Challenges of Cold Conditioning and Static Testing the Ares Demonstration Motor (DM-2)

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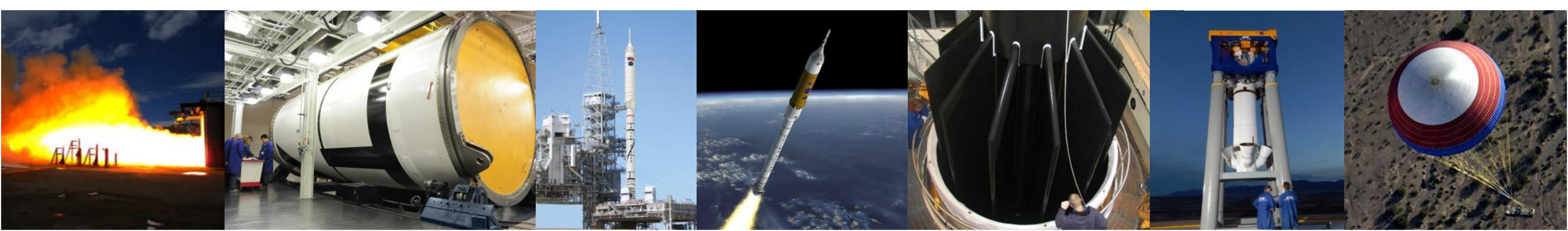
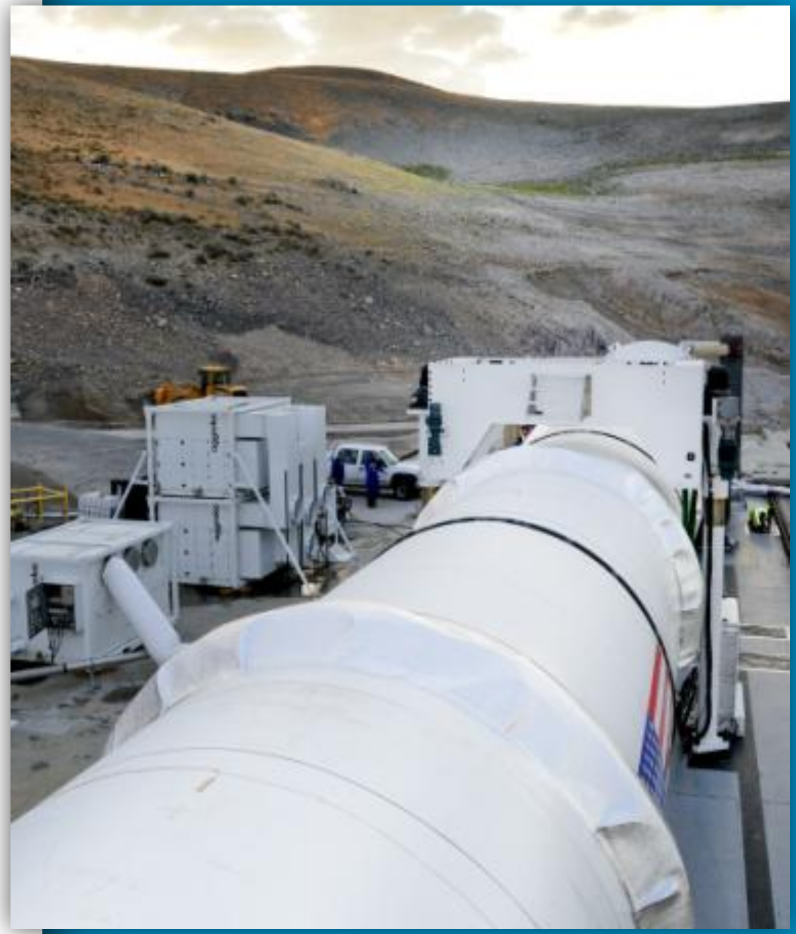


