

Power Measurements to Excavate Lunar Soil Simulant GRC-3B

Using Arc Backhoe Trajectories

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ABSTRACT

Understanding, mitigating, and minimizing power and mass requirements are crucial to developing the next generation excavation technologies for lunar and planetary in-situ resource utilization (ISRU). Towards this end, electrical power to the Advanced Planetary Excavator (APEX) was measured while excavating granular lunar soil simulant GRC-3B. Using a 21.6-cm wide bucket having a 30° leading edge, arc-shaped backhoe trajectories were dug to depths of 5, 10, and 20 cm with rake angles of 10, 20, and 30 degrees. Maximum net power, net energy, net energy per mass excavated, rate of mass excavated, horizontal distance from soil entry to exit (at bucket tip), and the trajectory to bucket volume percentage are presented to inform the scientific community as trajectories and designs are planned for future missions. Using APEX's capability to evaluate power and energy consumption of excavation tools and processes gives guidance to developing power requirements and efficient methods for lunar excavation.

INTRODUCTION

In support of NASA's In-Situ Resource Utilization (ISRU) efforts, an activity was undertaken at the Glenn Research Center in January of 2018 to measure the fundamental forces to excavate granular soils that may be encountered on the Moon and Mars. The Advanced Planetary Excavator (APEX), which was previously designed, built, and demonstrated on the JSC Centaur 2 rover, was used to make the measurements. The objectives were to measure the force required to dig various quantities of granular soil, both loose and compacted; use the data in an existing excavation analytical model to validate model algorithms; and to then use the model to generate appropriate excavator designs for various soil conditions (Proctor et al. 2021). As part of that effort power measurements were also taken and are the subject of this report. Many proposed ISRU activities involve excavating lunar regolith and power requirements are needed for mission planning. The devices and approaches to excavate, soil type, and soil condition can greatly affect the force, power, time, and energy needed for excavation. The APEX and the Excavation Lab provide a capability to evaluate the effectiveness and power requirements for various digging tools. This

presentation focuses on the power measurements to dig with a bucket on the APEX arm in lightly compacted and compacted granular lunar soil simulant, GRC-3B, using arc backhoe trajectories. The test apparatus, soil preparation, dig trajectories, and power measurement test results will be presented followed by a summary and conclusions.

TEST APPARATUS

The Excavation Lab (Figure 1) houses the Advanced Planetary Excavator (APEX), an electrically actuated backhoe arm with a bucket, a bin with pea gravel used for checkout testing, a larger soil bin containing the lunar soil simulant GRC-3B sitting on top of a shaker table used to compact the soil, and a platform scale with dump bin used to measure the amount of soil dug. The platform scale has a range of 0 to 2224 N and resolution of 0.22 N. A six-axis load cell is mounted between the arm and the bucket to measure digging forces. The aluminum bucket is 21.6 cm wide with a 25.4-cm wide steel leading edge with a 30-degree blade angle. Bucket volume is 15600 cm³. Bucket dimensions are shown in Figure 2. A digital power meter and 50-amp shunt are used to measure total DC power to the APEX.



Figure 1. Excavation Lab at NASA Glenn Research Center houses the Advanced Planetary Excavator (APEX) and soil bins inside a dust enclosure.

