Infrared Imagery of Solid Rocket Exhaust Plumes

Robert P. Moran
Thermal Analysis Branch, NASA Marshall Space Flight Center
Janice D Houston
Propulsion, Thermal and Acoustics Analysis Team, Jacobs ESTS Group

ABSTRACT

The Ares I Scale Model Acoustic Test program consisted of a series of 18 solid rocket motor static firings, simulating the liftoff conditions of the Ares I five-segment Reusable Solid Rocket Motor Vehicle. Primary test objectives included acquiring acoustic and pressure data which will be used to validate analytical models for the prediction of Ares 1 liftoff acoustics and ignition overpressure environments. The test article consisted of a 5% scale Ares I vehicle and launch tower mounted on the Mobile Launch Pad. The testing also incorporated several Water Sound Suppression Systems. Infrared imagery was employed during the solid rocket testing to support the validation or improvement of analytical models, and identify corollaries between rocket plume size or shape and the accompanying measured level of noise suppression obtained by water sound suppression systems.

NOMENCLATURE

ASMAT	Ares I Scale Model Acoustic Test
CFD	Computational Fluid Dynamics
ETA	East Test Area
fps	frames per second
IOP	Ignition Overpressure
IR	Infrared
LOA	Liftoff Acoustic
MLP	Mobile Launch Pad
MSFC	Marshall Space Flight Center
RSRMV	Reusable Solid Rocket Motor V
RSRM	Reusable Solid Rocket Motor
SRM	Solid Rocket Motor
TS 116	Test Stand 116
WSSS	Water Sound Suppression Systems
ZnSe	Zinc Selenide

INTRODUCTION

The Ares I Scale Model Acoustic Test (ASMAT) program was conducted at the NASA Marshall Space Flight Center (MSFC), East Test Area (ETA), Test Stand 116 (TS 116). The ASMAT test program consisted of 18 static firings: one hot fire of only the solid rocket motor (SRM) in a horizontal configuration and the remaining 17 hot fires in a vertical configuration. The vertical configuration incorporated a test article which included a 5% scale Ares I vehicle model and launch tower mounted on the Mobile Launch Pad (MLP). Figure 1 shows the configuration of the Ares I-X launch vehicle and the ASMAT scale model. Testing simulated the Ares I five-segment Reusable Solid Rocket Motor Vehicle (RSRMV) at various elevations and drifts during liftoff.

Fig. 1 Ares 1-X on the Mobile Launch Pad (MLP) at Kennedy Space Center Launch Complex 39-B and the ASMAT 5% scale model in a lift-off condition at MSFC ETA TS 116.

Primary test objectives of ASMAT included acquiring acoustic and pressure data which will be used to validate analytical models for the prediction of Ares 1 liftoff acoustics (LOA) and ignition overpressure (IOP) environments for the launch vehicle and the ML structure. Secondary test objectives included investigating the effectiveness of the Water Sound Suppression Systems (WSSS) which includes water bags, trench water, exhaust duct water and the above deck water injectors known as rainbirds. The use of infrared (IR) cameras helped to satisfy imaging requirements of the ASMAT testing as well as support the primary test objectives. Infrared imagery support objectives consisted of 1), providing support imagery for the validation or improvement of Computational Fluid Dynamics (CFD) analytical models, and 2) Identifying corollaries between solid rocket motor exhaust plume size or shape and the accompanying level of noise suppression achieved by the water sound suppression system.

A unique capability of infrared camera systems is the ability to capture highly detailed video or still images of areas or events which are not readily visible to the naked eye. Ideally, IR cameras are used where the emissivity values are large. For example infrared imagery of some solid rocket motor exhaust plumes can reveal features such as plume structure, turbulent flow and shock diamonds. The inclusion of IR cameras during ASMAT was to acquire these type of images. However it should be noted that these details are highly dependent on the composition of the solid fuel. Some fuels such as the Space Shuttle RSRM contain Aluminum, which is highly reflective and therefore has a lower emissivity, resulting in a low transmission in the infrared wavelengths to IR thermography devices. For the ASMAT RSRM, the solid fuel composition was not an obstacle for the capturing of IR images. The infrared images in shown Figure 2 clearly illustrate shock diamonds that could not be captured in the visible wavelengths.

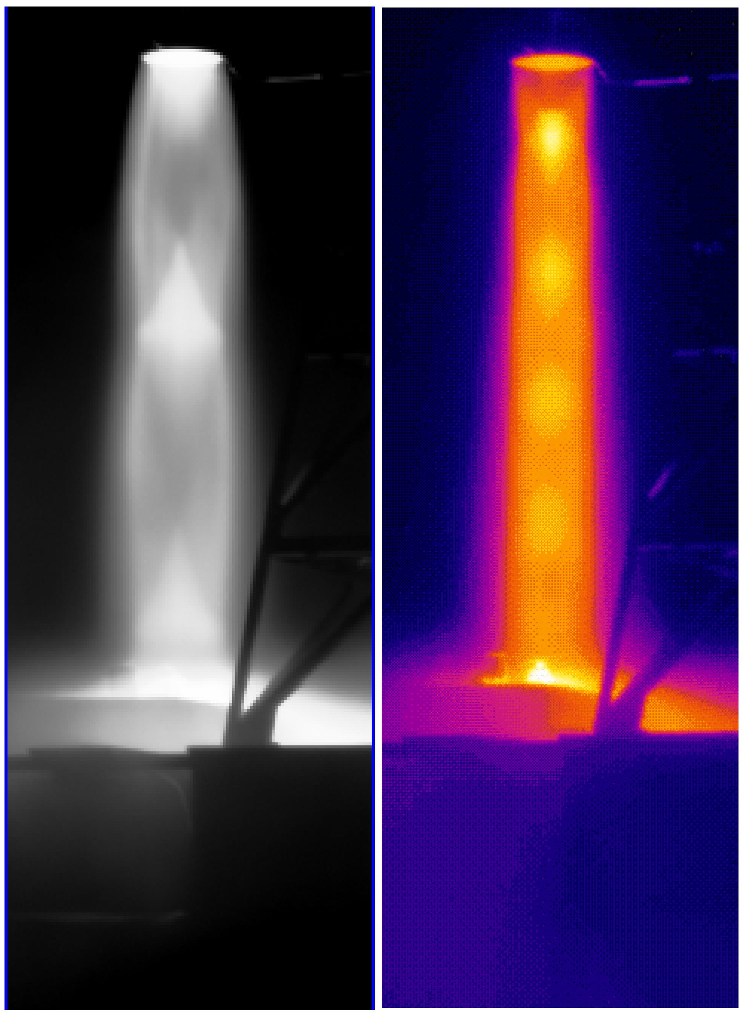


Fig 2. Infrared images (from SC655 IR Camera) taken during an ASMAT firing in the lift-off condition.

Testing of the water sound suppression system also created a challenging environment for acquiring infrared imagery data because water, water droplets, and steam serve to act as a barrier to heat transmission inhibiting the gathering of data through the wetted solid rocket engine plume. Figure 3, clearly reveals that the “No-water” infrared image offers far superior image detail when compared to the ”With-water” infrared image. The two images were taken during two separate ASMAT firings in the same liftoff condition but with different WSSS operating conditions: one test without water and the other test with water. The shock diamonds are clearly evident in the No-water image whereas the resulting steam obscures these features in the With-water image.

