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AFRL COMBUSTION SCIENCE BRANCH RESEARCH ACTIVITIES AND CAPABILITIES

R.D. Hancock, D.T. Shouse, F.R. Schauer, V.M. Belovich, J.R. Gord, J.S. Stutrud, J. Zelina, C.W. Frayne, R.F. Reich, J.A. Ehret, P.J. Litke, and W.M. Roquemore

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14. ABSTRACT
The Combustion Science Branch (AFRL/PRTC) of the Propulsion Directorate, Air Force Research Laboratory, is actively involved in fundamental and applied combustion research and development. In order to do this, combustion models and optical diagnostic techniques are developed and used to understand fundamental combustion processes. This understanding is then used in the development of high-performance, low-emissions combustor and propulsion concepts. The latest modeling and diagnostic innovations are applied to the various combustion experiments to enhance fundamental understanding and improve the design of the particular combustor and propulsion concepts. This paper is a top-level look at the research activities and the facilities of the Combustion Science Branch.

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AFRL Combustion Science Branch Research Activities and Capabilities

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Abstract

The Combustion Science Branch (AFRL/PRTS) of the Propulsion Directorate, Air Force Research Laboratory, is actively involved in fundamental and applied combustion research and development. In order to do this, combustion models and optical diagnostic techniques are developed and used to understand fundamental combustion processes. This understanding is then used in the development of high-performance, low-emissions combustor and propulsion concepts. The latest modeling and diagnostic innovations are applied to the various combustion experiments to enhance fundamental understanding and improve the design of the particular combustor and propulsion concepts. This paper is a top-level look at the research activities and the facilities of the Combustion Science Branch.

Introduction

The Air Force strategic vision for the 21st Century demands enabling propulsion and power solutions such as those currently under development in the Propulsion Directorate of the Air Force Research Laboratory. This strategic vision requires affordable, high-performance systems designed to ensure continued air and space superiority. Additionally, signature-reduction concerns and sensitivity to global environmental issues demand low-emissions performance of these propulsion systems. Often the very conditions that yield high performance (such as high-heat-release combustion) also contribute to the formation of undesirable engine emissions. Such challenges help define the mission of the Combustion Science Branch (AFRL/PRTS), Turbine Engine Division, Propulsion Directorate, Air Force Research Laboratory.

The Combustion Science Branch provides fundamental and applied combustion support in the development of advanced aeropropulsion systems. The performance and affordability goals driving development of air-breathing gas turbine engines are expressed in the Integrated High-Performance Turbine Engine Technology (IHPTET) program and the Versatile Affordable Advanced Turbine Engine (VAATE) program (Gahn and Morris, 2002). The IHPTET program was established in 1988 and teams the Air Force, Army, Navy, DARPA, NASA, and industry through cost-shared efforts designed to double propulsion capability by 2005. The VAATE program is focused on a 10X increase in affordability, which is basically defined as delta capability divided by delta cost, by the year 2017.

The Combustion Science Branch participates in the development of innovative combustor and propulsion concepts through efforts that include optical diagnostics development and application, simulation and modeling, fundamental studies of aviation fuel and its combustion, and the development of advanced prototypical hardware. The program structure of the Combustion Science Branch activity is illustrated in Fig. 1.

Working hand-in-hand with other Propulsion-Directorate elements and the engine manufacturers, Propulsion Directorate scientists and engineers seek to apply lessons learned from fundamental studies to the design, development, and testing of advanced combustor concepts consistent with IHPTET and VAATE visions. The Combustion Science Branch explores advanced propulsion concepts that will help to meet the goals of the IHPTET and VAATE programs. These concepts include the Trapped Vortex Combustor (TVC), Ultra-Compact Combustor (UCC), Inter-Turbine Burner (ITB), and Pulsed-Detonation Engines (PDE).

The Combustion Science Branch consists of Air Force scientists and engineers (both civil service and military) and numerous on-site contractors. PRTS has a wide variety of partners that include other DoD organizations, NASA, DoE, engine companies, universities, small businesses, and on-site contractors.

This paper briefly describes each of the major PRTS program elements shown in Fig. 1 and how they compliment one another in the development of advanced combustion and propulsion concepts. A description of four major test and evaluation facilities is also included.

