# APEX - An In-Situ Resource Utilization Excavation Research Tool

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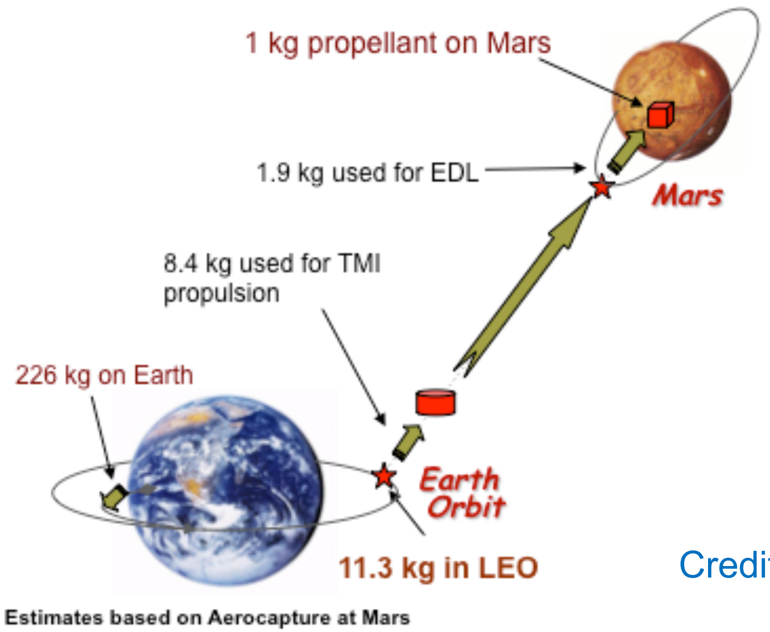
# ISRU Mission Impact

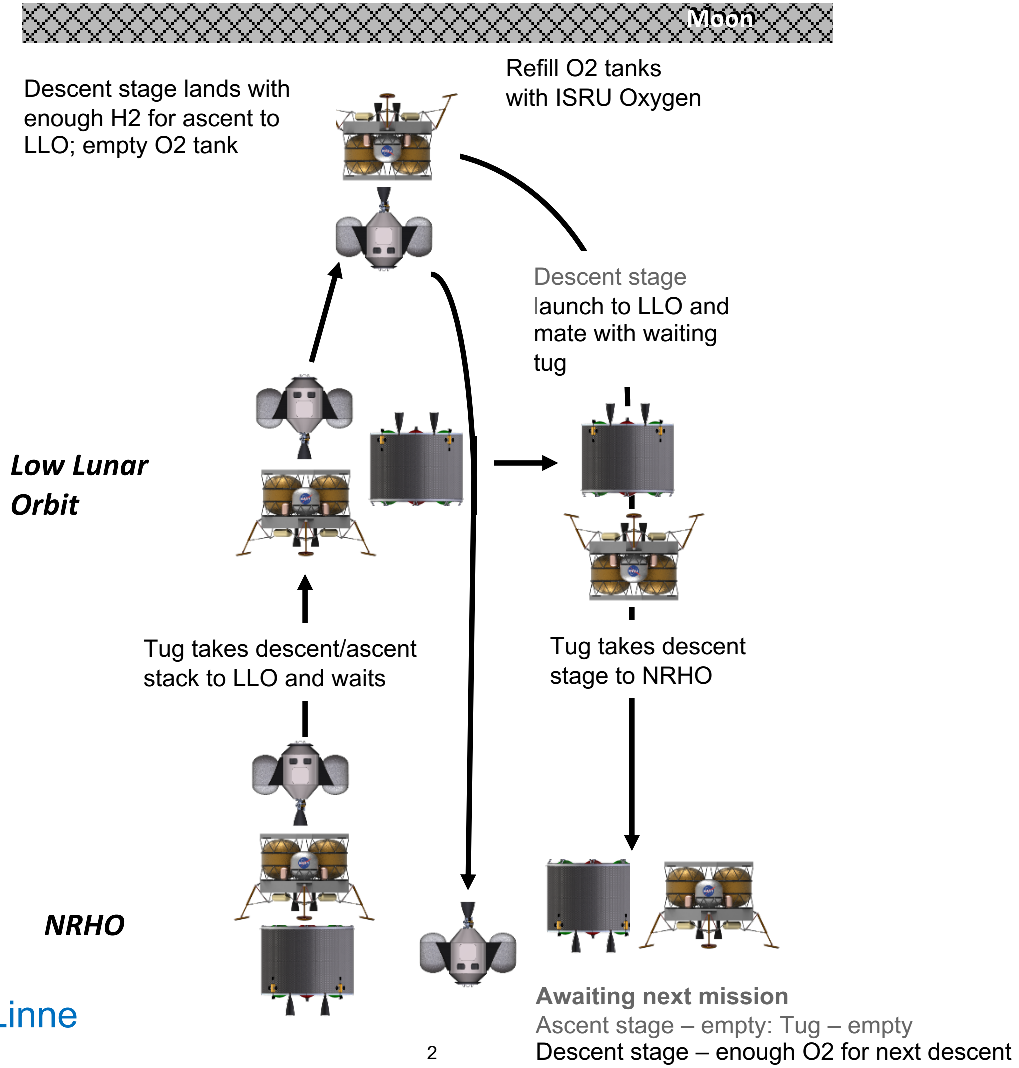
- Production of large amounts of consumables (propellants, life support) on the surface of the Moon or Mars significantly reduces launch costs and enables sustained exploration
  - Every 1 kg produced on the surface saves 7 to 11 kg launched to LEO (similar gear ratio for Moon and Mars)

