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Results of the International Space Station Interim Resistance Exercise Device Man-in-the-Loop Test

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February 2004

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Contents

Contents

(continued)

Acronyms

ASCR	Astronaut Strength and Rehabilitation
ISS	International Space Station
iRED	Interim Resistance Exercise Device
MILT	Man-in-the-Loop Test
NASA-JSC	National Aeronautics and Space Administration – Johnson Space Center

Abstract

The Interim Resistance Exercise Device (iRED), developed for the International Space Station (ISS), was evaluated using human subjects for a "Man-In-The-Loop Test" (MILT). Thirty-two human subjects exercised using the iRED in a test that was conducted over a 63-working-day period. The subjects performed the same exercises that will be used on board ISS, and the iRED operating constraints that are to be used on ISS were followed. In addition, eight of the subjects were astronauts who volunteered to be in the evaluation in order to become familiar with the iRED and provide a critique of the device. The MILT was scheduled to last for 57,000 exercise repetitions on the iRED. This number of repetitions was agreed to as a number typical of that expected during a 3-person, 17-week ISS Increment. One of the canisters of the iRED failed at the 49,683-repetition mark (87.1% of targeted goal). The remaining canister was operated using the plan for operations if one canister fails during flight (contingency operations). This canister remained functional past the 57,000-repetition mark. This report details the results of the iRED MILT, and lists specific recommendations regarding both operation of the iRED and future resistance exercise device development.

I. INTRODUCTION

Loss of muscular strength and endurance were common findings for crewmembers returning from even short-duration (i.e. Space Shuttle) flights and were reported during the Extended-Duration Orbiter Medical Project (1). These changes were particularly pronounced in the musculature of the trunk (back/abdomen) and upper leg. Strength and endurance decreases of the musculature supporting knee extension and flexion have also been observed in crewmembers returning from longer-duration (i.e., space station *Mir*) missions (2). In addition, muscle volume data of the legs and lower back indicate a decrease of approximately 15%-25% in crewmembers returning from longer-duration missions (3). Lean body mass and total body bone mineral content of these crewmembers were decreased by ~3.5%, and a regional bone mineral loss of 13% was observed in the pelvis.

Exercise during spaceflight has been proposed as a countermeasure against muscle strength and muscle volume loss, and against loss in bone mineral content. To date, the cycle ergometers and treadmills used on both U.S. and Russian spacecraft have been designed primarily to support aerobic activity. While some strength-type exercises have been performed, primarily bungee-supported resistance exercises performed on *Mir*, these do not appear to be completely effective in mitigating loss of muscular strength, lean body mass and bone mineral content. Indeed, the *Mir* data reported above are from astronauts and cosmonauts who participated in the Russian system of countermeasures, which included a bungee-supported resistive exercise component. These observations led to the recommendation for a device on ISS that will provide higher levels of resistance-type training during flight than has been possible to date.

The Interim Resistance Exercise Device (iRED) was developed for ISS, as a component of the Crew Health Care System hardware, to provide resistance exercise in a microgravity environment (Illustration 1).

The iRED mechanism, put in its simplest terms, is designed to allow an individual to exercise against resistance provided by an elastic polymer. The primary component of the iRED consists of two canisters, each of which contains a number of “flex packs” stacked on each other in series (Illustration 2).

Illustration 1. The iRED device, configured for heel-raise exercise. In this illustration, the exerciser is also using bungee augmentation (note the white Nomex-covered bungee cords behind the narrow primary iRED cord) to increase the total load applied.

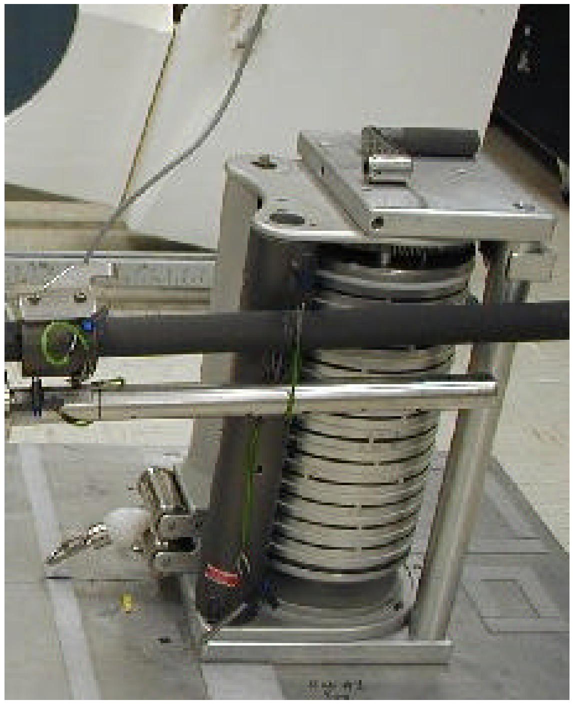

Illustration 2. An iRED canister with the outer cover removed. The flex pack rims are visible stacked in the iRED device.