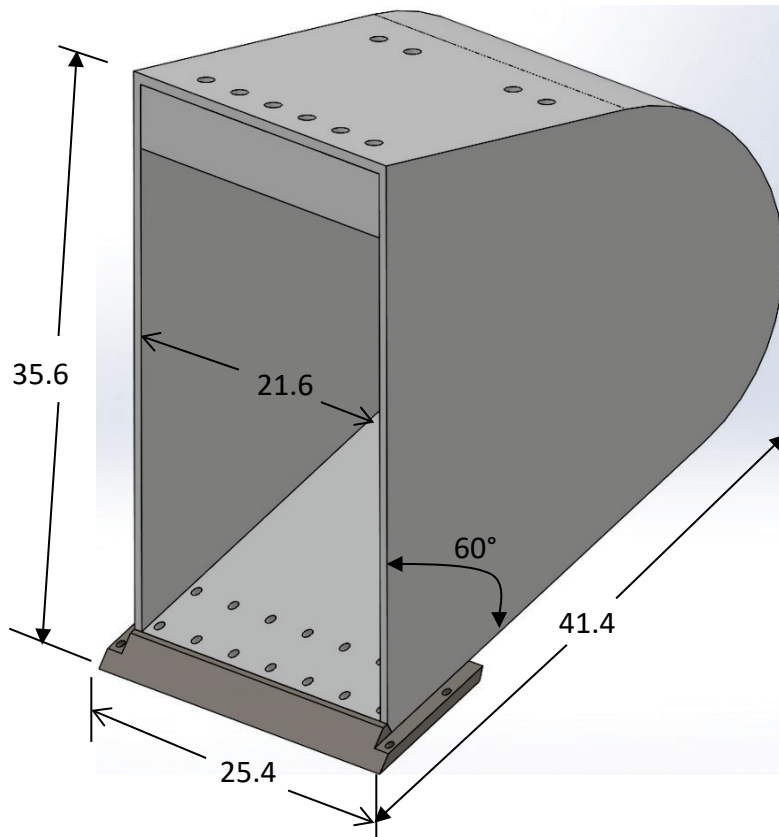


Figure 2. Bucket dimensions in cm.

Data Acquisition and Control. LabVIEW and NI CRIO and CANBUS are used to control the APEX and to record actuator position, active and inactive current, and bus power at 10 Hz. The load cell measurements are also recorded using LabVIEW. A power meter was used to record current, DC voltage and total power for an entire dig trajectory, and it has a USB connection for control and recording of data. Power data was recorded on a separate computer at 10 Hz. Load cell data was sampled and saved at 7 kHz and low pass filtered to remove high frequency effects outside the scope of this testing. All channels of LabVIEW system were re-sampled at 20 Hz to synchronize the time stamps and reduce data file size.

The APEX dig trajectory is operated by a feedforward position controller. Initially, the operator defines a desired dig profile in the Trajectory Designer application. The Trajectory Designer runs through a kinematics model and solves for the necessary joint angles in the robotic arm to achieve the targeted bucket motion path. The dig profile is then loaded in the APEX Trajectory Simulator for visual feedback as to how APEX would operate in real life. After verification, the dig profile is loaded into a LabVIEW VI that controls the linear actuators in APEX, which results in the dig trajectory. During the experiment, power, force, torque, and actuator position measurements were collected into data log files. All test data were calibrated by their respective reference air dig trajectory to “zero” the sensors.

GRC-3B. This lunar soil simulant was formulated of silica sand and silt to have mechanical properties that are similar to GRC-3 (He et al. 2013), but it is comprised of different source materials as the materials used for GRC-3 were no longer available. Initial tests of particle size distribution are comparable to GRC-3 and fall within the same range of one standard deviation around the average size distribution. GRC-3B has not yet been fully characterized. However, preliminary characterization test results were that the minimum and maximum densities are 1.486 and 1.918 g/cm³, respectively. Direct shear tests found the cohesion to be 0 and the internal friction angle to be 46.0 degrees based on the average (Zeng 2018).

SOIL PREPARATION

Prior to each test dig, the soil preparation method required three to four stages: (1) loosening the soil to return it to its original condition, (2) leveling to even out the soil distribution, (3) compacting the soil if required, and (4) recording soil strength as indicated by cone index gradient measurements. An auger was used to loosen the soil. For the tests conducted, the soil was compacted by operating the shaker table at a frequency of 60 Hz for 4 minutes. The vibration amplitude of the filled bin was 0.4759 mm at 60 Hz. No surcharge pressure was applied to the soil surface. After compacting the soil, the level of the GRC-3B in the bin was approximately 7.62 cm lower than before compaction, the soil surface was slightly undulating, and some migration of larger particles to the surface was evident. The bulk density of the GRC-3B at the lightly compacted and compacted test conditions is roughly estimated to be 1540 and 1750 kg/m³, respectively.