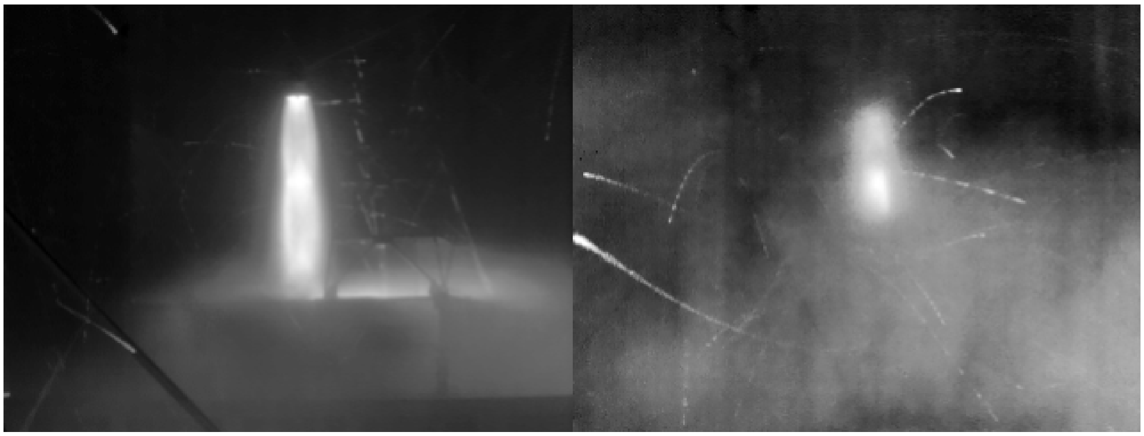


Fig 3. Comparison of ASMAT infrared images: no water versus with water in lift-off condition.

Figure 4 shows the results of a poor camera position in which the IR image captured the steam cloud produced by the interaction of the water and the ASMAT SRM plume, obscuring the plume features. Experimentation with camera position was ongoing throughout the ASMAT program in the hopes of improving results acquired during tests where the water sound suppression system was operational.

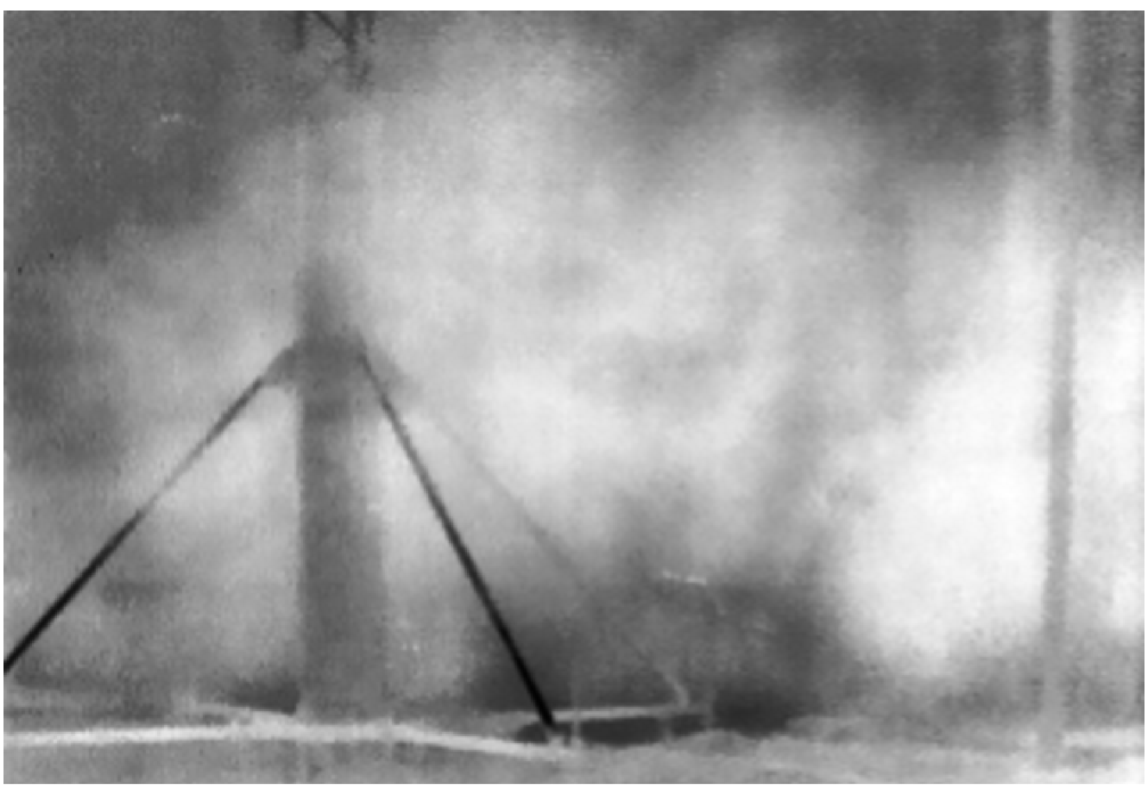


Fig 4. Obscured IR image due to steam produced by ASMAT SRM plume interacting with WSSS.

RESULTS AND DISCUSSION

Two IR cameras were typically utilized during each ASMAT firing. In particular, the FLIR T400 was used extensively during the ASMAT program. Figure 5 shows the typical setup of the FLIR T400 IR camera during an ASMAT firing. As can be seen, additional protective housing was necessary to safeguard the camera and support equipment from the harsh test environment. Sandbags were used to stabilize the camera from the ignition shockwave form the ASMAT SRM ignition. The protective housing and sandbags were used for all ASMAT IR cameras. Table 1 lists the properties of the T400 IR camera

Fig 5 Typical Infrared Camera ASMAT Test Setup. (NOTE: Zinc Selenide (ZnSe) IR window)

