Mechanism Development, Testing, and Lessons Learned for the Advanced Resistive Exercise Device

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Abstract

The Advanced Resistive Exercise Device (ARED) (Figure 1) has been developed at NASA Johnson Space Center, for the International Space Station (ISS) program. ARED is a multi-exercise, high-load resistive exercise device, designed for long duration, human space missions. ARED will enable astronauts to effectively maintain their muscle strength and bone mass in the micro-gravity environment more effectively than any other existing devices. ARED's resistance is provided via two, 20.3 cm (8 in) diameter vacuum cylinders, which provide a nearly constant resistance source. ARED also has a means to simulate the inertia that is felt during a 1-G exercise routine via the flywheel subassembly, which is directly tied to the motion of the ARED cylinders. ARED is scheduled to fly on flight ULF 2 to the ISS and will be located in Node 1. Presently, ARED is in the middle of its qualification and acceptance test program. An extensive testing program and engineering evaluation has increased the reliability of ARED by bringing potential design issues to light before flight production. Some of those design issues, resolutions, and design details will be discussed in this paper.

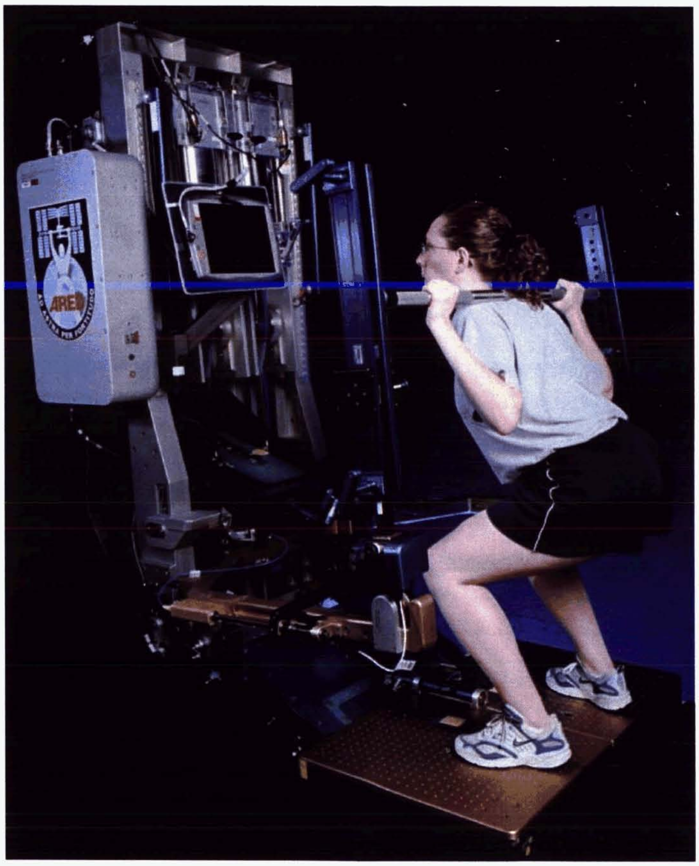

Figure 1. Test subject performing a squat on ARED

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Introduction and ARED Background

This paper will discuss the design, development, and testing of the Advanced Resistive Exercise Device for the International Space Station program. ARED is scheduled to fly on shuttle flight ULF2 and will be located in Node 1 of ISS. ARED is a multi-format resistive exercise machine specifically designed for a zero-gravity environment. Capable of 30 different exercises, ARED will be used daily by the astronauts aboard the ISS to counter the loss of muscle and bone mass associated with long duration human space missions. ARED is being developed at NASA's Johnson Space Center in the Biomedical System Division. The team consists of both civil servant and contractor engineers from many different organizations at JSC. ARED has been developed specifically to improve the on-orbit resistive exercise capability, reliability, and availability. The resistive force is generated by two, 200-mm (8-in) diameter dynamic vacuum cylinders. A vacuum exists on one side of the piston and atmospheric pressure exists on the other. The piston has a stroke of 30.5 cm (12 in) inside the cylinder. The cylinders are capable of delivering a nearly constant load. In combination with various mechanisms, ARED provides a range of 0 – 272 kgf (0 – 600 lbf) to the exerciser, which is important effective zero-g exercise. In addition, the flywheel mechanism simulates the inertial force component of lifting free weights in a 1-G environment. ARED thus provides a more complete weightlifting experience than any previous on-orbit resistance exercise device. It will allow astronauts to perform a wider variety of exercises at higher loads, higher speed, and longer stroke which, in turn, will enable them to maintain their health more effectively in a zero-gravity environment.

The need for ARED, arose out of reliability and performance concerns with previous resistance devices for ISS. ARED is being designed, tested, and certified for a 15-year service life, which is much longer than any previously designed device. This long service life is needed to support long duration space missions, which will require a robust and reliable weightlifting machine. ARED's predecessor, IRED, has a 0 – 136 kgf (0 – 300 lbf) load range whereas ARED will enable the crew to exercise up to 272 kgf (600 lbf). ARED will allow for a wide range of both bar exercises (squat, dead lift, heel raise, etc) and cable exercises (hip abductors, one-arm curls, etc). The load and stroke capability for bar exercises is 0 – 272 kgf (0 – 600 lbf) and a 76.2-cm (30-in) stroke. The load and stroke capability for cable exercises is 0 – 68 kgf (0 – 150 lbf) and a 183-cm (72-in) stroke. ARED's vacuum cylinders have a nearly constant loading profile, which is more medically advantageous than the varying loading profile that is provided by springs and rubber based exercise devices. In addition to providing more constant load than IRED, ARED attempts to simulate the inertia that is felt during free-weight, 1-G exercise by employing a flywheel that is directly tied to the motion of the cylinders. The differences are shown in Table 1.

