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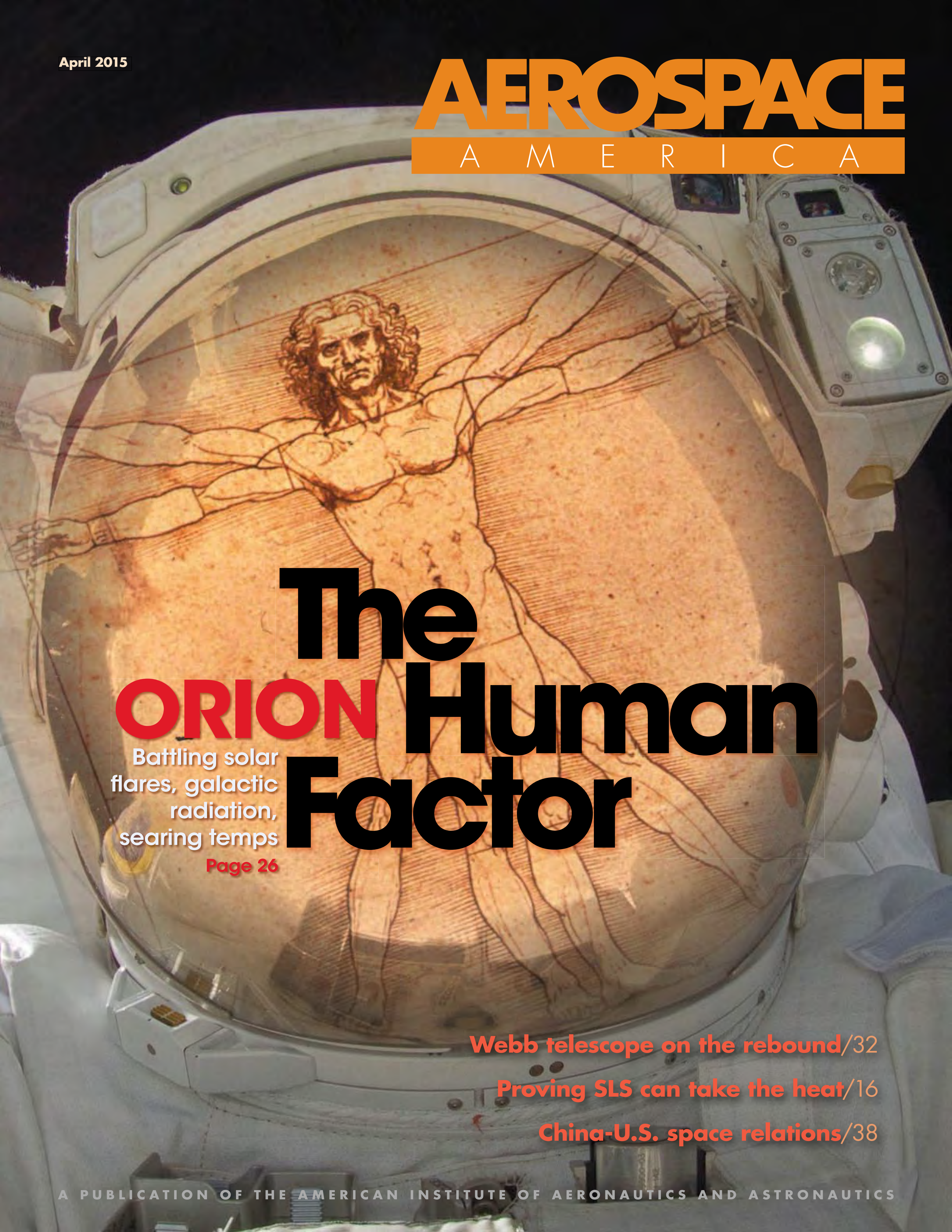

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Modeling heat off rocket engines

NASA needs to be sure the nozzles and heat shields of its new Space Launch System rockets will be able to handle the heat generated during liftoff and ascent. Henry Kenyon explains how engineers at Marshall Space Flight Center are turning to new tools and some Shuttle-era ones to measure the effects of the complicated heat flows that will envelope an SLS on every launch.

When NASA's Space Launch System heavy lift rocket roars into orbit in 2018 it will be the largest, most powerful launch vehicle ever flown by the space agency, able to haul up to 143 tons into orbit or launch an Orion crew capsule beyond low-Earth orbit. To get all this into space, the first stage of the SLS will rely on four liquid-fuel RS-25 rocket engines and two solid-fuel booster rockets, generating tremendous amounts of potentially dangerous heat around the vehicle's propulsion area.

By using a combination of scale models, sensors and analysis tools, engineers at NASA's Marshall Space Flight Center in Huntsville, Alabama, are working to ensure that the thermal protection systems in the rocket's lower, or base, area won't fail due to heat-related damage during launch and ascent.