TRAJECTORIES

Dig trajectory files were created and used to control the APEX for exact repeatability. The trajectories were first performed in air to establish the tare and then in GRC-3B. For each trajectory, three tests were conducted in air and one test was conducted in GRC-3B. Tests were conducted in both lightly compacted and compacted GRC-3B for backhoe arc trajectories with bucket rake angles of 10, 20, and 30 degrees at two different dig depths. For the lightly compacted soil the dig depths were 10 and 20 cm. For the compacted soil, the dig depths were 5 and 10 cm. A single backhoe trajectory in compacted GRC-3B at 20 cm depth was conducted, but the forces exceeded the load cell range. In all tests the bucket tip speed was 5 cm/s. The tests conducted are summarized in Table 1. Tests in lightly compacted GRC-3B were conducted first and then the tests in compacted GRC-3B were conducted.

Table 1. Summary of tests conducted.

<u>Tests Conducted</u>			
<u>Trajectory</u>	<u>Soil Condition</u>	<u>Rake Angle (°)</u>	<u>Depth (cm)</u>
Backhoe	Lightly Compacted	10	10
		20	
		30	
		10	20
		20	
		30	
Backhoe	Compacted	10	5
		20	
		30	
		10	10
		20	
		30	
Backhoe	Compacted	10	20*

*Load cell range was exceeded.

The backhoe arc trajectories were formulated to generate data for validation of a backhoe excavation model. As such, the wrist and shoulder joints of the APEX were fixed angles and the forearm swung around the elbow pivot point. Hence, the motion was driven by one linear actuator. The trajectory started with the bucket tip 2.54 cm above the soil surface and swung into the soil. For bucket rake angles of 10 and 20 degrees, the trajectories were planned so that the maximum depth of the dig occurred directly under the elbow pivot point. This point was unreachable with the 30-degree rake angle, so the target depth location was further away from the elbow pivot. All trajectories were stopped at the target bucket depth and rake angle and photographs were taken to show the amount of soil in the bucket and the bow wake of soil in front of the bucket. Then the arc trajectory was continued until the tip of the bucket was 2.54 cm above the soil level. Different trajectories were planned for the lightly compacted and compacted soil to accommodate the change in soil height in the bin.

For the 30-degree rake angle trajectories, the tip of the bucket went deeper into the soil to the maximum depth under the elbow pivot point; the rake angle at this point was much less than 30 degrees. For the 30-degree rake angle trajectories in compacted soil the maximum depths and corresponding rake angles were 10.1 cm and 12.2 degrees for the target depth of 5 cm and 14.6 cm and 13 degrees for target depth of 10 cm. For the 30-degree rake angle trajectories in lightly compacted soil the maximum depths were 15.4 cm and 24.5 cm for target depths of 10 and 20 cm, respectively. The power data for the entire backhoe trajectories are presented.

TEST RESULTS

The net power to dig in GRC-3B was calculated by subtracting the averaged power for the same trajectories in air from each trajectory in GRC-3B. The average standard deviation of the averaged power for the trajectories in air ranged from 1.1 to 3.8 W for the trajectories tested. The net power values reported herein are +/- 4 W, nominally. The maximum net power measured for each trajectory is summarized in Table 2.

Table 2. Summary of maximum net power for backhoe arc trajectories.

Rake (°)	Depth (cm)	Maximum net power in lightly compacted GRC-3B (W)	Maximum net power in compacted GRC-3B (W)
10	5	---	16.3
20	5	---	23.6
30	5	---	52.3
10	10	18.5	48.3
20	10	18.2	50.7
30	10	40	87.7
10	20	69.7	269.3
20	20	80	---
30	20	172.7	---

The maximum net power for the backhoe trajectories tested in lightly compacted GRC-3B ranged from 18 to 173 W and in compacted GRC-3B ranged from 16 to 269 W. The maximum net power is higher in compacted soil than in lightly compacted soil and is also higher for increased digging depth as expected. Increased rake angle also produced higher maximum net power results. It is interesting to note that for the compacted conditions the maximum net power for 5-cm depth and 30-degree rake angle (target) was 52.3 W, which has a maximum dig depth of 10.1 cm and rake angle when the bucket tip is under the elbow joint of 12.2 degrees, is very similar to the 48.3 W maximum net power for the 10-cm depth, 10-degree rake angle trajectory. Some sample plots of net power are presented and discussed for lightly compacted and compacted tests.