Each of the flex packs consists of an outer aluminum rim to which elastic polymer spokes are attached (Illustration 3).

Illustration 3. Top view of a flex pack in the iRED. The central metal shaft is inserted through the middle of the flex packs and allows utilization of all of the flex packs in the iRED for resistance loads.

At the center of each flex pack is an aluminum hub, to which the other ends of the elastic spokes are connected. The appearance of each individual flex pack is similar to a traditional bicycle wheel, with thick elastic spokes instead of thin metal ones. A metal shaft is fitted up through the aluminum hub in the center of the flex packs. The bottom of this shaft is fastened to a spiral pulley. A nylon cord is wrapped around the spiral pulley. One end of the nylon cord is attached to the spiral pulley, and the other end of the cord passes though two rollers to the exterior of the iRED canister. The nylon cord end on the exterior of the iRED passes through a stopper device consisting of an elliptically shaped plastic stopper and a metal protective ring. The cord termination point is interior to the protective metal ring and consists of the cord bending around a metal loop-guide, then being stitched back upon itself. The loop is threaded around a metal guide that is the interface between the iRED and the exercise-specific accessories (for example, a grip handle can be attached to the loop to perform arm-conditioning exercises, or the harness can be attached at the loop to perform squats and heel raises).

The "Man-In-the-Loop-Test" (MILT) of the iRED was conducted to evaluate the life cycle of the iRED using similar exercise and training configurations that will be used on ISS. The MILT marked the first time that human subjects tested all the components of the iRED in an integrated fashion. The iRED was life-cycle-tested as a unit using a mechanical test rig at Wyle Laboratories (test terminated in June 2000). During this testing, the iRED was exposed to 149,000 cycles before failure. Using a safety factor of 2, the iRED was flight certified for 74,500 cycles. It was postulated that the mechanical test rig did not adequately emulate the stresses on the iRED that would be imposed by usage of differing human subjects. Human subjects will impart varying angles of pull, velocities of use, etc., whereas the mechanical test rig did not. The MILT was to provide additional confidence that the device would function during its planned usage period (further defined in the methods section) on board ISS. In addition, before the MILT, members of the astronaut corps had relatively little experience with the iRED. Therefore, the purposes of the iRED MILT were to:

(1) Determine if the iRED device, when used by human subjects in a similar manner to the planned on-orbit use, would have an operational lifetime that would support a 3-person crew performing resistance exercise for an ISS Increment.

(2) Allow astronauts an opportunity to use the iRED and provide feedback.

(3) Document the degradation in forces due to wearing of the flex pack elastic polymer material over time.

(4) Identify any design modifications necessary to enhance the device.

II. METHODS

Three groups from NASA-JSC collaborated as a team for the conduct of the MILT: the Exercise Physiology Laboratory, the iRED Engineering group from the Engineering Directorate, and the Astronaut Strength and Conditioning group. The roles of these groups are outlined in Table 1.

Table 1. Groups Involved in the MILT and Their Roles

Exercise Physiology Lab	Hardware and Engineering Group	Astronaut Strength and Conditioning Group (ASCR)
Manage MILT evaluation Recruit subjects Conduct Test Readiness Review Develop exercise protocols for each subject (consult ASCR group for astronaut subjects) Train subjects in proper equipment usage and form Supervise and monitor all exercise sessions Collect and log evaluation data Calibrate canisters on weekly basis Prepare final report upon completion of testing	Provide input regarding hardware evaluation Provide hardware Support canister calibration Inspect hardware on a weekly basis Troubleshoot, if necessary Engineering personnel present during MILT sessions Provide input to final report content Determine test termination in event of iRED failure Collaborate in preparation of final report	Recruit astronauts to perform MILT evaluation, schedule through Exercise Physiology Lab Provide training support for the astronaut training sessions (at least during initial sessions for each astronaut)