Example of how 1 kg of propellant on surface adds up to big savings in LEO



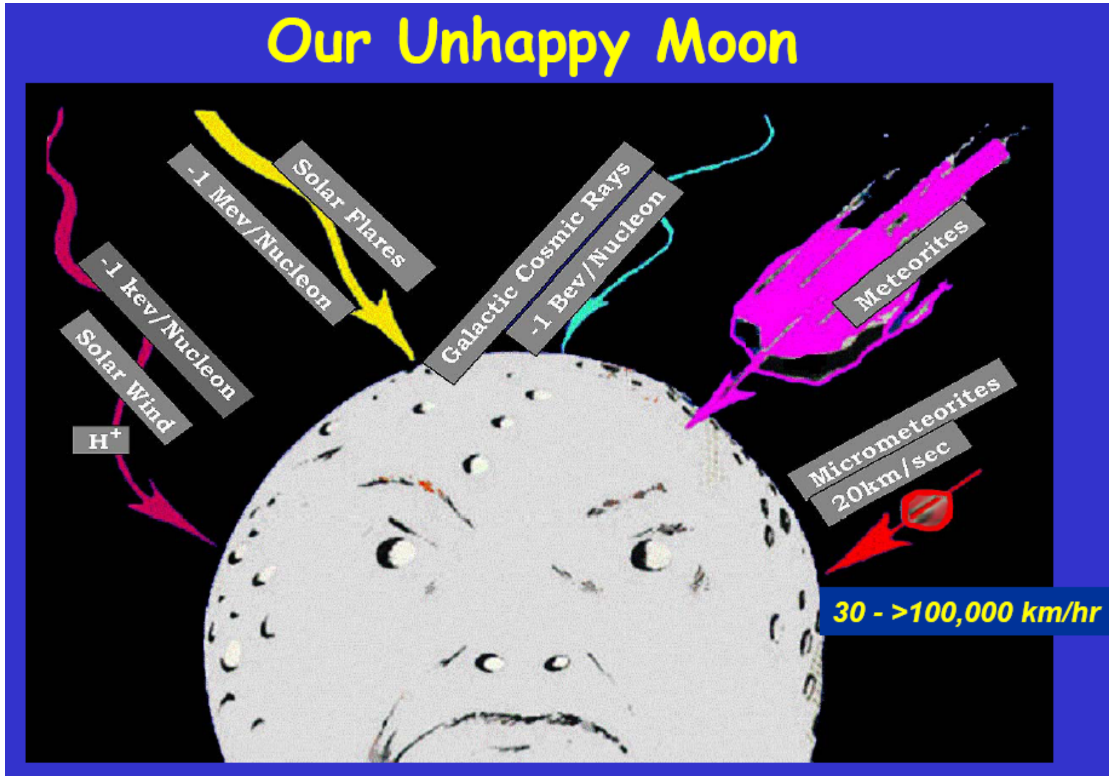

Credit: Diane Linne

**Mission Option Example: ISRU $O_2$ only for Descent Stage ascent/descent**



For lunar ISRU in the near term, autonomous or semi-autonomous robotic equipment will contend with:

- Temperature extremes,