Lightly compacted. The net power as a function of horizontal distance for the backhoe arc trajectory at 10-cm depth and 10-degree rake angle in lightly compacted GRC-3B is shown in Figure 3 as well as the depth of the trajectory. Start transients can be seen at the beginning of the “-IN” and “-OUT” trajectories. The digging was stopped after the “IN” trajectory to photograph the bow wake and the height of the soil in the bucket. Initially the net power is negative, or essentially zero, until the horizontal distance of

approximately 21 cm. The combined IN and OUT backhoe trajectories were planned to start and stop with the tip of the bucket 2.54 cm above the soil surface. The tip of the bucket enters the soil at a horizontal distance of 5 cm. However, the increase in net power begins between 14 and 15 cm horizontal distance. The corresponding force measurements show the horizontal force started to increase at the 5 cm horizontal distance and the vertical force began increasing at approximately 14 cm. The net power increases as the trajectory depth increases and nominally decreases as the depth decreases except that the maximum depth of the trajectory occurs at the horizontal distance of 50 cm and the maximum net power of 18.5 W occurred at the horizontal distance of 60 cm. This might be explained by the bow wake piling up soil in front of the bucket, effectively increasing the actual soil depth. The trajectory ended with a net power of approximately 5 W. The net energy for this trajectory was 142.2 W-s.

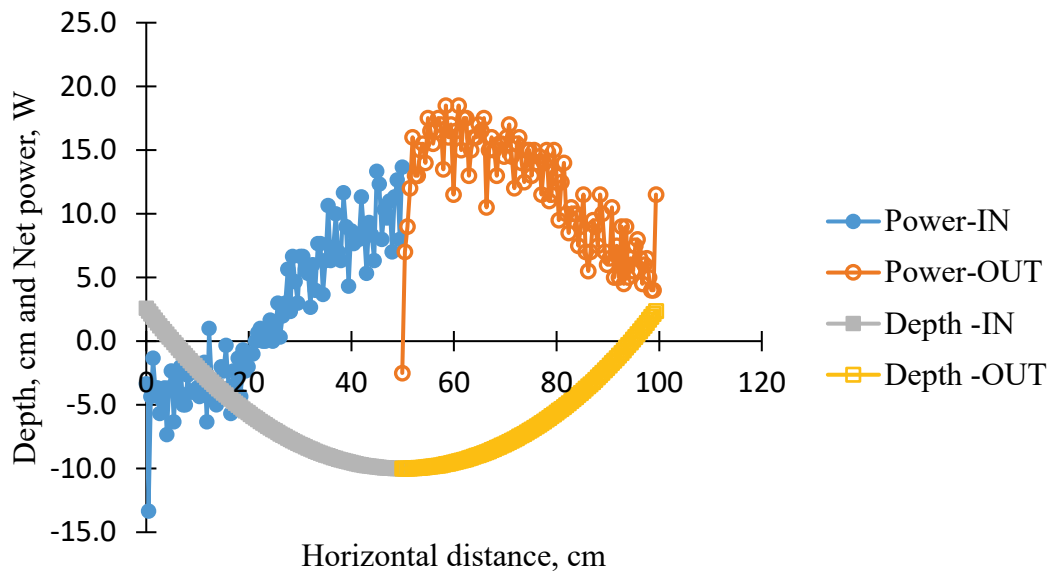


Figure 3. Net power and tip depth of backhoe trajectory in lightly compacted GRC-3B; 5 cm/s, 10° rake angle at 10-cm depth.