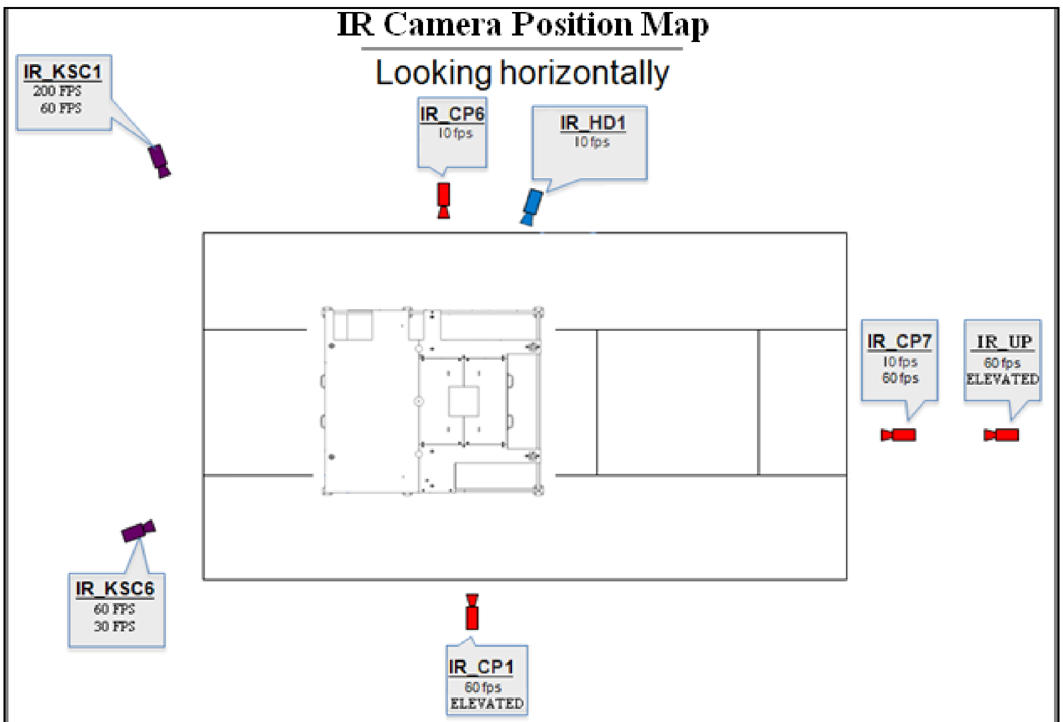
Table 1. FLIR T400 Camera Details

320x240 LW
25 deg lens
Temperature Range = 200°C to 1200°C
Recorded with ExaminIR Software
frames per second = 10
Emissivity = 0.99
Distance from heat source = 10.67 meters
Date Time = 05/19/2011 10:30 AM

Multiple IR camera types and locations were also employed throughout the ASMAT program in order to determine various cameras capabilities at capturing data in the ASMAT test environment. Table 2 provides the camera details for the various IR cameras used during the ASMAT program. Figure 6 shows the camera position map for all the IR cameras used during the ASMAT firings. Figure 7 shows the snapshot images of each of the IR camera fields of view.

Table 2. ASMAT IR Camera Details

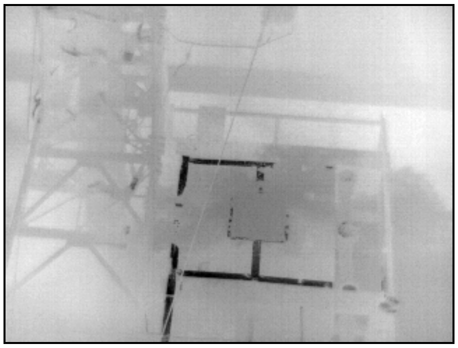
Camera	Camera No	Description
FLIR T400	C1	320X240 LW, 25 deg lens, 10 FPS
FLIR S65HS	C2	240X320, 20 deg integral lens, 60 FPS
FLIR SC3000	C3	240X320, 20 deg lens, 60 FPS
FLIR SC8000	C4	1024X1024, 100 deg lens, ND1 Filter, 60 FPS
FLIR SC640	C5	640X480, 12 deg lens, 30 FPS
FLIR SC655	C6	640X480, 55 mm lens, 200 fps



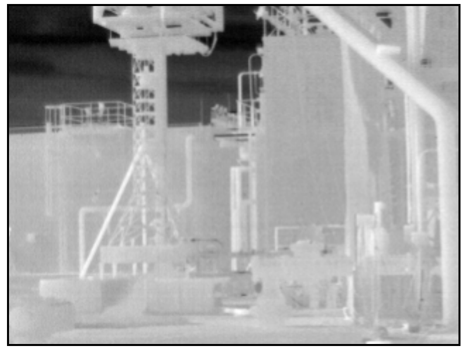
Camera No	Position
C2	IR CP1
C2, C5	IR KSC6
C3, C4, C6	IR KSC1
C1	IR CP6
C1	IR HD1
C1, C2	IR CP7
C2	IR UP

Fig 6. IR Camera Position Map and Key.

Infrared Camera position fields of View

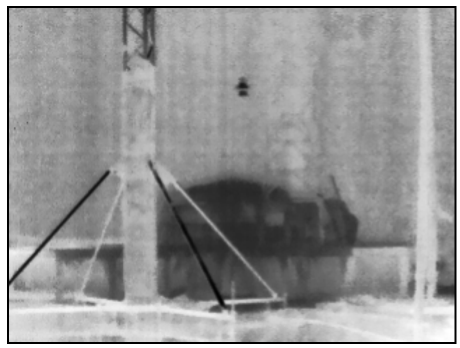


IR CP1



IR KSC6

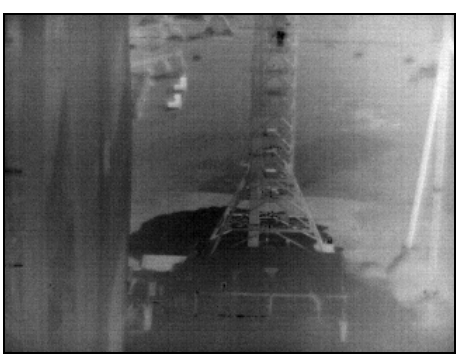
IR KSC1



IR CP6

IR HD1

IR CP7



IR UP

Fig 7. IR Snapshot View from Each ASMAT IR Camera Position.

IR Imagery Objectives

In total, 6 different IR cameras in 7 different locations where used during the ASMAT program which consisted of 18 SRM firings. Post processing of all of the IR cameras has been completed, resulting in the creation of over 80 videos and many additional still images.

Lessons learned include the need for a trigger start in order to compare the video images at the same times or equivalent frames between two tests, and the need for the identical camera in the identical position during sequential tests for proper comparison of images. For example all images addressing the secondary infrared imagery objective were obtained from the FLIR T400 infrared camera.

Secondary IR Imagery Objective

Identifying corollaries between the ASMAT SRM exhaust plume size or shape and the accompanying level of noise suppression achieved by the WSSS was difficult. Acquiring IR imagery data during the operation of the ASMAT WSSS created a challenging environment because water, water droplets, and steam serve to act as a barrier to heat transmission. Results from ASMAT 11 without WSSS compared to ASMAT 12 with WSSS are seen in Figure 8. The figure clearly reveals that the “No water” IR image offers far superior image detail when compared to the”With water” IR image. The two images were taken during two separate ASMAT firings in the same liftoff condition but different WSSS operating conditions: one test without water and the other test with water. The shock diamonds are clearly evident in the “No water” image whereas the resulting steam obscures these features in the “With water” image. The results from ASMAT 11 and 12 were determined to be inconclusive due to dissimilar camera positions for the two tests. For ASMAT 12, the IR camera was positioned along the same view angle as for ASMAT 11. However, the IR camera was moved back several feet from the test article during ASMAT 12 in the hopes of improving image capture when the WSSS was operational. It had originally been thought that it would be possible to scale the two images based on nozzle size. Unfortunately scaling the two images to equal size proved to be impossible due to the lack of fine detail obtained from the ASMAT 12 image.