- Hard vacuum,
- Direct solar and cosmic particle radiation, and




Credit: Dr. Kenneth Street

For lunar ISRU in the near term, autonomous or semi-autonomous robotic equipment will contend with:

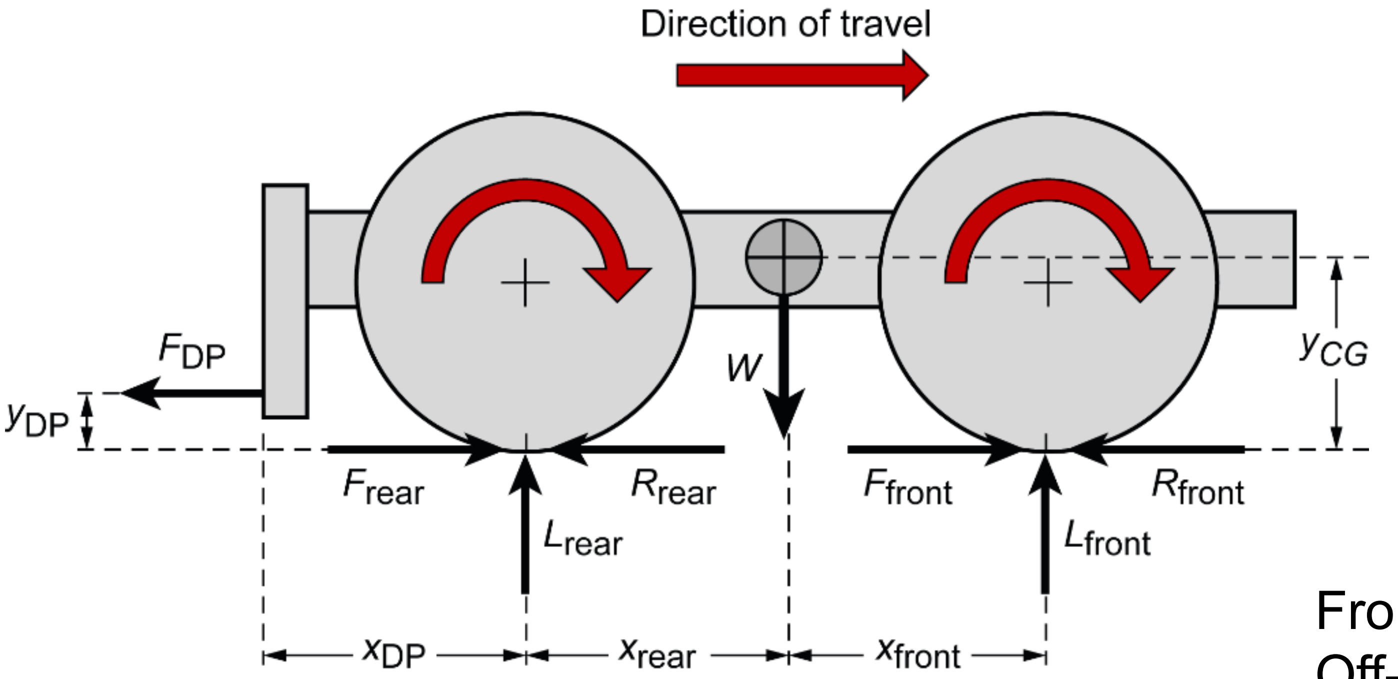
- Temperature extremes,
- Hard vacuum,
- Direct solar and cosmic particle radiation, and

