} \frac{P_{LP}}{P_{HP}} \sqrt{\frac{T_{HP}}{T_{LP}}} \quad (2.1-3)$$

Upon calculation, it was found that for a single fuel-air swirler operating at high-altitude windmilling conditions, the maximum air mass flow rate required for a single fuel-air swirler was 0.064 lb/sec. When scaling to an array of five fuel-air swirlers, this required mass flow rate was expanded to 0.32 lb/sec, or 19.2 lb/min. This design flow rate was further converted to SCFM to enable smooth interaction with the compressed air industry throughout the design process. Referencing the U.S. Standard Atmosphere 1976 atmospheric model, the standard sea level air density of 0.0765 lb/ft³ was utilized to find a required flow rate of 251 SCFM²⁶.

2.2 Vacuum

When approaching the issue of simulating the vacuum pressures of a high-altitude atmospheric environment, different methods of vacuum generation were considered. The HARTF exhaust conditions and composition became the primary points of focus when researching different vacuum generation technologies. The presence of unburnt liquid Jet-A fuel and water vapors at very low pressures and high temperatures presented concern when approaching the implementation of a vacuum pump system. The consideration for an independent vacuum pump was also due to the foreseen heavy demand of operating the HARTF, which would potentially lead to scheduling conflicts at the CFRL—with more than ten separate test facilities sharing two air compressor systems, independent operation became a goal. Furthermore, a new pump system could provide vacuum capability to other test facilities at the CFRL. These two considerations led the preliminary design approach towards a new pump system at the laboratory. Two vacuum pump technologies were initially discussed for this purpose, and vendors were approached to understand the consequences and the requirements of their implementation downstream of a high-temperature, low-pressure combustion application.

The first proposition for the HARTF vacuum generation duty became the liquid ring vacuum pump (LRVP), a rotating positive-displacement pump known for its abilities to handle the consumption of corrosive chemicals at most vacuum ranges. In principle, liquid ring vacuum pumps create vacuum suction by utilizing an impeller that is eccentrically-offset within a cylindrical chamber. The impeller spins a sealing liquid (water) along the inside of the chamber walls, creating a liquid “ring” that isolates the impeller vanes from the chamber walls. Between each vane and within the inner diameter of the liquid ring, pockets are formed, and these pockets enlarge and shrink in size as they travel along with

the eccentric impeller rotation. Gases enter these pockets with a generous volume and then exit after travelling around to the most eccentric location of the rotor, where the pocket volume is minimized. The result is substantial compression capability with a controllable volumetric flow rate^{10,15}. An example LRVP diagram is shown below in Figure 2.2-1.

Figure 2.2-1: Liquid ring vacuum pump principle of operation⁴⁵

Two companies were contacted regarding LRVP offerings for the HARTF vacuum requirements. Discussion began with NES Company, Inc., and Dekker Vacuum Technologies, Inc., and different pumps were sized and offered. Due to the expected nature of the HARTF application, namely the presence of unburnt liquid Jet-A fuel and water vapors mixing with the sealing liquid in the LRVP, both companies required a knock-out (KO) tank or liquid trap to be implemented upstream of the pump inlet. Additional stipulations required cooling of the combustion gases to below 150°F before mixing with the sealing liquid in the LRVP, so as not to cause the sealing water to boil at the intended

low-pressure conditions. To meet these demands, a KO tank was sized for the pumps offered and a water-tube heat exchanger was designed for cooling duty.

It was later found that a consistent 20 gal/min water flow rate from the Cincinnati water supply network could not be guaranteed at the construction site, which was required to create an adequate liquid ring within the pumps. To counter this issue, a partial-recovery system featuring a discharge separator was proposed to enable recovery of the sealing water to reduce the water demands of the LRVP. In the end, the footprint of the resulting LRVP assembly with the exhaust chiller, KO tank, pump, and partial-recovery system was found to require an area of up to 342 ft². To provide for this footprint, a small building for the LRVP assembly was proposed and discussed with contractors. In the end, a pump location was selected on the grounds of the CFRL, and a plumbing system was proposed to bring the vacuum service Building A of the CFRL. The pressure losses associated with the proposed plumbing system were found to require the vacuum pumps to be resized for a pressure limit of 2.0 psia and a volume flow rate of 2,200 ACFM at the pressure condition. This resizing required larger capacity pump systems than originally requested.

In calculating the considerable cost of all of the required equipment and necessary additions to the LRVP system, as well as discussing the complexity of its maintenance and operation procedures, research on alternative vacuum pump technologies began. Rotary screw vacuum pumps were sought as the second option and meetings were held with Sullair and Air Technologies. In principle, a rotary screw compressor utilizes the meshing of two helical screws, or rotors, to compress gases from the inlet to the outlet. The gases travel through the screw threads and discharge as the helical screws mesh with tighter and tighter tolerances^{25,47}. These principles of operation are shown in Fig. 2.2-2.

Figure 2.2-2: Rotary screw principle of operation^{42,46}

During the initial correspondence with the two companies, the rotary screw vacuum pump options seemed to be suitable alternatives to the LRVP systems for the intended HARTF application without requiring high flow rates of water. With footprints similar to those of the LRVP systems, and the similar necessities of KO tanks and exhaust cooling, a similar building to house the system was required. While the costs of implementing a partial-recovery system were eliminated, the final figures for integrating a rotary screw vacuum pump system at the CFRL remained quite similar to the LRVP options, just outside the allotted budget for the project. Furthermore, both vendors stressed concerns over liquid Jet-A fuel droplets entering the rotary screws of the compressor, which would see high

temperatures at the locations of tightest clearance—temperatures exceeding the flash point of Jet-A. In the end, issues with the budget and concerns regarding operational safety led the HARTF vacuum duty design away from an independent vacuum pump system.

After realizing the difficulties and expense of creating an independent vacuum pump system for the HARTF, consideration was given to the two air compressors already in use at the CFRL and the possibility of implementing an air jet ejector was considered, as air jet ejectors were found to be implemented on other altitude test rigs^{22,38}. Air jet ejectors operate without moving parts and do not interact directly with an electrical pump system. They are driven entirely by compressed air, referred to as the motive air. The motive air moves through a small converging-diverging (C-D) nozzle and accelerates to supersonic speeds. This high-velocity flow significantly reduces the internal pressure of the ejector air chamber, generating suction. Flows are allowed to be sucked into the chamber through an opening referred to as the suction inlet. These flows mix directly with the high-velocity stream of motive air. The mixture of the two flows enters a second C-D nozzle, or diffuser, that decelerates the flow to a subsonic condition at the exhaust^{9,40}.

The substantial benefits of air jet ejectors are not limited to their abilities to handle corrosive liquids and high temperatures, they are also relatively mobile and highly modular, which means they can be implemented in series to create an ejector array to achieve lower pressures and higher flow rates⁹. Their motive nozzles may even be replaced to accommodate different flow regimes. As noted earlier, however, air jet ejectors require a powerful and reliable supply of compressed air. At the CFRL, there are two operational air compressors. The SFC 250 from Kaeser Compressors, Inc. can provide air flow rates of 1.8 lb/sec at a pressure of 100 psig and the GA90FF from Atlas Copco Compressors LLC can provide air flow rates of 0.6 lb/sec at a pressure of 150 psig. These air compressors are

utilized in many different test facilities throughout the CFRL. The initial design steps of the HARTF led the vacuum duty accommodation away from utilizing these compressors to prevent scheduling conflicts, but this was found to be unavoidable after failing to find a suitable vacuum pump option. To provide adequate vacuum service for the HARTF design requirements, it was decided that an air jet ejector would be utilized with the high-capacity SFC 250 air compressor.

In the past, a small air jet ejector array was implemented in the sub-atmospheric test rig at the CFRL, but this test rig was only designed for cold spray testing with a confined pressure range. For the vacuum duty required by the HARTF, a much larger system would be necessary to meet the 4.0 psia pressure limit while providing a flow rate of 251 SCFM. Noting the SFC 250 flow capacity of 1.8 lb/sec at 100 psig, Gardner Denver Nash and Graham Corporation were each contacted to discuss and size an air jet ejector suitable for the HARTF application. The design by Graham Corporation was ultimately selected, which called for an 8" Nominal Pipe Size (NPS) suction pipe diameter and required approximately 7' × 3' × 3' of space, as shown in a section view in Fig. 2.2-3 below.

Figure 2.2-3: Air jet ejector sectional view, sized for HARTF flow requirements

All wetted surfaces of the air jet ejector were designed to be stainless steel to accommodate different types of exhaust gases and liquids. The air jet ejector was also found to accommodate high exhaust

gas temperatures and could thus be attached directly to the exhaust section of the HARTF, without requiring an exhaust gas chiller. Due to this accommodation, little piping was necessary to separate the air jet ejector from the test rig, eliminating losses that were unavoidable when designing an independent LRVP or rotary screw vacuum pump system.

Figure 2.2-4: HARTF air jet ejector suction pressure as a function of suction mass flow

The final performance curve of the air jet ejector is shown above in Fig. 2.2-4 when 100 psig and 1.67 lb/sec is seen at the motive inlet. In the final air jet ejector design, the desired HARTF conditions of 4.0 psia pressure and a suction air mass flow rate of 0.32 lb/sec were taken into consideration, but oversizing was performed to provide confidence in the design point. To meet the required pressure point of 4.0 psia, for example, additional suction mass flow is required: 0.35 lb/sec compared to the 0.32 lb/sec originally calculated for the design. This additional mass flow can be supplied through a

bypass air line leading directly to the atmosphere. Fitted with a control valve, the bypass can establish the simulated altitude pressure condition without changing the air flow rates within the test section. By oversizing the air jet ejector, this degree of altitude pressure simulation control could be accomplished even with the most demanding gas turbine combustor hardware arrangement.

In July 2013, after the air jet ejector designed by Graham Corporation was found to satisfy the requirements of the HARTF vacuum service, its purchase order was completed. During the lead time following this purchase, additional systems were designed to provide for smooth operation in the HARTF—controlling and maintaining an accurate high-altitude simulation while also controlling the operation of an inline gas turbine combustor sector. These supplemental designs are discussed in the following sections: *2.4 Systems Concept*, *2.5 Plumbing & Structure*, and *2.6 Control & Measurement*.

2.3 Cryogenics

The secondary priority for the HARTF design was the creation of a low-temperature environment within the gas turbine combustor sector. Two methods were proposed to tackle the issue of cryogenic air-chilling—direct chilling through cryogenic mixing and indirect chilling through the implementation of a heat exchanger.

2.3.1 Cryogenic Mixing

The cryogenic mixing method, or cryogenic air creation method, was the initial approach towards reducing test section air temperatures to below -50°F. The general idea was to simply send a cryogenic mixture of the two major air components, nitrogen and oxygen, into the warm air stream flowing into

the fuel-air swirlers. The result would be a cooled mixture of air, composed of both natural and artificial air components. To accomplish this, liquid oxygen (LOX) and liquid nitrogen (LIN) would be purchased in high-pressure cylinders. Their liquid flows would be sent through mass flow meters and pneumatic control valves, regulated to mix together at a ratio of 76.5% N₂ and 23.5% O₂ by mass to create an artificial air mixture with very low temperatures. This mixture would then be injected into the warm air stream of the facility to cool it down from room temperature (85°F) to the intended low temperature condition (-50°F). The maintenance of the mixture would be accomplished with control software that would communicate with the LOX and LIN mass flow meters and control valves.

$$T_{\text{Mix}} = \frac{m_1 c_1 T_1 + m_2 c_2 T_2 + \dots + m_n c_n T_n}{m_1 c_1 + m_2 c_2 + \dots + m_n c_n} \quad (2.3-1)$$

$$T_{\text{Mix}} = \frac{m_{\text{Air}} c_{\text{Air}} T_{\text{Air}} + m_{\text{N}_2} c_{\text{N}_2} T_{\text{N}_2} + m_{\text{O}_2} c_{\text{O}_2} T_{\text{O}_2}}{m_{\text{Air}} c_{\text{Air}} + m_{\text{N}_2} c_{\text{N}_2} + m_{\text{O}_2} c_{\text{O}_2}} \quad (2.3-2)$$

To anticipate the flow requirements of both the LIN and LOX components, an iterative calculator was written in Microsoft Excel utilizing Eq. 2.3-1 as organized in Eq. 2.3-2. This equation—typically utilized to find the final temperature of a fluid mixture created with different component fluids at varying temperatures, in this case warm compressed air, cryogenic N₂, and cryogenic O₂—was iteratively solved to find three unknowns: the flow rates of each fluid required to create an acceptable air mixture with a resulting temperature of -50°F. It was found that to obtain a final air mass flow rate of 251 SCFM at -50°F, flow rates of 73.9 SCFM of N₂ at -280°F and 19.8 SCFM of O₂ at -280°F would be required to mix with 158 SCFM of compressed air at 85°F.