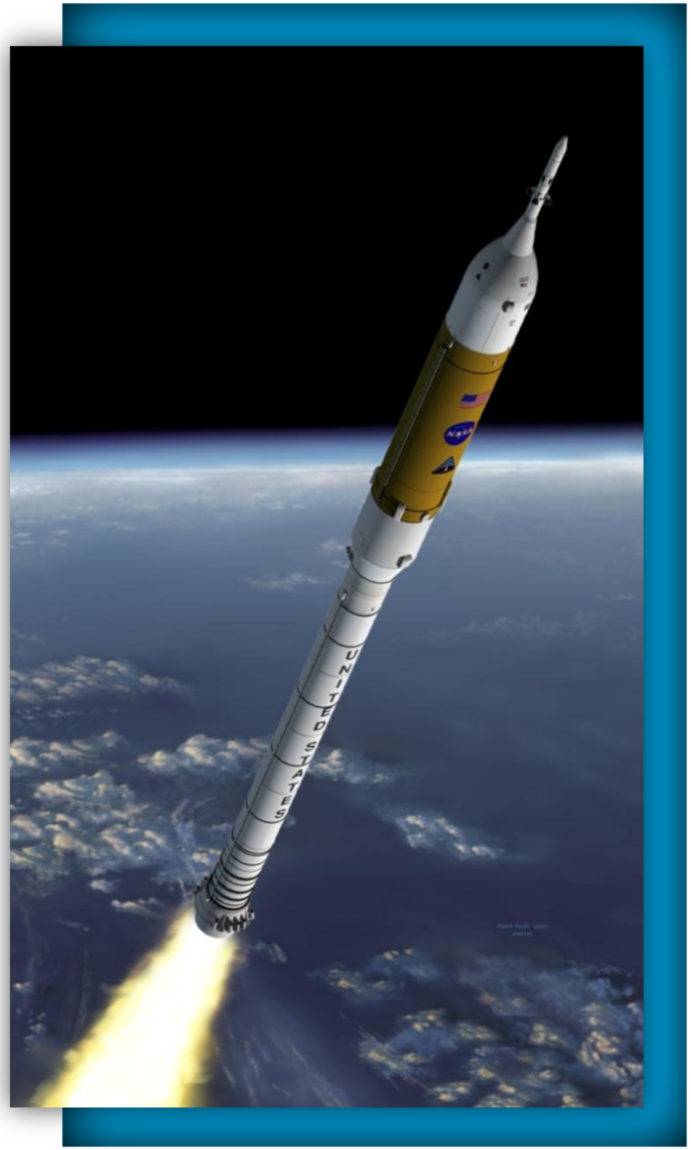
Introduction

- The Ares first stage rocket is a "human-rated" motor capable of producing and sustaining 3.5 million pounds of thrust throughout it's two-minute burn period
- A series of demonstration motors (DM) will be tested in different conditioned environments to confirm they meet all design specifications
- The second demonstration motor (DM-2) was designated to be a "cold motor", this means the internal propellant mean bulk temperature (PMBT)
  was 40 +5\-3 °F
  - The motor was subjected to subfreezing temperatures for two months
- All design requirements and program goals were specific to DM-2



Objectives

- PMBT needed to be 40 +5/-3 °F
  - Needed an accurate predictive model to assess the temperature and time required to achieve the desired PMBT
  - Conditioning equipment needed to be able to provide continuous airflow for at least two months
  - Temperature needed to be modulated to accommodate conditioning needs
- Thrust vector control system needed to stay warm during conditioning
- O-rings needed to be 32 to 38 °F at time of test
  - Joint shrouds were required to externally cool field joints after building roll back
- Over 764 channels of instrumentation needed to be installed to support DM-2



T-97 Modifications

- The motor was assembled and conditioned in a removable test bay
  - The bay is 205 ft by 32 ft by 31 ft with three sections: forward, center, and aft
- New air inlet and return ports and larger ducting was installed to support conditioning for the aft section
- The fresh air supply was rerouted away from the return supply
- Port adapters were installed over all inlet and outlet air supply ports
  - The adapters were heavily insulated to prevent temperature loss and ice buildup

Multiple points of leakage

- Aft pits: There are two 25 ft by 14 ft by 10 ft underground rooms located directly beneath the aft end of the motor. The pits house the aft thrust stand and cabling hookups for the instrumentation tunnels
  - These pits provided a direct path for cold air to flow down out of the bay and into a large array of tunnels
  - Doors were installed for each room, thick insulation cork was used to plug any leakage points
  - Two layers of thermal insulative blankets were laid over the grating of T-97 block air flow