- Dust -

Harrison Schmitt, last astronaut to leave the Moon, is credited with citing dust as the number one environmental problem on the Moon

Apollo astronaut Gene Cernan covered with lunar dust during the Apollo 17 mission

For ISRU lunar excavation, reduced gravity (versus Earth) also implies reduced reaction force that autonomous or semi-autonomous robotic equipment can exert:




From: “Drawbar Pull (DP) Procedures for Off-Road Vehicle Testing”, C. Creager, V. Asnani, H. Oravec, and A. Woodward, NASA TP-2017-219384 (2017).

For ISRU excavation there are a number of bucket force (continuum) models, as well as increasingly capable codes (e.g. Discrete Element Modeling) to compare with experiment

**Force Model References**:


Balovnev, V.I. New Methods for Calculating Resistance to Cutting Soil, Amerind Publishing (Translation) translator and Rosvuzizdat, New Delhi, Available form National Technical Services, Springfield, VA 22161, 1983 and 1963

Alekseeva T, Artem'ev K, Bromberg A, Voitsekhovskii R, Ul'yanov N. Machines for earthmoving work: theory and calculations. New Delhi, Moscow: Amerind Publishing Co. Mashinostroenoe; 1985. 1972

Zelenin A, Balovnev V, Kerov I. Machines for moving the earth: fundamentals of the theory of soil loosening, modeling of work processes and forecasting machine parameters. New Delhi, Moscow: Amerind Publishing Co. Mashinostroenoe; 1985. 1975

Terzaghi K., Theoretical soil mechanics, New York, NY: John Wiley and Sons, Inc.: 1943

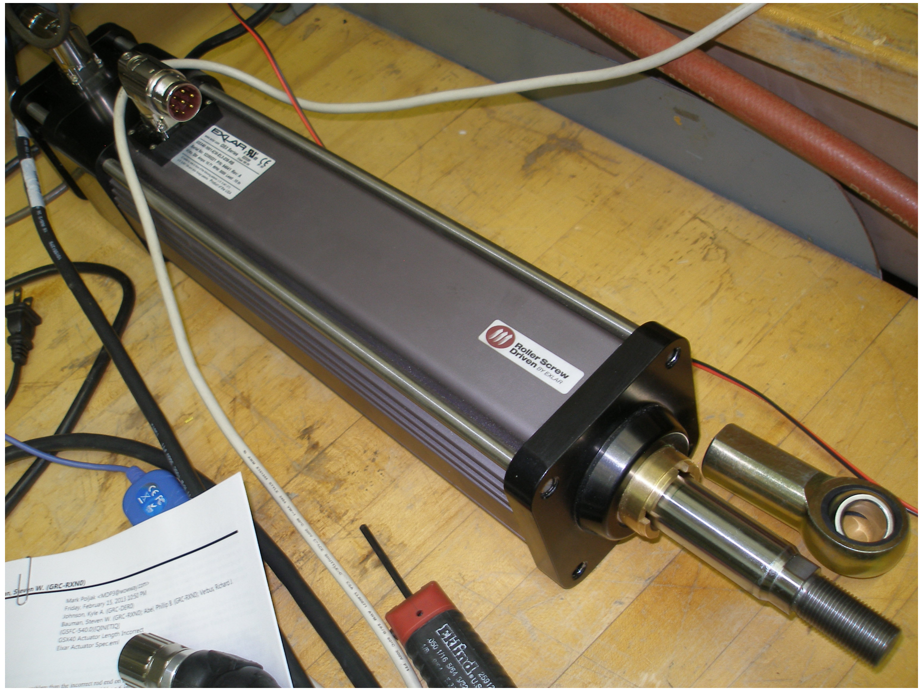

Comparison to force models both validates our understanding of the (low end) forces and bounds the required reaction force using traditional excavation methods