The space agency hasn't designed a launch vehicle like the SLS since the Space Shuttle in the 1970s. Lack of in-house knowledge forced the Marshall team to relearn old techniques, such as the building of scale rocket models to test base heating. But this process also allowed the use of new tools unavailable to previous generations of engineers, such as fluid computational dynamics to model heat flows, laser spectrometry and high-speed infrared cameras to study engine plumes, and new heat-resistant materials to build the test models' engine nozzles. This suite of tools and expertise could also be applied to develop new generations of spacecraft and planetary exploration probes.

All multi-engine rockets experience base heating during launch. This combination of convection (air and hot exhaust gases) and radiation (heat from the exhaust plumes) affects the lower half of the launch vehicle. This heating is dynamic, changing in intensity and location during the various stages of ascent as atmospheric pressure drops.

Four distinct base heating phases take place during a launch, explains Mark Seaford, an engineer with Marshall's SLS Base Heating Program. The first occurs at low altitude at the start of the launch. Here, the individual rocket engine plumes are separate and air naturally flows across and down the rocket's base, cooling it. Phase two occurs at intermediate altitudes where the jet of air moving across the base competes with an updraft jet created by the interaction of multiple rocket plumes, such as those on the SLS. Base heating remains relatively low at this stage, he says.

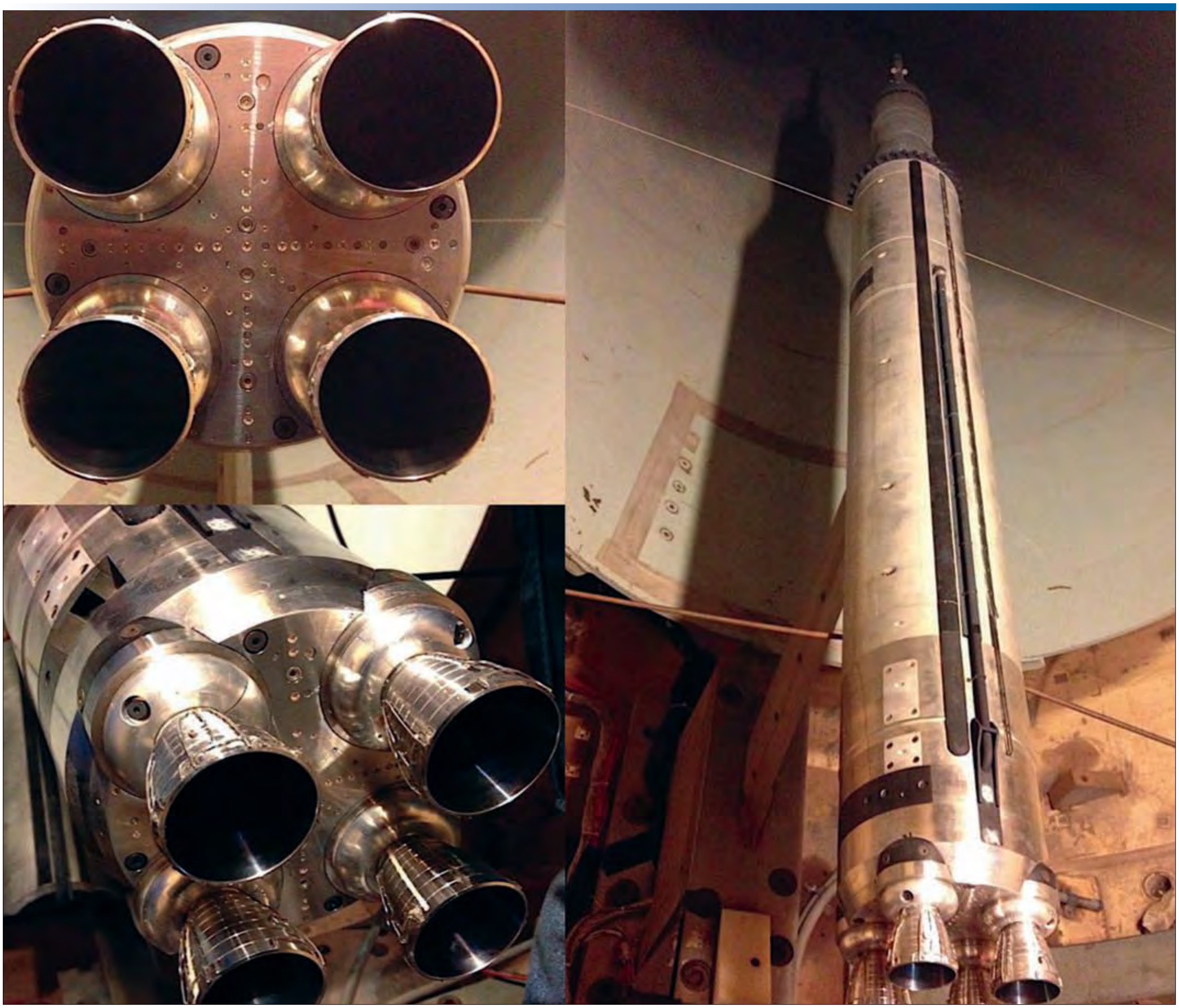
Maximum base heating takes place at high altitudes where the different rocket plumes expand and combine into a single plume because of low atmospheric pressure. The airflow over the base decreases and hot exhaust gases come into contact with the rocket's base plate, which leads to peak temperatures, Seaford says. Temperatures plateau during the fourth stage as the rocket reaches the edge of space. Here the engine plumes remain combined and hot gases recirculate around the rocket's base.