Table 1. Comparison chart of ARED vs. IRED

	ARED	IRED
Maximum Bar Exercise Load	272 kgf (600 lbf)	136 kgf (300 lbf)
Maximum Bar Exercise Stroke	76.2 cm (30 in)	127 cm (50 in) at low loads 56 cm (22 in) at high load
Maximum Cable Exercise Load	68 kgf (150 lbf)	68 kgf (150 lbf)
Maximum Cable Exercise Stroke	183 cm (72 in)	127 cm (50 in) at low loads 56 cm (22 in) at high load
1-g Free-Weight Inertial Component	Yes	No
Force Profile	Nearly constant throughout stroke	Linearly increasing during stroke

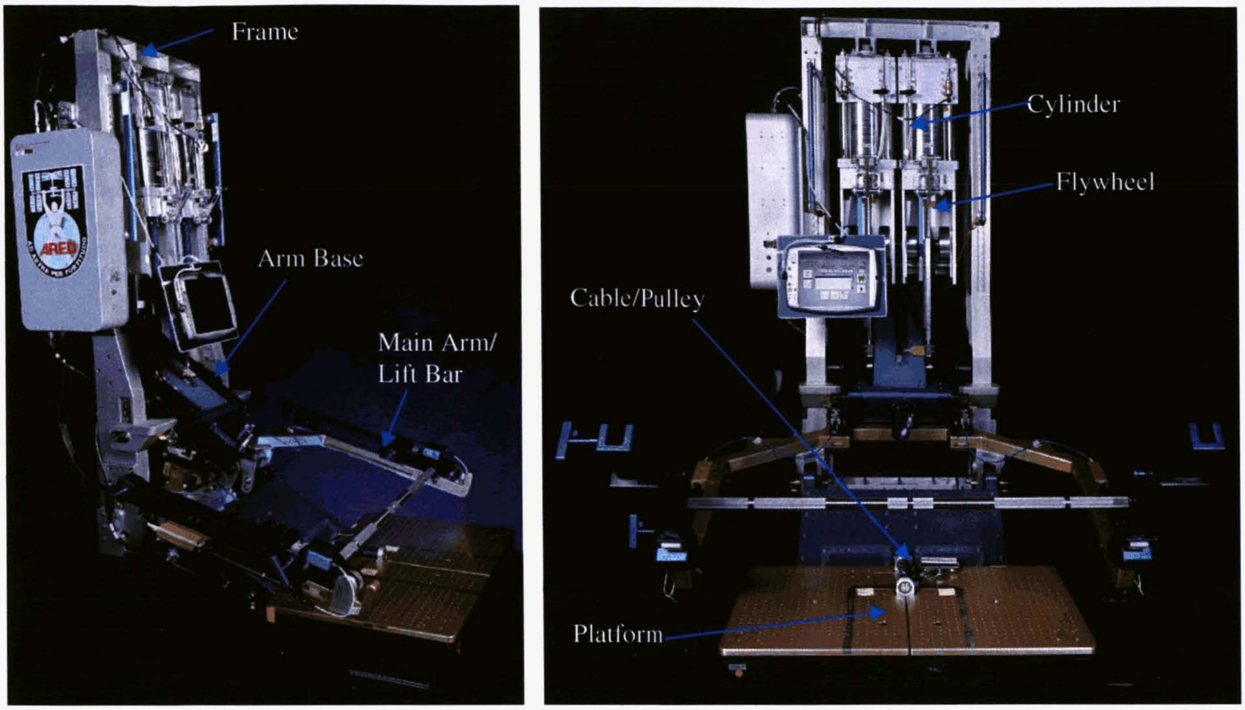

Figure 2. ARED - Man in the Loop Testing Unit - Profile and Front View

General ARED Mechanism Overview

ARED has seven main subsystems (Figure 2); vacuum cylinders, flywheels, frame, platform, arm base, cable-pulley, and the main arm/lift bar. A motion schematic for a squat on ARED is shown in Figure 3. The vacuum cylinders are the main generators of resistive force for ARED. The details of the cylinders will be discussed fully in the next section. The piston rods are attached to the arm base assembly.

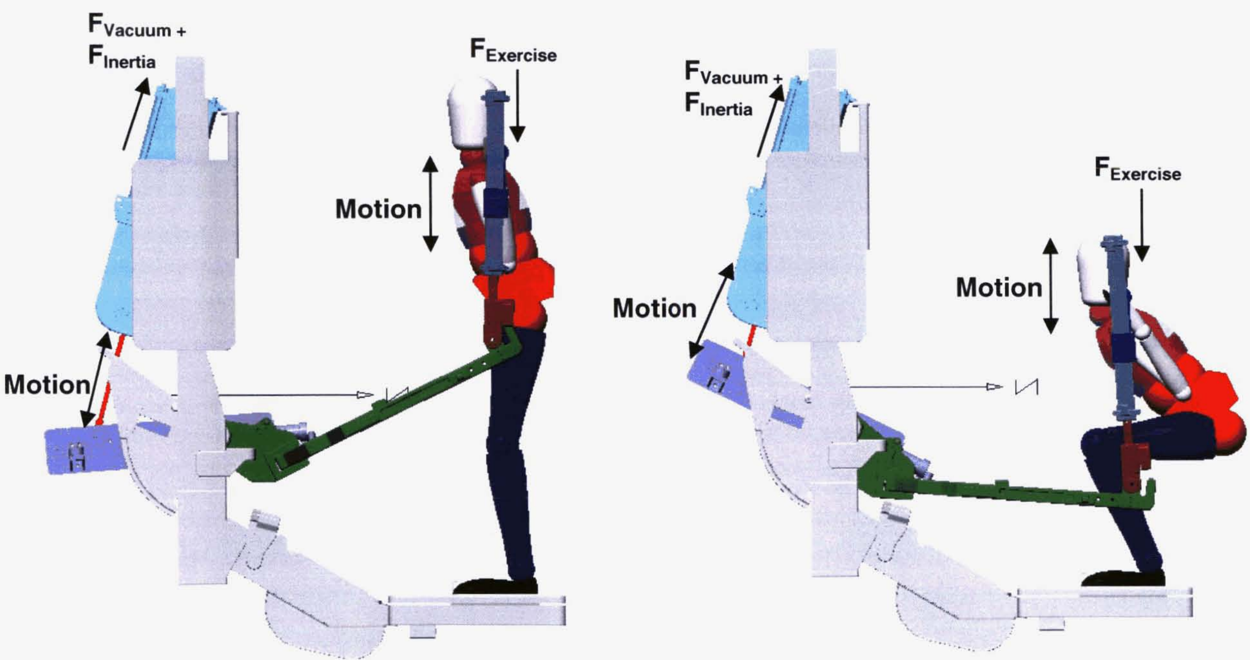

Figure 3. Schematic of ARED showing motion and simple free body diagram

The main purpose of the arm base assembly (Figure 4) is to provide a mechanism to adjust the load setting. A ball screw in the arm base provides this function. By turning the ball screw, the attachment point of the piston rods moves along the ball screw. This changes the moment arm between the pivot point and the cylinder load application point and allow for load adjustment at 1-lb increment. The arm base assembly transfers the load from the cylinders to both the bar and cable exercise hardware. The dual nature of the arm base minimizes the reconfiguration required to switch between the two types of exercises, resulting in a more efficient exercise routine. Details of the arm base will be discussed later.