A. Overview of Evaluation Design

The MILT consisted of subjects performing exercises on the iRED. The iRED used for the MILT was similar in all major respects to the flight iRED. However, there were some minor differences. One of the MILT iRED canisters had three small (1-inch × 3-inch) observation windows cut into the canister shell, which were covered by transparent plastic tape. During the exercise sessions for a subset of the subjects, load cells were inserted between the iRED accessories (long bar or harness) and the cord loop to measure the pull forces. These subjects performed their exercises on a wooden platform that rested on top of the iRED mounting plate between the canisters. This platform elevated the subjects 6.5 inches to account for the 6.5-inch length of the load cells. The iRED Engineering group evaluated these minor configuration differences and judged them to have no effect on the function, performance, and longevity of the iRED.

The iRED was operated within the restrictions imposed by the iRED design team. These restrictions are contained in Table 2.

Table 2. iRED Canister and Flex Pack Restrictions

- Do Not Exceed a load of 150 lb/canister
- Do Not Exceed 22 inches of cord extension at loads of > 105 lb/canister
- Do Not Exceed 25 inches of cord extension at loads between 85-105 lb/canister
- Do Not Exceed 50 inches of cord extension at loads of < 85 lb/canister
- Do Not Exceed 300 repetitions/hour on either canister
- Do Not Exceed 1,200 repetitions on either canister in a 24-hour period
- A Rest Period of 30 minutes is required if the 300 repetition/hour limit is met

The iRED cords were marked at 22, 25, and 50 inches of extension, facilitating compliance with the cord extension restrictions. The iRED cords of ISS are marked in a similar pattern. The target number of repetitions for the MILT was 57,000. This number was determined before beginning the MILT by calculating the number of repetitions needed to support the most common usage scenarios for the iRED during a 17-week ISS Increment composed of three crew members (Table 3).

None of the usage scenarios was precisely 57,000 repetitions; however, representatives from each group involved in testing (the Exercise Physiology Laboratory, the iRED Engineering group, and the Astronaut Strength and Conditioning group) agreed that 57,000 represented a realistic value for flight. Because the MILT was to be reflective of how iRED was to be used on orbit, only the inspection and maintenance procedures that could be accomplished on board ISS were allowed. Specifically, inspection of and repairs to any component of the iRED that is not accessible in flight (such as the flex packs) were not performed during the MILT. The criteria used for the termination of the MILT are listed in Table 4.

Table 3. Three Usage Scenarios for iRED Exercise During Flight

Variables	Scenario #1	Scenario #2	Scenario#3
Number of crew	3	3	3
Flight Duration (Weeks)	17	17	17
Sessions/Week	5	6	6
Exercises/Session	6	6	6
Sets/Exercise	3	3	4
Reps./Set	10	10	8
Total Reps. (Product of Variables)	45,900	55,080	58,752

Table 4. iRED MILT Termination Criteria

The MILT will terminate under the following conditions:

- A failure in the iRED occurs such that the device cannot be operated safely, and the failure is one that could not be repaired during an ISS mission (e.g., a cord break could be repaired on orbit, flex-pack failures could not).
- The Engineering Directorate will be consulted if such a failure occurs, and will make a determination regarding final test termination based on failure.
- Minor defects, such as “can scraping,” that do not present a safety hazard shall not be a basis for test termination. However, the iRED canisters will not be opened to inspect the problem, as this may induce a failure unrelated to the iRED operation.
- Attainment of the target number of repetitions on the device.

B. Subjects

Thirty-two subjects participated in the iRED MILT. All subjects passed at least a Modified Air Force Class III physical, and none had histories of orthopedic or musculoskeletal problems that would limit their performance of exercise on the iRED. The subjects included individuals who were participating in an iRED training study, concurrently being conducted to determine the effectiveness of iRED training on muscular strength, a group of astronaut participants, and a group of individuals who were recruited specifically for the MILT evaluation. The distribution of these subject groups is contained in Table 5.

Table 5. iRED MILT Subject Distribution

Subgroup	n	Males	Females
Astronaut Subjects	8	6	2
iRED Training Subjects	8	8	0
MILT Specific Subjects	16	12	4
Total	32	26	6

C. iRED Exercises

The muscle groups that can be trained, and the specific exercises that can be performed, with iRED are contained in Table 6.