Optical Diagnostics

The development and application of laser-based diagnostic techniques are integrated throughout PRTS

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programs. These techniques represent powerful tools for non-invasive flowfield visualization and quantification of fluid parameters and key species concentrations. At a fundamental level, diagnostics provide data essential to achieving a detailed understanding of the chemistry and physics of combusting flowfields. In addition, these data are essential for validating combustion models and combustor-design codes that promise to usher in a new era in propulsion-system development. At a more applied level, hardened diagnostics provide the propulsion engineer with performance data critical to the systems-engineering process. Diagnostics also promise to play an important role in fielded propulsion systems as elements in control and optimization schemes.

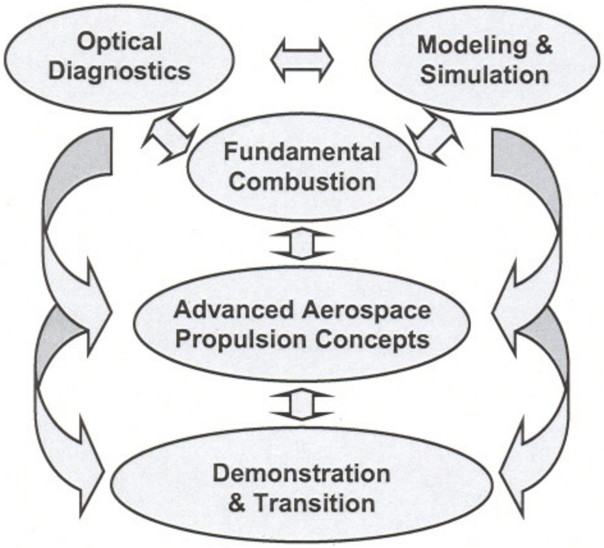

Figure 1. PRTS Program Structure

A three-phase process is used in the development and application of laser-based diagnostic techniques. In the initial phase, emphasis is placed on the diagnostic technique itself—on the chemistry and physics that define the measurement and the hardware (sources, optics, detectors, etc.) and software necessary to accomplish that measurement. During this phase, a research-grade instrument is typically employed to study a well-characterized flowfield in a laboratory environment. While this phase of the diagnostics-development is essential and exciting, the ultimate utility of a diagnostic technique is significantly limited if it is never applied beyond the laboratory phase. During the second phase, a hardened version of the research-grade instrument is applied to make measurements in an engineering facility. The emphasis in this phase shifts from the diagnostic technique to the engineering application, such as gas turbine combustor development. During the final phase of the process, a miniaturized and robust diagnostic device is incorporated into the final product, such as an actual gas turbine engine, for on-board sensing and control.

Modeling & Simulation

The purpose of the PRTS modeling and simulation (M&S) program is to develop and evaluate temporally and spatially evolving direct numerical simulations for fundamental combustion studies and combustor concept design. Many of the direct numerical simulations of fundamental flames are done using a Computational Fluid Dynamics with Chemistry (CFDC) code (Katta et al., 1994) known as UNICORN (UNsteady Ignition and COmbustion with ReactioNs). UNICORN is a time-dependent, axisymmetric mathematical model that solves the axial- and radial-momentum equations, continuity, and enthalpy- and species-conservation equations to simulate a variety of dynamic flames (Roquemore and Katta, 1998). From its conception, the development of UNICORN has been strongly coupled with fundamental experiments. This allows for the evaluation of the chemistry and transport models used in the code and improves its ability to predict complex dynamic characteristics of combusting flows.

Modeling of advanced combustor concepts is also conducted in-house using the commercially available FLUENT code, or is done by one of the engine companies using their proprietary codes. This allows for the prediction of combustor performance prior to the actual experiment and a shorter, more effective, design cycle.

Fundamental Combustion

Fundamental combustion studies are performed by PRTS to enhance the basic understanding of combustion processes important to devices like gas turbine and pulsed-detonation engines. One fundamental combustion study is described below.

A study of particular interest involves vortex-flame interactions. Turbulent flames like those found in many practical combustion devices consist of vortical structures of unburned reactants and burned products colliding with flame surfaces. Figure 2 illustrates experiments in which this very complex interaction is simplified by creating a single vortex that collides with a well-characterized flame front.