Understanding how that heat travels and ensuring that heat shielding and dissipation techniques are working properly is vital to avoid the formation of dangerous hot spots. Improper base heating mitigation led to a string of rocket explosions in the 1950s. Using scale models to test rockets for base heating also dates from this period. The first models were developed in the late 1950s to help better understand and solve heating issues for the Saturn rocket program, explains Manish Mehta, the Base Heating Program's lead engineer.

Subscale models

To test the SLS design's base heating dynamics, NASA engineers, working with CUBRC Inc. — a research, testing and systems integration company based in Buffalo — built several functional subscale test models. Manufactured to 2 percent scale, the models are 6.5 feet long with a base diameter of 6 inches without the solid rocket motors. The booster rockets add an additional 6 inches to the model's diameter, Mehta says. Instead of liquid oxygen, the model's simulated R-25 engines burn a combination of gaseous oxygen and hydrogen while the solid rocket boosters use solid fuel.

The models are tested in an 8-foot



Model rockets: NASA is using miniature Space Launch System rockets to understand the heat patterns that will be produced by the new rocket's RS-25 engines. This 6.5-foot-tall model is located at contractor CUBRC's facility in Buffalo.

NASA/Marshall Space Flight Center

diameter shock tunnel at CUBRC's LENS II facility in Buffalo. Shock tunnels simulate and model a rocket's transition from sub- to supersonic speeds. These tunnel tests are short, lasting only 50 to 150 milliseconds. The engines fire briefly to reduce the amount of heat to which the hardware (especially the engine nozzle throats) is exposed. This is because heat flux — the amount of heat transferred through a surface or material — is inversely proportional to the radius of the engine nozzle's throat, Seaford says. In a small-scale model, the heat flux is much higher than in a full-scale flight engine. Additionally, unlike a full-scale system, there is no active cooling of the nozzles, so short durations test runs prevent damage to the model.

"You can't run it very long or else you'll get a burn through," he explains.

One of the initial challenges in running such tests was that the last time they were run was for the Space Shuttle program. "It's been 40-plus years since we've designed such a propulsion system for short-duration testing and much of the corporate knowledge went away with it," Mehta says. The program's initial phase was to train its young engineers in the model testing process and develop new models.

A major hurdle was designing model engine motors that performed like full-scale engines. Seaford notes that the model engines used in the Shuttle-era tests ran at pressures that were 50 percent less than the projected engine pressure of the full-scale system. This contrasts with the SLS models that run at 80 percent of expected operational pressures. The engineering team was able to gather data in 40-millisecond windows during testing — about twice as long as the data similar Shuttle-era tests were able to collect, Seaford says.

Better diagnostic tools

The NASA team also benefits from technologies that previous base heating efforts did not have, such as advanced diagnostics tools to create sophisticated models of engine exhaust plume flow fields as they pass different Mach speeds and altitudes with varying air density, says Aaron Dufrene, technical lead at CUBRC.

Tunable diode absorption laser spectroscopy allows engineers to study the gas temperature in a rocket's exhaust plume as it interacts with the base of the vehicle. This is the first time the non-intrusive laser diagnostic system has been used in a base heating test program, Mehta says. This is critical to verifying SLS base thermal environments to properly size the rocket's thermal protection system, he adds.

Other important tools that were previously unavailable are high-speed mid- and long-wave infrared cameras to view engine exhaust plumes. Mehta notes that much of a rocket's plume cannot be seen with the naked eye during ascent. But infrared cameras provide engineers with insight into the physics of exhaust plume dynamics. The infrared cameras used by NASA are capable of capturing 10 to 20 infrared images during a multimillisecond test. Such imagery was not available in the past and offers a better means to understand base air and gas flows, according to Mehta.

The SLS base heating team also took advantage of new materials to make the model's rocket engine nozzles more heat-resistant than older test models, like those used in the Shuttle program. Some of the materials are resistant to high temperatures and resilient to thermal shock — when different parts of an object, such as a heat shield or rocket nozzle, expand at different rates.

After a brief hiatus in February, the Base Heating team plans to kick off another round of tests. So far, ascent tests have been completed, covering performance at altitudes of 70,000 to 195,000 feet. Additional tests will cover "engine out" scenarios in which an engine fails to ignite or stops during launch as well as simulating additional rocket stages.

Besides supporting the SLS efforts, Mehta notes that NASA now has an in-house capability and expertise to evaluate and model spacecraft rocket plume environments. Other applications for this process include developing future launch systems for NASA, the Defense Department or private industry; modeling more powerful versions of the SLS boosters; and developing planetary landers and studying liftoff/plume environments.

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