The net power for the backhoe trajectory in lightly compacted GRC-3B at 20-cm depth and 10-degree rake angle is shown Figure 4 for comparison. The maximum net power at 20-cm depth was 3.8 times greater than at 10-cm depth for this rake angle and similarly occurs past the mid-point of the trajectory at 83.4 cm. The horizontal distance from tip entry into to exit out of the GRC-3B was 123 cm compared to 89 cm for the trajectory at 10-cm depth. The shapes of the net power curves at 10- and 20-degree rake angles at 20-cm depth and at 10-cm depth are similar.

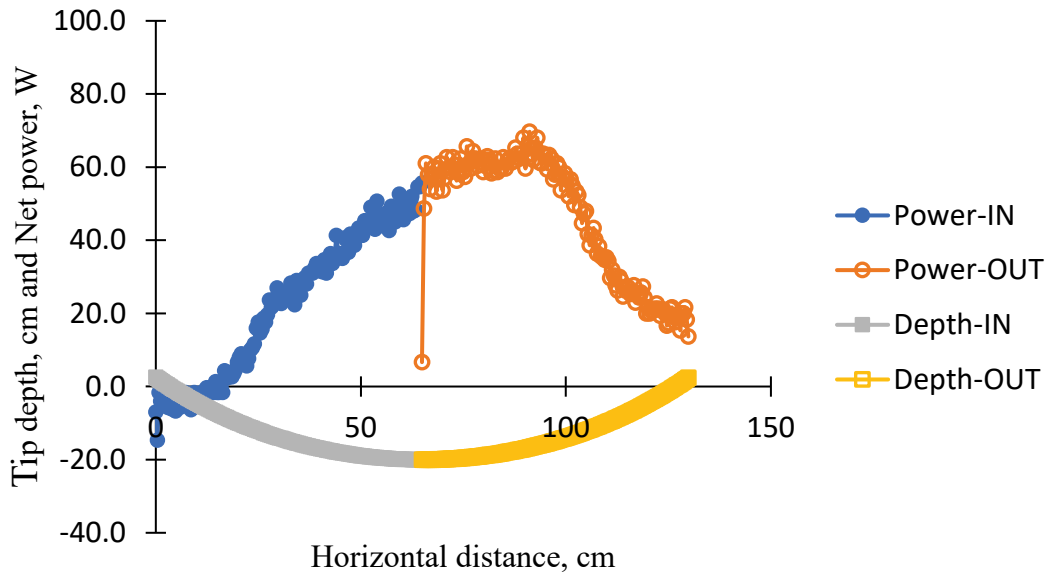


Figure 4. Net power and tip depth of backhoe trajectory in lightly compacted GRC-3B; 5 cm/s, 10° rake angle at 20-cm depth.

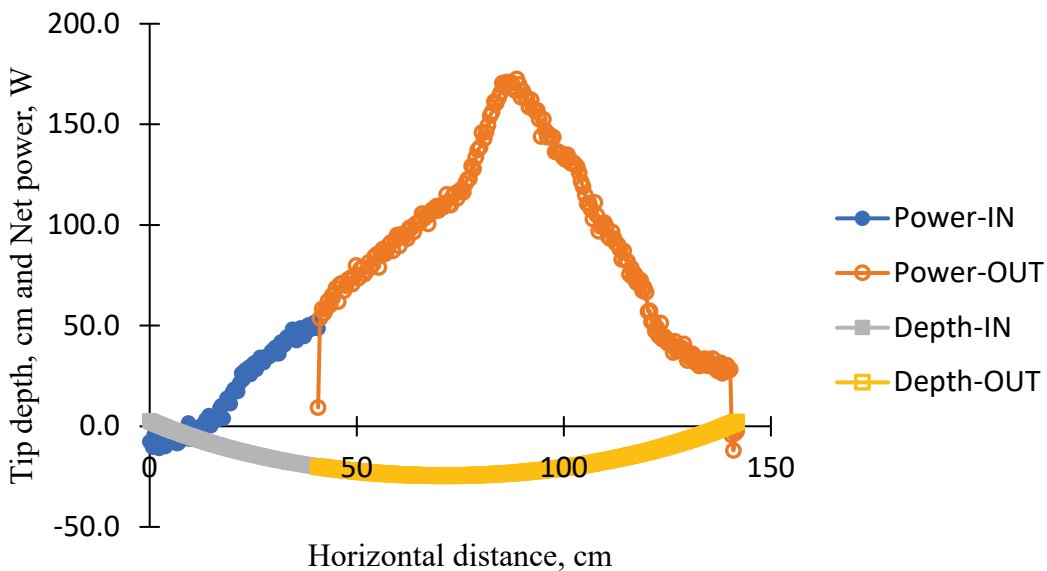


Figure 5. Net power and tip depth of backhoe dig in lightly compacted GRC-3B; 5 cm/s, 30° rake angle at 20-cm depth.