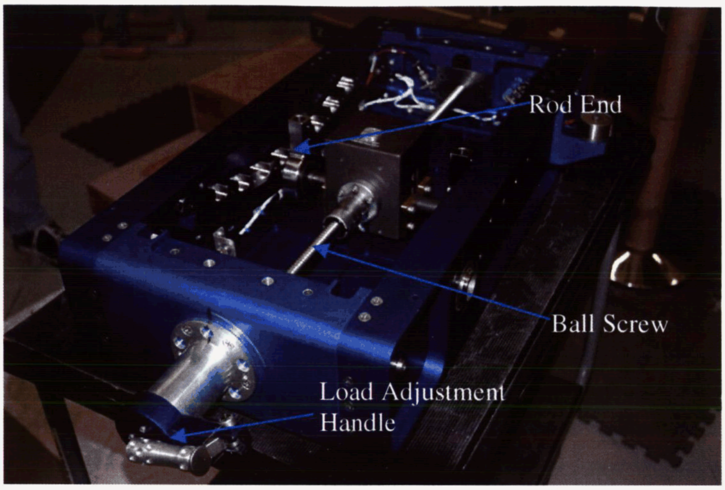

Figure 4. ARED Arm Base Assembly (Top Cover Removed)

The flywheel assembly is mounted to an end cap of the cylinder and directly meshes with the motion of the piston by means of a gear and gear rack. The details of the flywheel assembly will be discussed in the next section.

The main arm and lift bar assembly (Figure 2) transfers the load from the arm base to the exerciser. The main arm assembly lifts the front end of the arm base using a contact surface. The lift bar portion of the assembly allows for bar adjustment from 25.4 cm (10 in) above the platform to 183 cm (72 in) above the platform. This wide range of adjustment allows for any bar exercise from a dead-lift to a squat and accommodates a range of human subject from 5th-percentile Asian female to 95th-percentile American male. As with free weights, the position of the bar can also be "racked" using the upper stop mechanism. The upper stop mechanism allows the crew to start the squat and heel-raise exercises from a standing position.

The cable-pulley assembly also transfers the load from the arm base to the subject. The cable arms push down on the rear portion of the arm base assembly (Figure 5). The cable-pulley assembly enables a variety of cable exercises such as one-arm cable row, hip abductions, and one-arm curls. It employs a series of pulleys, timing belts, and cables to achieve this function. One of the pulleys in the assembly is cammed to compensate for geometry changes during the stroke in order to create a constant load at the end of the exercise rope. The pulley ratios provide a maximum of 136 kgf (300 lbf) and 183 cm (72 in) of stroke.

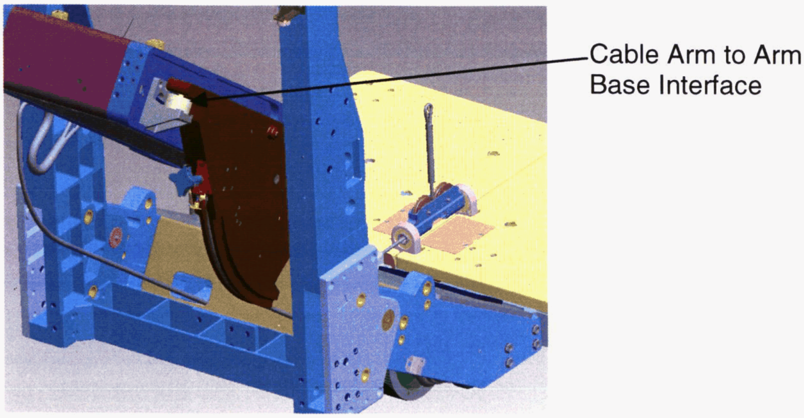

Figure 5. Detail showing the cable arms pushing on the back of the arm base assembly

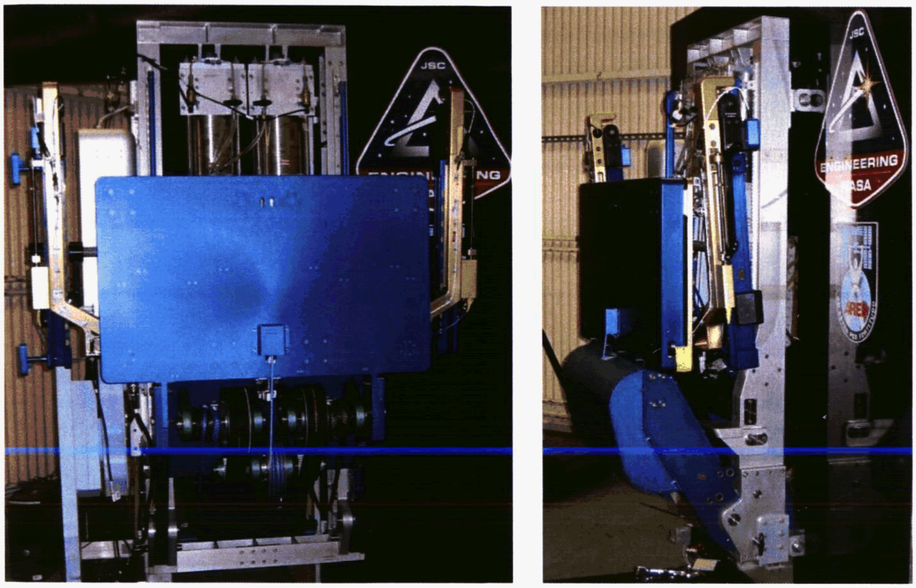

Figure 6. ARED in the folded configuration
Front view shows the details of the cable pulley mechanism.

The platform (Figure 7) assembly's main purpose is to provide an adequate exercise surface and to provide containment for some of the pulleys for the cable-pulley mechanism. Its secondary purpose is to house load cells and wiring for the instrumentation system. The platform and main arm also can be folded up (Figure 6) to aid in storage and crew translation on ISS.

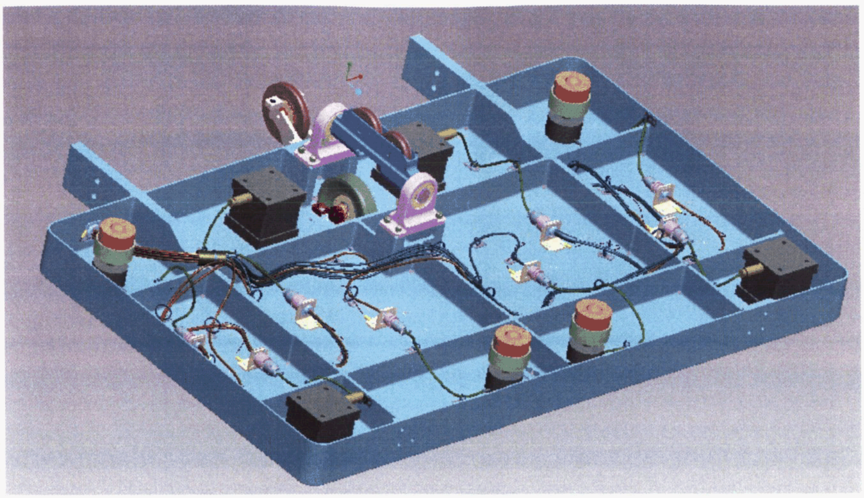

Figure 7. Picture of the platform CAD model with the footplates removed.
This shows the electronics inside the platform assembly.