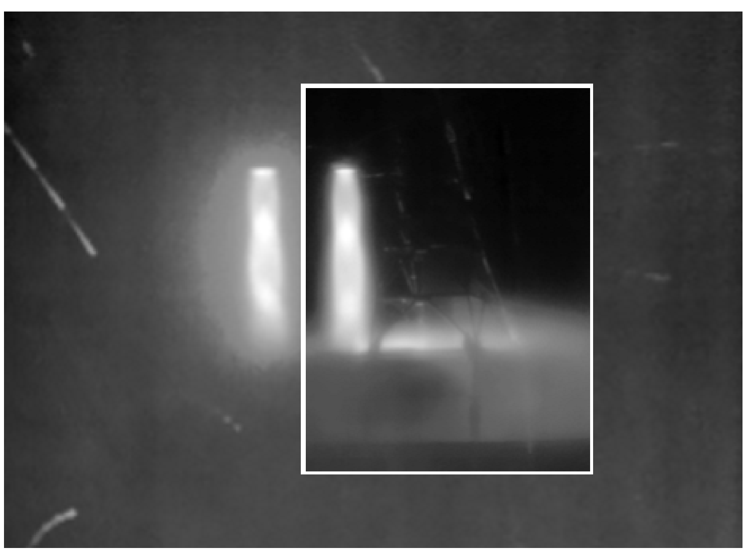


Fig 8. ASMAT 11 (without WSSS) inset into ASMAT 12 (with WSSS).

Results from ASMAT13 with WSSS as compared to ASMAT 14 without WSSS revealed no influence in exhaust plume circumferential shape as seen in Figure 9. Exhaust plume length may have been influenced. However, it is more likely that the plume lengths are similar but obscured in the ASMAT13 image because of water from the WSSS acting as a heat shield.

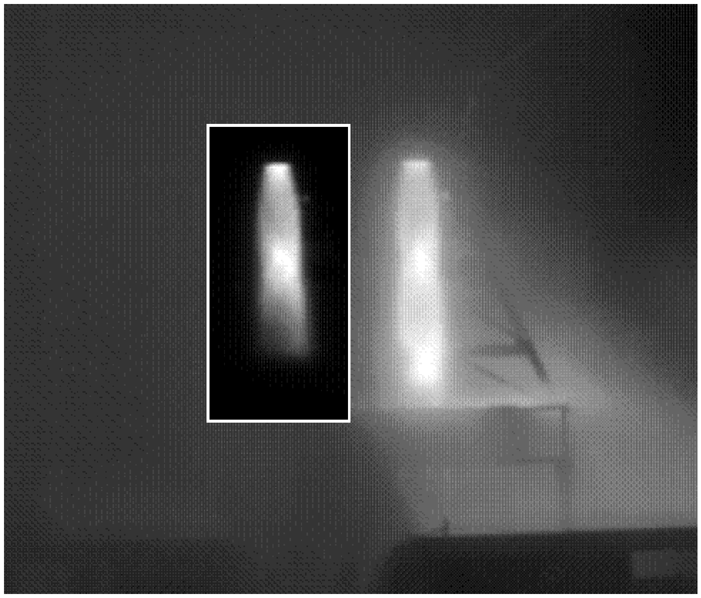


Fig 9. ASMAT 13(with WSSS) inset into ASMAT 14 (without WSSS).

Results from ASMAT 16 with WSSS as compared to ASMAT 15 without WSSS revealed no influence in exhaust plume circumferential shape as seen in Figure 10. Here again the exhaust plume length may have been influenced in ASMAT16 by the WSSS but it is more likely that the plume is obscured by water and steam.

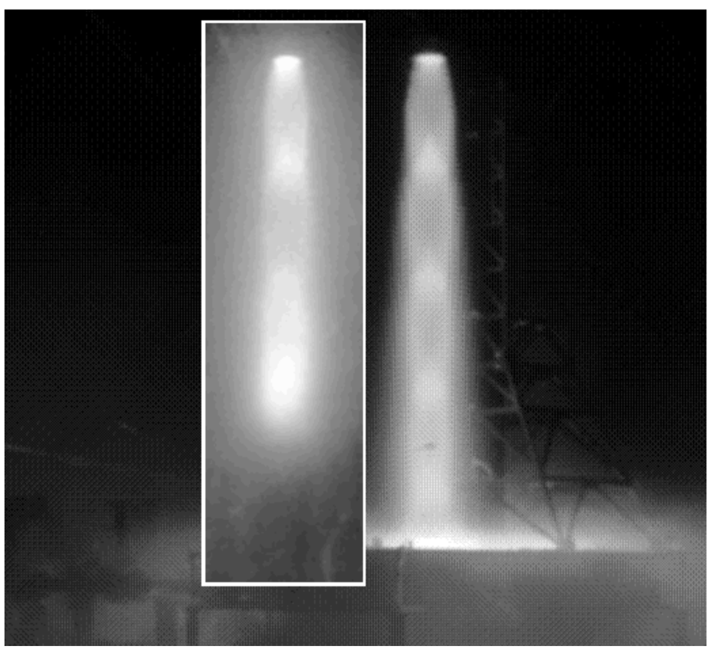


Fig 10 ASMAT 16 (with WSSS) inset into ASMAT 15 (without WSSS)

Primary Infrared Imagery Objective

Efforts to meet the primary objective of providing imagery for the validation or improvement of CFD analytical models were a resounding success. Figure 11 shows IR time lapsed images of the ASMAT SRM plume from ignition to burnout. The plume structure and Mach disks are clearly visible.

