

EXTRATERRESTRIAL SURFACE PROPULSION SYSTEMS

Old Dominion University
Mechanical Engineering and Mechanics Department
Norfolk, Virginia

Professor Robert L. Ash
Dexter L. Blackstock, Teaching Assistant
K. Barnhouse, Z. Charalambous, J. Coats, J. Danagan, T. Davis,
J. Dickens, P. Harris, G. Horner, T. James III, W. Johnston, R. Krueger,
A. Lucero, J. McWithey, E. Morris Jr., A. Nelson, R. Rayno, J.
Scheiderer, E. Schneider, G. Singer, C. Wallace

Abstract

Lunar traction systems, Mars oxygen production, and Mars methane engine operation were the three topics studied during 1992. An elastic loop track system for lunar construction operations was redesigned and is being tested. A great deal of work on simulating the lunar environment to facilitate traction testing has been reported. Operation of an oxygen processor under vacuum conditions has been the focus of another design team. They have redesigned the processor facility, including improved seals and heat shields. Assuming methane and oxygen can be produced from surface resources on Mars, a third design team has addressed the problem of using Mars atmospheric carbon dioxide to control combustion temperatures in an internal combustion engine. That team has identified appropriate tests and instrumentation. They have reported on the test rig that they designed and the computer-based system for acquiring data.

Tracked Lunar Construction Vehicles

Lunar regolith (soil) will be used as a construction material for future bases on the moon.¹ Hence, there will be a need for construction machinery that can excavate and/or move significant quantities of lunar soil. While current versions of lunar and Mars rover designs utilize six-wheeled vehicles, tracked vehicles have been the preferred configurations for terrestrial, earth-moving applications. The work reported here is a continuation of the study of tracked vehicle concepts for lunar construction operations.

Trautwein² reported on a Lockheed "loopwheel" design for a Mars rover. The loopwheel concept utilized a continuous elastic loop or track and looked very similar to a terrestrial tracked vehicle, except that the Lockheed elastic track supported the vehicle. The loopwheel design or Elastic Loop Mobility System (ELMS) thus produces a different footprint when it traverses soil than the footprint produced by a conventional linked track terrestrial vehicle. Since the loop section between the wheels (or drive drums) supports the vehicle, it exerts a larger downward pressure force than its linked track counterpart. As a consequence, ELMS can combine the tractive performance attributes of tracked vehicles with the suspension and load distribution characteristics of pressurized tires. However, performance data for these systems is lacking and no attempts to evaluate ELMS for lunar construction applications have been reported.

Elastic Loop Mobility System

It is assumed that the tracks are driven by electric motors located within the wheels (drive drums) used to drive the loops. In that way, the motors can be sealed hermetically in the drive drums, and the drive drums can be connected to the construction vehicle frame via a pivoted interface. The interface can carry electrical connections and coolant passages, which will be required to cool the motors, but do not transmit mechanical shaft power. Since construction operations will likely take place via either fully autonomous or teleoperated control, these vehicles must be very reliable and simple to repair. Hence, the elastic loop and drive drum units, along with the ancillary hardware, should be modular.

The elastic loop mobility system is shown schematically in Figure 1. The design is a 1/6 scale approximation of the lunar construction utility vehicle (LCUV), defined in an unpublished Advanced Program Office study at Johnson Space Center in 1988. That study determined that an LCUV with a 25,000 kg payload capability was required for robotic construction operations on the moon. Their vehicle mass allowance was 7500 kg (making a maximum total mass of 32,500 kg.), and they assumed a tracked vehicle with a total footprint area (two tracks) of 6.8 m^2 . Hence, the maximum pressure that is anticipated for the full scale vehicle on the lunar surface ($g=1.622 \text{ m/s}^2$) was estimated to be 8000 Pa. For terrestrial tests, using the 1/6 scale model, the maximum design load is equivalent to a total vehicle mass of 225 kg. The minimum lunar vehicle load corresponds to an unloaded LCUV and yields a footprint pressure on the order of 2000 Pa, which is equivalent to a prototype mass of 56 kg (124 lb). Initial traction testing has been directed toward the lightly loaded configuration.