Once these flow requirements were determined, Wright Brothers, Inc. was contacted, and it was found that these high flow demands would require four 450-liter tanks of LIN and one 450-liter tank of LOX to accommodate sustained testing for eight hours, or one test day. Regular downtime would be required during the week between each test day, which was not desirable. Additionally, the five cylinders would require a 45 ft² footprint with adequate forklift accessibility. While discussion continued on the cryogenic mixing method, issues of safety involved with bringing large volumes of LOX to an academic research site became clearer, requiring extensive oxygen-clean certifications of the facility. It was determined that the secondary option of obtaining a cryogenic heat exchanger would be the preferred alternative at the expense of greater LIN demand.

2.3.2 Heat Exchanger

The cryogenic heat exchanger method became the air chilling method of choice due to its elimination of the risks associated with installing LOX service at the CFRL. For the HARTF heat exchanger application, LIN was selected as the cryogenic service fluid for its ease of use and its inert properties. Various companies were contacted to discuss a cryogenic heat exchanger that could chill an air flow rate of 251 SCFM at a temperature of 85°F down to a temperature of -50°F in a low-pressure environment, implementing LIN as its service fluid. In the end, one company was found to accommodate the HARTF chilling requirements—Xchanger, Inc. Their modular C-Series heat exchanger was chosen, illustrated in Fig. 2.3-1.

This heat exchanger utilizes a fin-tube core, or a series of tubes with rectangular fin collars, to maximize cooling surface area. During operation, LIN flows through the tubes from the service inlet to the service outlet, chilling both the tube walls and the fins attached to them.

Figure 2.3-1: HARTF cryogenic heat exchanger sectional view

For the aforementioned chilling requirement, it was found that the heat exchanger would require a flow rate of 81 SCFM of LIN, a higher LIN service requirement than that of the cryogenic mixing air chilling method. With this increase in LIN demand, it was found that five 450-liter tanks quoted previously by Wright Brothers, Inc. would be necessary to accommodate eight hours, or one day, of test time.

With a similar 45 ft² footprint the five cylinders, the heat exchanger air chilling method would not remove the necessity for construction site planning and would further require additional installation costs. However, priority was given towards the elimination of the risks associated with LOX service, and the heat exchanger air chilling method was ultimately chosen.

2.4 Systems Concept

Once the methods for vacuum generation and cryogenic chilling were determined, the HARTF systems were conceptualized. As these systems concepts were decided upon, a graphical schematic was drawn, seen in Figure 2.4-1 on the following page.

To understand the systems necessary for accomplishing the main HARTF goals of performing high-altitude relight testing on gas turbine engine combustor hardware, predictions were made regarding the flow behaviors that would occur during the planned test procedures for the facility. The procedures for operating the air jet ejector, for example, were not found to require motive air ramping, and overpressure conditions were also not found to be an issue. Due to these realizations, control valves and pressure regulators were not deemed necessary when connecting the air jet ejector to the SFC 250 air compressor, and a simple shut-off valve would be placed on the line alone.

The air jet ejector flow behavior was further understood to react according to different changes in the atmospheric conditions present on its suction side. As mentioned earlier, a bypass air line would be necessary to meet the flow requirements set by the air jet ejector design. Operation of the bypass air line would modulate make-up air flow rates leading into the suction side of the air jet ejector, or the additional air mass flow rates that would be required to set a certain simulated altitude pressure condition in the combustor test section. For example, to simulate the atmospheric pressure of a 20,000 ft altitude, the air jet ejector would require a mass flow rate of 0.74 lb/sec to enter its suction side, referencing the performance curve shown previously in Fig. 2.2-4. If at the specific flow condition chosen, the combustor hardware arrangement required an air mass flow rate of only 0.20 lb/sec, the bypass air line would be required to make up the remaining air mass flow rate necessary to reach the

20,000 ft altitude pressure condition: 0.54 lb/sec. To enable fine control of these flow rates, a pneumatic control valve was proposed for the bypass air line. It was also determined that the bypass air line would be connected to the GA90FF air compressor to achieve the high air mass flow rates that would be required in three different testing scenarios—when simulating low altitude pressure conditions, when implementing small combustor test hardware, or when implementing a combustor test sector with a reduced number of swirl cups.

When predicting ignition testing flow behavior, it was understood that flow temperatures would rise during successful ignition attempts and that these higher temperatures would result in climbing suction pressures, which would lower the simulated altitude and simultaneously reduce the pressure drop across the fuel-air swirlers. While these events were deemed unavoidable, water injection cooling nozzles were proposed for the exhaust section upstream of the air jet ejector to limit the impact of rising temperatures on the altitude simulation. Furthermore, to inhibit the injection of mineral deposits into the HARTF and risk their circulation to the optically-clear windows on the combustor test section, it was determined that these water injection cooling nozzles would be connected to the de-ionized water pump system at the CFRL. These nozzles would be implemented only after high temperatures were held in the exhaust, so as not to disturb the combustion processes.

Similar approaches towards understanding flow behavior were made to conceptualize the upstream systems of the test facility. For example, the presence of vacuum generation and fluctuating flow conditions in the downstream sections warranted research into fixing the air mass flow rates traveling to the combustor test section. By fixing the upstream air mass flow rates, the changing pressures and temperatures due to successful ignition events and fluctuating altitude conditions would have little effect on the controlled air mass flow rates through the combustor sector. To fix the upstream air

mass flow rates, a sonic choke was proposed. In principle, a sonic choke—a C-D nozzle, critical orifice plate, de Laval nozzle, or critical flow venturi—is implemented to fix mass flow rates by accelerating flows to a sonic condition in its throat. When this sonic condition is present, the pressure fluctuations or changes in the flow structure downstream of the choke are unable to communicate back to the upstream side, thus fixing the air mass flow rate. As discussed in the air jet ejector design earlier, the motive air C-D nozzle is an example of a sonic choke. To establish a sonic condition, a considerable pressure drop and a small throat area are required. The upstream pressure must also be held constant to maintain a constant mass flow through the device. For sustaining a choked condition at all times, it was decided that the main air line would be connected to the GA90FF air compressor that would supply the bypass air line. For control over the air pressures upstream of the sonic choke, a pneumatic pressure regulator was chosen to be implemented.

Figure 2.4-1: Graphical schematic for HARTF systems concepts

The benefits of fixing the main air mass flow rates would also extend to the operation of the cryogenic heat exchanger. By fixing the air mass flow rate through the heat exchanger, few changes in its LIN service flow rate would be necessary to maintain steady heat exchange during testing. It was decided that the heat exchanger would be placed downstream of the sonic choke for this reasons.

Beyond the air flow maintenance upstream and downstream of the combustor test section, a fuel control system would be required to ensure smooth ignition testing. The high-pressure Jet-A fuel pump at the CFRL was chosen to be utilized in conjunction with a shut-off valve and pneumatic pressure regulator to meet any fuel pressure requirements. It was also decided that the fuel line would be fitted with a Coriolis mass flow meter to monitor injected fuel flow rates with accuracy.

2.5 Plumbing & Structure

After conceptualizing the HARTF systems, the design of the HARTF plumbing and structure began. The initial design phase started with two considerations in mind—ease of operation and hardware adaptation—which led the HARTF design approach in a direction that emphasized mobility and modularity. In early 2013, the HARTF was designed to be a small test rig that move in and out of the facility bay doors at Building A of the CFRL, to accommodate both a large range of different test hardware configurations and various diagnostic tools. In early 2014, however, during the construction of Building B Annex at the CFRL, a brand new test cell was designated and dedicated to house a permanent facility for high-altitude relight testing. The mobile facility design was thus considered impractical for the new test cell, and the HARTF was redesigned to make use of its new space. However, many of the structural design elements that were implemented in the mobile facility design were adapted to the final permanent facility design, which can be seen in the following sections.

2.5.1 Mobile Facility Design

The HARTF was initially designed to have a compact plumbing system and to be supported by mobile carts built out of extruded aluminum framing purchased from Bosch Rexroth. SolidWorks, a solid modeling computer-aided design program produced by Dassault Systèmes, was implemented to accurately design the plumbing system and structural frame.

To appropriately size the test rig and begin its plumbing design, the air jet ejector purchased from Graham Corporation was dimensioned and modeled. The air jet ejector was utilized as a type of baseline for the plumbing system design, which began with the exhaust section directly upstream of the 8" ANSI B16.5 Class 300 suction flange of the air jet ejector⁷. To adequately size the exhaust section, future testing applications were discussed and flow behavior predictions were made. As mentioned earlier, when considering the high-altitude relight testing that would be performed on the test rig, it was determined that the ignition events occurring in the test section would directly alter the altitude simulation—it was predicted that, during an ignition event, both the increased mass flow from the fuel addition and the rising temperatures and pressures resulting from the combustion processes would lead to sharp reductions in the simulated altitude. To help combat these effects on the altitude simulation setpoint, a larger 12" pipe diameter was proposed for the exhaust section, which would provide a greater suction volume that would dampen or delay the response of the air jet ejector to changing conditions in the test section. In choosing the materials and wall thickness for the exhaust section, type 304 stainless steel was selected for its strength and corrosion resistance properties and a Schedule 40 wall thickness was deemed necessary in the event that the HARTF would ever be repurposed to support high-pressure combustion and spray testing.

After choosing the exhaust section piping material, the design proceeded with adding the bypass air branch. As discussed in 2.4 *Systems Concept*, it was determined that the bypass air line would be linked to the GA90FF air compressor at the CFRL to enable higher air mass flow rates into the air jet ejector suction port. The expected pressure differential in the bypass air line would exceed 150 psid, leading to high flow velocities and unsteady flow structures. To reduce the velocities of the bypass air flow entering the exhaust section and provide for smooth altitude simulation control, a 4" NPS pipe size was chosen for the bypass air branch on the exhaust section, four times larger than the anticipated 1" NPS bypass air control valve pipe size. Additionally, it was determined that the bypass air branch should enter the exhaust section at an angle, and a 45° lateral pipe wye was chosen for the design.

Nine ports were then added to the 45° lateral pipe wye design—one 1" NPS port downstream of the bypass air branch for liquid draining, six 1" NPS ports upstream of the bypass air branch for installing water injection cooling nozzles and for providing additional make-up air paths that could aid in establishing lower altitude simulation setpoints, and two 1/4" NPS ports at the exhaust section inlet for monitoring exhaust gas temperatures and pressures. To re-iterate the operation of the air jet ejector, by enabling more air mass flow into its suction port, the generated vacuum strength will decrease and suction pressures will rise, simulating the atmospheric pressures of lower altitudes. It was determined that the maximum air mass flow rates from the bypass air line alone would be insufficient in simulating low altitudes. For example, to simulate an altitude of 10,000 ft, the air jet ejector would require an air mass flow rate of 0.94 lb/sec to enter its suction port. The GA90FF air compressor supplying both the main air and bypass air lines was limited to a maximum air mass flow rate of 0.6 lb/sec. By adding make-up air ports to the exhaust section, it was possible to extend the range of low altitudes that the bypass air line could control.

The final exhaust section design called for a 12" × 12" × 4" NPS Sch. 40s T-304L 45° lateral reducing wye modified with seven 1" pipe couplings and two ¼" pipe couplings welded in a custom arrangement. To attach the exhaust section to the air jet ejector purchased from Graham Corporation, a 12" × 8" NPS pipe reducer was implemented. In its design, the reducer would be welded to an ANSI B16.5 Class 300 type 304 stainless steel weld neck flange on its 8" side to mate with the suction port of the air jet ejector, and a Class 150 weld neck flange of the same material and specification on its 12" side to mate with the exhaust section. The exhaust section would then be welded with Class 150 slip-on flanges of the same material and specification on all sides. The 4" bypass air branch would include a 45° elbow to bring the bypass air line parallel to the exhaust plumbing section. Pipe fittings would be added to reduce the bypass air pipe size down to the 1" NPS pipe size chosen for the bypass air control valve.

For adapting the chosen five-cup research combustor test section—detailed in *3.1 Test Hardware*—to the exhaust section, custom flange adapters were designed, featuring 12" ANSI B16.5 Class 150 type 304 stainless steel blind flanges and four ¼"-thick type 304 stainless steel walls for each adapter. Vacuum-sealed attachment plates were then designed to complete the test section adaptation to the custom flange adapters. The downstream flange adapter was modified to provide ports for accessing the immediate exhaust gas stream with diagnostic tools. The upstream flange adapter was modified to have one removable wall to provide access to the fuel-air mixers, fuel nozzles, and fuel circuit, and one wall for fuel and measurement ports.

The upstream plumbing system was designed without the addition of the cryogenic heat exchanger for the initial construction of the facility. The upstream plumbing system consisted of an arrangement of reducing pipe fittings to bring the test section pipe diameter of 12" NPS down to 1" NPS. A critical

orifice plate was proposed for the sonic choke method, and was placed at a manageable distance away from the proposed main air pneumatic pressure regulator. Both the bypass and main air lines were designed to exist on the same level and connect to the GA90FF air compressor supply lines with flexible hoses. An early model of the HARTF plumbing concept is shown below in Fig. 2.5-1, complete with three optional 12" NPS pipe spacers on the exhaust section. In this model, the plumbing system is color-coded: yellow pipes for compressed air and red pipes for exhaust gases.