Figure 5 shows the net power for the trajectory in lightly compacted GRC-3B with a 30-degree rake angle at 20-cm depth. For this trajectory the maximum depth was 24.5 cm because the target rake angle and depth could not be reached directly under the elbow joint. The net power curve for the backhoe trajectory at 30-degree rake angle

has four different rates of increase or slopes which become increasingly larger with horizontal distance before the net power begins to drop. Perhaps this is due to the bow wake of the soil increasing the soil depth until the pile collapses into the bucket.

Compacted. The net power curves for the backhoe trajectories in compacted GRC-3B at 5-cm depth are similar in shape to those for the trajectories in lightly compacted soil at 10-cm. The net power for the backhoe trajectories in compacted GRC-3B at 10-cm depth all have curve shapes of the “mesa” variety, meaning the net power rises fairly quickly and, although fluctuating, levels off for about 30 to 40 cm before decreasing. Compared to the trajectories at the same depth, the maximum net power in compacted GRC-3B was 2.2 to 2.8 times higher than in lightly compacted GRC-3B.

Figure 6 shows the net power for the backhoe trajectory in compacted GRC-3B with a 10-degree rake angle at 10-cm depth as a function of horizontal distance. In this figure the mechanical power is also shown. Mechanical power is calculated from the net x and y forces measured with the load cell and is the power consumed due to interaction with the soil. The percentage ratio of the mechanical power to wall power approaches roughly 50 to 60 percent as the trajectory depth and forces increase.

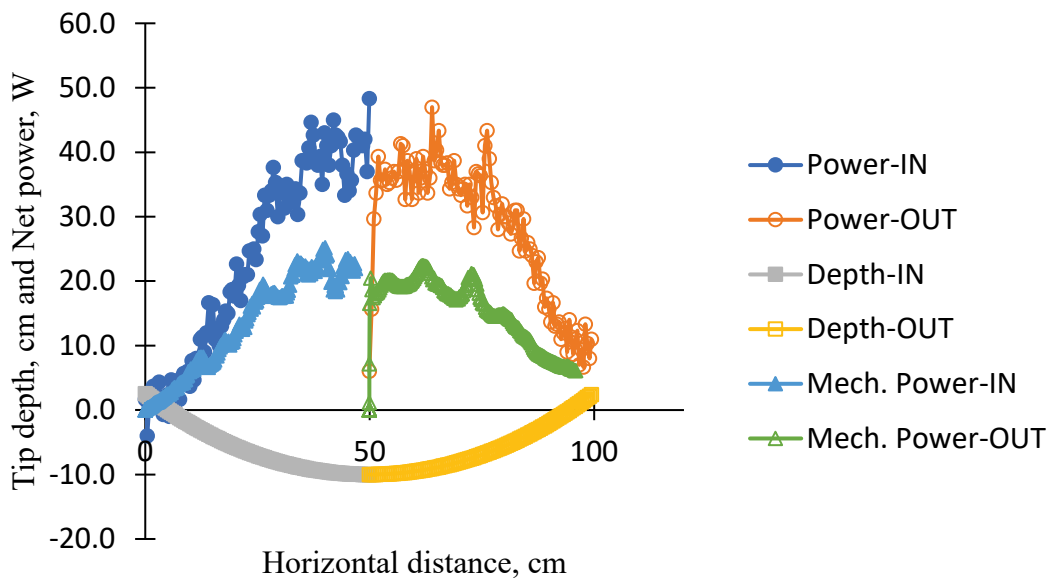


Figure 6. Net power, mechanical power, and tip depth of backhoe trajectory in compacted GRC-3B; 5 cm/s, 10° rake angle at 10-cm depth.