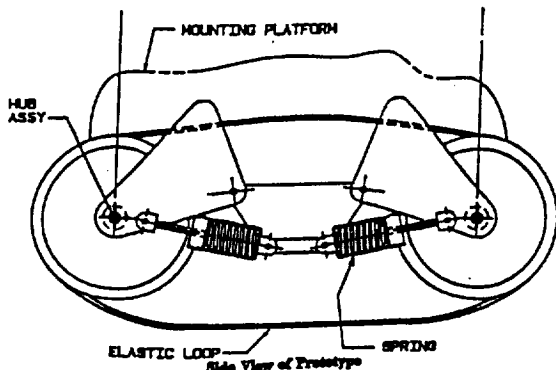


Fig. 1 Schematic view of ELMS prototype track

By preserving the track contact width to length ratio between the prototype and the full scale vehicle, track-side (above ground) interaction with the soil can be made insensitive to lunar gravity effects by loading the track with an appropriate force. Hence, a total track load of 124 lb on earth simulates the full scale, unloaded LCUV on the moon.

The 1992 design utilized new elastic loops (tracks), made of 1060 carbon steel, 1.3 mm (0.05 in.) thick, 203 mm (8 in.) wide, and 2311 mm (91 in.) in circumference.

The loops were joined by lapping the steel belts with a 32 mm overlap that utilized round head machine screws spanning the belt 25.4 mm apart. A continuous neoprene rubber gearbelt (Figure 2.), 50.8 mm wide with a tooth spacing of 22.2 mm (7/8 in.), was fastened to the inside of the steel loop using countersunk, flathead screws, spaced at every fifth rubber tooth.

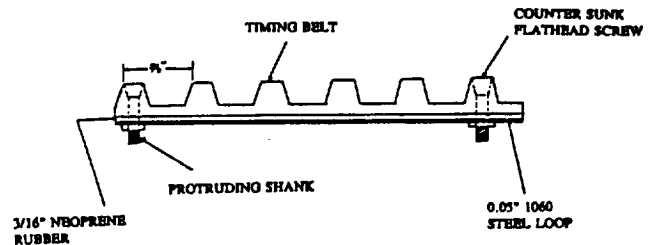


Fig. 2 Side view of gearbelt loop connection

The polyvinyl chloride (PVC) plastic drive drums were 305 mm (12 in.) in diameter and 203 mm wide. The drive drums had teeth machined into them with the same 22.2 mm or 7/8 in pitch as the gearbelt. The gearbelts were restrained by 76 mm (3 in.) wide, 4.8 mm (3/16 in.) thick rubber strips mounted on each side of the drive drum, as shown in Figure 3.

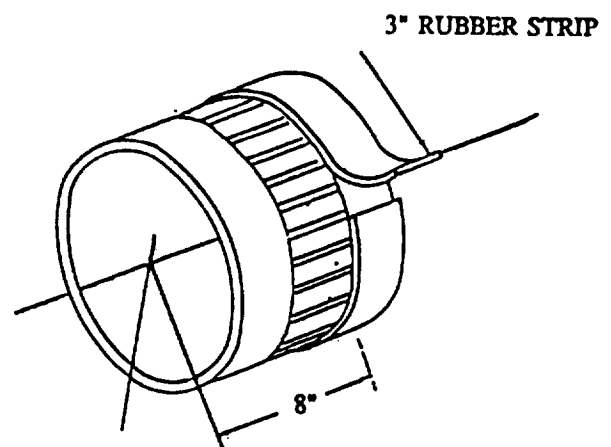


Fig. 3 Schematic of drive drum

The drive system was completely redesigned in order to enhance reliability and reparability. The new design utilized new motor mounts and sealed ball bearings to eliminate previous problems with assembly and wear. Details of the new design are contained in the final team report. Preliminary tests have confirmed the improved performance of the new design and validated the finite element analyses of the track.