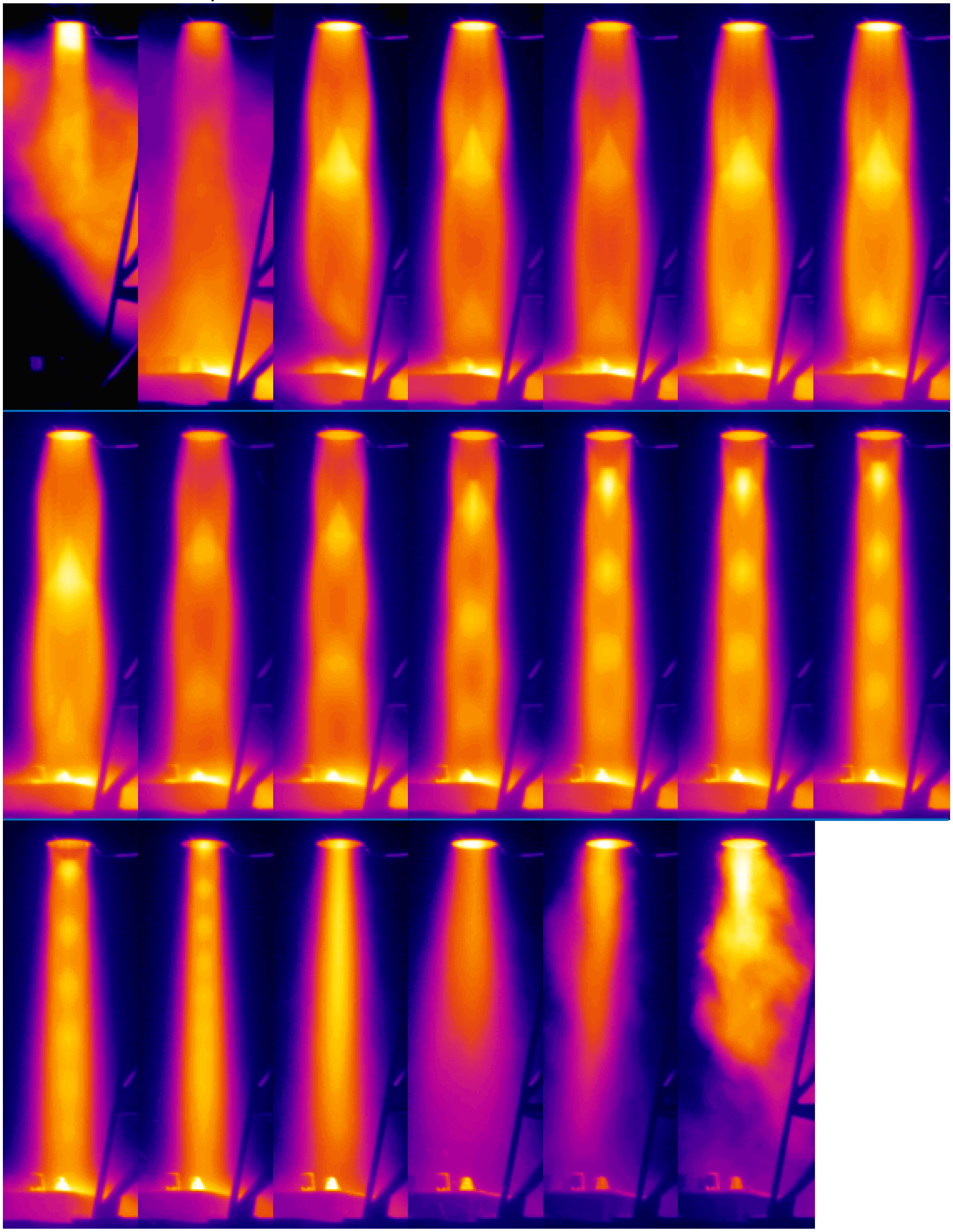


Fig 11. Spectacular IR data obtained of an ASMAT SRM plume using the FLIR SC655 Camera.

SUMMARY AND CONCLUSIONS

The use of infrared (IR) cameras during the ASMAT program was beneficial. The resulting IR images satisfied the primary objective of providing imagery for the validation or improvement of CFD models. Regarding the secondary objective, efforts to determine the effect of the WSSS on SRM exhaust plume size and shape were inconclusive because water, water droplets, and steam serve to act as a heat shield inhibiting the gathering of IR imagery data.

Robert Moran/MSFC ER43
256-544-4005
robert.p.moran@nansa.gov

Janice Houston/Jacobs ESTS Group
256-961-1419
janice.d.houston@nasa.gov

Infrared Imagery of Solid Rocket Exhaust Plumes

Background

- **The Ares I Scale Model Acoustic Test (ASMAT) program consisted of 18 solid rocket engine tests simulating the Ares I five-segment reusable solid rocket motor vehicle (RSRMV)**
  - Tests performed at the Marshall Space Flight Center (MSFC) East Test Area (ETA), Test Stand 116 (TS 116)
- **Test article consisted of a 5% scaled Ares I vehicle at various elevations during lift-off and drift from the launch tower mounted on the Mobile Launcher (ML) System**

Fig 1. Ares 1-X on the Mobile Launch Pad (MLP) at Kennedy Space Center Launch Complex 39-B and the ASMAT 5% scale model in a lift-off condition at Marshall Space Flight Center East Test Area Test Stand 116.

ASMAT Objectives

Primary ASMAT Objectives

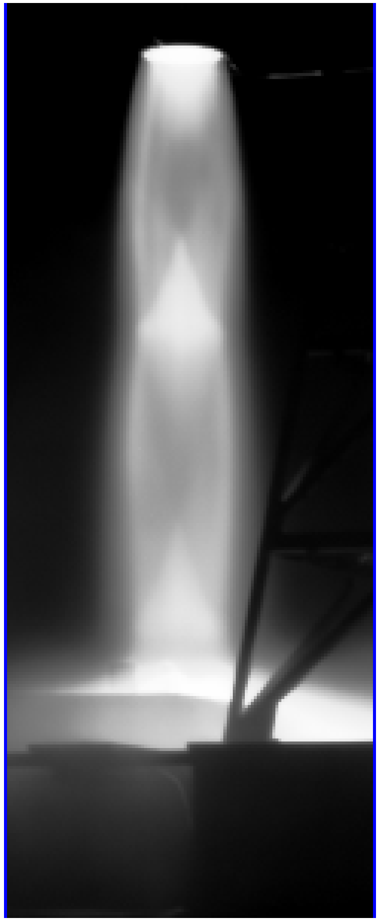
- **Acquire acoustic and pressure data for the validation or improvement of analytical models**
  - Analytical Models are used for the prediction of Vehicle, and Mobile Launcher (ML) structure Lift-Off Acoustic (LOA) and Ignition Overpressure (IOP) environments
- **Investigate the effectiveness of the water sound suppression system**
  - water bags, trench water, exhaust duct water, and above deck water injectors known as rainbirds

Infrared Imagery Support Objectives

- **Provide support data for the validation or improvement of analytical models**
- **Identify corollaries between solid rocket motor exhaust plume size or shape and the accompanying level of noise suppression achieved by the water sound suppression system**
  - Typically two infrared cameras were employed during each ASMAT test
    - 6 different camera models were utilized throughout testing in 7 different locations
  - 80 movies and additional still images were produced during post processing
  - Videos and still images have been provided to the client (MSFC ER42 Fluid Dynamics Branch)

Infrared Camera Capability

Infrared camera systems are uniquely capable of capturing highly detailed video or still images of areas or events which are not readily visible to the naked eye