T-97 Modifications (cont)

- The forward thrust block is a large cement block used in conjunction with the steel thrust stand and acts as the primary flight restraint for the motor
  - Large gaps exist around the thrust block to allow the building to be rolled back and cameras to be installed
  - Several thermal cement blankets were used to block gaps between the block and the bay
- The inflatable rubber seal was replaced and gaps in the corners filled with insulation
- During conditioning access was restricted to one access door
- A wireless monitoring system was installed
  - Multiple sensors were installed throughout the bay allowing real-time assessment of the bay throughout conditioning
    - Sensors were installed on both the north and south side of all three sections and positioned to be in line with the top, center, and bottom of the motor
    - Other sensors were installed in each section inlet vent to monitor the source temperature entering the building

T-97 Modifications (cont)

- All the conditioning ports are located on the north side of the bay. Most of the inlet vents are located above the top of the motor
  - Stratification was a major concern and has been an issue in past conditioning efforts
- To mitigate some of the stratification issues, the existing fans above the motor were activated during conditioning to circulate the air around the bay
  - This significantly reduced stratification

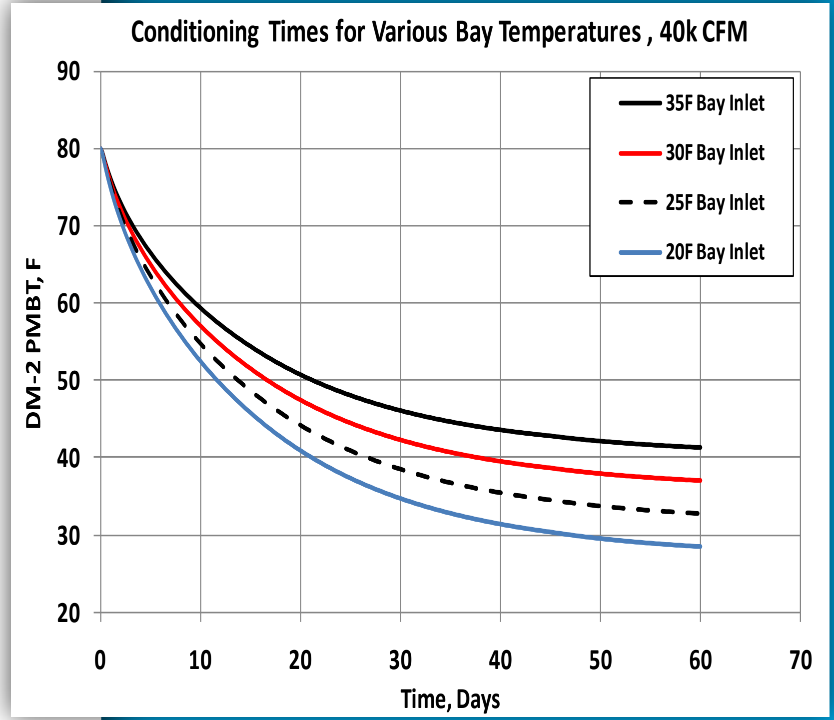
Thermal Analytical Model

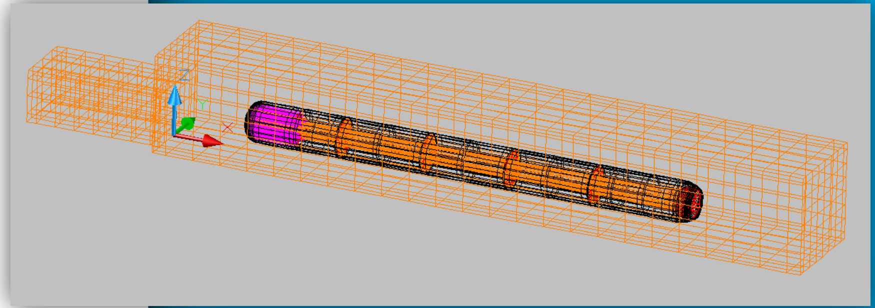
Predictive thermal analysis model

- Older models did not account for all variables and thus were not highly accurate in predicting conditioning needs and timelines
- A new 3-D thermal analytical model was designed to incorporate the major heat sinks including five-segment motor characteristics:
    - 155 ft long and 12 ft in diameter
    - Over 1.3 million pounds of solid propellant and over 130,000 pounds of insulation and steel case
    - Forward cement thrust block and steel thrust stand
    - Center support stand, aft thrust stand, and side load fixture
    - Assumed a constant 10 ft depth of cement for locations where it actually varied from 5 to 20 ft
  - It incorporated the average solar radiation and radiation heat exchange from the surrounding terrain for the months of July and August
  - The model approximated the building's insulation factor to be R40