Vacuum Cylinder Design Details

There are two vacuum cylinders (Figure 8) used on ARED. Each cylinder provides a constant 340-kgf (750-lbf) load. The design uses a standard cylinder/piston concept with endplates and four tie rods holding the assembly together.

The original cylinder shell was made of 6061-T6 Al, anodized on the outer surface, and left bare on a 16 RMS ID surface. Braycote 601 lubricant was applied to the entire ID of the cylinder shell. Early vacuum cylinder tests indicated that the surface finish of the interior surface, measured in RMS, is the critical parameter in maintaining a vacuum, while the piston is moving. The current flight design calls for a 20.3-cm (8-in) ID with an 8 RMS or better surface finish, 4.8-mm (0.19-in) wall thickness, and is 38.1 cm (15 in) in length. To achieve the best possible surface finish, three different manufacturing methods were tried; ground and honed, electro polish, and hand polish. Results showed that the ground and honed process provided a more consistent and controlled surface finish while maintaining the required roundness. To date, the best surface finish achieved is less than 1 RMS on an aluminum 6061-T6 cylinders, manufactured at the Micro-machining Department at NASA's Glenn Research Center.

The current flight piston design is made from 6061-T651 Al using a Nylon Molygard wear strip and a self lubricating Carboxilated Nitrile U-ring seal from Parker Hannifin Corporation. The open end of the U-ring seal is oriented toward the pressure side of the piston. Braycote 601 lubricant is applied to the wearstrip and u-ring seal. Three different wearstrip/u-ring seal combinations were evaluated to achieve the most efficient vacuum under dynamic conditions.

1. A single wearstrip with a single u-ring seal.
2. A single wearstrip with 2 u-ring seals.
3. A single wearstrip with a spring-energized u-ring seal.

Through a series of tests, it was determined that option 1 worked well as long as the manufacturing and assembly tolerances (Figure 8) were controlled. With such a large diameter piston/cylinder and long stroke, it was important to maintain perpendicularity and parallelism between the piston, piston shaft, and cylinder wall. A jig was designed to assist in assembling the cylinder and piston to the required alignment.

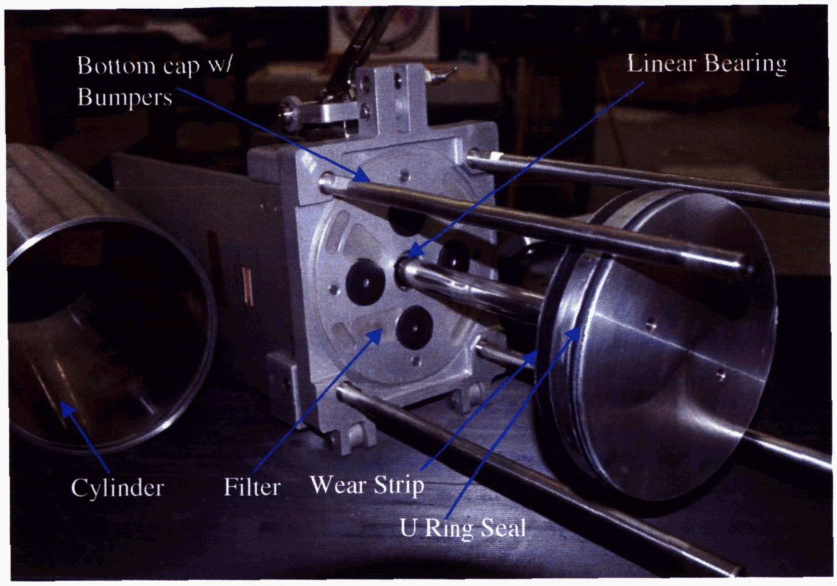

Figure 8. Piston/Cylinder Design

The bottom end cap design, also 6061, includes a Linear Bearing packed with Rheolube 2000 grease. This bearing interfaces with the piston shaft made of 15-5 PH stainless steel and heat treated to a H1025 condition. The shaft has a circular cross section the length of the piston stroke that interfaces with the linear bearing. The remaining portion of the shaft is rectangular for attaching a gear rack used to drive the flywheel. The bottom cap design includes a Fluorocarbon rubber bumper and a 3.2-mm (0.125-in) thick polyester grade polyurethane foam filter. The foam filter was added to the bottom end cap design to restrict airborne debris from being sucked into the cylinder. The rubber bumper prevents piston damage in the event of bottoming out during assembly (Figure 8).

The head cap, on the vacuum side of the piston, is 6061 Al and is sealed with the cylinder shell using a standard Butyle rubber o-ring seal. The head cap also includes a relief valve and a fluorocarbon rubber bumper. To evacuate the cylinder, the relief valve is opened and the piston is pushed to the top of the stroke and bottomed out against the rubber bumper. The valve is then closed (Figure 9), and a vacuum is established.

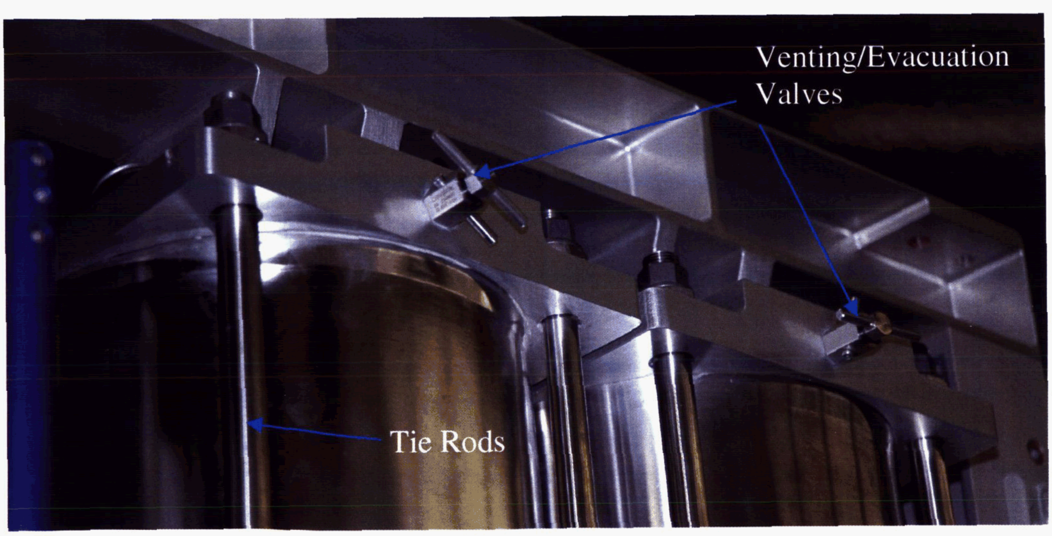

Figure 9. Assembled Cylinders showing top caps and valves for venting/evacuation

Design Details – Flywheel Assembly

The flywheel assembly is the component of ARED that simulates the inertial effect of weightlifting in 1-g environment. When lifting free weights in 1-g, the total foot reaction force is dependent on the acceleration of weights on the exerciser's shoulders. While performing a squat, this inertial effect creates a spike in load at the bottom of the stroke and load relief at the top of the stroke. The exercise physiology community speculates that this inertia spike plays a major role in increasing bone density in 1-g and, by the same effect, slows the rate that bone density is lost in a zero-g environment.