HARTF SYSTEM HARDWARE

Combustion Research Laboratory
Department of Aerospace Engineering and Engineering Mechanics
College of Engineering and Applied Science
University of Cincinnati

Figure 2.5-1: 3-D model of original mobile HARTF plumbing concept

Carts were then designed to support the plumbing system, utilizing the Bosch Rexroth aluminum framing library to accurately dimension available framing components. Casters were included on the carts to allow for mobility. To mount the plumbing system to the proprietary framing offered by Bosch Rexroth, 1/2"-thick carbon steel flange holders were custom-designed for the 12" ANSI B16.5 Class 150 flanges throughout the plumbing system. For the standalone ejector cart, three flange holders were designed for its flanges—two 8" ANSI B16.5 Class 300 flanges at the diffuser exhaust and suction inlet and one 3" ANSI B16.5 Class 300 flange at the motive inlet.

In designing the mobile carts for the test rig, it was decided that there would be a total of three carts: one cart for the air jet ejector and two carts for the main facility—the exhaust and upstream sections. These carts were designed to lift the main flow axis of the test facility to a height of 4'3", just under the average chest height of the personnel at the CFRL, to allow for ease of hardware access and operation. The two carts for the main facility were also designed to support the plumbing system from above to provide space to install the cryogenic heat exchanger on the lower level later in the design phase. An early model showing the breakdown of the cart system design is shown below in Fig. 2.5-2. The cryogenic heat exchanger addition, as well as the proposed fuel control circuit, comprised of a shut-off valve, fuel pressure regulator, and Coriolis fuel mass flow meter, are not depicted. These additions would be installed on the frame of the upstream section cart.

Figure 2.5-2: 3-D model of original mobile HARTF design, showing cart separation

In late 2013, construction began on Building B Annex at the CFRL and by early 2014, it was decided that a test cell would be dedicated to house the HARTF. The test cell was first dimensioned and modeled together with the original mobile facility design to gauge the potential rig placement and orientation. It was found that the test cell floorplan would be unable to accommodate the entire length of the test rig while still allowing the inside cell doors to be opened. These circumstances would require the air jet ejector cart to be detached from the test rig in between test times. Detaching and reattaching the air jet ejector during each day of testing was not an ideal situation. Not only would the set-up and teardown times be significant for each test day, the sealing process for the air jet ejector suction flange connection would require excessive expense. The high-temperature Grafoil gasket seals that would be implemented, while effective and reusable, were known to fall apart due to their short service lives. A model of the mobile HARTF design placed inside its designated test cell is shown below in Fig. 2.5-3, with the ejector cart placed outside of the test cell bay doors in its operational testing configuration.

Figure 2.5-3: 3-D model of original mobile HARTF design, in proposed test configuration

2.5.2 Permanent Facility Design

Due to the impractical nature of implementing the mobile HARTF design to the new test cell designated for its use, the HARTF was redesigned. The redesign would utilize the new test cell as a structural component and, as a whole, be permanent in nature. The modularity of the mobile facility would be retained with respect to the active test section, but the passive components—the air jet ejector, cryogenic heat exchanger, and air supply plumbing systems—would be installed in the test cell itself, independent of the test rig.

The first step towards adapting the HARTF systems concepts to the new test cell was to find efficient ways for installing the different plumbing and structural components that would remain static throughout the HARTF lifetime. Some of these components would even be moved outside of the test cell, as its location in Building B Annex happened to be at the end of the length of the building, located on a corner. With this location, different plumbing and structural components of the HARTF could be extended beyond two different walls of the building. First, it was decided that the air jet ejector would be moved outside and mounted to the northeast wall. To attach both the air line from the SFC 250 air compressor and the exhaust section plumbing to the air jet ejector, piping would be fully welded in place rather than requiring heavy flanged connections. It was decided that the air jet ejector would be oriented horizontally to prevent liquids and particulates from settling in and clogging the motive air nozzle, similar to its orientation in the mobile HARTF design. Its position, however, was changed so that it would be raised above the concrete pads surrounding the building. Not only would these pads be utilized as driveways for forklift access to the building, the space directly outside of the test cell would be allotted for the LIN service tanks, which were over 6' in height. The chosen wall of the test cell was also found to be fitted with a louvered fan exhaust system at a height of around 10'.

For these reasons, the height of the air jet ejector motive flow axis was chosen be at 13.5' from the ground. With this height, ample space was provided for potential support brackets, and the internal volume of the exhaust section with the additional plumbing was expanded to 10.3 ft³, or to 194% of its original 5.33 ft³ volume. These design changes can be seen below in Fig. 2.5-4.

Figure 2.5-4: 3-D model of HARTF plumbing system redesign

The pipe wye of the original mobile facility design was moved outside to clean up the area surrounding the test section. With this new location, a large bypass air control valve could be mounted to the inside wall of the test cell away from the test hardware. All nine ports that were added to the pipe wye design for drainage, make-up air, and exhaust gas monitoring, were moved to a new 3'-long 12" NPS exhaust

pipe that would be placed directly downstream of the test section, located inside of the test cell walls. To provide a drainage port for the new bypass air branch, which was no longer flowing downward into the exhaust section, a 1" NPS pipe coupling was added on its lowest point outside of the test cell walls. This port could also be used for providing additional make-up air.

With these design changes, it was important to find adequate support methods for the new exhaust plumbing systems. To manage the weight, which was estimated to be 1,130 pounds including the air jet ejector, a pipe stanchion was proposed to be welded beneath the 12" NPS pipe elbow and anchored to the concrete pad. The pipe stanchion would be assembled with of a 6" NPS Sch. 80 painted steel base stanchion and a 5" NPS Sch. 40 painted steel extension stanchion. A drain would be added to the bottom of the base stanchion to allow internal condensation to escape. To provide additional support and balance to the exhaust plumbing system, 30" × 4" × 4" × 1/2" angle iron brackets were designed to support the motive and diffuser flanges of the air jet ejector, utilizing the designed flange holders. It was understood that the plumbing system would experience minimal vibration during its operation, thus rigid angle iron brackets were deemed suitable. To evaluate the strength of the angle iron bracket design, a simple linear finite element stress analysis was performed in SolidWorks. The results, shown below in Fig. 2.5-5, indicate a maximum deflection of 0.001" when bearing a total load of 2,000 lb at the flange holder attachment points. When considering the strength of the proposed pipe stanchion, these simple angle iron brackets were determined to be sufficient in providing additional balance and support for the exhaust plumbing system. The final design would include anchor plates to be mounted within the test cell to distribute the forces on the cinderblock walls. By adding the angle iron brackets, the air jet ejector could be mounted on its own. It was planned to have the air jet ejector mounted before the exhaust system plumbing, which would ease construction.

Figure 2.5-5: Linear FEA stress analysis of air jet ejector angle iron bracket design

As seen earlier in Fig. 2.5-4, the upstream systems cart from the mobile HARTF design was carried over to the permanent facility design to create a support platform for the test section, fuel circuit, and any proposed diagnostic equipment. However, the main air line was moved to a permanent placement on the northwest wall of the test cell. With this new location, manual operation of different control devices, as well as the assembly, disassembly, and maintenance of plumbing hardware could be accomplished without interfering with the local test rig. Also, with the new wall space, a large high-flow silica gel desiccant air dryer could be added to reduce the humidity in the main lines. Wall mounting of the upstream plumbing would be accomplished with steel framing from Unistrut U.S.

The proposed cryogenic heat exchanger location was also changed to the northwest wall, to be mounted downstream of the main air line sonic choke. Utilizing an angle iron bracket design similar to the design used for the air jet ejector, the cryogenic heat exchanger would be mounted on the wall at a height of 10'. For providing LIN service to the cryogenic heat exchanger, 1/2" vacuum-jacketed

piping from Acme Cryogenics, Inc. was designed to run into the test cell from the LIN tanks that would sit outside of the northeast wall. In principle, this vacuum-jacketed piping would effectively suppress conductive, convective, and radiative heat transfer by thermally isolating the service fluid. In its design, LIN would flow through a 1/2" outer-diameter tube (ODT), surrounded by a 2" ODT jacket. The space between the two would be fully evacuated, removing any media that would allow convective heat transfer between them. Polished surfaces and low-conductivity spacers would assist the assembly in reducing radiative and conductive heat transfer, respectively, as indicated below in Fig. 2.5-6.

Figure 2.5-6: Vacuum-jacketed pipe section view⁴⁴

These vacuum-jacketed lines were designed to be mounted to the outer northeast wall, supported by Unistrut U.S. steel framing, and they would split into three branches to allow three active LIN tank connections at a time. Pressure relief valves would be added to the lines to prevent overpressure conditions. For the nitrogen exhaust, 1" NPS Sch. 40s stainless steel piping was chosen to send the nitrogen gases out of the test cell. This exhaust line would be adapted to a 100' hose that would travel

away from the building to prevent nitrogen from flooding either the test cell or the Building B Annex HVAC systems that would be installed nearby.

In addition to the vacuum-jacketed LIN service lines, vacuum-jacketed plumbing was proposed to be implemented on the main air line to travel from the cryogenic heat exchanger on the northwest wall over to the test section. This plumbing section would be purchased as a single rigid vacuum-jacketed pipe spool, to be hung from support struts in the ceiling of the test cell with pipe hangars. By implementing vacuum-jacketed plumbing on the main air line, the cold air temperatures exiting the cryogenic heat exchanger would be better ensured at the test section location. The spool was determined to require a diameter of 2" ODT by utilizing Darcy-Weisbach friction equations.

To complete the permanent HARTF facility design, modifications were then made to the upstream facility cart design. With the additional space gained by moving the cryogenic heat exchanger to the northwest wall, a three-dimensional traverse system was proposed to be installed on the lower level of the upstream facility cart. The traverse system would enable additional diagnostic tools to be implemented in the facility, such as LDV and PDPA. Furthermore, with the removal of the cryogenic heat exchanger, the cart height could be reduced to support the facility plumbing system from underneath, minimizing the amount of support framing required. Linear guide rails and arms with roller bearings were then designed to both support the test section upstream flange adapter and enable smooth separation of the test section assembly. To permit the upstream plumbing section to move on the cart, flexible high-temperature Teflon fuel lines would replace the rigid stainless steel tubing that was originally proposed for the fuel control circuit.

3-D models of the final HARTF design are detailed on the following page in Fig. 2.5-7.

Figure 2.5-7: 3-D models of final HARTF design

2.6 Control & Measurement

After establishing the HARTF systems concepts and scoping out the general plumbing and structural designs for the test facility, the control and measurement devices were selected.

2.6.1 Control Devices

Moving from upstream to downstream in the systems concepts schematic in Fig. 2.4-1, the first control on the main air line is the manual shut-off valve located downstream of the air compressor. In its design, the air manifold in Building B Annex that would be supplied by the GA90FF air compressor would be constructed with a 3" NPS pipe size and fitted with 3" flanged butterfly valves in each test cell. In the HARTF, it was proposed that the 3" NPS pipe size would be reduced to a 2" NPS pipe size downstream of the butterfly valve. Following this reduction, a small air manifold was designed with three branches—one for the main air line, one for the bypass air line, and one for supplying the pneumatic control devices in the test facility. Each of these branches were given their own manual shut-off valves to enable flow isolation and flow checking.

Downstream of the main air line shut-off valve, a pneumatic pressure regulator would be installed to enable remote control of the air pressures upstream of the sonic choke. For this control, the Jordan Valve Mark 66 air-loaded $C_v = 9.5$ pressure regulator was chosen. Rather than utilizing a spring and poppet design, the Mark 66 features a sliding gate mechanism connected directly to its diaphragm, enabling smooth, uniform flows and precise pressure regulation with the aid of an electro-pneumatic controller. To control the pneumatic air pressures that would be sent to the Mark 66 up to 120 psig, the Fairchild T9000 controller was selected.

To fix the main air flow rate with a sonic choke, discussion began with fixed-area critical flow venturi nozzles. However, for the HARTF testing application, mass flows would be required to be fixed over a wide range of different operating conditions, depending on either the altitude simulation or the implemented combustor test hardware. To accommodate this range of operating conditions, the single point design of a fixed-area critical flow venturi nozzle would not be suitable, and purchasing multiple nozzles for different testing applications was not considered economically sound. Adjustable area venturi valves were also researched, but due to expense, critical orifice plates were conclusively selected as the main air sonic choke method. A 1" NPS ANSI B16.5 Class 300 flange assembly was chosen due to the large array of compatible orifice plates already available at the CFRL. Standard bore diameters would range from 1/8" to 1/2" depending on the flow requirements during testing.

On the bypass air branch, one control would be necessary: the pneumatic bypass control valve. When selecting this valve, it was important to remember the pressure differential that would exceed 150 psid in the bypass air line. Tight sealing under vacuum conditions and short valve response times were also desirable, leading the valve selection to a globe valve. To reduce costs, as well as shorten the valve stroke to reduce response times, a 1" pipe size was chosen for the valve. After discussing potential options with local vendors, the Koso Hammel Dahl G120 equal-percentage $C_v = 13.4$ globe valve, the Koso Hammel Dahl D/R Series spring-diaphragm pneumatic linear actuator, and the Metso Neles ND9000 intelligent valve controller were selected for the application.