Table 6. Muscle Groups and Exercises Supported by iRED

Muscle Group	Exercise
Erector spinae	Squats, good mornings, dead lifts
Iliopsoas, abdominals	Knee raises, hammer throws
Gluteus maximus, medius, minimus, tensor fasciae latae	Squats, hip abductions
Adductors, gracilis	Hip adductions
Quadriceps	Narrow stance squats, leg presses
Hamstrings	Leg curls, squats, good mornings, dead lifts
Gastrocnemius, soleus	Heel raises
Latissimus dorsi, teres major	Bent-over rows
Anterior, medial, posterior deltoid	Upright rows, shoulder raises, shoulder presses, hammer throws
Trapezius	Upright rows
Triceps, biceps	Bicep curls, tricep extensions, shoulder presses, hammer throws
Wrist extensors, flexors	Wrist curls

Of these, three are considered “core” exercises that will be performed by all ISS crew. These exercises, the squat, the heel raise, and the dead lift, are exercises that place relatively heavy loads along the long axis of the skeleton and provide training to the trunk and lower extremity musculature. The subjects who were participants in the iRED training study performed exercise sessions consisting exclusively of these core exercises.

In order to make the MILT valid in terms of iRED use pattern, the subjects recruited specifically for the MILT performed primarily the upper-body and some lighter-load lower-extremity conditioning exercises. These exercises will be performed on orbit to maintain strength in selected muscle groups. For example, extravehicular activity crewmembers will be assigned exercises such as upright rows, bent-over rows, shoulder press, and wrist curls, which are tailored to maintain shoulder and arm strength. The astronaut participants of the MILT performed both the core and ancillary exercises on the iRED. This allowed the astronauts to use the device in all of its configurations and provided them with maximum exposure to the iRED.

D. Calibration, Canister Inspection, and Cord Maintenance

Upon initial delivery to the testing site, and weekly thereafter, the iRED loads were measured throughout the operational range (iRED Settings 0-11, or up to 150 lb) of the canisters. The iRED canisters were delivered with index markers on the load indicators ranging from 0-15. These indicator markers are unitless numbers, but were used to provide consistent loads (at any given setting) from one session to another. During calibration, the canister cord was pulled a fixed distance (22 inches) at a constant cadence (2 seconds per cord extension, 2 seconds per cord retraction) at iRED settings 0-11 in one setting increments. Load was measured using a load cell (Entran Model No. ELPS-T3E-500L) placed in line with the iRED cord and interfaced with a PC via a National Instruments DAQ-1200 PCMCIA card. Labview 5.1 (National Instruments) was used to record and display the load data. Five samples at each iRED setting were acquired, with the high and low samples rejected and the three middle values averaged to determine the load at each setting. The load cells were also calibrated weekly using known reference weights. The calibration data is presented in the results section.

Representatives from the iRED Engineering group inspected the iRED canisters during each week of the MILT. The inspection consisted of visual scanning of the canisters and all external components of the iRED, including an inspection of the condition of the iRED cords. The iRED cords were replaced approximately every 19,000 cycles. The 19,000-cycle limit was based on previous wear testing and will be performed during ISS flights.

E. Monitoring of Subjects and Recording of Repetition Data

During every exercise session, two exercise trainers and an iRED engineer were present. One of the trainers recorded the exercise, load (iRED setting), and number of repetitions after each exercise performed. Comments were solicited from each subject during and after the exercise sessions, and the exercise data and comments were entered into a standardized form. The exercise and repetition data were entered into a master log book that was updated on a daily basis.

III. RESULTS/DISCUSSION

A. Study Duration/Number of Repetitions

The entire period of the MILT evaluation spanned 63 working days. The two iRED canisters were identified as serial numbers 1007 and 1008. Canister 1008 failed after 49,683 repetitions (87.1% of the targeted goal). Canister 1007 continued to perform well throughout the evaluation, and was still performing well when the MILT was terminated at 57,560 repetitions (Figure 1).