Modeling results from UNICORN predicted that with hydrogen fuel under specific conditions the flame was locally quenched, not at the location of maximum stretch, but along a ring on the sides of the vortex. The experiment was then conducted and the results predicted by the model were observed (Gord et al., 1999). Experiments like these are used to evaluate the numerical models and investigate fundamental chemistry and physics as they apply to the combustion processes that take place in advanced combustors.

Experiment Model

Figure 2. Vortex-Flame Interactions Experiment and Model Showing Local Extinction

Advanced Aerospace Propulsion Concepts

The purpose of the advanced aerospace propulsion concept portion of the PRTS program is to develop and evaluate advanced combustor and propulsion concepts for air-breathing systems. This development process is done in connection with the Components Branch (PRTC) of the Propulsion Directorate, which is ultimately responsible for combustor integration into gas turbine engines. These ideas are often pursued with the involvement of engine manufacturers through contracts. The testing and evaluation work is centered in PRTS laboratories, but the engine manufacturers are actively involved in every aspect of the program.

The Combustion Science Branch facilities enable the evaluation of combustion ideas from the bench top through combustor-sector demonstrations. Further development continues through support from other Air Force organizations and from engine company in-house research and development dollars. An example of a new in-house combustor concept called the Ultra-Compact Combustor (UCC) is shown in Fig. 3. The combustor has the potential to reduce combustor length by 50% while maintaining performance (Roquemore et al., 2001).

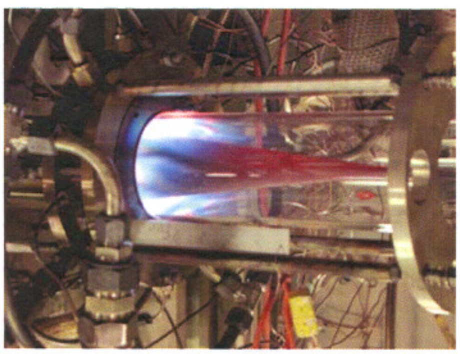

Figure 3. Ultra-Compact Combustor

Facilities

There are four major facilities/complexes that are utilized to test and evaluate fundamental and applied combustor concepts. Each facility is described below.

Combustion and Laser Diagnostics Research Complex (CLDRC)

The CLDRC is a world-class laser diagnostics complex that includes eight test cells in Buildings 490 and 5 of Wright Patterson Air Force Base (WPAFB) dedicated to the development of optical diagnostics and an understanding of fundamental combustion phenomena (Fig. 4). The optical diagnostics that are developed within the CDLRC are then intermittently applied in five additional combustor test cells on-site, or at university or contractor facilities throughout the world. A multitude of diagnostics are available including CARS, PIV, LDV, PDPA, TGS, LIF, PLIF, MHz imaging, terahertz radiation, and ultrafast-laser techniques to name a few.

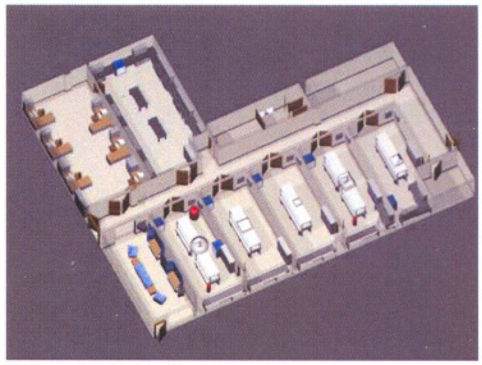

Figure 4. CLDRC Building 5 Laboratory

Atmospheric-Pressure Combustor Research Complex (APCRC)

The Atmospheric-Pressure Combustor Research Complex includes three test cells (151, 152, and 153) in Building 490 at WPAFB. They were designed for the experimental exploration of advanced combustion concepts under atmospheric-pressure conditions with elevated inlet-air temperatures. Combustor test sections of various designs can be easily installed in the facilities, and each provides generous optical access to the combustion flowfield. Test cell 151 can accept two combustors at any given time. Test sections are typically designed to contain single-cup or dual-cup combustor-dome configurations. Three separate metered, controlled, and heated air lines provide combustion air to the test article. These three lines supply dome or main air (15 lbm/min at 700°F), primary-zone air (7 lbm/min at 700°F), and secondary-zone or cooling air (7 lbm/min at 700°F). Higher air mass flowrates are achievable at temperatures below 700°F. Figure 5 is a photograph of the research facility with a swirl-stabilized combustor in place (Zelina et al., 2002).