A similar control valve was discussed for the LIN service line. To allow remote control of the LIN service fluid flow rates that would lower the main air temperatures exiting the cryogenic heat exchanger, an extended-neck cryogenic globe valve was discussed with Acme Cryogenics, Inc. to be welded to the indoor vacuum-jacketed pipe spool on the LIN service line. The 1/2" vacuum-jacketed

CVI Model V-1080 $C_v = 6.0$ control valve was selected, complete with a CVI 88 Series piston-style pneumatic actuator and a Fisher FIELDVUE DVC2000 digital valve controller.

For the fuel control circuit, as shown in the systems concepts schematic in Fig. 2.4-1, both a shut-off valve and fuel pressure regulator would be installed. When utilizing the high-pressure Jet-A fuel pump that would be constructed in Building B Annex, these valves would be required to be rated for 6,000 psig to function at all fuel pump pressure settings. To accommodate these high fuel pressures, a manual $\frac{1}{2}$ " ultra-high-pressure stainless steel ball valve was selected for the fuel shut-off valve, and a $\frac{1}{2}$ " TESCO 26-2000 Series high-pressure low-flow piston-sensed $C_v = 0.06$ regulator was selected for the fuel pressure regulator. The 26-2000 Series pressure regulator would be able to handle inlet fuel pressures of up to 10,000 psig and reduce outlet fuel pressures to a range of 10-1,500 psig. With the addition of a TESCO spring-diaphragm pneumatic linear actuator and the TESCO ER5000 Series electro-pneumatic controller, regulating the fuel pressure would be accomplished remotely.

In addition to fuel pressure control, it was determined that on-off solenoid valves would be desirable at a location as close to the fuel injectors as possible. It was understood that the vacuum pressures within the test section during high-altitude relight testing would exert a suction force on the fuel nozzles at all times, which would continue to evacuate the fuel circuit lines until any pressure differential was eliminated. Not only would this send undesired fuel into the test section following an ignition test, it would create an empty volume in the fuel circuit that would slowly fill with fuel during the next ignition test—an unavoidable fuel ramping condition—causing a delay to occur in obtaining the desired fuel injection flow rates. The ramping condition would lead to fuel injection with low flow rates and poor atomization quality, saturating the test section with fuel before reaching the ignition point. Depending on the fuel circuit volume evacuated, the time delay could be significant. For these

reasons, high-pressure type 430 stainless steel magnetic fuel solenoid valves would be added to the individual lines of each fuel nozzle at a location as close to the nozzles as possible: on the upstream air chamber side wall. A sixth solenoid valve would be installed upstream of the nozzle circuit manifold, allowing the individual fuel lines to fill and pressurize before permitting injection.

For the water injection cooling nozzles on the exhaust section, it was determined that only a simple shut-off valve would be necessary for reducing the high exhaust section temperatures that would reduce the altitude simulation setpoint and lead to inconsistent ignition data between tests. The high-pressure de-ionized water pump manifold in Building B Annex would include shut-off valves in each test cell, which eliminated the need for acquiring additional control hardware for water injection.

The air jet ejector motive air supply, connected to the SFC 250 air compressor, also did not require additional control hardware. The 4" NPS air manifold that would be constructed in Building B Annex to be supplied by the SFC 250 air compressor would include butterfly shut-off valves in each test cell. Plumbing to the air jet ejector motive inlet would be welded directly without additional controls.

2.6.2 Measurement Devices

The primary measurements that would be taken in the HARTF would include pressure, temperature, and fuel mass flow. Later in the facility design, humidity measurement also became desirable.

Differential pressure transducers became the vacuum pressure measurement devices of choice to allow all vacuum pressure measurements to be compared with the same source—the varying barometric pressure in the test cell. To measure vacuum pressure with a differential pressure transducer, the low

pressures of interest would be connected to the positive pressure ports of the differential pressure transducers. The negative pressure ports of the transducers would then be left open to the barometric pressure present in the test cell. With this method, a pressure measurement of -10.7 psid would be obtained in a 14.7 psia test cell when measuring a 4.0 psia pressure source. After browsing suitable differential pressure measurement devices, the Siemens SITRANS P500 differential pressure transducer was selected to measure the vacuum pressure measurement points. These transducers were selected for their high measurement accuracy of less than or equal to 0.03% for a TurnDown of 10:1. Five SITRANS P500 pressure transducers were purchased, to measure the air jet ejector suction pressure, the test section pressure, the pressure in the upstream air chamber, the pressure downstream of the main air orifice plate, and the pressure within the fuel circuit manifold directly upstream of the fuel nozzle solenoid valves.

For high pressure measurements, which would include the air jet ejector motive inlet pressure and the pressure that would be modulated upstream of the main air orifice plate, the Siemens SITRANS P DS III pressure transducers were chosen. These transducers, while also more cost effective, were also selected for their measurement accuracy of less than or equal to 0.065%.

To monitor the barometric pressure in the test cell, the OMEGA Engineering iBTHX-W iServer MicroServer barometric pressure, temperature, and humidity transmitter was selected. This device was chosen due to its ability to be accessed virtually over the local network at the CFRL.

Type K thermocouples from OMEGA Engineering were selected to monitor the air temperatures in the air jet ejector and exhaust sections due to their abilities in measuring high temperatures with appreciable accuracy. Type T thermocouples from OMEGA Engineering were selected to monitor

the air temperatures in the upstream main air sections and the nitrogen temperatures in the cryogenic heat exchanger exhaust line due to their abilities in measuring cryogenic temperatures with appreciable accuracy. These thermocouples were purchased in short 1/8" diameter probe configurations, to be inserted into the facility plumbing systems with compression tube fittings purchased from Swagelok.

To accomplish Jet-A fuel mass flow measurement, a Micro Motion CMF010S Coriolis-type flow meter already belonging to the CFRL would be implemented. Utilizing the Coriolis method, this flow meter could measure Jet-A fuel mass flow rates without calibrating for different test conditions: pressure, temperature, or density.

When implementing the cryogenic heat exchanger during later testing, it became apparent that the elements within the silica gel desiccant air dryer would lose their drying effectiveness over time as they became saturated, and that the impacts would be seen long before the elements would visibly change color, as they are designed to do when saturated. Due to the negative impacts of humidity when chilling the air to subzero temperatures, the OMEGA Engineering HX94 relative humidity and temperature probe was selected to be installed in the main air line downstream of the orifice plate.

2.7 Software Interfacing

Due to the complex nature of both the HARTF systems design and the flow behaviors that would occur during testing, software was written in LabVIEW to allow real-time monitoring of the atmospheric conditions within the facility and to also provide user-friendly remote control capabilities. To manage all of the analog inputs from the measurement devices and the analog outputs to the control devices, different interfacing hardware compatible with LabVIEW were researched and

selected. The National Instruments (NI) cDAQ-9178 CompactDAQ 8-slot USB chassis was chosen as a hub that would support an array of different input and output modules.

When selecting each pressure transducer for the facility, 4-20 mA current output options were chosen for communicating the pressure signals. The fuel mass flow meter was also found to be configured to send 4-20 mA output signals to communicate mass flow. To read these current signals, the NI 9208 16-channel current input module was selected for the NI cDAQ-9178 chassis. The module features 24-bit resolution and a maximum data rate of 500 samples per second. The channels are not read simultaneously, however, meaning that when utilizing 16 channels, measurements are taken with a maximum data rate of 31.25 Hz per channel. If higher data rates are ever required by different testing applications in the future, two of the NI 9203 8-channel current input modules could be purchased and installed, which feature 16-bit resolution and a maximum data rate of 200,000 samples per second, meaning a 25 kHz maximum data rate per channel when utilizing all channels. If channels would ever be required to be read simultaneously with precision, it was found that NI could provide other suitable modules that would be compatible with the NI cDAQ-9178 chassis.

For reading temperature measurements from the thermocouples in the facility, the NI 9213 16-channel thermocouple module was selected, featuring 24-bit resolution and a maximum data rate of 100 Hz per channel. This module was selected over a voltage input module due to its ease of use and calibration. If higher data rates are required in the future, voltage input modules could be obtained.

Each control valve and pressure regulator in the facility was selected to utilize 4-20 mA current signals. For controlling these devices, multiple NI 9265 4-channel current output modules were selected, featuring 16-bit resolution and simultaneous data rates of 100 kHz per channel. An additional module

was selected to control each of the six solenoid valves that would be placed on the fuel circuit. The solenoid valves were selected to open when excited with a 120V AC signal. To enable remote on/off control of these signals, solid-state relay switches were purchased with control voltages of 5V DC. Therefore, a module that could send an on/off 5V DC signal was selected—the NI 9401 8-channel 5V transistor-transistor-logic (TTL) bidirectional input/output (I/O) module.

HARTF DATA ACQUISITION AND CONTROL SYSTEM DIAGRAM

Figure 2.7-1: Diagram for interfacing facility devices with the data acquisition and control system

After completing these selections for the HARTF data acquisition and control system, the chosen modules were studied and a simple guide for wiring and interfacing the measurement and control devices in the facility was drawn, seen above in Fig. 2.7-1.

The software for the data acquisition and control system was then written in LabVIEW. It was desired to have each measurement taken in the facility displayed on one panel with active plots, accompanied by user-friendly toggle switches and slide controls. The software would also log every data point displayed on the front panel with accurate timestamping. To accomplish this, the NI-DAQmx driver software suite was utilized to write programs for reading signals from the measurement modules. Timing information was written to accurately log the data. A data rate of 50 Hz was selected to read signals from each measurement device. An update rate of 5 Hz was then chosen for the front panel. Thus, 10 measurements taken at 50 Hz would be averaged to produce each data point displayed on the front panel and sent to the log file. To ensure accurate signal translation, the calibration curves delivered with each device were programmed into the software.

As mentioned earlier, for the front panel, it was decided that all measurements and corresponding calculations would be updated at the same rate. To accomplish this, the bulk of the facility measurement code was designed to run in a singular while loop that would terminate by user command. Data logging would persist throughout the duration of its operation. For sending signals to the different control devices, separate NI-DAQmx driver software was implemented within individual while loops that would operate simultaneously and independently of the core measurement loop. By running these loops simultaneously, each device could be operated immediately without relying on separate functions to complete beforehand. On the front panel, these controls would be represented with manual slider controls that would also allow numerical input.

Example screenshots of the front panel design and different sections of code are shown in Fig. 2.7-2 and Fig. 2.7-3. Future additions would include a 3-D model of the facility with numerical overlays to allow easy data interpretation for personnel unfamiliar with the test facility. Additions would also include video cameras integrated in real-time to monitor spark ignition events within the test section.

Figure 2.7-2: Example front panel design (top) and measurement code (bottom) of HARTF LabVIEW software interface

Figure 2.7-3: Data handling code (top) and device control code (bottom) of HARTF LabVIEW software interface

2.8 Construction

Initial construction of the HARTF began in May 2014 during the final stages of the Building B Annex construction at the CFRL, which was not completed until July 2014. The custom flange holder designs were first fabricated by L.A.B. Quality Machining, Inc. to mount the air jet ejector to its support brackets and the exhaust plumbing section flanges to the facility frame. The air jet ejector support brackets, the outdoor exhaust plumbing section, the motive air supply line, the outdoor section of the bypass line, and the supporting pipe stanchion were welded and installed by Ken Neyer Plumbing, Inc. The completed assembly is shown in an early photograph below in Fig. 2.8-1. A view from the inside the test cell upon completion is shown in Fig. 2.8-2

Figure 2.8-1: Downstream HARTF plumbing installation (outside wall)

Figure 2.8-2: Downstream HARTF plumbing installation (inside wall)

Following this initial contracted plumbing installation, much of the remaining construction was completed by hand. The Bosch Rexroth framing pieces that would become the facility cart were moved into Building B Annex and assembled by the last week of May 2014. In the week following, the upstream piping and associated Unistrut U.S. wall support pieces were obtained, assembled, and installed. By the first week of June 2014, the upstream air plumbing sections, the test cell workbench, and the cell toolbox were completed. This construction progress can be seen below in Fig. 2.8-3. To note, the cryogenic heat exchanger and respective plumbing sections would not be installed until 2015, to first prove the facility concept with pressure testing and successful ignition testing at room temperatures. The silica gel desiccant air dryer would also be installed on the upstream air line with the cryogenic heat exchanger installation.

Figure 2.8-3: Framing, upstream plumbing section, and desk completion

In June 2014, Machine Development Corporation was contracted to mount the bypass air control valve to the northeast wall and fabricate the custom exhaust plumbing section. The valve was installed with anchor plates on the outside wall and was mounted with a spring tensioner to provide additional support and to allow the valve to be properly leveled. By the second week of July, the custom exhaust plumbing section, test section, and upstream air chamber were installed with their respective measurement and control devices by hand. To mount the exhaust plumbing section to the frame, the custom flange holders that were fabricated by L.A.B. Quality Machining, Inc. were first installed to the cart. A hydraulic crane was then implemented to lift and position the exhaust plumbing section onto the flange holders. These construction items were completed by July 18th, 2014, and the HARTF became operational for pressure testing. The core facility completion can be seen in Fig. 2.8-4.