# Fortunately, we have a tool to investigate excavation force reduction in the laboratory - the Advanced Planetary Excavator (APEX)

APEX field demonstration at NASA Johnson Space Center “Rock Yard” - mounted on Centaur 2 in 2014 with KSC “Badger” percussive bucket - (Human Robotic Systems Project, led by JSC)

Reasons to use APEX - It is a lunar excavation tool analog, designed to illustrate required characteristics:

- All electric actuation - lack of hydraulic oil provides wider temperature range tolerance
- Electric actuators can be made vacuum compatible (lubricants & materials selection)



High force linear electric actuator

Reasons to use APEX - It is a lunar excavation tool analog, designed to illustrate required characteristics:

- “Inverted” actuation design - rather than external hydraulic pistons, electric actuators are captured inside the arm segments
- Better thermal management
- Slight added radiation protection afforded by arm enclosures
- Only sealed rotary joints are presented to dusty environment

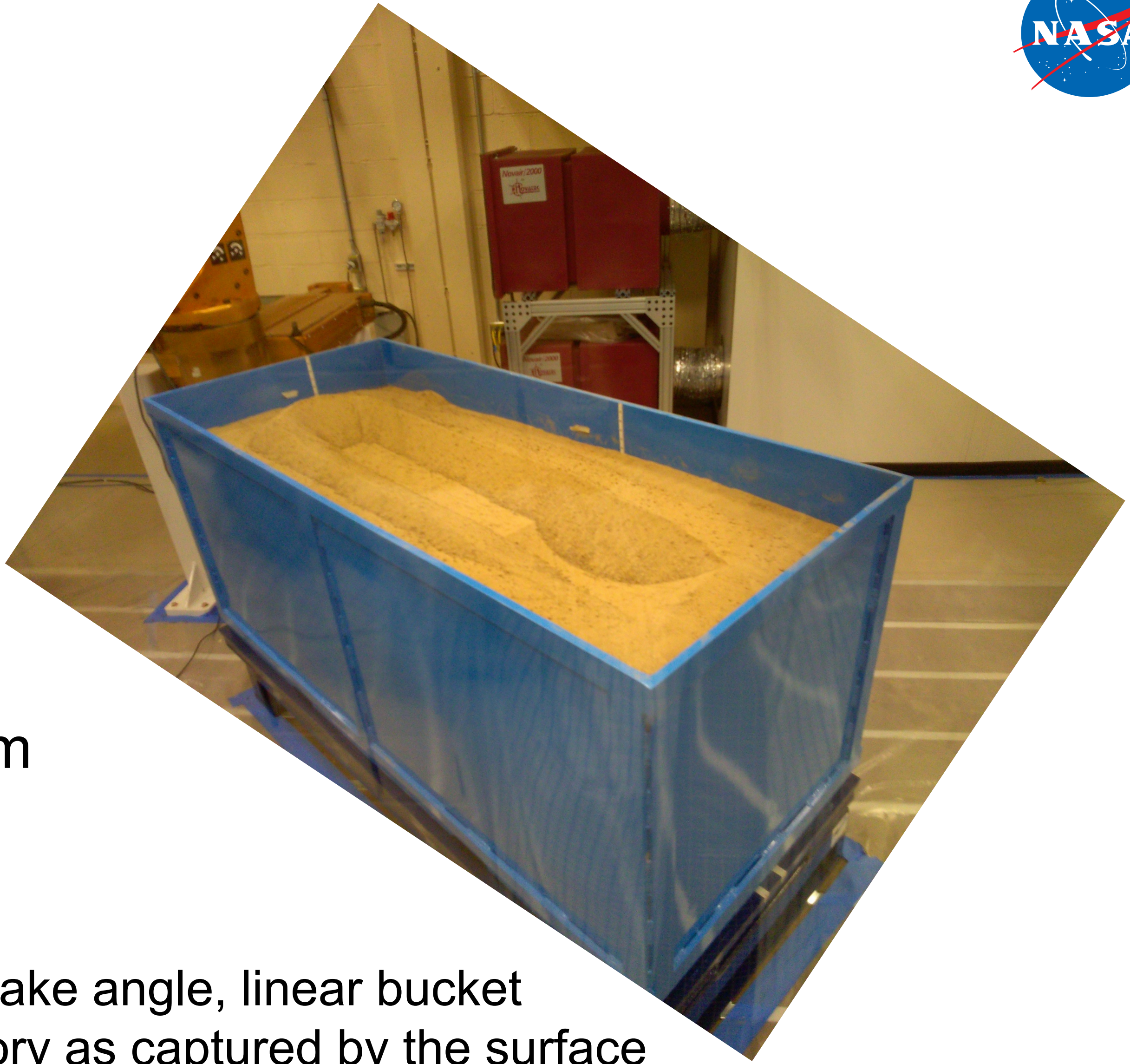
Reasons to use APEX - It is a lunar excavation tool analog, designed to illustrate desired characteristics:

- Internal routing of power and communications, inside the arm segments by design, provide both electric power and full ethernet connectivity - available to end effectors at the wrist plate

(note the six-axis load cell mounted between APEX and the bucket)

Utility of APEX - We are currently investigating how to minimize the reaction force required of a vehicle for lunar excavation - starting with baseline force measurements in lunar simulant.

APEX provides a repeatable, high-stiffness, multiple degree of freedom positioner for precise bucket trajectories.



Fixed rake angle, linear bucket trajectory as captured by the surface

Utility of APEX - We are currently investigating how to minimize the reaction force required of a vehicle for lunar excavation - e.g.

APEX could position and measure the reaction force reduction from counter-rotating bucket drums - including the down-force required.

Percussive buckets, ultrasonic teeth, counter-rotating bucket wheels - all could be quantitatively compared.

Regolith Advanced Surface Systems Operations Robot (RASSOR) KSC Swamp Works

Utility of APEX - With power and high speed data available to any end effector, multiple (non-excavation) “tools” could be adapted to standard quick-disconnects, such as a down-hole camera or spectrometer.

APEX could provide a platform for research to minimize the “interface penalty” associated with modular components / robotics via a robust, low-profile, remote quick-disconnect.

Quick-disconnect needed -
GRC Excavation Laboratory

## Some APEX robotic arm specifications

- Four degree of freedom including turret (vertical rotation axis)
- Reach (w/ bucket): horizontal 2.3 m radius, vertical 1 m below grade
- Mass: 405 kg
- Max. actuator force (shoulder): 50,000+ N (11,300 lbf)
- Max. force on bucket, arm fully extended (approx. 10:1 mechanical disadvantage): approx. 5,000 N (1,130 lbf)
- Power to implements (at wrist plate): nominal 230 VDC, 5 A fused
- Data to implements (at wrist plate): Ethernet - RJ45

APEX was designed to interface with and be powered by the Centaur 2 mobility platform robot at the NASA Johnson Space Center

## Summary

- For lunar ISRU, even “simple” excavation and material transport - on the lunar surface - will be challenging for unattended, multi-year autonomous or semi-autonomous robotic operations

- A precise high-force robotic arm, APEX, is being applied to basic excavation force measurements now, to provide a basis for investigating how to minimize excavator traction forces required

- The APEX design can further serve as a platform for developing robotic modularity components

# Thank-you!