The facility has two identical fuel systems that supply liquid fuels (e.g., JP-8, ethanol) at rates of 1.0 gpm and pressures to 400 psig. The two systems are configured to accommodate fuel staging for staged-combustor systems operating in the facility. Fuel flows are metered with coriolis flowmeters and controlled via remotely located valves. A gaseous fuel system also exists to deliver propane or methane to the test article.

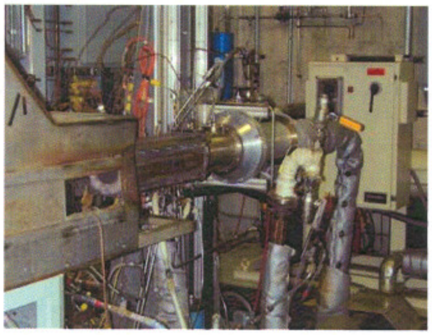

Figure 5. Atmospheric-Pressure Combustion Research Facility

The facility utilizes PC-based LabView software for data acquisition. The system is configured with 64 K-type thermocouple channels for the facility and test article, as well as Type B channels for water-cooled thermocouple rakes. Incorporated are 32 pressure channels connected to a variety of psia, psid, and psig transducers. Gas-emission samples are analyzed on-line through the LabView software using gas sampling instruments configured to measure NO_x, CO, CO_2, UHC, and O_2. Gas samples are analyzed in accordance with Aerospace Recommended Practices. Optical diagnostics are often used in this facility to investigate the various combustor concepts.

Test cell 152, shown in Fig. 6, has very similar capabilities as test cell 151 but is used primarily for the evaluation of fuel additives. A generic single-nozzle combustor is installed to provide a repeatable flame for detailed emissions sampling and optical diagnostic purposes.

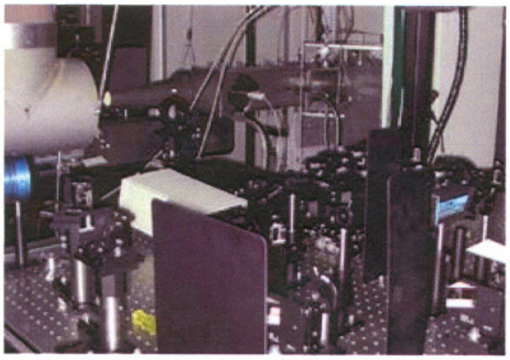

Figure 6. Test Cell 152

Test cell 153, shown in Fig. 7, is currently devoted to well-stirred reactor studies. Both liquid and gaseous fuels are used in the combustor rig, and the facility is fed by the same air supply as the other two cells in the APCRC. A unique instrument, the Particulate Matter Characterization and Monitoring System (PMCMS), is used for the determination of the particle size distribution, and the chemical characterization of the soot and gaseous emissions from the WSR.

Figure 7. Test Cell 153 Well-Stirred Reactor

High-Pressure Combustor Research Facility (HPCRF)

The High-Pressure Combustor Research Facility housed in Building 18 Room 20 at WPAFB was designed for the experimental exploration of advanced combustor concepts under conditions simulating actual gas turbine engine operation. The facility includes two flowpaths. One provides high-pressure combustion testing at pressures to 45 atm (~660 psig), while the other provides testing to 22 atm (~325 psig). The 45-atm system currently provides no optical access to the combustion flowfield. The 20-atm system, which houses a single- or dual-dome combustor sector, incorporates a rectangular test section with generous optical access provided via windows on four sides. Figure 8 shows an operating combustor and the associated optical diagnostics used to determine gas temperatures. With 2.5-inch-thick optical-grade fused-silica windows installed, the maximum test-section operating pressure is derated to 15 atm. With stainless-steel blanks installed, the full 20-atm test-section capability is achievable (Shouse et al., 2001)

The facility was designed to accommodate an optical diagnostics system that encompasses the test section. Typical diagnostics include coherent anti-Stokes Raman spectroscopy (CARS) and transient grating spectroscopy (TGS) for temperature measurements and planar laser-induced fluorescence (PLIF) for flow visualization and quantification of key combustion species. Encoded translation stages controlling the transmitting and receiving optics permit full three-dimensional spatial resolution of the test-section flowfield.