Thermal Analytical Model (cont)

- Model assumed constant air flow of 40,000 cfm into the building
- The model looked at four different temperatures between 20 to 35 °F
  - However, for case temperature restriction the 30 and 35 °F temperatures were most weighted
- The model predicted that the conditioning temperature needed to be at least 30 °F for 45 to 60 days to achieve the PMBT goal (conservative estimate)
- The model was used to predict the warming of the motor during door up, building off activities; it underestimated the heating of the motor





Conditioning Equipment

Aggreko was contracted to provide heavy-duty conditioning equipment for this test

- The equipment needed to provide continuous subfreezing temperatures to the building for a minimum of two months
- The equipment needed to provide at least 20 °F inlet air to the building
- The equipment needed to modulate temperatures and air flow speeds to the building
- Air must be filtered to prevent contamination of the motor and the conditioning fluid used should be environmentally friendly

Conditioning Equipment (cont)

Equipment set-up consisted of:

- Two 200-ton chillers filled with a 50% propylene glycol solution called “brine”
  - Capable of cooling the brine solution to -10 °F; however, the colder the temperature the less capacity. For this conditioning effort, the capacity of an individual chiller was approximately 85 tons
- Two 1,000-gpm pumps
- Two 500-kW diesel generators
  - Primary purpose was to provide power for the chillers; however, cabling was pre-routed to allow all the equipment to run off the generators
- 2,300-gal double-walled fuel tank

Conditioning Equipment (cont)

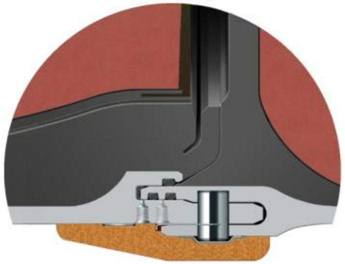
- Six 120-ton air handler units (AHU) provided the main conditioning to the building
  - Set up in a double-stack configuration, which was key to providing continuous air flow into the building
  - The AHUs pulled air out of the building and blew it over coils containing the chilled brine solution then blew the conditioned air back into the building
  - Because of moisture in the air and the temperature differences, ice would build up on the coils. As ice built up, the air flow and conditioning was impeded. The double-stack allowed one handler to run in defrost mode while the other was running
- A seventh AHU was combined with a 5,000-cfm dehumidifier and 20-ton air conditioner to provide fresh air into the building

Thrust Vector Control

- Internal components within the nozzle that are responsible for vectoring needed to be kept at 64 to 94 °F during conditioning
- A nozzle skirt was installed to close off and insulate the nozzle cavity. A separate conditioning cart was used to blow in heated air
  - The conditioning cart had to run at full capacity at approximately 170 °F at its source, but was barely maintaining the minimum acceptance range. This was mainly due to leakage through the skirt
  - Aluminum foil bubble wrap was added to the skirt to act as an air block and provide additional insulation. This allowed main conditioning to achieve lower temperatures

Joint Conditioning

- To verify sealing surface capabilities at extreme low temperatures and eliminate the need for joint heaters, the O-rings needed to be between 32 and 38 °F at the time of static test
  - Newly designed conditioning shrouds were used to externally cool each of the four field joints after the test bay building was rolled back Shrouds were designed to be easily installed and not damage the motor during test. The temperature and air speed could also be controlled for each joint
  - Even though the O-rings needed to be freezing, the J-leg feature and insulation inboard were not supposed to get below 35 °F
  - Conditioning had to be turned off one hour prior to static test to prevent any negative influence of the measurement data
  - It was determined by thermal analysis that even with active conditioning, the heat from the sun would warm the joints beyond an acceptable range after 10 a.m.