Simulated Lunar Traction Tests

Some literature is available on predicting the behavior of tracked vehicles under different soil conditions (see Bekker^{3,4} and Garber and Wong,⁵ in addition to Trautwein²). However, the behavior of this loopwheel, or ELMS, in a lunar environment has not been studied or reported.

Carrier⁶ has reported on Soviet experiments with wheeled vehicles and soil characterization on the lunar surface, starting with their Lunokhod rover vehicle performance data in 1971. The Lunokhod vehicle had open wheels with grousers and carried a cone penetrometer experiment which was used to measure load-bearing properties of lunar soil. In addition, Perkins¹ has produced an extensive literature survey of lunar soil measurements and predictions. The influence of gravity, packing density, vacuum, soil composition, grain size, grain shape, and electrostatic forces on soil behavior must all be considered. However, Perkins' survey indicated that most researchers consider lunar soil to behave similarly to wet beach sand. Hence, some traction testing at Virginia Beach, Virginia, will be reported at a later date. However, the 1992 design team considered establishing the equivalence between terrestrial simulations and lunar behavior to be a critical requirement.

Tests were conducted to determine the minimum traction test soil volume dimensions (diameter and depth of contained soil simulant) required to minimize the influence of testbed containment on the measurements. The influence of footprint size on soil sinkage depth was studied using three track footprint models. The track footprints were made by wrapping galvanized sheet metal (air conditioning duct) around wooden contours cut in the shape of the envisaged track. Tested model track widths were 13 mm, 28.5 mm and 38 mm, with length-to-width

ratios of 4, 3.67 and 3.67, respectively. For these "track penetration" tests, the minimum soil volume was determined to be 300 mm (diameter) by 125 mm (depth). The test data were not controlled adequately, and subsequent tests will be reported more fully.

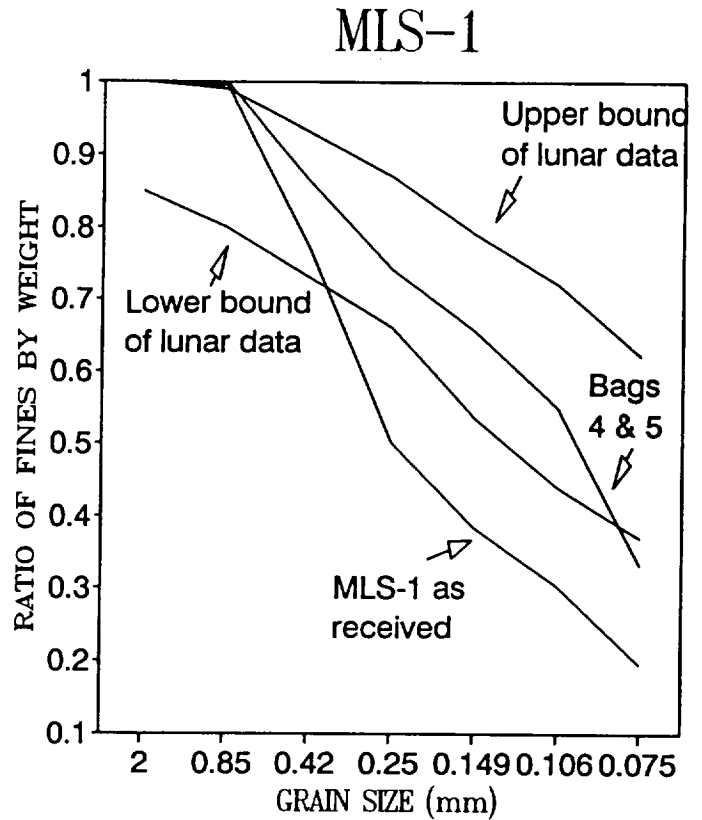


Fig. 4 Comparison of grain size distribution between MLS-1 lunar simulant and lunar soil distribution bonds

Wieblen and Gordon,⁷ have studied lunar surface conditions and made recommendations on how lunar soil can be simulated. On the basis of their study, they determined that lunar soil can be approximated closely by material from an abandoned rock quarry in Duluth, Minnesota. By crushing, grinding, and then sieving the rock, they have been able to approximate lunar particle shape, angularity, and size. However, this mined basalt does not contain the glass fraction associated with lunar soil. They were able to produce the glass agglutinates using a plasma torch furnace. Weiblen, Murawa, and Reid⁸ have reported on preparation and validation of Minnesota Lunar Simulant (MLS-1); nearly 50 kg of MLS-1 simulant was procured from Dr. Weiblen at the University of Minnesota. The soil particle distributions

from the MLS-1 shipment (different bags of material) are compared in Figure 4. Additional details concerning the lunar simulant properties and comparisons are in the full 1992 team report.