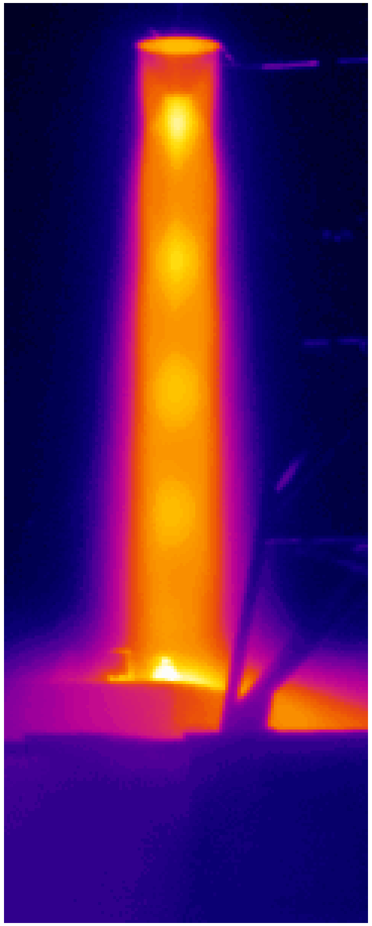
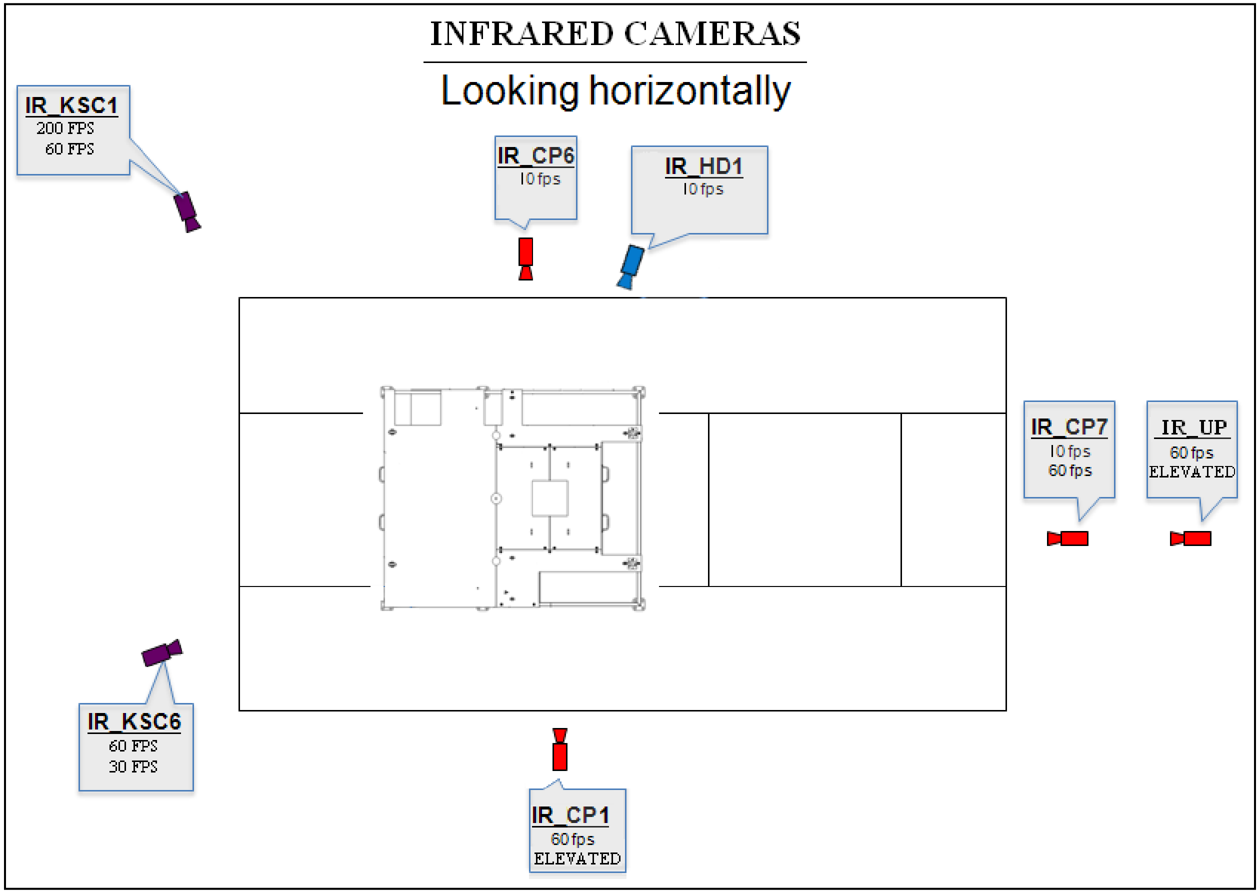


Fig 2. Infrared images (from SC655 IR Camera) taken during an ASMAT firing in the lift-off condition.

Infrared Camera Position Map

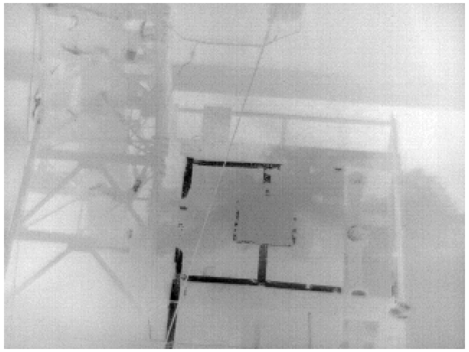


Camera	Camera No	Description
FLIR T400	C1	320X240 LW, 25 deg lens, 10 FPS
FLIR S65HS	C2	240X320, 20 deg integral lens, 60 FPS
FLIR SC3000	C3	240X320, 20 deg lens, 60 FPS
FLIR SC8000	C4	1024X1024, 100 deg lens, ND1 Filter, 60 FPS
FLIR SC640	C5	640X480, 12 deg lens, 30 FPS
FLIR SC655	C6	640X480, 55 mm lens, 200 fps

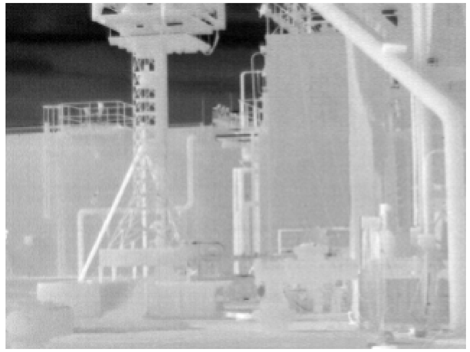
Key

Camera No	Position
C2	IR CP1
C2, C5	IR KSC6
C3, C4, C6	IR KSC1
C1	IR CP6
C1	IR HD1
C1, C2	IR CP7
C2	IR UP

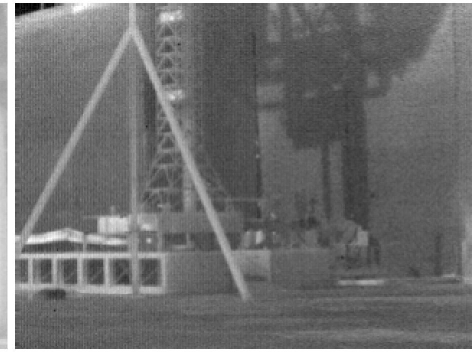
Position View



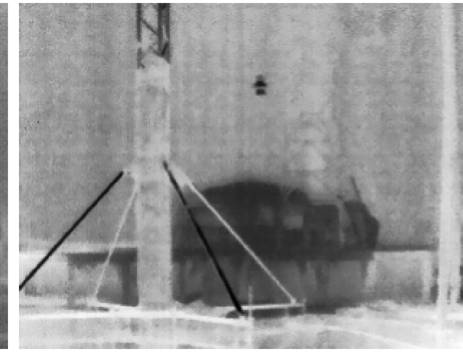
IR CP1



IR KSC6



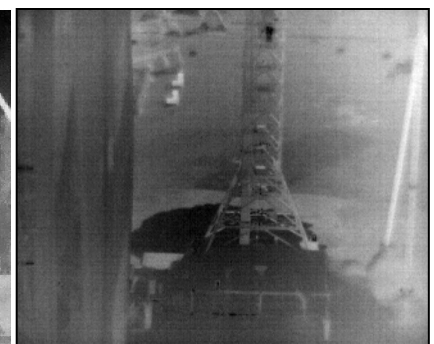
IR KSC1



CP6

IR HD1

IR CP7



IR UP

Fig 3. Image view from each infrared camera position outlined by the Camera Position Map (previous slide)