Figure 2.8-4: Early construction completion, operational for pressure testing

For integrating fuel capability, the high-pressure Jet-A fuel pump in Building B Annex would not be completed until the following months. However, a tank of Jet-A fuel was temporarily utilized for preliminary ignition testing, pressurized with the pneumatic air manifold on the main air line. After installing the fuel nozzles and fuel-air swirlers into the upstream air chamber, as well as connecting the spark ignition system, the first successful room temperature ignition test was conducted on August 5th, 2014 with a combustor back pressure corresponding to an altitude of 32,000 ft.

In the weeks following, the plumbing sections for the fuel control circuit and the water injection cooling nozzles were installed and mounted to the northwest and southwest walls of the test cell. The installation of the fuel control circuit assembly on the frame, including the fuel pressure regulator, five-branch fuel manifold, and manifold solenoid valve, was completed by the second week of

October 2014. With its completion, live ignition demonstrations were performed at room temperature with varying altitude pressure simulations throughout the remainder of the year.

After conducting successful pressure and ignition testing during the end of 2014, motions were made towards installing the cryogenic heat exchanger and the vacuum-jacketed piping in the facility. The construction for mounting the heat exchanger to the northwest wall of the test cell and installing the vacuum-jacketed LIN piping from Acme Cryogenics, Inc. on the outside of the northeast wall was completed by the end of February 2015, contracted through Driekast Piping Corporation. The main air line modifications to complete the upstream connections to the cryogenic heat exchanger, which including the installation of the silica gel desiccant air dryer, were then completed by hand. The nitrogen exhaust line that would run outside of the northeast wall of the test cell was also installed. Shortly afterward, 450-liter Mega-Cyl LIN tanks were rented through Wright Brothers, Inc. and delivered to the test cell. Successful ignition testing with combustor back pressures exceeding 30,000 ft altitude pressure and with air temperatures below -70°F were achieved during the first week of April 2015, signifying the completion of the primary HARTF goals. At this stage, however, the LIN consumption to achieve low air temperatures was excessive, pending the installation of the main air line vacuum-jacketed piping section.

Acme Cryogenics, Inc. completed fabrication and delivery of the main air vacuum-jacketed piping section, which would connect the cryogenic heat exchanger to the test section, in July 2015. Upon delivery, the main air line was disassembled and the new piping section was installed by hand. To expand upon the insulation offered by the vacuum-jacketed piping section, additional foam insulation was purchased and installed on the non-insulated pipe fittings connected to the upstream air chamber. The upstream air chamber walls were also coated with foam insulation to reduce heat transfer during

cryogenic testing. After the upstream air chamber walls were insulated, the fuel solenoid valves for each fuel nozzle were installed directly outside, which were unable to operate at very low temperatures.

In preparation for future testing applications that would require extensive diagnostics, including laser Dopple velocimetry (LDV) and phase Doppler particle analysis (PDPA), a large three-axis traverse system was installed on the lower level of the facility frame. The HARTF, in its fully-operational state during October 2015, can be seen below in Fig. 2.8-5 and Fig. 2.8-6.

Figure 2.8-5: Completed HARTF construction, following months of testing

Figure 2.8-6: Completed HARTF construction, following months of testing

Chapter 3: Experimental Evaluation

3.1 Evaluation Scope

Throughout the different stages of the HARTF construction and following its completion in July 2015, the facility was experimentally evaluated in its abilities to function as designed. Preliminary testing included evaluating the performance of the air jet ejector in reducing the pressures within the HARTF to those experienced at high altitudes, and the cryogenic heat exchanger was evaluated in its abilities to chill air temperatures at the test section location. Ignition testing was then performed at room temperature and atmospheric pressure conditions, room temperature and sub-atmospheric conditions, and high-altitude conditions—sub-atmospheric temperature and pressure conditions. These tests were performed to evaluate proper operating procedures for test facility and to evaluate how well the facility could accommodate ignition testing on gas turbine engine combustor hardware while simulating different altitude conditions. To perform these evaluations, an in-house research combustor test sector and ignition system were implemented.

3.2 Test Hardware

To evaluate the abilities of the different HARTF components to function as designed, a combination of in-house test hardware was utilized and adapted to the facility to replicate industrial gas turbine engine combustor hardware that would be implemented in the future. This combination included a research combustor sector—a linearly-arranged five-swirler array fitted with five high-swirl counter-rotating radial-radial fuel-air swirlers and five single-orifice pressure-swirl fuel atomizers. To adapt the research combustor sector to the facility, its associated upstream air chamber and test section were

utilized with a fabricated downstream adapter flange. Performing ignition within the test section was accomplished with an in-house aircraft jet engine exciter-igniter spark ignition system. These hardware components are detailed below.

3.2.1 Fuel-Air Swirlers

The fuel-air swirlers implemented in the adapted research combustor sector were previously designed at the CFRL and have been implemented in many aerodynamics and combustion dynamics studies focusing on multi-swirler interaction¹⁶. The fuel-air swirler assemblies include an inner primary radial swirler and an outer secondary radial swirler, which are counter-rotating. When viewing the swirlers from upstream to downstream, the primary air is swirled in a clockwise pattern and the secondary air is swirled in a counter-clockwise pattern. In their design, the primary and secondary swirlers feature 16 and 12 straight vanes with angles of 53° and 70° , respectively. The flare is designed with a 54° half diverging angle and the swirler exit diameter is 1". A 3-D model of the swirler assembly is shown below in Fig. 3.2-1¹⁶.

Figure 3.2-1: Fuel-air swirler assembly¹⁶

In previous studies, a rough average effective flow area of the fuel-air swirler assemblies was found to be 0.138 in^2 at an absolute pressure drop of around 0.57 psid ¹⁶. Notably, these tests were performed at atmospheric conditions and the effective area measurements for each of the five employed swirlers was found to vary between each other. The effective area measurements were also found to increase with pressure drop. Although these test conditions differ greatly from the majority of the intended test conditions that would be encountered during high-altitude relight testing at the HARTF, the average 0.138 in^2 effective area measurement was utilized to quickly gauge the main air mass flow rate during the experimental HARTF evaluations.

3.2.2 Fuel Atomizers

Simplex nozzles, or industrial single-orifice pressure-swirl atomizers, shown in Fig. 3.2-2, were implemented with the fuel-air swirlers. In previous testing, these nozzles were shown to yield a spray angle of 75° and flow numbers (FN) ranging from 0.81-0.86 when injecting liquid Jet-A fuel with a 50 psid pressure drop. These flow numbers were found to vary between each of the five atomizers¹⁶.

Figure 3.2-2: Fuel atomizer implemented, true dimensions (left, bottom right¹⁶), internal mechanisms (top right⁴¹)

To pinpoint the exact operating characteristics of these fuel atomizers when configured in a five-atomizer arrangement and adapted to the HARTF fuel control circuit, flow testing was performed on the atomizers at atmospheric conditions following their installation in the test facility. The CMF010S fuel flow meter and the SITRANS P500 pressure transducer of the HARTF fuel control circuit were utilized to find a relationship between the total fuel mass flow rate flowing through the collection of five fuel atomizers and the pressure drop existing across them. In the five-atomizer arrangement, each fuel line was connected to the five-branch fuel manifold of the fuel control circuit. The manifold fuel pressures were first raised to 40 psig and then reduced slowly to zero, allowing measurements to settle while the total fuel mass flow rate of all five atomizers was observed. The results were found to yield a relationship that could be approximated with either an asymmetric sigmoidal curve or a power curve, specified in Eq. 3.2-1 and Eq. 3.2-2, respectively, with units of lb/hr for $\dot{m}$ and psid for ΔP .

$$\dot{m} = f + \frac{a - f}{\left(1 + \left(\frac{\Delta P}{d}\right)^b\right)^g} \quad \text{where} \quad \begin{cases} a = -5.497 \\ b = 2.524 \times 10^{-1} \\ d = 2.435 \times 10^{10} \\ f = 3.469 \times 10^7 \\ g = 1.346 \times 10^{-4} \end{cases} \quad (3.2-1)$$

$$\dot{m} = a \cdot \Delta P^b \quad \text{where} \quad \begin{cases} a = 5.807 \\ b = 3.886 \times 10^{-1} \end{cases} \quad (3.2-2)$$

The continuous measurements from the atomizer flow testing are shown below in Fig. 3.2-2, with data highlighted for when the measurements settled. The asymmetric sigmoidal and power curves are then plotted against the settled data points and compared with the average FN = 0.835 curve, which was measured previously.

Figure 3.2-3: Flow testing of five-atomizer arrangement, measurements (top) and approximations (bottom)

These test results show that the flow characteristics of the five-atomizer array cannot be approximated with the average $FN = 0.835$ relationship that was found in previous studies. For pressure drops up to 20 psid, the asymmetric sigmoidal relationship fits the experimental data with greater accuracy, yielding an R^2 value of 99.8%. The power relationship fits the experimental data with an R^2 value of 98.9% and seems to become more accurate than the asymmetric sigmoidal relationship at higher pressure drops. The $FN = 0.835$ relationship is only accurate at the highest pressure drop tested. By finding these relationships, accurate fuel flow rate approximations can be made with simple pressure drop measurements as opposed to relying on the CMF010S fuel flow meter, which was found to surge when performing on/off switching of the fuel atomizer solenoid valves during ignition testing, yielding dynamic and inaccurate mass flow rate measurements.

3.2.3 Test Sector

The five fuel-air swirlers and fuel atomizers were configured within a rectangular test sector in a linear array pattern. The test sector was previously designed for multi-swirler aerodynamics and combustion dynamics research, featuring two chambers: an upstream air chamber and an optically-accessible combustion chamber¹⁶.

The upstream air chamber was designed to create a large stagnation volume to aid in the development of uniform upstream air pressures, enabling a total pressure approximation with a simple static pressure measurement. Furthermore, the upstream air chamber was designed to provide a mounting surface for the fuel-air swirler attachment plates and the dome surface plate. As seen in Fig. 3.2-4 below, the dome surface exhibits little to no recession below the flares of the fuel-air swirlers. In their arrangement, the fuel-air swirlers were spaced 1" apart with $\frac{1}{2}$ " wall distances¹⁶.

Figure 3.2-4: Linear arrangement of fuel-air swirlers and fuel atomizers with attachment plates and dome plate¹⁶

Figure 3.2-5: Test section design¹⁶

The combustion chamber, or test section, was designed as a simple rectangular chamber with three primary modifications—windows to accommodate optically-accessible combustion and spray testing, windows to enable laser lightsheet injection, and panels for adapting the spark igniter and measurement devices. Its internal geometry yielded a flow cross-section of 10" × 2" and three of its walls were utilized for access. Two 8.5" × 4" panels were installed in the near field to configure quartz glass windows for observation or a central spark igniter adapter plate. A third panel was installed on one of the endplates to configure a laser lightsheet access window, to image the plane intersecting the flow axes of all five swirlers, similar to a periscope lightsheet method^{28,29}. Measurement ports could also be utilized on this endplate panel. These can be seen in Fig. 3.2-5 and Fig. 3.2-6.

Figure 3.2-6: Slip-on design of test section exhaust adapter flange

To adapt the test section to the HARTF, a 12" ANSI B16.5 Class 150 type 304 stainless steel blind flange was machined by Machine Development Corporation with support walls. Due to the amount of thermal cycles that the type 304 stainless steel test section had previously undergone during atmospheric combustion testing while oriented vertically and exhausting to ambient conditions, it was found to be impractical to try to machine modifications to the downstream edges to secure bolt

connections. Therefore, the walls of the custom flange were designed to interface with the inner walls of the test section, forming a slip-on connection. The walls were designed with $\frac{1}{4}$ " thickness and would enter with a 3" depth, reducing the test section flow area from $10'' \times 2''$ to $9.5'' \times 1.5''$. This design can be seen in Fig. 3.2-6—the upstream air chamber wall and corresponding fuel-air swirlers were replaced with a dummy plate for this image. To ensure vacuum-sealing of this slip-on connection, a high-temperature ceramic putty, activated with air exposure, was formed over the wall interfaces.

3.2.4 Ignition System

For igniting the combustor test section, an in-house industrial exciter-igniter ignition system was utilized, comparable to systems offered by Unison Industries, LLC, Woodward, Inc., or Champion Aerospace for small aircraft jet engines. An example is shown in Fig. 3.2-7. The igniter tip featured a high-voltage shunted-type surface gap between a center primary electrode and a coaxial annular ground electrode, and was mounted flush with the inner wall surface of the test section 1" downstream of the center fuel-air swirler. The spark energy was measured to be 2.0 joules, and when utilizing high-speed video, spark plasma was found to visibly persist for $310 \mu\text{s}$ upon firing, yielding a 6.4 kW power estimation. During all ignition testing, the spark timing was held around 1 Hz.

Figure 3.2-7: Gas turbine engine exciter-igniter system⁴³

3.3 Pressure Testing

Pressure testing of the HARTF was performed following its core construction completion in the summer of 2014 to evaluate the performance of the air jet ejector and to find leaks throughout the test facility plumbing systems. These tests also served to familiarize personnel with the HARTF start-up procedure, outlined below.