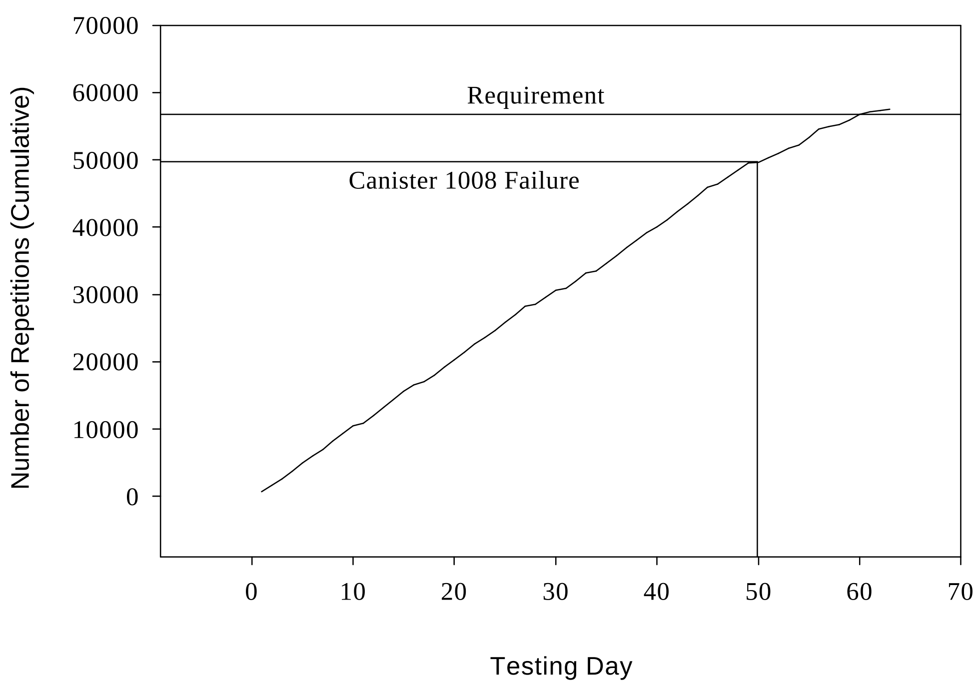

Figure 1. Number of repetitions vs. test duration for the MILT.

B. Load Distribution of Repetitions

The distribution of repetitions across loads was bimodal, with the peaks occurring near the extreme ends of the canister settings (Figure 2). This distribution occurred because the upper-body exercises are performed primarily at lower loads (i.e., lower canister settings), and the lower-body exercises required the higher loads. A calculation of the expected distribution of repetitions across an increment, using the exercise prescription projected for the ISS Increment 1 crew is not identical, but is similar to the distribution observed in the MILT study (Figure 3). After Canister 1008 failed, the exercises performed on Canister 1007 were primarily upper-body exercises. Thus, the distribution of loading with one canister only shifted toward the lower loads (Figure 4).

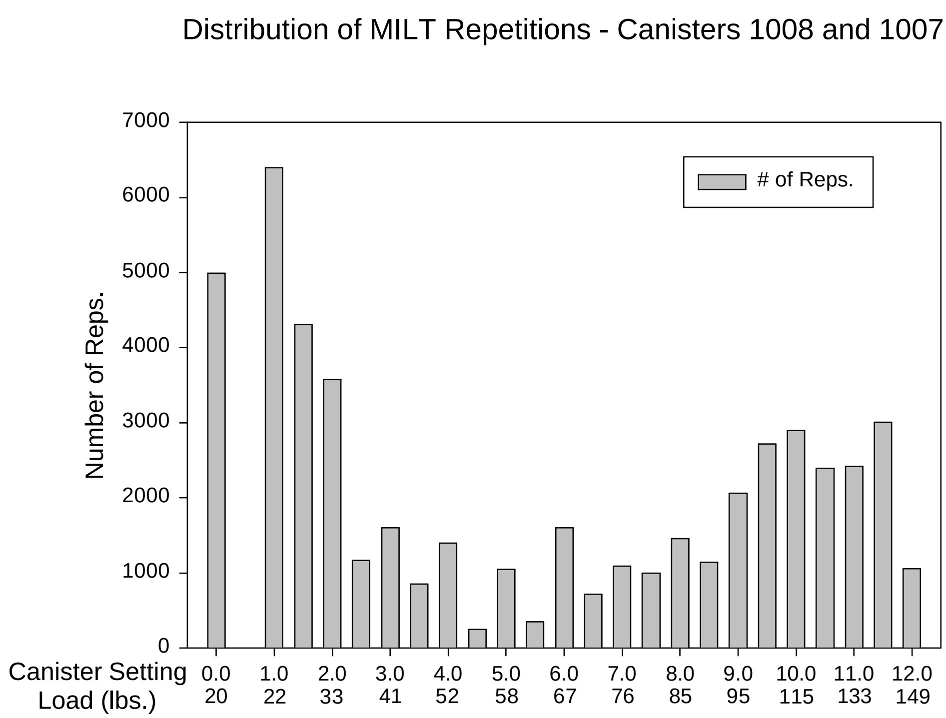

Figure 2. Distribution of repetitions across iRED canister settings during the MILT.