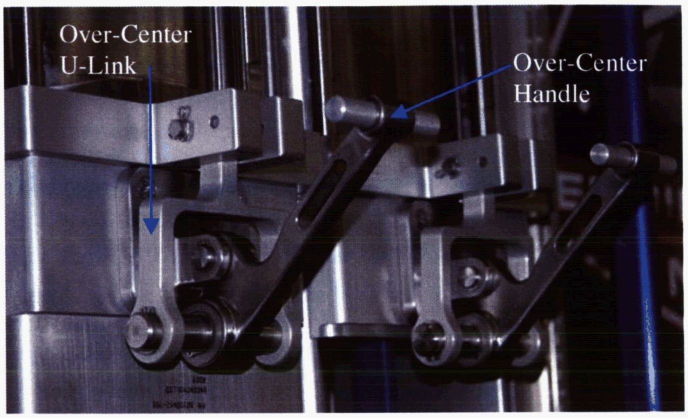

Figure 10. Picture showing the over-center mechanisms, in the locked position, between the flywheel and cylinder assembly

The flywheel assembly mounts to one end of the cylinder assembly. It attaches using a hinge and an over-center mechanism (Figure 10). The purpose of this attachment method is to allow for the flywheel mechanism to be engaged and disengaged depending on the exercise and the preference of the user. A U-link (Figure 11) deforms during actuation and allows for the mechanism to go over-center. The design of the U-link was challenging, because it had to elongate by 0.43 mm (0.017 in) and still be under the allowed stress limits. After using the first prototype, it was obvious that the tolerance stack-up between the hinge and the over-center mechanism made a significant difference in the over-center force. In order to better control the over-center force, an eccentric spline bushing (Figure 11) was used in the over-center handle. The hole in the bushing is 0.64 mm (0.025 in) off-set from the center of the bushing. The offset allows for small adjustment of the over-center force.

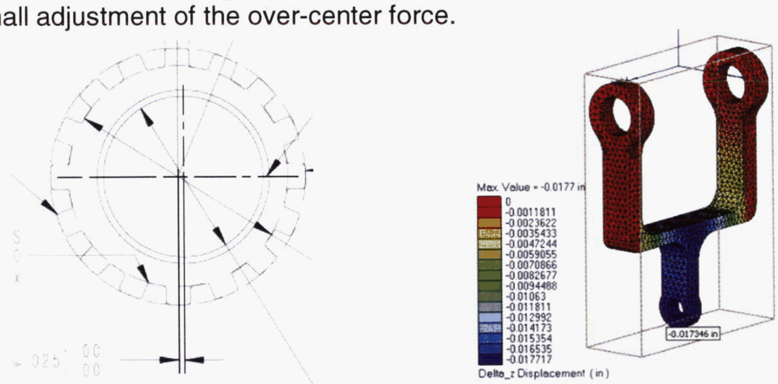

Figure 11. Detail of spline bushing and displacement analysis of the over-center u-link.

The heart of the flywheel assembly is a set of three gears and two inertial flywheels (Figure 12). The spur gear meshes with a spur gear rack on the piston rod which makes the motion of the flywheels directly tied to the motion of the cylinders of ARED. The flywheels provide the most load and rotate the fastest at the higher load settings of ARED due to the longer cylinder stroke. This flywheel design uses a fixed gear ratio and a fixed mass for the flywheels. While this design is simple, it only allows for the inertia to be tuned to one combination of exercise subject mass, exercise subject deceleration, and free weight mass. The ARED flywheels do not account for the changes in the exerciser subject's mass. They do, however, adjust to the exercise subject's deceleration and free weight load. The flywheels add more load into the system at higher load settings, because the piston moves further per stroke, in the same amount of time. Also, a faster deceleration of the exercise subject causes the flywheel to decelerate faster as well. This increases the inertial load felt at the lift bar. In the beginning of the project, the flywheels were tuned to a 227-kgf (500-lbf) squat setting on ARED with a 2 second period and 76.2-cm (30-in) stroke. After ARED is on-orbit for a significant amount of time, the flywheels could be tuned to a more optimal load setting and stroke. This would need to be determined from statistical analysis of the exercise frequency, load, and stroke data from on-orbit use. A chart showing the calculated variation from the true 1-G inertia is below (Figure 13).

The assembly contains one spur gear and two helical gears. The spur gear has a 38-mm (1.5-in) pitch diameter, the large helical gear has a 127-mm (5.0-in) pitch diameter, and the small helical gear has a 38-mm (1.5-in) pitch diameter. The spur gear is made out of 17-4 PH SS and the teeth are also ion nitrided to provide a longer life of the gear teeth and to prevent pitting. The helical gears experience lower loads and are not ion nitrided. The initial prototype of the flywheel assembly used two lubrication methods to determine which would perform better. One gear set employed standard lubrication (Rheolube 2000) while the other had a ceramic dry-film lubrication called Vitro-lube. Our initial life-cycle test showed that standard lubrication was more reliable. Early in our life-cycle test, the Vitro-lube began to flake off significantly. As a result, the team opted to go with standard lubrication.