3.3.1 Operating Procedure

- 1) Initialize the HARTF software interface first to begin live monitoring of the different environmental conditions throughout the test facility.
- 2) During software initialization, specify a filename to begin data logging.
- 3) Ensure software settings of zero pressure and zero valve position are, by default, specified for the Mark 66 main air pressure regulator and the G120 bypass air control valve, respectively.
- 4) Following HARTF software initialization, turn on the SFC 250 and GA90FF air compressors to pressurize the Building B Annex air manifolds.
- 5) Manually open the 3” NPS butterfly valve connected to the air manifold supplied by the GA90FF air compressor, pressurizing the three-branch air manifold that supplies the main air line, the bypass air line, and the manifold for the pneumatic air lines.
- 6) Manually open the shut-off valve for the pneumatic air line manifold to pressurize the different pneumatic air lines in the test facility.

- 7) Manually modulate the two small air pressure regulators placed on the pneumatic air lines leading to the T9000 controller, which controls the Mark 66 main air pressure regulator, and the ND9000 controller, which controls the G120 bypass air control valve, to find their required pneumatic supply pressures. The T9000 controller utilizes up to 120 psig and the ND9000 controller utilizes less than 60 psig. While receiving its pneumatic supply pressure, the ND9000 controller, already receiving a signal for zero valve position from the software interface, should close the G120 bypass air control valve, a fail-open device.
- 8) Manually open the bypass air shut-off valve to supply the bypass air line.
- 9) Manually open the main air shut-off valve to supply the main air line. While supplied with air pressure and receiving a zero pressure signal from the software interface, the T9000 controller should ensure the Mark 66 air pressure regulator remains closed.
- 10) Manually open the 4" NPS butterfly valve connected to the air manifold supplied by the SFC 250 air compressor, pressurizing the motive air inlet of the air jet ejector. Once fully opened, the air jet ejector suction inlet pressure will reduce to its lowest point.
- 11) If the air jet ejector begins breaking, or surging, indicated by loud blasts of sound and unstable suction pressures, increase the suction inlet mass flow. This condition may occur if the SFC 250 air compressor is functioning on a high-pressure, low-flow configuration, which may be required by other test facilities at the CFRL. To increase the suction inlet mass flow, increase the bypass air control valve setting with software interface.
- 12) With stable air jet ejector suction pressures, modulate the main air pressure setpoint and bypass air control valve position with the HARTF software interface as desired.

3.3.2 Test Results

When performing pressure testing on the facility, it was found that the suction air pressure of the air jet ejector could be reduced to below 1.7 psia, corresponding to altitudes beyond 45,000 ft, when closing off all sources of suction air mass flow. These results are shown below in Fig. 3.3-1.

Figure 3.3-1: Air jet ejector start-up performance

This performance, however, was found to vary greatly with the pressure setting of the SFC 250 air compressor, which would change from a high-flow, low-pressure configuration to a low-flow, high-pressure configuration throughout the calendar year to accommodate the test requirements of the other test cells in operation at the CFRL. If the SFC 250 was set at a high-pressure operating condition,

it would be unable to maintain the air mass flow rate required by the air jet ejector motive nozzle design. It was found that the air jet ejector would first experience an overpressure condition at the motive nozzle, providing an increase in suction performance for a short duration. Within 5-30 minutes, depending on the SFC 250 operating configuration, the SFC 250 air receiver tank would noticeably begin to deplete, seen as pressure decay at the air jet ejector motive inlet. Eventually, the motive inlet pressure would fall below the 100 psig design requirement, leading to a loss in suction performance. As a consequence, it was understood that the SFC 250 settings would be required to change if long-duration and stable vacuum performance was desired or if higher vacuum performance was desired for short durations, and changing the SFC 250 air compressor settings would require scheduling arrangements at the CFRL.

The performance curve of the air jet ejector in Fig. 2.2-4 shows that the 2.0 psia suction pressure condition is expected with a suction air mass flow rate of 0.15 lb/sec. To meet this performance curve, a 100 psig motive inlet pressure is required, but it was found that this pressure could not be guaranteed at all times due to the aforementioned reasons. It must also be mentioned that during the design and construction process of the HARTF, the air jet ejector was purchased in July 2013 to be implemented in the mobile HARTF design, which would occupy a testing space in Building A of the CFRL. The length of the 4" NPS plumbing run from the SFC 250 air compressor to its proposed location in Building A was estimated to be around 100 ft. Following the construction of Building B Annex, the new pipeline from the SFC 250 to the HARTF test cell found to cover over 500 ft, and with many more fittings and the addition of a large-volume compressed air filter, some pressure loss was noticeable. Thus, it was found that to improve the performance of the air jet ejector at its current location, an updated motive nozzle design would be required. A new motive nozzle could easily be installed to replace the current design if future test applications required higher vacuum performance.

Figure 3.3-2: Experimental air jet ejector performance with high-pressure SFC 250 configuration

During the different pressure tests, the air jet ejector suction inlet pressures were monitored based on the motive inlet pressures. It was observed that for a pressure setting of 160 psig at the SFC 250—widely preferred by the majority of the test facilities at the CFRL—the pressure at the air jet ejector suction inlet would reduce to below 1.7 psia and then begin to rise for 10-20 minutes, eventually settling around 3.5 psia or above after the air jet ejector motive inlet pressure settled below 80 psig. A pressure test performed while the SFC 250 pressure setting was locked at 160 psig is shown above in Fig. 3.3-2 while the air jet ejector motive inlet pressure fell from 88 psig to 86 psig. These tests were conducted with the test facility plumbing sections closed, although some sealing problems and leakage can be expected. The suction mass flow rate was calculated with the equal percentage mass flow curves for the $C_v = 13.4$ bypass control valve. The start-up response is shown below in Fig. 3.3-3. It can be

seen that as the air jet ejector motive inlet pressure falls, the suction inlet pressures and corresponding test section pressures rise, but at much different rates. Following the opening of the motive inlet air, the motive inlet pressure may drop by 0.25 psi/min with a corresponding pressure rise of 0.005 psi/min at the suction inlet and test section. The absolute suction pressure rise can be simplified to 2% of the absolute motive inlet pressure loss. Fig. 3.3-2 shows an extended look at the motive inlet pressures, where a time of 10 minutes is required before stable motive inlet pressures are achieved.

Figure 3.3-3: Motive inlet pressure loss and suction pressure rise following start-up

Figure 3.3-4: Motive inlet pressure loss following start-up

With respect to the air jet ejector operating characteristics, a breaking or surging condition was often found, characterized by unstable suction inlet pressures as a result of the motive air stream injecting mass into the suction inlet where it accumulates and entrains back into the motive air stream. This condition was readily found when opening the motive air 4" NPS butterfly valve quickly or when offering no mass flow on the suction inlet side. This condition could also occur when quickly closing the bypass control valve, the main air supply, or the additional make-up ports on the exhaust section following their use. This breaking condition is illustrated below in Fig. 3.3-5, which shows the result of an uncorrected breaking condition following a fast opening of the motive air 4" NPS butterfly valve with no suction mass flow. In Fig. 3.3-6, a breaking condition is seen following the closing of one make-up port on the exhaust section after it had been open while the main air and bypass air lines were closed. Correction was accomplished with bypass air modulation.

Figure 3.3-5: Uncorrected breaking condition

Figure 3.3-6: Corrected breaking condition

Following the pressure tests, the performance of the air jet ejector was found to be satisfactory. It was understood that any vacuum performance shortcomings occurred as a result of the air jet ejector relocation and the scheduling conflicts with the SFC 250 air compressor. Motive nozzle replacement was proposed as an option for improving vacuum performance at the expense of suction mass flow. Breaking conditions were found during test preparation but were easily managed.

3.4 Cryogenics Testing

Following the installation of the cryogenic heat exchanger and vacuum-jacketed lines in 2015, tests were performed to evaluate the operating characteristics and the capabilities of the selected HARTF cryogenic air-chilling method. Due to the cost of utilizing LIN, including paying for the LIN product, the cylinder rental, and the delivery, the tests were performed at the operating conditions of the implemented test hardware, which required much lower air flow rates than the rated air flow rates for the heat exchanger. The operating procedure outlined below became the standard operating procedure for later tests, following the process of learning how to operate the LIN cylinders and the cryogenic heat exchanger.

3.4.1 Operating Procedure

- 1) First perform the steps outlined in *3.3.1 Operating Procedure*.
- 2) Utilize the software interface to set a zero valve position for the V-1080 LIN control valve. This setting should be default upon software initialization.
- 3) Manually modulate the small pressure regulator on the pneumatic air line connected to the DVC2000 controller on the V-1080 LIN control valve. No more than 60 psig is required.
- 4) Set a pressure of 10 psig or above for the main air pressure regulator with the software interface to establish an air flow rate through the cryogenic heat exchanger.
- 5) Set a valve position of 5% for the V-1080 LIN control valve with the software interface to help mitigate an overpressure condition when first operating the LIN cylinders.

- 6) Manually open the LIQUID valve on one of the LIN cylinders connected to the LIN manifold outside of the test cell. Open the valve very slowly until the LIN manifold safety relief releases some pressure, indicated by short bursts of nitrogen gas, and then close the valve very slowly until the bursts are eliminated. Do not fully close the valve. This procedure is necessary to prevent LIN waste and overpressure conditions.
- 7) With the software interface, monitor the LIN exhaust temperature. If it does not readily begin to fall, the LIQUID valve on the LIN cylinder is not sufficiently open. Repeat step 6. The V-1080 LIN control valve position setting may also be increased from 5%, but with a valve position of 5%, a response should be seen at the LIN exhaust thermocouple immediately.
- 8) As the LIN exhaust temperatures fall, use the software interface to establish the simulated altitude pressure condition and the highest test hardware flow condition with the bypass control valve position settings and the main air regulator pressure settings, respectively.
- 9) Observe the upstream air chamber and the LIN exhaust temperatures throughout the chilling process after the required test conditions have been established.
 - a. If the upstream air chamber temperature is higher than desired and if the LIN exhaust temperature stabilizes around -320°F, LIN is being wasted. Reduce the LIN control valve position setting to improve heat transfer efficiency.
 - b. If the upstream air chamber temperature is higher than desired and if the LIN exhaust temperature stabilizes above -100°F, LIN is being wasted. Increase the LIN control valve position setting to improve heat transfer efficiency.
- 10) Repeat step 9 until the LIN exhaust temperature stabilizes between -100°F and -320°F.

- 11) Perform testing at the highest test hardware flow condition first and then move to the lowest test hardware flow conditions to prevent over-chilling and difficult temperature cycling. The main air temperature sensed at the upstream air chamber will fall as the main air flow rate is increased and as the cold temperatures within the cryogenic heat exchanger are carried more quickly away from their source and downstream through the chilled plumbing system. If chilling to -50°F with a low flow rate and then a higher flow rate is desired during testing, the air temperature sensed at the upstream air chamber will be much colder than -50°F when introduced with the higher flow rate. The cryogenic heat exchanger must then be allowed to warm and re-chill to slowly find the desired temperature. When moving from high flow rate test conditions to low flow rate test conditions, the cryogenic heat exchanger may not require cycling, and can be provided with a steady LIN supply to accommodate all testing conditions.
- 12) If different altitude simulations are to be performed, it may be more efficient to move from the highest altitude condition to the lowest altitude condition. Within reason, the lower and warmer altitudes can be tested within a chilled test facility as it begins to warm following the shut-off of the LIN supply.

3.4.2 Test Results

The cryogenic heat exchanger was found to effectively chill the main air flow down to the desired temperature limit of -50°F with the implemented test hardware. These temperatures could be achieved at a range of different flow requirements and pressure conditions. During testing, chilling was performed at atmospheric pressures and at sub-atmospheric pressures down to 3.5 psia, and it was found that the air temperatures in the air chamber upstream of the test section could be reduced under

-75°F at tested flow rates of up to 0.10 lb/sec. One test is shown below in Fig. 3.4-1, illustrating typical air-chilling time response. Vertical lines denote changes occurring throughout the test duration, and the two different temperature measurements are plotted on separate vertical axes.

Figure 3.4-1: Time response of air temperature reduction with cryogenic heat exchanger

These results were obtained directly following the opening of the LIN cylinder LIQUID valve. The test began with atmospheric back pressure, and a main air flow rate of 0.04 lb/sec was initialized at 1.5 minutes. Although the chilling rate is non-linear, it can be seen that the temperature in the upstream

air chamber began to fall from 73°F to 21°F at an average rate of 12.4 °F/min while the LIN exhaust temperature was stable at -310°F. Following an adjustment to the LIN control valve and the LIN cylinder LIQUID valve to attempt to find a more efficient heat exchanger operating characteristic at around 6 and 10 minutes, respectively, the air jet ejector was activated at around 11 minutes and the upstream air chamber pressure was reduced to 4.0 psia. As the temperature difference between the air chamber temperature and the LIN exhaust temperature began to decrease, the cooling rate was slowed from the earlier average of 12.4 °F/min to an average of 8.1 °F/min from 8°F to -20°F. After the main air flow rate was increased to 0.08 lb/sec at 15.4 minutes, an average cooling rate of 5.0 °F/min was observed from -25°F to -50°F. While this particular test was not conducted according to the refined operating procedure detailed in *3.4.1 Operating Procedure*, it can be seen that the cryogenic heat exchanger was successful in reducing the upstream air chamber temperatures to the required temperature of -50°F with a back pressure of 4.0 psia, corresponding to an altitude above 30,000 ft. For the implemented test sector, it was found that around 15 minutes would be necessary to chill the main air plumbing sections to the low temperatures required for high-altitude relight testing.