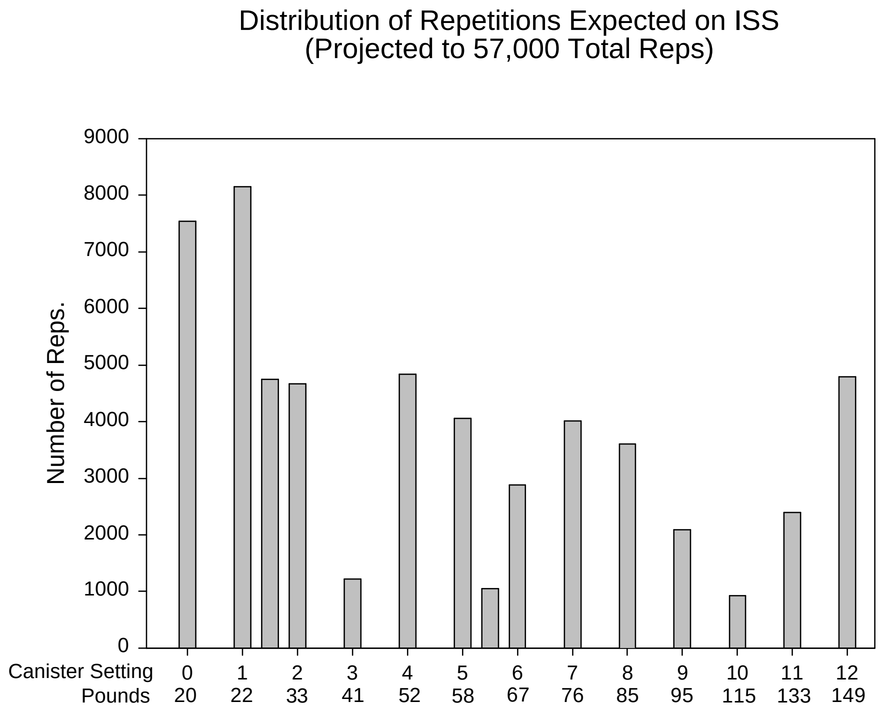

Figure 3. **Distribution of repetitions expected for an ISS crew of astronauts of above-average strength.**