Camera Parameters and Protective Housing

Flir T400 Camera Settings

320x240 LW
25 deg lens
Temperature Range = 200˚ C to 1200˚ C
Recorded with ExaminIR
frames per second = 10
Emissivity = 0.99
Distance from heat source = 10.67 M
Date Time = 05/19/2011 10:30 AM

Fig 4. Typical camera setup

Challenges

- **Ares scale model testing incorporated several water sound suppression systems**
  - water bags, trench water, exhaust duct water, and above deck water injectors known as rainbirds
  - Operation was dependent upon the test case
- **Water sound suppression system created a challenging environment for acquiring infrared imagery data**
  - Water, water droplets, and steam serve to act as a heat shield inhibiting the gathering of data through the wetted solid rocket motor exhaust plume.
  - Difficult to identify good camera positions
    - Needed trigger start in order to compare images at like instances between two tests
    - Needed identical camera in identical position for close comparison of images obtained during differing tests

Fig 5. Deleterious effect of wetted exhaust plume on infrared image gathering taken during ASMAT 12

ASMAT 11 vs ASMAT 12

<u>Secondary Infrared Imagery Objective</u>

Identify corollaries between solid rocket motor exhaust plume size or shape and the accompanying level of noise suppression achieved by the water sound suppression system

- **Results from ASMAT 11 with water sound suppression system off compared to ASMAT 12 with water sound suppression system on were inconclusive**
  - Position of camera was different for ASMAT 11 versus ASMAT 12
  - Scaling the two images to equal size proved to be impossible due to the lack of fine detail obtained from the ASMAT 12 imagery

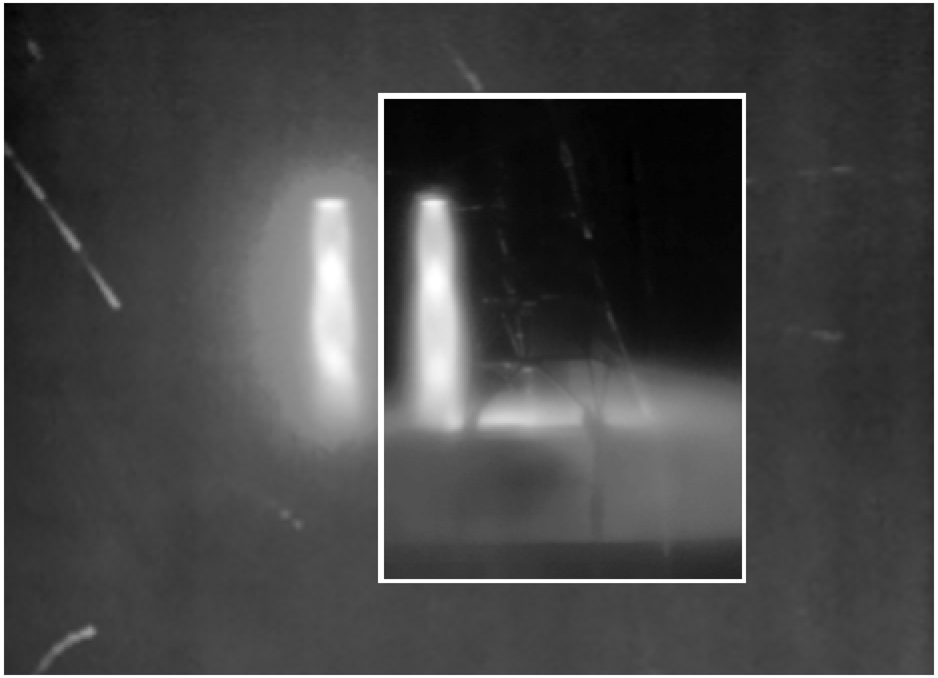


Fig 6. ASMAT 11 (No water) inset into ASMAT 12 (with water)

ASMAT 13 vs ASMAT 14

- **Results from ASMAT 13 with water sound suppression system (WSSS) on compared to ASMAT 14 with WSSS off revealed no influence in exhaust plume circumferential shape, exhaust plume length may have been influenced but it was more likely because of a water heat shield**
  - Position of camera was identical for ASMAT 13 versus ASMAT 14
  - Improved plume detail was obtained from the ASMAT 13 imagery

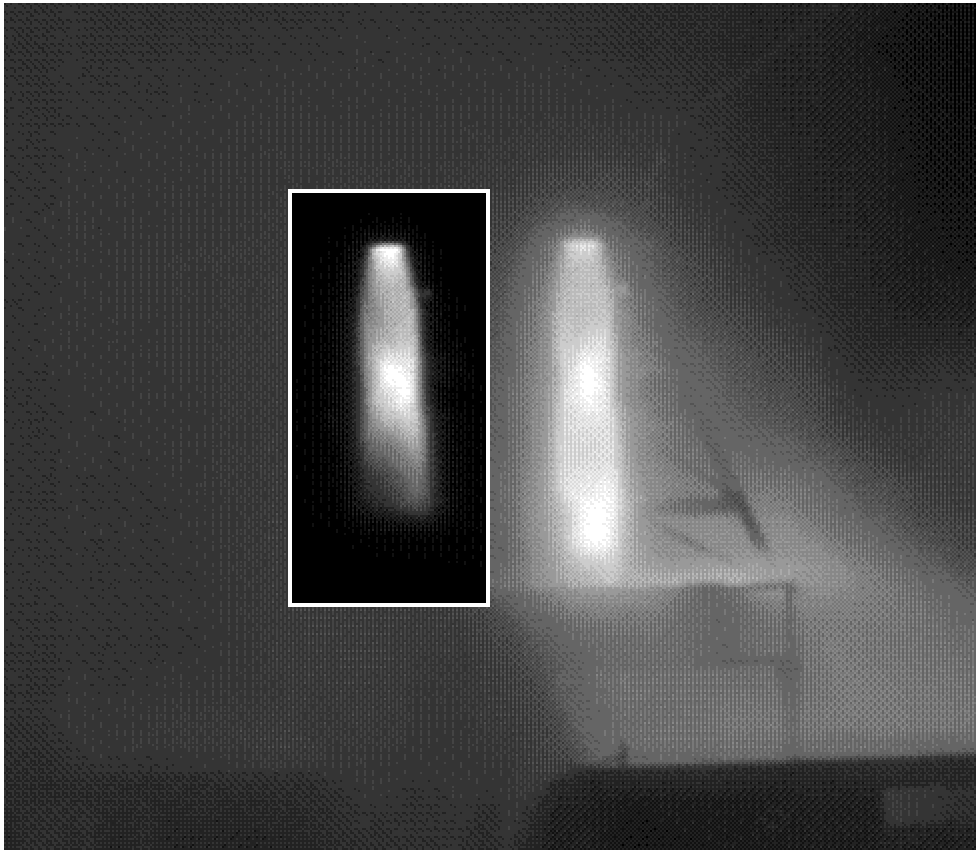


Fig 7. ASMAT 13 (With water) inset into ASMAT 14 (No water)

ASMAT 15 vs ASMAT 16

- **Results from ASMAT 16 with water sound suppression system (WSSS) on compared to ASMAT 15 with WSSS off revealed no influence in exhaust plume circumferential shape, exhaust plume length may have been influenced but it was more likely because of a water heat shield**
  - Position of camera was identical for ASMAT 15 versus ASMAT 16
  - Improved plume detail was obtained from the ASMAT 16 imagery