Energy and Mass of soil dug. Summaries of the net energy and mass of GRC-3B dug using backhoe trajectories in lightly compacted and compacted soil conditions are shown in Tables 3 and 4, respectively. Note that the net energy is only the energy to move the bucket through the soil. Additional energy would be needed to close the bucket and lift the soil in it to a desired height. The net energy per mass of GRC-3B dug was computed and is also included in Tables 3 and 4, for lightly compacted and compacted conditions, respectively. Characteristics of the trajectories, specifically the horizontal distance between bucket tip entry and exit, the ratio of the trajectory volume to the bucket volume, and time of the trajectory, are also presented in these tables as is the mass of GRC-3B dug per time of the trajectory. The dig with the highest net energy was in compacted GRC-3B at 20-cm depth with a 10-degree rake angle. The volume of this trajectory was 233 percent of the bucket volume. The trajectory volume was calculated as the bucket width of 21.6 cm multiplied by the area of a circular segment created by the trajectory and the soil surface, where the distance between the tip entry and exit is the chord length of the segment and the depth is the height of the segment. For all the backhoe trajectory tests conducted the net energy ranged from 134.7 to 3240.5 W-s, the energy per mass of GRC-3B dug ranged from 12.3 to 73.3 W-s/kg GRC-3B, and the mass of GRC-3B dug per time of the trajectory ranged from 0.36 to 1.09 kg/s.

Comparing the trajectories at 10 and 20 degree rake angles at the same depth and in the same soil condition one can see that the net energy and the energy per mass dug was lower and the mass dug per time was higher for the 10 degree rake angle trajectory. Hence the trajectories with 10- degree rake angle are more favorable than the 20-degree rake angle. In the lightly compacted GRC-3B, doubling the depth of the dig from 10 to 20 cm increased the trajectory to bucket volume ratio by 2.8 times, increased the net energy by 6.6 times, and increased the energy per mass dug by 2.7 times for the 10 degree rake angle. For the 20-degree rake angle the bucket volume ratio increased by 2.8 times, the net energy increased by 7.2 times and the energy per mass dug increased by 2.5 times. In compacted GRC-3B doubling the depth of the trajectory from 5 to 10 cm increased the trajectory to bucket volume ratio by 2.8 times for both 10 and 20 degree rake angles, and increased net energy by 3.9 and 3.1 times and increased the energy per mass dug by 1.4 and 1.2 times for 10 and 20 degree rake angles, respectively.

Comparison of the 30-degree rake angle trajectories results to those of the 10- and 20-degree rake angles cannot be made since the depth of the trajectories was different. However, comparison can be made between the 30-degree rake angle trajectories in lightly compacted and compacted GRC-3B at 10-cm depth which was really 15.4 and 14.6 cm in lightly compacted and compacted GRC-3, respectively. For these digs the trajectory to bucket volume ratios are nearly the same, with the trajectory volume exceeding the bucket volume by 60 percent. The net energy increased by a factor of 2.1 and the energy per mass of GRC-3B dug increased by a factor of 1.7 when digging in compacted GRC-3B compared to lightly compacted GRC-3B.

Table 3. Summary of results in lightly compacted GRC-3B.

Rake (°)	Depth (cm)	Distance between tip entry and exit (cm)	Trajectory to bucket volume ratio, (%)	Time (s)	Mass Dug (kg)	Net Energy (W-s)	Net Energy Per Mass dug (W-s/kg)	Mass /time (kg/s)
10	10	89	83	20.7	11.59	142.2	12.27	0.56
20	10	91	85	21.0	9.21	142.6	15.48	0.44
30 (11.7)	10 (15.4)	110	159	24.9	21.05 ¹	512.3	24.34	0.85
10	20	123	232	28.0	27.71	934.9	33.74	0.99
20	20	125.6	236	28.5	26.38 ²	1022.3	38.75	0.93
30 (13.4)	20 (24.5)	135.7	315	31.0	29.21 ³	2139.2	73.24	0.94

¹Max depth of swing out was 15.4 cm. ²Bucket over full; ³Some spillage. Max depth on swing out was 24.5 cm.