Beyond the evaluation of the cryogenic heat exchanger to provide adequate air-chilling service for the implemented test sector, the vacuum-jacketed air line was also observed for its effectiveness at thermally-isolating the main air flow by comparing cooling rates in tests conducted prior to obtaining the vacuum-jacketed main air line. In Fig. 3.4-2, a main air flow rate of 0.10 lb/sec was implemented with a LIN exhaust temperature of -310°F. For this test, an un-insulated plumbing section connected the cryogenic heat exchanger to the upstream air chamber. It can be seen that 9.4 minutes were required to chill the air chamber from 0°F to a temperature of -50°F, compared to the 7.4 minutes required for the test conducted with the vacuum-jacketed lines Fig. 3.4-1. Additionally, -50°F was only achieved after ice had formed over the air chamber walls, which was observed at around 8.5 minutes.

Figure 3.4-2: Rapid temperature decay following chamber wall ice formation (top) and corresponding pressure rise due to frost formation in the fuel-air s*wirlers (bottom)

In additional tests, it was found that when operating with a 0.10 lb/sec main air flow rate and a 4.0 psia back pressure, 22 minutes would be required to chill the air chamber from 70°F to -50°F. With the vacuum-jacketed air lines, the time required was found to be 15 minutes when operating with a 0.04 lb/sec main air flow rate and a 4.0 psia back pressure. It is clear that the vacuum-jacketed air lines are greatly effective in thermally-isolating the main air flows, in minimizing LIN waste, and in providing a more stable chilling characteristic.

Figure 3.4-3: Frost formation in fuel-air swirler passages

It should be noted that humidity was found to affect the upstream air chamber pressure and the corresponding pressure drop across the fuel-air swirlers when chilling the main air flows to subzero temperatures. Observations were made on the fuel-air swirlers through the test section window and noticeable frost formation was found within the fuel-air swirler passages, which was understood to lead to a reduction in effective flow area. Two photographs are shown in Fig. 3.4-3. During long-duration testing with very low temperatures, this frost formation was found worsen and entirely block the primary swirler passages, restricting fuel injection. An example of the pressure rise due to this

reduction in fuel-air swirler effective flow area can be seen in Fig. 3.4-2 above. At -15°F, the air chamber pressures are seen to rise. This phenomenon became critical when performing high-altitude relight testing, and steps towards mitigation included regularly recharging and replacing the silica gel desiccant air dryer filter elements as well as the aforementioned purchase of a relative humidity sensor to be installed in the main air line upstream of the cryogenic heat exchanger.

3.5 Ignition Testing

Ignition testing was performed with the implemented test sector at an array of different testing conditions characterized by the following: atmospheric pressure and room temperature, sub-atmospheric pressure and room temperature, and high-altitude—sub-atmospheric pressure and sub-atmospheric temperature. Each of these tests were performed with the fuel-control and ignition operating procedure outlined below. During the atmospheric pressure tests, the air jet ejector was not operated, and during the room temperature tests, the cryogenic heat exchanger was not operated.

3.5.1 Operating Procedure

- 1) First perform the steps outlined in *3.3.1 Operating Procedure* and *3.4.1 Operating Procedure* as necessary to prepare the facility environment as desired.
- 2) Utilize the software interface to set a zero pressure setting for the 26-2000 Series fuel pressure regulator. This setting should be default upon software initialization.
- 3) Manually modulate the small pressure regulator on the pneumatic air line connected to the ER5000 controller on the 26-2000 Series fuel pressure regulator to 30 psig.

- 4) Manually turn on the Building B Annex de-ionized water pump.
- 5) Manually turn on the Building B Annex high-pressure Jet-A fuel pump.
- 6) Manually modulate the pressure settings of the fuel pump to set pressures higher than what will be tested during ignition testing.
- 7) Manually open the fuel shut-off valve in the test cell to pressurize the fuel circuit.
- 8) If performing testing at atmospheric pressures, turn on the test cell ventilation system. The air jet ejector will provide adequate ventilation when in use for sub-atmospheric pressure tests.
- 9) Set the fuel control circuit pressure as desired with the software interface, monitoring the fuel circuit pressure. The calculated pressure drop between the fuel circuit pressure and the test section pressure should indicate the potential fuel flow rate after the fuel atomizers are pressurized with the fuel circuit pressure. The calculated fuel-air equivalence ratio will compare this predicted fuel flow rate with the current air flow rate through the test sector. It is suggested to pressurize the fuel circuit with a pressure that will yield an equivalence ratio higher than necessary for ignition. If the pressure is lower, ignition may not be guaranteed and the combustion chamber will unnecessarily become saturated with fuel upon test failure.
- 10) After all of the facility test conditions have been set, manually turn on the ignition system.
- 11) Turn on the five-branch fuel manifold solenoid valve with the software interface. Ensure that the fuel manifold pressure rises to the fuel pressure desired. This pressure should, again, be higher than the pressure believed to be required for ignition. Ensure the updated fuel flow rate and equivalence ratio predictions are satisfactory.

- 12) Once the manifold is pressurized with fuel, close the fuel manifold solenoid valve.
- 13) Begin firing the spark igniter while turning on the fuel atomizer solenoid valves with the software interface. As the fuel manifold pressure drops to the pressure believed to be required for ignition, turn on the fuel manifold solenoid valve with the software interface. If performed correctly, the fuel manifold pressure should fall and rise through a short range of fuel pressures and ignition should occur.
- 14) If ignition does not occur during or after this sequence, turn off the fuel atomizer solenoid valve and then stop firing the spark igniter. Troubleshoot the operating test conditions. Experimentally, ignition has been found to be easier at higher fuel flow rates, thus it may be necessary to increase the fuel pressure regulator pressure setting with the software interface.
- 15) Repeat steps 12-14 until ignition is successful.
- 16) Upon successful ignition, stop firing the spark igniter and allow the test sector to combust for 20-30 seconds, or as long as desired.
- 17) To end the combustion process, turn off the fuel atomizer solenoid valves with the software interface while firing the spark igniter to help combust any residual fuel injection.
- 18) If the ignition events become more explosive, indicated by an explosion of high-speed flames moving from downstream to upstream, the combustion chamber or exhaust section may have become flooded with wasted fuel from earlier ignition failures or with unburnt fuel due to inefficient combustion at the chosen test conditions. The accumulated fuel will begin to evaporate due to the elevated temperatures from the combustion process and the low pressures encountered when operating at sub-atmospheric pressure conditions. The ignition

of these fuel vapors will lead to inaccurate combustor ignition data. Two different methods can be utilized to remove the accumulated fuel from the facility.

- a. Pause the short-duration cycling of ignition tests and allow the test sector to combust for long-duration. This will sufficiently heat the exhaust section to begin burning the accumulated fuel. The air jet ejector can also be utilized to help aid in the combustion process. If possible, raise the simulated altitude by reducing the suction pressure, bringing the exhaust section pressures closer to the Jet-A fuel vapor pressure to aid in the burn. Once completed, follow step 15 to end the combustion process. Then, manually turn on the water injection cooling nozzle shut-off valve to cool the exhaust section. Monitor the exhaust section temperatures with the software interface. Manually turn off the water injection cooling nozzle shut-off valve after the exhaust section temperatures reduce to 500°F to prevent liquid water accumulation in the exhaust section. Water boils at 126°F at 2.0 psia and 212°F at 14.7 psia. It is important to maintain a significant temperature difference to heat the water to its boiling point.
- b. If it is desired to recover and recycle the fuel accumulated in the exhaust section, the exhaust section pressure must be atmospheric. If the air jet ejector and bypass control valves are in use, they should be shut down. First, set a zero valve position setting in the software interface for the bypass control valve and then manually close the 4" NPS butterfly valve on the air line connected to the air jet ejector motive inlet. Once the pressures in the exhaust section reach atmospheric pressure, manually open the exhaust section drain shut-off valve, emptying the exhaust section contents into a container to be transported to the CFRL petroleum recycling or waste disposal locations. Close the exhaust section drain shut-off valve and then follow the necessary steps to return the facility environment back to the required test conditions.

3.5.2 Ignition Determination

To determine the instantaneous moment of ignition for low-pressure ignition testing, temperature measurements were not utilized due to sufficient lag in thermocouple response, even when inserting a thermocouple probe tip near the primary combustion zone of the top fuel-air swirler of the implemented combustor test sector. Instead, the pressure response at the air jet ejector suction and test section was monitored. It was found that the ignition event would induce a pressure pulse that would temporarily affect the air jet ejector suction performance, giving a small but noticeable pressure rise. The resulting pressure rise at the test section would then be seen within the next second and the test section temperatures would begin to rise shortly afterward. Frequently, the fuel flow rate rise would increase by 1 lb/hr per second, and by utilizing this method of ignition determination, measurements became more repeatable between ignition tests.

Two example ignition tests are shown below in Fig. 3.5-1. The vacuum pressure measurement axis is shown on the left and the total fuel flow rate axis are shown on the right. The ignition points are shown with a black cross, indicating the last measurement preceding the pressure pulse sensed at the air jet ejector suction. A very short delay is assumed to take place between the moment of ignition and the moment the pressure pulse is seen at the pressure transducers. With a data-logging rate of 5 Hz, and with each data point an average of 10 measurements taken at 50 Hz, this assumption was shown to be reliable. Between the two tests, there is 0.1% error in the total fuel flow rate at the ignition point, even with slightly different fuel ramping characteristics. The error between the absolute fuel-air swirler pressure drops is roughly 4.2%. A more robust method in the future would include synchronized timing with the exciter-igniter spark ignition system, which was regularly utilized by other test facilities at the CFRL and was never permanently installed at the HARTF.

Figure 3.5-1: Ignition determination and repeatability with instantaneous pressure rise

3.5.3 Air Mass Flow Calculation

It should be noted that in the following ignition studies, which were performed to evaluate the ignition testing capabilities of the HARTF rather than to draw an accurate ignition loop for the implemented test hardware, Eq. 3.5-1 below was utilized to calculate the air mass flow rate across all test conditions, using the effective flow area of the fuel-air swirlers previously measured—0.138 in² per swirler¹⁶. This method was utilized due to ease of use as many different orifice plates with varying bore diameters were implemented to accommodate the different test conditions. For these reasons, the orifice plate bore diameters and discharge coefficients were also not recorded during testing. In Eq. 3.5-1, location 3 and 4 refer to the upstream air chamber and test section, respectively.

$$\dot{m} = A_{\text{eff}} \sqrt{2\rho_3 \Delta P_{3-4}} \quad (3.5-1)$$

$$\dot{m} = C_D A \sqrt{k\rho_0 P_0 \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}} \quad (3.5-2)$$

For future studies, software interface modifications were proposed which would replace the air mass flow-effective flow area calculation with the more robust choked flow equation, Eq. 3.5-2—where location 0 is upstream of the main air orifice plate—and allow the user to enter orifice plate bore diameters and discharge coefficients for record. This clarification is necessary because for many of the following test conditions, the air mass flow rates calculated from the measured effective flow area were found to be greater than the flow rates calculated from the choked orifice plate equation where the bore diameters and discharge coefficients were known, especially when simulating high-altitude conditions. For reference, the effective flow area was measured at atmospheric conditions and was

found to increase with pressure drop¹⁶ and vary between the fuel-air swirlers¹⁶, leading to some inaccuracies in its utilization for this application. It can therefore be assumed that the following ignition test results are better than what might be realistic—with higher air mass flow rate calculations, the resulting fuel-air equivalence ratios are decreased, yielding better ignition performance.

3.5.4 Atmospheric Test Results

Atmospheric ignition tests were performed with an atmospheric back pressure, corresponding to a barometric pressure measurement of 14.28 psia. The main air flow was not heated or chilled, and temperature measurements throughout the test facility were steady at 80°F. The implemented combustor test sector was operated at varying pressure drops, defined as the difference between the total upstream air chamber pressure and the combustion chamber pressure, divided by total upstream air chamber pressure. When referencing a gas turbine combustor, this pressure drop can be considered equivalent to $\Delta P_{3-4}/P_3$, the difference between the total combustor inlet pressure and the total combustor outlet pressure divided by the total combustor inlet pressure. Pressure drops of 0.5%, 1.0%, 2.0%, and 4.0% were tested, with five tests performed per pressure drop. The average, minimum, and maximum equivalence ratios at ignition are shown below in Fig. 3.5-2.

As expected, with less air flow rate to aid in droplet atomization, higher fuel-air equivalence ratios are required for ignition. At a pressure drop of 0.5%, an average fuel-air equivalence ratio of 1.3 is required, compared to 0.7 at a pressure drop of 4.0%. With higher fuel flow rates, the pressure-swirl fuel atomizers were found to better atomize the fuel droplets, aiding in ignition while yielding larger amounts of fuel flow. It can also be seen that with reduced air flow rates, the ignition point can become less reliable and more inconsistent.