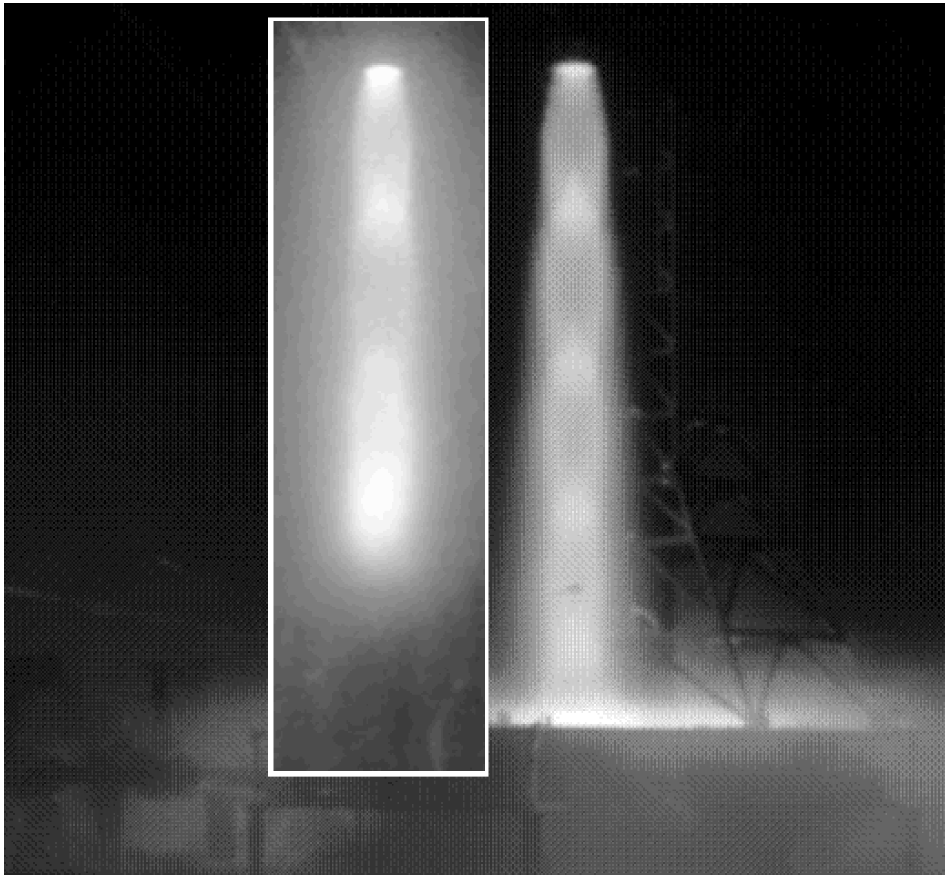


Fig 8. ASMAT 16 (With water) inset into ASMAT 15 (No water)

Detailed Images

Primary Infrared Imagery Objective

- **Provide support data for the validation or improvement of analytical models**

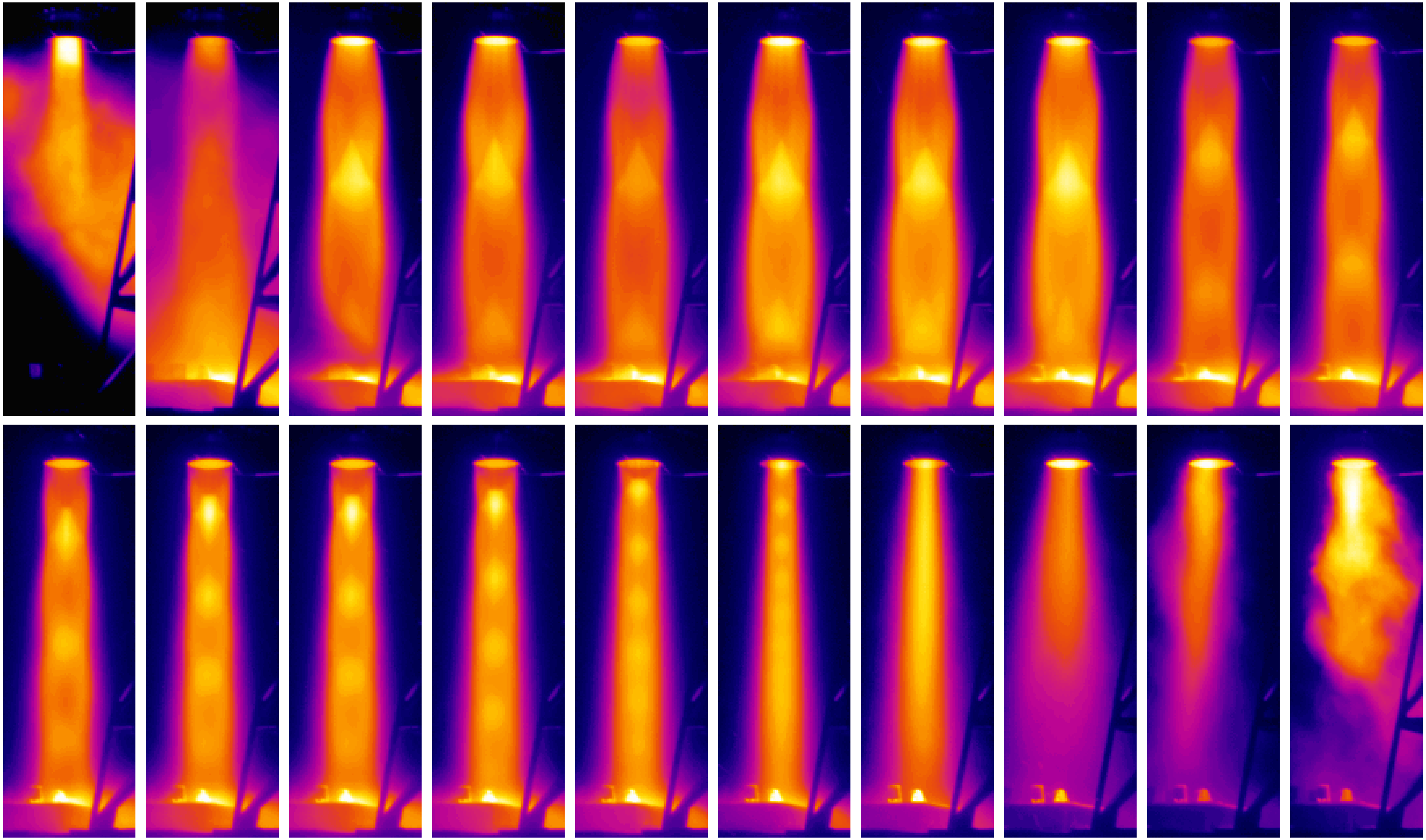


Fig 9. ASMAT 7 SC655 Camera

Conclusion

- Satisfied primary objective of providing imagery for the validation or improvement of Computational Fluid Dynamics models.
- Secondary objective determining the effect of the Water Sound Suppression System on solid rocket motor exhaust plume size and shape were inconclusive