Table 4. Summary of results in compacted GRC-3B.

Rake (°)	Depth (cm)	Distance between tip entry and exit (cm)	Trajectory to bucket volume ratio, (%)	Time (s)	Mass Dug (kg)	Net Energy (W-s)	Net Energy Per Mass dug (W-s/kg)	Mass /time (kg/s)
10	5	64	30	16.1	6.96	134.7	19.78	0.43
20	5	65	30	16.3	5.85	186.8	31.93	0.36
30 (12.2)	5 (10.1)	90.1	85	20.9	18.69 ¹	542.8	29.04	0.89
10	10	89.6	83	20.6	19.00	532.6	28.03	0.92
20	10	91	85	21	15.22	584.9	38.43	0.72
30 (13)	10 (14.6)	117.7	161	24.5	26.78 ²	1088.0	40.63	1.09
10	20	123.5	233	28.1		3240.5		

¹Max depth on swing out was 10.1 cm; ²Max depth on swing out was 14.6 cm.

SUMMARY AND CONCLUSIONS

To summarize, the power to dig in granular lunar regolith simulant, GRC-3B, using a 21.6-cm wide aluminum bucket with a 30-degree steel leading edge attached to the Advanced Planetary Excavator (APEX) was measured. Tests were conducted in lightly compacted and compacted soil conditions, at dig depths of 5, 10, and 20 cm, and rake angles of 10, 20, and 30 degrees using an arc backhoe trajectory. The trajectories were

also conducted in air to determine the net power to excavate GRC-3B, i.e., the power the digging tool must deliver to the soil to excavate it in addition to the power to move the tool. Maximum net power, net energy, net energy per mass excavated, and rate of mass excavated are tabulated and presented as well as the bucket tip soil entry to exit horizontal distance and the trajectory volume to bucket volume ratio to inform mission planning.

The maximum net power for the backhoe trajectories tested in lightly compacted GRC-3B ranged from 18 to 173 W and in compacted GRC-3B ranged from 16 to 269 W. The net energy for the backhoe trajectories ranged from 135 to 3240 W-s. The energy per mass GRC-3B dug with backhoe trajectories ranged from 12.3 to 73.2 W-s/kg in lightly compacted conditions and from 19.8 to 40.6 W-s/kg in compacted conditions. The rate of mass excavated ranged from 0.36 to 1.09 kg/s. These values do not include lifting the bucket up out of the soil. Soil condition, dig depth, rake angle, and trajectory to bucket volume ratio all affect the net power and energy needed to excavate lunar regolith and the rate at which it can be acquired. The mechanical power, the power consumed by interaction of the bucket with the soil, approached 50 to 60 percent of the net wall power in compacted soil as trajectory depth and forces increased. Power requirements need to account for inefficiencies converting electrical power to mechanical power and could be approximately double the mechanical power due to tool interaction with the soil.

The power measurements provided here for excavating in granular lunar soil simulant, GRC-3B, can provide some insight and guidance to mission planners in developing power requirements for lunar excavation and to designers in developing energy efficient excavation tools and processes. Efforts to correlate properties and behavior of GRC-3B in ambient earth environment to those of lunar regolith in vacuum conditions are recommended as well as additional excavation tests for long-term repeatability. The APEX and the Excavation Lab provide a capability to evaluate the effectiveness, efficiency, and power requirements for various digging tools.

REFERENCES

- He, C., Zeng, X., and Wilkinson, A. (2013). "Geotechnical Properties of GRC-3 Lunar Simulant," *J. Aerospace Eng.* 2013.26:528-534, ASCE.
- Proctor, M., Johnson, K., Thomas, F., and Hau, Y. (2021) "Force Measurements to Excavate Lightly Compacted Granular Lunar Soil Simulant GRC-3B." ASCE Earth and Space Conference.
- Zeng, X. (2018). "Geotechnical Properties of GRC-3B". NASA PC11524609.