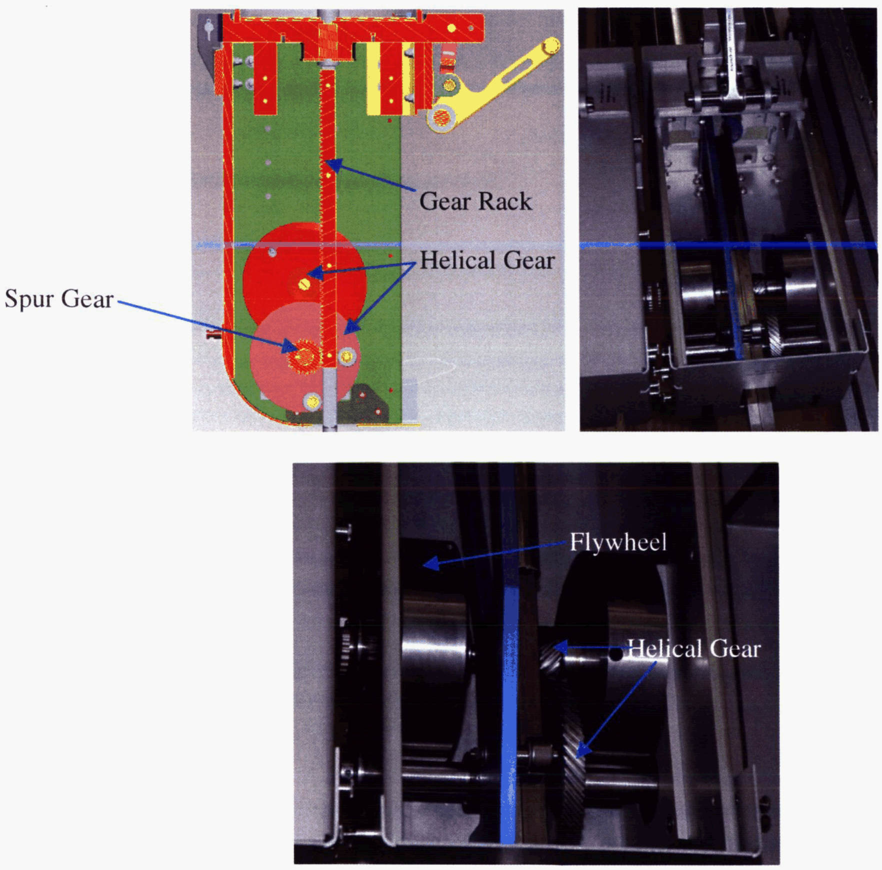

Figure 12. Flywheel assembly with front cover removed and close up of gears and flywheels. The spur gear is not visible. A cross-section view through the spur gear teeth is also shown for clarity.

The flywheels are 14 cm (5.5 in) in diameter and 4 cm (1.6 in) thick, stainless steel. As mentioned previously, their inertial properties and the gear ratios were specifically chosen for the 227-kgf (500-lbf) load setting on ARED. The flywheels can see a maximum speed of 800 rpm. Therefore, when the exerciser reaches the bottom of the stroke, and stops the flywheels from spinning, the flywheels could deliver a maximum of 91 kgf (200 lbf) extra at the lift bar. This would occur at the 272-kgf (600-lbf) load setting, 76.2-cm (30-in) stroke, and a 2 second period. It is highly unlikely that anyone will exercise at this load, speed, and stroke. However, these parameters were the maximum range of the project's requirements.

In order to protect the exerciser and the ARED hardware from overloading, the flywheels are directly in line with a friction disk slip-clutch. This slip-clutch is set to slip at 3.39 N•m (30 in•lbf) of torque which is less than 10% more torque than the maximum load described in the previous paragraph. The slip-clutch eliminates concerns of excessive loading being imparted on the device.

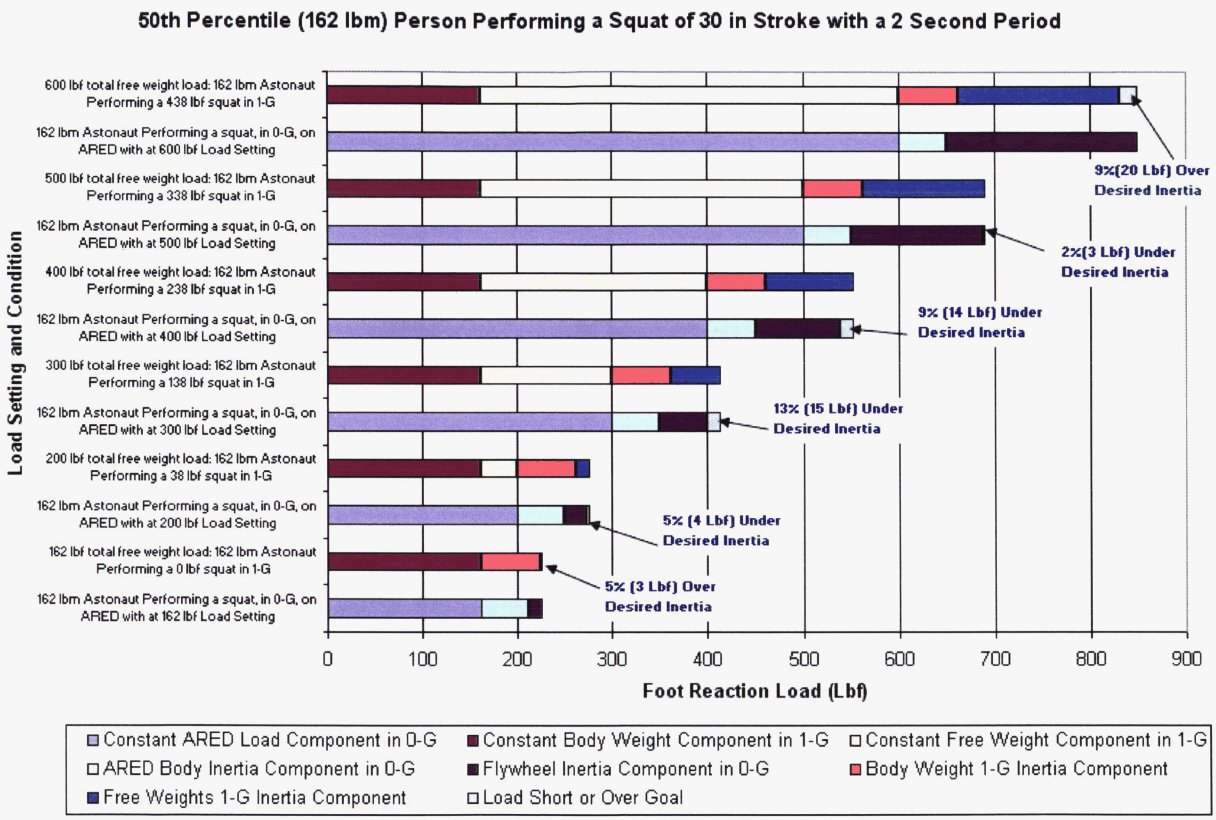

Figure 13. Chart comparing the load contributions during 1-G free weight squat exercise and squat exercise on ARED in a 0-G environment. This chart is for a 50th percentile astronaut performing a 76.2-cm (30-in) squat with a 2 second period at 45.4-kgf (100-lbf) increments. It shows that the inertial variation between ARED exercise and 1-G exercise is relatively small.