A comparison between the sinkage depth for sand and MLS-1 at various loadings (pressures) is shown in Figure 5.

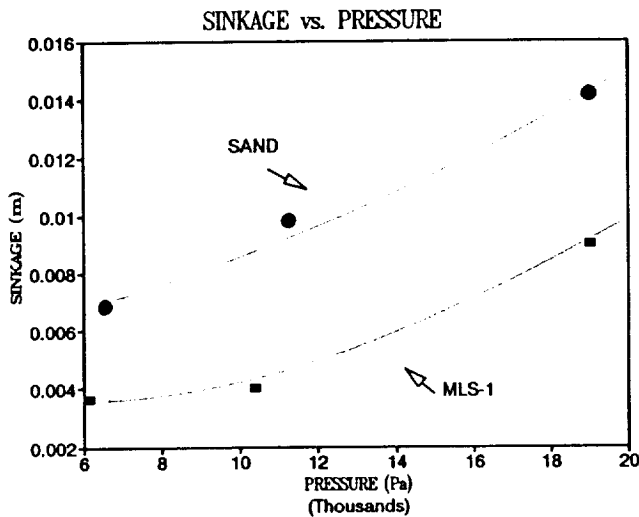


Fig. 5 Comparison of probe sinkage depth as a function of applied pressure, for sand and lunar simulant (MLS-1)

Shear tests for the track units, with and without grousers, were considered, both in air and in vacuum. The influence of gravity was also a concern. The only way gravity effects could be considered was to find soil grains that were the same shape and size as lunar soil but with much lower density (preferably 1/6); no such materials have been identified at this time. A vacuum facility has been built to study the influence of vacuum on shear and traction properties. However, the initial vacuum chamber lid design was found to exhibit excessive deflections during testing and a new design is required. That facility and its modifications will be reported by a future design team.

A "full scale" (for the 1/6 scale prototype) traction test bed was designed and built. The testbed was made of plywood and 2 x 4's and was hinged so that, when filled with sand, the testbed grade could be adjusted until the

ELMS started to slide. That testbed is shown schematically in Figure 6.

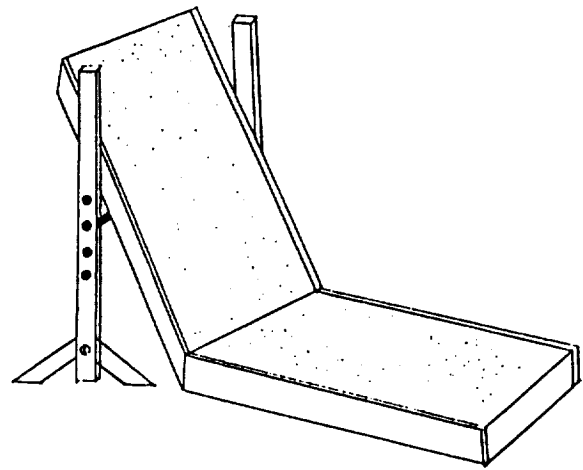


Fig. 6 Schematic of ELMS traction testbed

Summary

The 1992 LCUV Design Team has made significant progress in developing a traction test program that can permit the evaluation of elastic loop track systems for lunar construction operations. While the tests performed this semester are preliminary, a variety of more detailed future design projects that can contribute to the evaluation of future lunar construction vehicles have been identified.