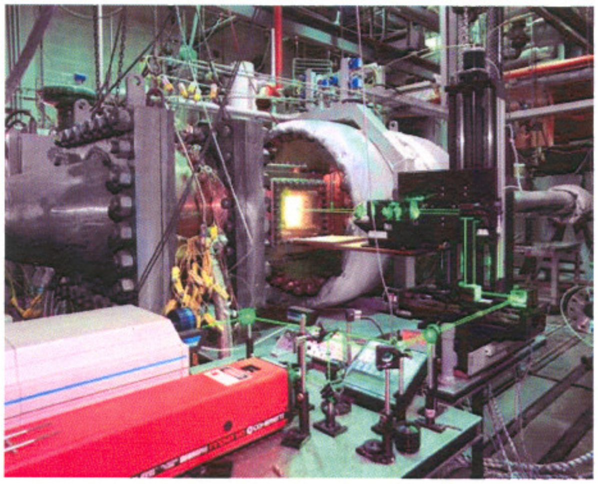

Figure 8. HPCRF Combustor Sector Test

Two Ingersoll-Rand air compressors provide air mass-flow rates of 34 lbm/s at pressures to 750 psig. Air is routed through a natural-gas-fired, non-vitiated heater that can deliver 34-lbm/s airflows to the facility at temperatures to 1100°F. Flows to the single-cup combustor system are maintained at 13 lbm/s and 1100°F, while flows to the sector-combustor system are maintained at 25 lbm/s and 1100°F. In both cases, combustor airflows are measured via a flow venturi located in the inlet piping system.

The facility is connected to four Ingersoll-Rand exhausters that can achieve sub-atmospheric pressures in the exhaust-piping header. Exhaust gases are removed from the facility at a sufficiently high rate to provide altitude-testing capability. The facility can be configured to operate at combustor-test-section pressures as low as 0.20 atm, simulating altitudes beyond 45,000 feet.

The facility requires large amounts of cooling water to quench hot exhaust gases and actively cool thermocouples and emission probes located at the exit of the combustor. Water is delivered to the combustor test section at flow rates in excess of 100 gpm and delivery pressures to 900 psig. Prior to pressurization and delivery, the water is conditioned with a reverse osmosis (RO) system. Large storage tanks hold over 12,000 gallons of pre-treated water for each test.

The facility has two identical fuel systems that supply liquid fuel to each test section at rates of 8 gpm and pressures to 2000 psig. The two systems are configured to accommodate fuel staging for staged combustor systems operating in the facility. Fuel flows are metered with turbine flowmeters.

The facility utilizes a Sun Workstation coupled to a Camac system for data acquisition. The system is configured with 108 K-type thermocouple channels for the facility and test article, as well as Type B channels for water-cooled thermocouple rakes. Incorporated are 48 pressure channels connected to a variety of psia, psid, and psig transducers. A Kulite dynamic-pressure-transducer system is employed to investigate combustor instabilities through data collected on-line with a 16-channel high-density multiplex PCM data recorder. Gas-emission samples are analyzed on-line through the Sun Workstation using Beckman instruments configured to measure NO_x, CO, CO_2, UHC, and O_2. Smoke samples are also analyzed using a Roseco Engine Analysis system. Gas samples are collected using a unique multiple line heated sampling system specially built for use with high-pressure tests. Twenty probe samples may be collected individually or simultaneously at choked flow conditions. Gas and smoke samples are analyzed in accordance with Aerospace Recommended Practices (ARP).

Pulsed Detonation Research Facility (PDRF)

D-Bay is a formerly mothballed, full-scale, sea-level/static engine test facility that has been converted to perform both full-scale and component testing of pulsed combustors and/or detonation engines. The facility is explosion proof and can measure up to 60,000 pounds of static thrust. A damped thrust stand of 10 to 1,000+ lbf average thrust capacity now sits on the static thrust stand for pulsed-detonation engine testing.