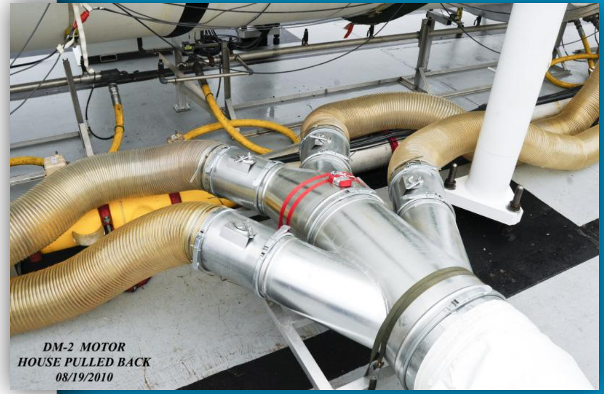


Field Joint

Joint Shrouds

Shroud design consisted of six elements:

- Aluminum braces acted as ribs for the shrouds to provide structure
  - Secured to the case by two 139-lb magnets
  - Twelve braces were installed on each field joint
- Aluminum air inlets were designed with a 12-in. diameter to accommodate needed air flow rate per the thermal analysis
  - Secured to the case by eight 139-lb magnets and shroud material
- Electrostatic dissipative ducting
- Aluminum air flow manifold was designed to connect to the Aggreko equipment and flow air to each joint. The manifold had regulators to restrict air flow to individual joints



Joint Shrouds (cont)

- Aluminum foil bubble wrap was used as the shrouding material. It was chosen because it is an excellent air block; it reflects approximately 97% of the radiant energy; it has an adequate insulation factor up to -4 °F; and it is thin, light-weight, and flexible
  - Each roll was 4 ft by 75 ft, which would adequately cover the joints
- High-strength aluminum foil tape was used to secure the shroud material to the case. The tape had a high adhesion-to-steel ratio and was acceptable to -65 °F
- Temperature and air speed were monitored with a hand-held manometer. The temperature could be regulated by adjusting the manifold, AHU, and chiller

Instrumentation and Safety

- Over 764 data channels were recorded, 460 specifically for DM-2
  - The instrumentation recorded temperature, displacement, erosion rates, and pressure and dimensional changes throughout the motor during static test
  - All instrumentation needed to be bonded to the motor prior to conditioning because the adhesive had a specific tolerance range
  - During conditioning, all data channels were connected to multiple data acquisition systems
  - A series of system checkouts and dry runs was also performed
- Personnel had to work for extended periods of time in freezing temperatures while the outside temperature was near 100 °F. It was necessary to train all personnel on how to identify and treat symptoms of cold and heat stress. Of particular emphasis was the possibility of thermal shock that a body could experience when transitioning quickly between the two extremes

Conditioning

- The actual PMBT is calculated from a functional thermal model
  - This model incorporates temperature data collected from a series of thermocouples (TC) located at various positions on the motor case and inner diameter of the propellant
- Conditioning began on July 6, 2010. The PMBT was calculated to be 78 °F
- The building's temperature was gradually lowered until the inlet temperature was 35 °F. This temperature was held for three days in order to draw out the moisture and prevent freezing
  - The joint shrouds were installed during this time period

Conditioning (cont)

- The inlet temperature was then lowered to approximately 30 °F. Two challenges arose that impeded the conditioning from going lower
  - There was a 22 °F temperature limit on the metal hardware. Because of an inherent TC error, an additional 2 degrees was added to the restriction
  - Because of the locations of the conditioning vents, cold air was blowing directly onto the motor case. This caused some localized cold spots, which were as much as 12 °F colder then the rest of the motor
  - The solution was to install air flow barriers over all the conditioning vents. This eliminated the direct flow onto the motor and further reduced the stratification
- The conditioning equipment had difficulty maintaining consistent temperatures in the bay, especially during the hottest times of the day. One of the main reasons for this was the sun's heat on the hoses caused the brine to heat up on its way to the AHUs thus making the cooling not as efficient
  - The solution was to lay aluminum foil bubble wrap over the hoses. The foil bubble wrap reflected most of the sun's radiant heat and provided insulation for the hoses. After this, the equipment was able to maintain more consistent temperatures in the bay