Mars Methane Engine

Since carbon dioxide (from Mars' atmosphere) and water (from Mars' North pole or from permafrost) are likely to be the only feedstock ingredients utilized by early Martian surface outposts, it is likely that methane and oxygen will be the earliest *in situ*-produced fuel and oxidizer on Mars. Furthermore, because the feedstock molecules are water and carbon dioxide, it is very likely that methane and oxygen will be produced in their stoichiometric ratio. Unlike air-breathing propulsion systems on Earth, nitrogen is not available as a diluent to control the combustion temperature on Mars. Furthermore, it will not be desirable to shift the amount

of methane and oxygen consumed away from the stoichiometric mixture because of the hardware and energy costs associated with producing each propellant molecule. Consequently, it is desirable to consider using carbon dioxide from Mars' atmosphere as a diluent to control combustion temperatures. The 1992 Mars methane engine design team has progressed from operating an internal combustion engine with controlled ratios of methane, oxygen, and carbon dioxide to developing instrumentation and test plans for conducting a computer-based study of parametric design data for internal combustion engine operations on Mars.

A one-cylinder Megatech Mark III laboratory engine was used in the preliminary tests. Spark advance and compression ratio could be varied for that engine. Since most engine research programs are concerned with engine performance rather than the fuel and oxidizer behavior, considerable research was directed toward defining appropriate tests. Ferguson⁹ has indicated that the variation of spark advance for maximum engine rpm with different fuel-oxidizer-diluent settings is useful in evaluating propellant performance. In addition, since the fuel, oxidizer and diluent are pressurized, accurate measurements of cylinder pressure as a function of cylinder volume were required to determine horsepower and fuel consumption data. Instrumentation and data acquisition requirements have been defined in terms of measuring these parameters.

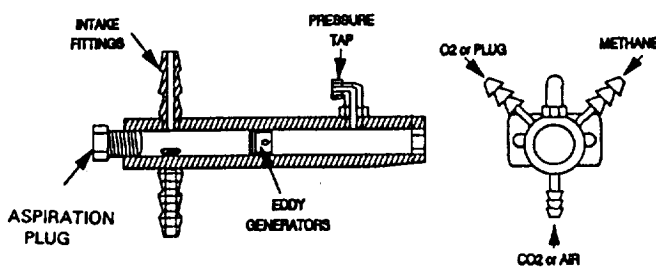


Fig. 7 Schematic view of the three-gas carburetor design

A carburetor had to be designed to permit mixing of gaseous methane with oxygen and carbon dioxide. That design is shown schematically in Figure 7. Cylindrical rod

vortex or eddy generators were incorporated in the design to facilitate mixing of the three gases.

Gas flows were measured using rotameters. Air flows (baseline tests) and carbon dioxide flows were measured with a Cole-Parmer (Model N064--63C) rotameter, while methane and oxygen flows were each measured with Cole-Parmer Model N064-63ST rotameters. Depending on the float configuration, flow rates could be measured between 100 and 60,000 standard cubic centimeters per minute (SCCM).

Instrumentation was not available for measuring instantaneous combustion chamber pressures. Dr. David L. Reuss of General Motors Research Laboratories in Warren, Michigan, assisted the design team in selecting an appropriate pressure transducer. An AVL North American piezoelectric pressure transducer (Model 8QP500c) and a Model 3057-A01 charge amplifier unit were selected. The cylinder head of the Megatech engine was modified to accommodate the pressure transducer and to incorporate its water cooling requirements.

An optical encoder was selected as the device to measure engine crank position. Since crank position can be related directly to instantaneous volume, accurate instantaneous crank position data were required. A Lucas Ledex optical encoder, Model K3DM-100-5 SE-4A-M, was selected. That encoder produces 100 pulses per revolution, providing adequate resolution of position for an engine crank with an appreciable moment of inertia and preventing significant high frequency fluctuations. Considerable design effort was devoted to protecting the encoder from both the mechanical energy and vibrations produced by the engine.

Exhaust temperatures were measured with a chromel-alumel (type-K) thermocouple probe. The probe was housed in a 1.6 mm diameter Inconel 600 sheath and could tolerate temperatures up to 1400° K. The thermocouple probe extended into the muffler and was in close proximity to the exhaust valve. Provisions were made in the muffler to facilitate exhaust gas sampling for a gas chromatograph analysis.