Figure 3.5-2: Atmospheric ignition test results

High-speed video was shot with a Vision Research, Inc. Phantom v7.3 camera during the ignition process to observe flame propagation. Selected images from the 0.5% and 4.0% pressure drop video captures are shown in Fig. 3.5-3 highlighting the different stages of flame kernel propagation to the throughout the test sector. For the atmospheric pressure, room-temperature ignition tests, all test conditions were found to result in full sector combustion. At low equivalence ratios, seen at the 4.0% pressure drop condition, predominant blue flames are seen with small yellow flamelets pulsating from the primary combustion zone to downstream. Flame kernel propagation was observed to lift from the center fuel-air swirler to the neighboring fuel-air swirler above, with full sector ignition following shortly afterward. At high equivalence ratios, seen at the 0.5% pressure drop condition, very yellow flames, indicative of fuel-rich combustion, fill the test section. Flame kernel propagation was observed to fall from the center fuel-air swirler downwards to the neighboring fuel-air swirler below, with fuel sector ignition following shortly thereafter. For all cases, full sector ignition occurred in under 1 sec.

Figure 3.5-3: High-speed atmospheric ignition test captures

3.5.5 Low-Pressure Test Results

Low-pressure ignition tests were performed with varying back pressures corresponding to the pressures at altitudes of 10,000 ft, 25,000 ft, and 31,000 ft. The main air flow was not heated or chilled, and temperature measurements throughout the test facility were steady between 75°F and 85°F.

Pressure drops of 0.5%, 1.0%, 2.0%, and 4.0% were tested, with five tests performed per pressure drop. The average equivalence ratios at ignition are shown below in Fig. 3.5-4 for each of the three altitude pressure conditions.

Figure 3.5-4: Sub-atmospheric ignition test results

Successful ignition with the sub-atmospheric pressures required much higher fuel-air ratios than the atmospheric pressure ignition tests. It can be seen that with lower back pressures, corresponding to higher altitudes, the required equivalence ratio for successful ignition increases greatly. For 0.5% pressure drop, fuel-air equivalence ratios higher than 4.5 were required for back pressures of 4.17 psia, corresponding to an altitude of 31,000 ft, but for 10.1 psia, or 10,000 ft altitude pressure, a fuel-air equivalence ratio of less than 2.0 was required. At higher pressure drop conditions, such as 4.0%, there is little variation in the ignition requirements for each altitude pressure condition. Understanding is further expanded when plotting these results with the absolute pressure drop, seen in Fig. 3.5-5.

Fuel-Air Equivalence Ratio at Sector Ignition Inlet Air Temperature: 75°F to 85°F

Figure 3.5-5 Atmospheric and sub-atmospheric ignition test results

It is clear from plotting these results with the absolute pressure drop that higher altitudes yield smaller absolute pressure drops. For example, with a back pressure of 4.17 psia, corresponding to an altitude of 31,000 ft, a 4.0% pressure drop yields only 4.81 inH₂O, less than half of the 11.7 inH₂O pressure drop available at 10,000 ft. It can be seen that the absolute pressure drops greater than 4.0 inH₂O require very similar fuel-air ratios for ignition, utilizing the higher available air momentum to assist in droplet atomization. However, for pressure drops lower than 4.0 inH₂O, the equivalence ratios necessary for ignition vary greatly between the different altitude conditions, relying more on the atomization provided by the fuel pressure in the pressure-swirl fuel atomizers. At these higher equivalence ratios, it is naturally understood that the majority of the injected fuel flow remains unburned, passing to the downstream.

To visibly observe the ignition and flame behavior of these highly fuel-rich mixtures, high-speed video was recorded of the ignition processes. Three sets of images are shown below in Fig. 3.5-6, illustrating the visible behavior of the flames at the lowest pressure drop, 0.5%, at the different back pressure conditions. It can be seen in the lower back pressure cases—5.46 and 4.17 psia—that small pockets of fine droplets ignite into flame kernels, momentarily heating their proximal environment, and propagate without a connected form. The propagation is seen to be disconnected due to the reliance on evaporation to ignite the neighboring droplets. The surfaces of the neighboring droplets are seen to slowly evaporate, mix with air, and burn with a type of pre-mixed visible flame characteristic. However, these kernels rarely burn completely in the primary combustion zone. Their complete ignition does not occur until they pass downstream. For the 5.46 psia case, flames are seen to anchor in the CTRZ, with rich burning pulsations that move downstream. For the 4.17 psia case, the flames remain lifted and never anchor, appearing and reappearing as fuel vapors become available. High amounts of injected fuel is seen to accumulate on the chamber window and walls, remaining unburned.

Figure 3.5-6: High-speed low-pressure ignition test captures

3.5.6 High-Altitude Test Results

High-altitude ignition tests were performed with varying back pressures and upstream air chamber temperatures corresponding to the pressures and temperatures of 10,000 ft, 25,000 ft, and 31,000 ft altitudes. Pressure drops of 0.5%, 1.0%, 2.0%, and 4.0% were tested, with five tests performed per pressure drop. The average, minimum, and maximum equivalence ratios at ignition are shown below in Fig. 3.5-7. These cold temperature cases are then compared in Fig. 3.5-8 with the previous low-pressure results, in Fig. 3.5-9 with absolute pressure drop, and data is listed in Table 1. It can readily be seen that when simulating the cold temperatures experienced at high altitude, ignition becomes much more difficult, and higher fuel pressures are necessary for the single-orifice pressure-swirl atomizers to generate droplet sizes small enough to obtain flame kernel propagation.

Figure 3.5-7: High-altitude ignition test results

Figure 3.5-8: High-altitude ignition test results comparison

Figure 3.5-9: High-altitude ignition test results comparison with absolute pressure drop

Fuel-Air Equivalence Ratio at Ignition					Absolute Pressure Drop				
Alt.	$\Delta P_{3-4}/P_3$				P ₄	$\Delta P_{3-4}/P_3$			
	0.5%	1.0%	2.0%	4.0%		0.5%	1.0%	2.0%	4.0%
31,000 ft	6.97	4.50	3.45	2.73	4.17	0.58	1.17	2.36	4.81
25,000 ft	4.78	3.25	1.87	1.46	5.46	0.76	1.53	3.09	6.30
10,000 ft	2.52	1.68	1.28	0.97	10.1	1.41	2.83	5.71	11.66
Ground	1.30	1.07	0.86	0.70	14.3	1.99	4.00	8.07	16.49
					psia	inH ₂ O			

Table 1: High-altitude ignition test data

When viewing these plots, the 31,000 ft altitude simulation case may stand out. Ignition is increasingly difficult, even for the 4.0% pressure drop case. Incredible fuel pressures are necessary to obtain successful ignition. It is obvious that these equivalence ratios do not adequately characterize the combustion process, because so much fuel is left unburned. These cases are characterized by lifted flames that never fully anchor in the CTRZ. Massive amounts of fuel are sent downstream into the exhaust section, or when considering a real gas turbine engine, the turbine. These large amounts of fuel are heated but may never fully ignite. Following each high-altitude test case with cryogenic air chilling, the exhaust section was found to contain liquid pools with standing flames, which were allowed to burn or to be drained before the next ignition test. The exhaust section would heat to 1,000°F or higher while the CTRZ within the test section remained cool under 500°F. When removing one of the make-up air ports on the exhaust section during the 10,000 ft and 25,000 ft altitude simulations, it was visually confirmed that long flames would attach to the downstream side of the test section exhaust flange adapter, propagating deep into the exhaust plumbing. This is to highlight the difficulty in performing high-altitude relight. Granted, these tests were performed at the worst possible conditions—where the temperature at the combustor inlet is equivalent to the temperature of the altitude environment and the back pressure is equivalent to the altitude barometric pressure. In a real relight scenario, the gas turbine engine may be substantially warmer with some small pressure addition from the compressor³⁰.

Figure 3.5-10: High-speed high-altitude ignition test captures

High-speed video was captured of the high-altitude simulations. To prevent condensate from accumulating on the outside of the test section window, a heat gun was held on the window, set at a temperature of 200°F. Due to its operation, the test section chamber wall temperature prior to ignition would be somewhat higher than the air chamber temperature. Some images from the high-speed video recordings are shown above in Fig. 3.5-10, highlighting the 0.5% pressure drop cases for 10,000 ft and 31,000 ft altitude simulations. It can be seen that even for the 10,000 ft altitude simulation case, there

are some fuel-rich lifted flames dominating the primary combustion zone. Subtle blue flames are also seen to anchor in the CTRZ. For the 31,000 ft altitude simulation case, there is no flame anchoring present, with the majority of the visible flame kernels fluttering near the downstream edge of the glass. These flame kernels preside due to the heat of the flames attached in the exhaust section.

As mentioned in *3.4 Cryogenics Testing*, frost formation became an issue when simulating high altitudes. With frost formation in the fuel-air swirler passages, effective flow area reductions would lead to rises in air chamber pressure, as the main air flow rate was fixed far upstream at the critical orifice plate. With the fixed air mass flow rate entering the air chamber, the air chamber pressure rise, and the effective area restriction, higher air velocities were found to exit the fuel-air swirlers, corresponding to an increase in the pressure drop. To counter this situation during testing, the main air flow rate was pulsed to break apart some of the frost that had accumulated. The pressure drop percentage across the fuel-air swirlers was then found following these pulsations, and the ignition tests were performed. Understandably, by testing at equivalent pressure drops but with reduced effective flow areas, the air mass flow rate yield would be lower than expected through the fuel-air swirlers. Due to these reasons, the 25,000 ft and 31,000 ft altitude ignition results may not be reliable, with even lower air mass flow rates than calculated. However, for the present study, these high-altitude ignition tests served as a proof of the HARTF testing capability and adequate for troubleshooting inherent design flaws—namely, the poor drying capability of the silica gel desiccant dryer on the main air line.

It should also be mentioned that the exciter-igniter spark ignition system was powerful and slow-firing. A weaker variable-power spark ignition system was temporarily researched and assembled, but would not be completed and installed until a later date. The aid of variable power spark ignition system would enable more realistic ignition testing capabilities¹.

Chapter 4: Conclusions

A high-altitude relight test facility was designed and constructed to aid in the research and the development of current and future industrial gas turbine engine combustor technologies, with a focus on providing comprehensive diagnostic tools to evaluate high-altitude relight performance. The facility was designed to provide back pressure vacuum generation down to 4.0 psia with a maximum mass flow of 0.32 lb/sec, as well as to provide air-chilling capabilities to cool the desired 0.32 lb/sec down to -50°F. The facility was experimentally evaluated with these goals in mind, even though the research combustor sector utilized was much smaller than the hardware design point for the facility. Pressure testing, cryogenics testing, and ignition testing were all performed with this hardware, and were successful in evaluating the respective facility performance. The HARTF was found to be a suitable testbed for simulating high-altitude conditions and for performing many different diagnostic tests on gas turbine engine combustor hardware.

It was found that the SFC 250 air compressor at the CFRL would be required to operate with a high-mass-flow configuration, rather than the high-pressure configuration preferred by other CFRL test facilities, to enable the air jet ejector to operate with its designed performance. If this configuration change is found to be difficult in the future, a new motive nozzle design can be fabricated and installed within the air jet ejector to accommodate the test requirements of the other test facilities.

Furthermore, it was found that the silica gel desiccant air dryer on the main air line was insufficient in providing reliable humidity reduction for the high-altitude simulations that required subzero air temperatures. The cryogenic air chilling performance was not found to be impacted, but frost accumulation on the fuel-air swirlers became an issue when measuring air mass flow rate and when

ensuring realistic operating conditions. While the humidity at high altitudes is understood to change with the weather, it is also understood that some moisture may precipitate out and drop to lower altitudes. To mitigate these issues, a humidity sensor was purchased to be installed on the test facility main air line at a future time to provide main air humidity measurements downstream of the silica gel desiccant air dryer. These measurements should enable research into future facility modifications to ensure sufficient drying performance. The silica gel desiccant dryer on the main air line should remain a temporary solution until better main air drying methods are found, which would then be decided upon according to budgetary constraints.

The ignition testing performed on the research combustor test sector found that a more robust mass flow measurement method would better suit the range of different operating conditions and test hardware that would be implemented in the future. Software interface modifications and calibration testing was discussed accordingly. The ignition testing also provided substantial familiarization with the test facility operation, enabling future work with more complicated diagnostic tools.

Future work was discussed to include emissions measurements that would evaluate combustion efficiency. Modifications to the research combustor test sector would see converging walls installed to mimic the geometry of industrial gas turbine engine combustion chambers. Emissions probes would be designed and installed to enable testing. Additionally, the 3-D traverse system would be implemented for PDPA measurements on low-pressure combustion sprays. This would be accomplished with the forward-scattering technique, seeing the implementation of two quartz glass panels. Finally, an engine manufacturer was contacted about the implementation of an optically-accessible multi-swirler industrial gas turbine combustor test sector. This real hardware was ultimately obtained and ongoing test plans will see its adaptation to the HARTF in the future.

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