Design Details – Arm Base Slider

Each cylinder shaft is attached to the arm base slider through a rod-end with a spherical bearing. The slider is attached to a ball screw, in the arm base, with a slider housing (Figure 14Figure 16Figure 17). The ball screw is used to adjust the exercise load of ARED. This is done by changing the moment arm between the pivot point of the arm base and where the cylinders attach. A scale and position indicator is provided on the arm base cover to aid in this load adjustment. The attachment to the ball screw uses a housing/slider design that follows curved tracks (Figure 17) on the sides of the arm base with cam rollers.

The track is curved to minimize force non-linearity as a function of load adjustment. The slider moves up and down inside the housing, which is attached to the ball screw, as the slider follows the tracks (Figure 17).

The life cycle design requirement for ARED is 15 years. A preliminary test was run on an engineering unit of the arm base and cylinders at various load settings. During this test, at a 181-kgf (400-lbf) load setting, the slider housing broke into 2 pieces (Figure 15) at 318,000 total cycles. After close evaluation, it was determined that the stress analysis overlooked a critical load case. There was more moment on the housing than first calculated and a fatigue analysis had not been done. As a result of the improved analysis, the slider housing was thickened and strengthened with closeout plates. The original housing was made of 7075 Al with a Tufram surface coating to increase surface hardness, extend wear, and reduce friction. During the test, the slider did not slide very well along the Tufram surface. As a result, rollers were also added to the slider design to reduce friction and to implement a zero clearance fit between the slider and housing. With the new rollers added to the slider, steel wear plates had to be added to the inside of the slider housing (Figure 16), to increase the life of the assembly.

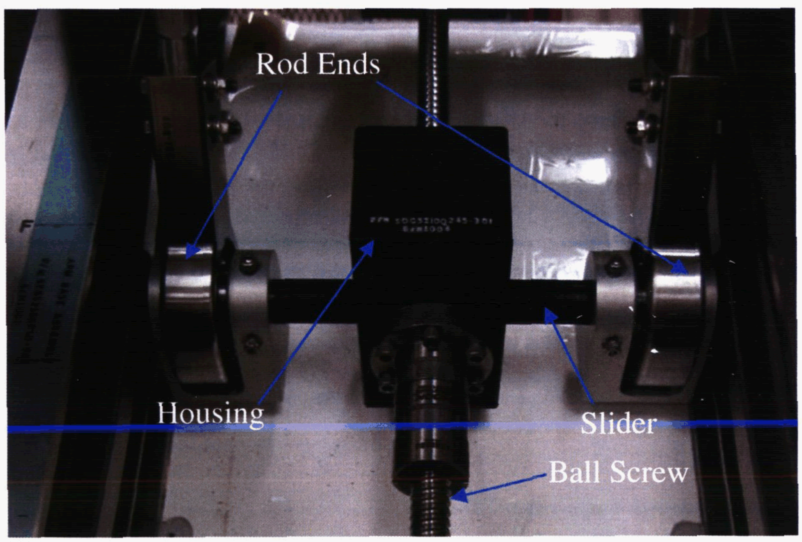

Figure 14. Old Slider/Housing Design for Arm Base

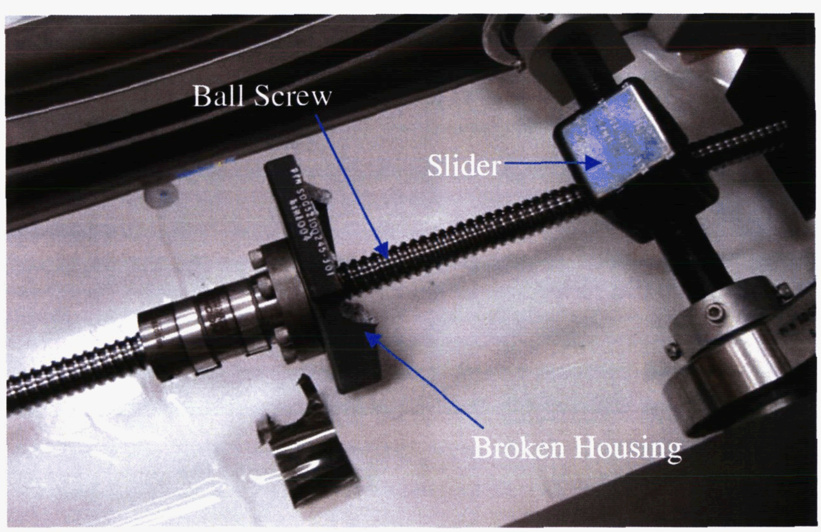

Figure 15. Old Slider/Housing design during life cycle test showing broken Housing

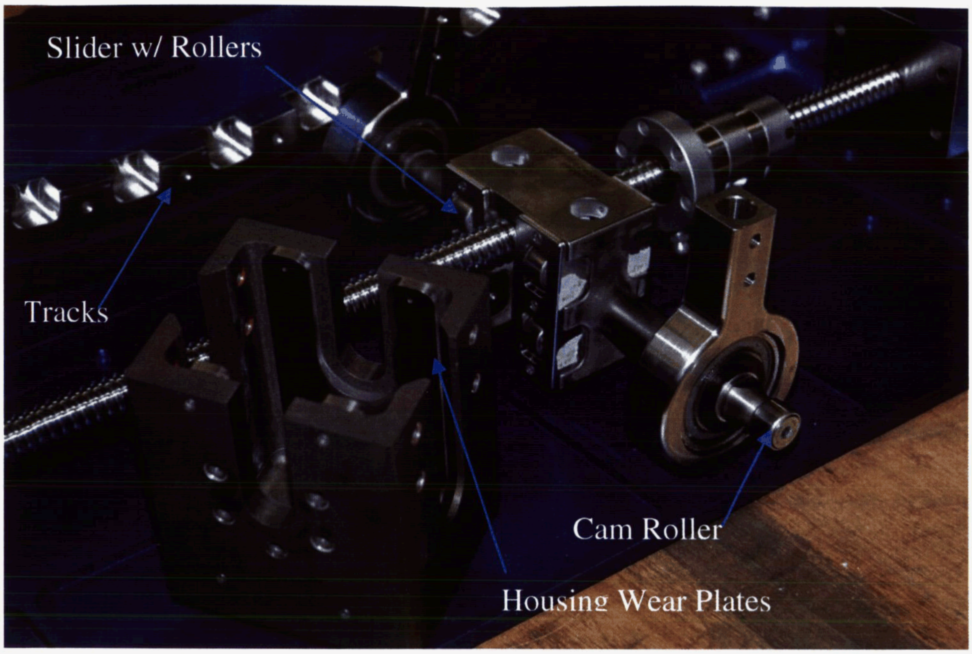

Figure 16. New Slider/Housing Design showing slider w/ rollers and Housing wear plates