An IBM PC-based data acquisition system has been selected for recording pressure, crank position, and speed data. A Data Translation unit, Model LPC LAB-SP0159, has been used to acquire the encoder signal and record

chamber pressures. Each encoder pulse (every 3.6°) triggers a pressure measurement. A schematic view of the overall system layout is shown in Figure 8. It is expected that the data acquisition system will be modified to acquire exhaust temperature data in follow-on work. Experiments will be performed during the summer.

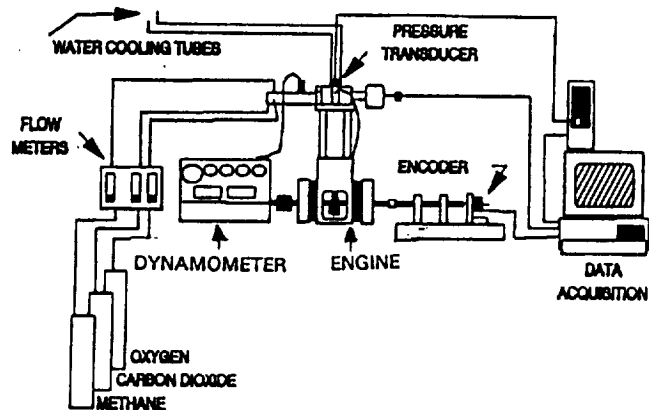


Fig. 8 Schematic layout of Mars methane engine test unit

Low Pressure Mars Oxygen Production

Ash, Dowler and Varsi¹⁰ reported on the feasibility of *in situ* propellant production on Mars in 1978. Through the support of The Planetary Society and USRA, the design team designed and built an electrochemical processor that demonstrated that oxygen could be produced directly from Mars' atmosphere.¹¹ Subsequently, Ramohalli and coworkers at the University of Arizona¹² have improved and refined the zirconia-based oxygen separation technology. However, virtually all of the performance data have been produced at cell operating pressures near 1 bar. Since the surface pressure on Mars is on the order of 7 mb, the need to impose a compression ratio in excess of 140:1 on the feedstock is questionable.

The current design group has focused on modifying the oxygen processor to enable repeatable measurements at operating pressures on the order of 100 mb. Due to the cell operating temperatures (on the order of 1000° K), start-up and shut-down cycles have created severe problems in maintaining vacuum integrity. The design team has been able to accomplish the tedious task of

isolating a number of leaks, including a problem with the ceramic (alumina) housing which encased the zirconia cell. It was discovered that the flange region at the top of the ceramic housing (Figure 9) leaked, even though it appeared to be a continuous part. Further investigation showed that the O-ring seal between the face plate and ceramic housing had also melted. Hence, a major effort was devoted to redesigning the upper part of the oven unit to reduce the temperatures in that zone. A 3M epoxy that could maintain the ceramic seal was found, and the aluminum heat shield, shown schematically in Figure 10, was found to be capable of lowering the flange-ceramic housing interface temperatures to acceptable levels to protect the O-ring seal.