Conditioning (cont)

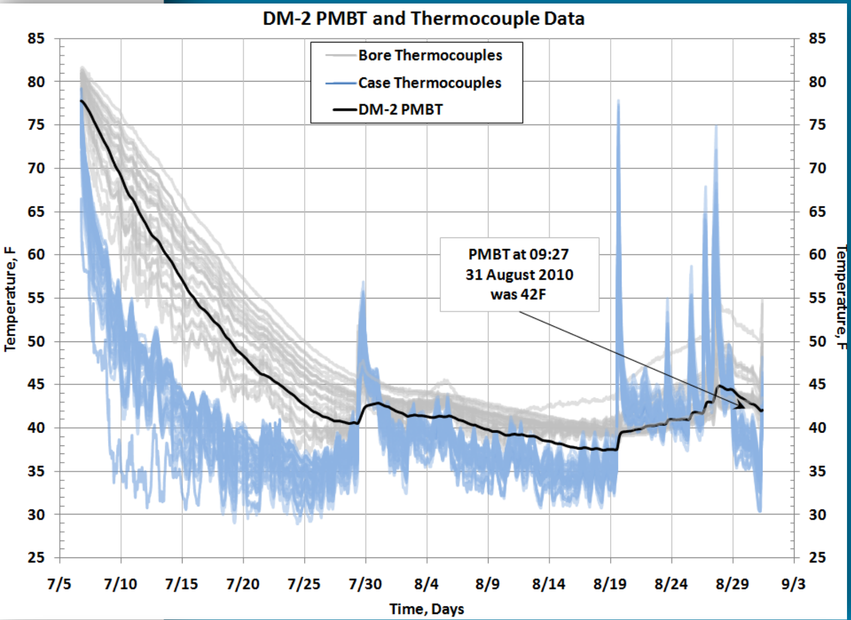
- Conditioning was lost twice due to power outages at T-97. Because of preemptive measures to pre-route cabling, the power was quickly reinstated by running everything off the generators
- There were several necessary activities that could not be performed with the conditioning running, including: laser alignment of stands, radiometers, and cameras; hydrazine set-up and dry runs; and quench boom and joint shroud dry runs
- The first of these activities was the alignment of the side load fixture using a laser tracking system. The equipment needed to be at least 50 °F to function properly
  - It was expected that the aft section would acclimate quickly and the forward slowly. Some condensation was expected. The predictive thermal model predicted the motor would warm up less then a degree for the day
- Conditioning was turned off at 7 am and the aft door rolled up. The entire building rapidly increased in temperature and condensation formed immediately on any metal surface. The amount of this condensation was much more then expected
- The building was closed at 11:00 am after the alignment but conditioning could not be reinstated until all possible design and safety concerns were reviewed

Conditioning (cont)

- There was a concern about the possibility of ice forming in the carbon fiber rope (CFR) located in a nozzle joint. There was no previous data to ensure that the CFR would function properly if the ice were to instantly turn into steam during the static test
- The nozzle conditioning cart was used to warm the joint from the inside out. Three TCs were installed near the groove of the joint to ensure that the CFR would not get below 35 °F
- The overall PMBT of the motor increased approximately 3 °F, which was greater then the model predicted
- The main conditioning was reinstated at 4:30 pm that same day. The temperature was slowly reduced to 35° F, this temperature was maintained for a few more days so the moisture could be drawn out of the building
- After this issue, it was decided to continue to run the conditioning in the building once the door was rolled up. This allowed the motor to slowly acclimate to the outside conditions. After it reached equilibrium, the conditioning could then be turned off. This corrective action worked and condensation events were eliminated

Conditioning (cont)

- Inlet temperatures were kept between 28 to 30 °F
- The 13 days prior to static test consisted of dry runs, hot spin tests, and radiometer and camera alignments
- Because of all the heating of the motor for these building-off activities, the last three days were dedicate to conditioning. The inlet temperature was dropped to 20 to 22 °F
- On the day of the test the building was pulled before dawn and joint shroud conditioning was activated
- The PMBT at the time of static test was calculated to be 42 °F.
- The O-rings were calculated to be 32 to 34 °F



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