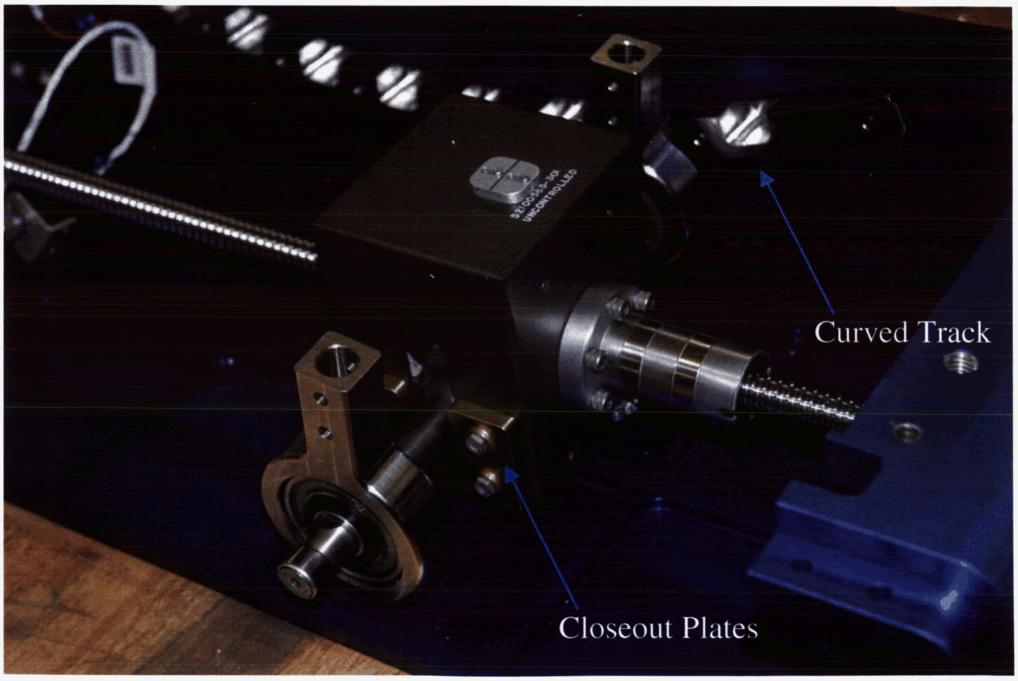

Figure 17. New Slider/Housing design attached to ball screw showing closeout plates

The team also performed an engineering life cycle test on the arm base/load adjustment components. This test rotated the ball screw and drove the rod ends back and forth along the length of the arm base. The purpose of this test was to prove the critical components in the arm base assembly. This test was a success and cycled the ball screw for 33,000 m (1.3 million in) of travel, before failure. Assuming a six person ISS crew and various uncertainty factors, this would be enough ballscrew life to last for ~14 years on-orbit. According to Nook, the manufacturer of the ball screw, the failure was a classical fatigue failure of a ball screw and ball nut assembly.

Testing – Development

As has been discussed, ARED is well into the testing phase of the project. Below is a summary of ARED's testing program.

<u>Preliminary Life Cycle Units</u>
Two life cycle test rigs were built. Rig 1 was intended to exercise the cylinder/flywheel, the main arm, the arm base, and the pivot arm. Rig 2 was intended to exercise the ball screw and the arm base slider housing. Rig 1 was used to evaluate different design parameters, especially in the piston/cylinder interface. At the end of development phase, rig 1 has accumulated 320,000 cycles. Rig 2, as mentioned in the previous section, produced 1.3 M inches on travel on the ball screw. Both Rig 1 and Rig 2 will be modified and upgraded to serve as the qualification lifecycle test beds.

<u>Hi-Fidelity Engineering Unit</u>
Lessons learned from testing on Rig 1 and Rig 2 were incorporated into the design. To further increase confidence in the design, a Hi-Fidelity Engineering Unit was constructed, using near-flight-quality drawings. This Hi-Fidelity Engineering Unit was used for Man-In-The-Loop testing, with the intent of evaluating human-machine interface issues and ergonomic issues. Over a period of five months, forty-three human subjects performed 700 workout sessions on this unit, accumulating over 150,000 cycles. The unit was also used extensively by the team to evaluate various design modifications as well as to develop operational and maintenance procedures. In addition, astronauts with long-duration spaceflight experience on both Shuttle and ISS were invited to exercise on ARED to identify issues unique to zero-gravity such as the location of handrails and foot restraints.

Certification of Flight and Qualification Units

Having established high confidence through development testing on Rig 1 and Rig 2 and the Hi-Fidelity Engineering Unit, production of three flight-quality ARED units are underway and should be nearing completion at the time of this symposium. One unit (Dash 301) will be designated for delivery to the International Space Station, the second unit (Dash 302) will serve as the Lifecycle Qualification Unit, and the last unit (Dash 303) will be the General Qualification Unit.

The ARED Qualification and Acceptance Test Plan stipulates that each of ARED's components must be subjected to an Acceptance Vibration Test (AVT). This test is intended to be a workmanship screen. The Flight Unit, Dash 301 will then undergo a series of functional tests and packaged for launch. Dash 302, after a series of functional tests, will be installed on Rig 1 and Rig 2 and undergo continuous lifecycle testing. Current requirements state that ARED must successfully complete 1.5 M cycles on the ground in order to qualify the Flight unit for one year of on-orbit usage (6 crew members, exercising 1.5 hours per day, and 6 days per week). Results from lifecycle testing on Dash 302 will be used to determine maintenance and re-supply plan for the on-orbit Flight Unit. Dash 303, will be subjected to a launch vibration test (QVT) and an acoustic emission test. In between these tests, Dash 303 will undergo a series of functional tests.

At the conclusion of the Qualification and Acceptance Test Program, Dash 303, along with the Hi-Fidelity Engineering Unit, will become crew training units and/or research test beds for ground-based physiological studies.

Conclusion

The most important lesson that the team has learned in the course of the ARED project is that prototyping and development testing is paramount and indispensable for developing a robust, reliable, complex mechanical system. Good initial designs are important as well, but nothing can replace developmental testing as a means to flush out design, manufacturing, assembly, and human-machine issues. Although not popular, a prototype-centric development phase, in advance of flight production, will result in fewer design problems, fewer modifications, fewer design iterations and, in the long run, decreases cost and schedule. As a result of ARED's extensive prototyping and testing, both in the developmental phase and the certification phase, the team is extremely confident that ARED will perform well on the International Space Station and provide years of effective resistive exercise for the crew. Furthermore, as NASA prepares to implement the President's Exploration Initiatives, ARED's technology will be mature and proven in time to support long-duration expedition to the Moon and Mars.