Up to 6 lbm/sec of 100 psi air is available, and the high-capacity inlet and exhaust stacks are useful for self-aspirating designs and atmospheric exhaust. A direct connection to a liquid fuel farm via a high-pressure/high-capacity fuel pump retains the facility's ability to feed large-scale 60,000 lbf thrust engines. The facility and PDE are shown in Fig. 9.

Critical flow nozzles are used to obtain choked-flow measurements of air, purge air, hydrogen, and propane. These measurements are then available for accurate measurement of the air/fuel going into a pulsed engine. These choke points isolate the measurements from the downstream pressure oscillations of pulsed valves.

In addition to conventional (low-frequency) data acquisition and control systems, the facility is equipped with up to 16 channels of high-frequency data acquisition of up to 5 MHz. These may be used for high-frequency pressure transducers, thermocouples, photodiodes, or advanced laser diagnostics. A 1 MHz framing rate digital camera is also available for advanced laser diagnostics and imaging techniques.

Due to the critical timing issues in pulsed-detonation engine operations, the high frequency valving tends to be both expensive and highly constrained. During the design of the research PDE, many options were considered that were either too expensive, had severe limitations in operating range, or both. The final design was based upon an extremely cheap, mass-produced valve system

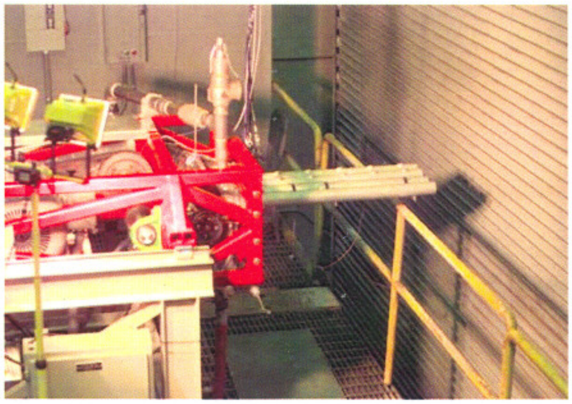

Figure 9. Innovative Applications of Technology to Test Hardware (PDE's)

that was acquired from a salvage yard. It is based upon a General Motors Quad 4, DOHC cylinder head, as commonly found in the Pontiac Grand Am automobile.

The operating conditions of PDE's are very similar to internal combustion engines, and many of the components can be shared. By driving the overhead cams with an electric motor, the four valves in each of the four cylinders can be made to operate at various frequencies. Provisions for lubrication, cooling, ignition, and fuel delivery are integral to the cylinder head/intake manifold assembly (Schauer et al., 2001).

The two intake valves in each cylinder are used to feed premixed air and fuel into detonation tubes, which are attached to an adapter plate secured by the head bolts. The exhaust valves are run in reverse with cold air used as a purge cycle to buffer hot products from igniting the next incoming charge and to convectively cool the inside of the detonation tube walls. The extra valves in this four valve per cylinder design could also be used for an axial predetonator if necessary.

Somewhat uniquely, this PDE is operated premixed, minimizing mixing and stratification issues. Up to four detonation tubes can be run 90 degrees out of phase, with various sizes ranging up to 3.5 inches in diameter. A rotary position sensor is adapted to the intake camshaft to provide both an index and relative position of the valve timing sequence. This signal serves as the master timing signal for the ignition and data acquisition systems.

The engine is used for performance validation and as a test-bed for research of detonation initiation, deflagration to detonation minimization, heat transfer, noise levels, and multi-tube interactions.

Summary and Conclusions

The Air Force Research Laboratory Propulsion Directorate is actively involved in the test and evaluation of advanced combustor concepts for gas turbine combustors and other propulsion systems. The Combustion Science Branch focuses on the importance of understanding the basic physics and chemistry associated with a particular combustor concept. PRTS has a unique blend of optical diagnostic, modeling and simulation, and fundamental combustion and fluid dynamic capabilities that dramatically strengthen its ability to participate in the design and development of advanced combustor and propulsion concepts. The goal is to develop concepts that when converted into production hardware will be affordable, provide high-performance, and produce minimal emissions. As these criteria are met, the Air Force will continue to have propulsion and power solutions to meet its propulsion requirements for the 21st century.

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