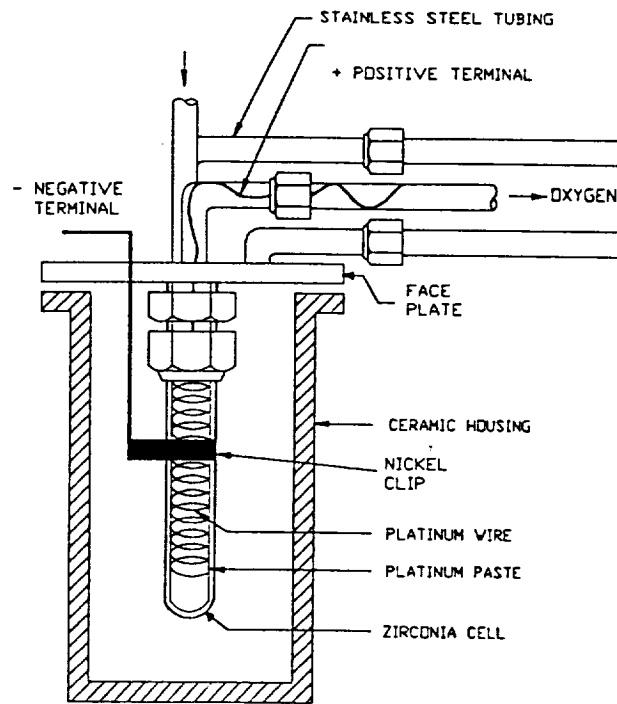


Fig. 9 Schematic of oven cell unit assembly

The other area of investigation was to characterize the electrical behavior of the zirconia cell at different operating temperatures. Problems were encountered there in isolating the cell electrically from the remainder of the system. The electrical connections have been modified as shown in Figure 9, to facilitate those

measurements. Tests will be conducted during the summer to validate the performance.

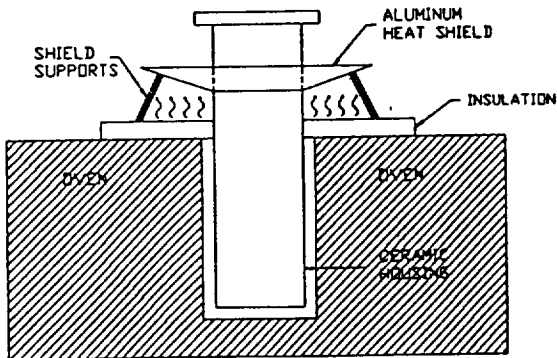


Fig. 10 Schematic view of conical heat shield used to protect the flange region

References

- Perkins, S.W. "Modeling of Regolith Structure Interaction in Extraterrestrial Constructed Facilities," Ph.D. Dissertation, University of Colorado Center for Space Construction, 1991.
- Trautwein, W. "Operational Loopwheel Suspension Systems for a Mars Rover Demonstration Model," Lockheed Missiles and Space Co. Report, LMSC-TRD 568800, July 1972.
- Bekker, M.G. Off Road Locomotion, University of Michigan Press: Ann Arbor, MI, 1960.
- Bekker, M.G. Introduction to Terrain-Vehicle Systems, University of Michigan Press: Ann Arbor, MI, 1969.
- Garber, M. and Wong, J.Y., "Prediction of Ground Pressure Distribution Under Tracked Vehicles -- An Analytical Method for Predicting Ground Pressure Distribution," J. Terramechanics, Vol. 18, pp. 1-23, 1981.
- Carrier, W.D. III. "Soviet Rover Systems," AIAA Space Programs and Technologies Conference, Huntsville, AL, Paper number 92-1487, 1992.
- Weiblen, P.W. and Gordon, K.L. "Characteristics of a Simulant for Lunar Surface Materials," Symposium on Lunar Bases and Space Activities in the 21st Century, Paper No. LBS-88-213, Houston, 1988.
- Weiblen, P.W., Murawa, M.J. and Reid, K.J. "Preparation of Simulant for Lunar Surface Materials," Proceedings of the Aerospace Division of the ASCE, Space 1990 Conference, Albuquerque, NM, April 1990.
- Ferguson, C.R. International Combustion Engines, John Wiley and Sons: New York, 1986.
- Ash, R.L., Dowler, W.L., and Varsi, G. "Feasibility of Rocket Propellant Production on Mars," Acta Astronautica, Vol. 5, pp. 705-724, 1978.
- Ash, R.L., Werne, J.A., and Haywood, M.B. "Design of a Mars Oxygen Processor," The Case for Mars III, Edited by C. Stoker, AAS Science and Technology Series, Vol. 75, pp. 479-487, 1989.
- Colvin, J., Schallhorn, P., and Ramohalli, K. "Full System Engineering Design and Operation of an Oxygen Plant", 27th AIAA/SAE/ASME/ASEE Joint Propulsion Conference, Sacramento, CA. Paper No. 91-2444, 1991.