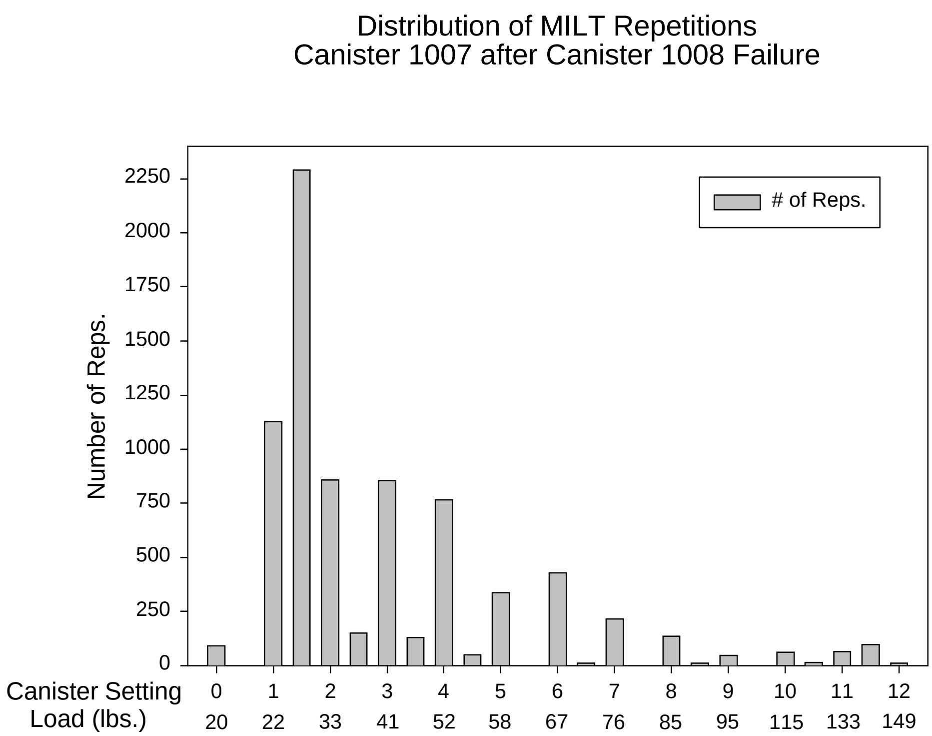

Figure 4. **Distribution of repetitions for Canister 1007 during contingency use.**

C. Canister Calibration

The canister setting vs. load characteristics for Canister 1007 did not change throughout the duration of the MILT (Figure 5). It should be noted that the canisters were delivered after a 1,800-cycle "break-in" period was conducted. The break-in period is conducted to minimize the change in the force curve over time, and is conducted on any canisters delivered for flight. Because the flight canisters are delivered with 1,800 cycles applied prior to launch, the break-in cycles were not included in the repetition count for the MILT.

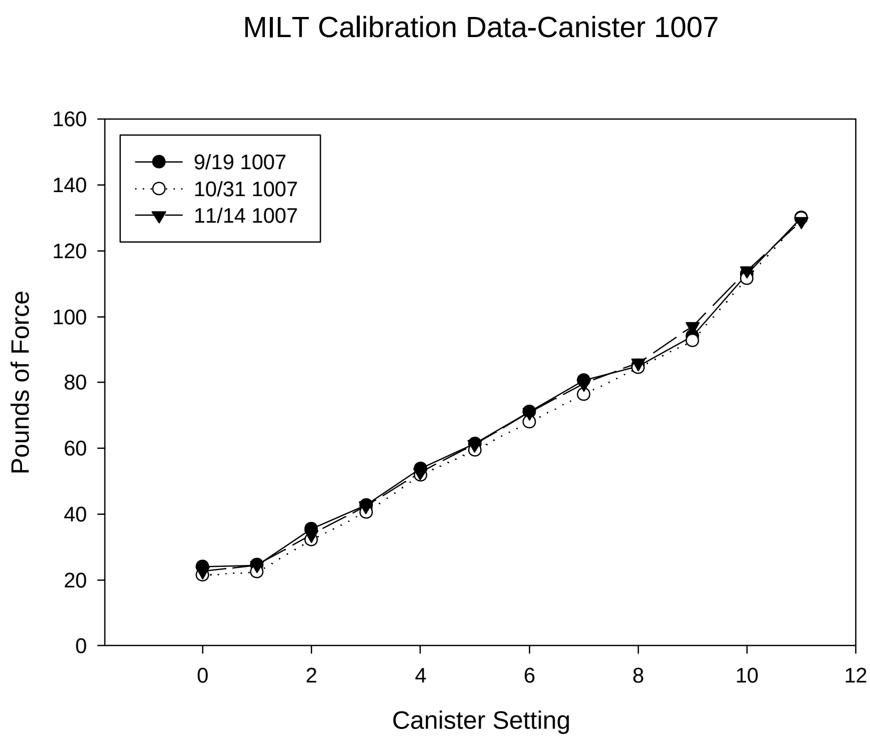

Figure 5. Calibration results for Canister 1007. Note that the force at any given setting did not change over the duration of the evaluation.

Prior to the MILT, it was hypothesized that some decrease in the force at any given setting over the course of a flight would still occur due to wearing of the flex pack elastic material. The canister setting vs. load characteristics were also maintained for Canister 1008 up until the week of failure (11/14/2000), when the loads observed at the two highest settings (canister markings 10 and 11) were elevated (Figure 6). Canister 1008 exhibited metal-to-metal scraping/brushing noises at settings 10 and 11, and the increased load was likely due to mechanical friction of the flex pack rims rubbing against the inner surface of the iRED canister at these settings. Because the calibration data did not indicate any differences until the iRED was very near failure, an increase in the load as observed in Canister 1008 may be used as a sign of imminent canister failure, particularly if accompanied by scraping sounds from the affected canister. However, the calibration data will not likely be helpful in predicting canister failure until such a failure is imminent.

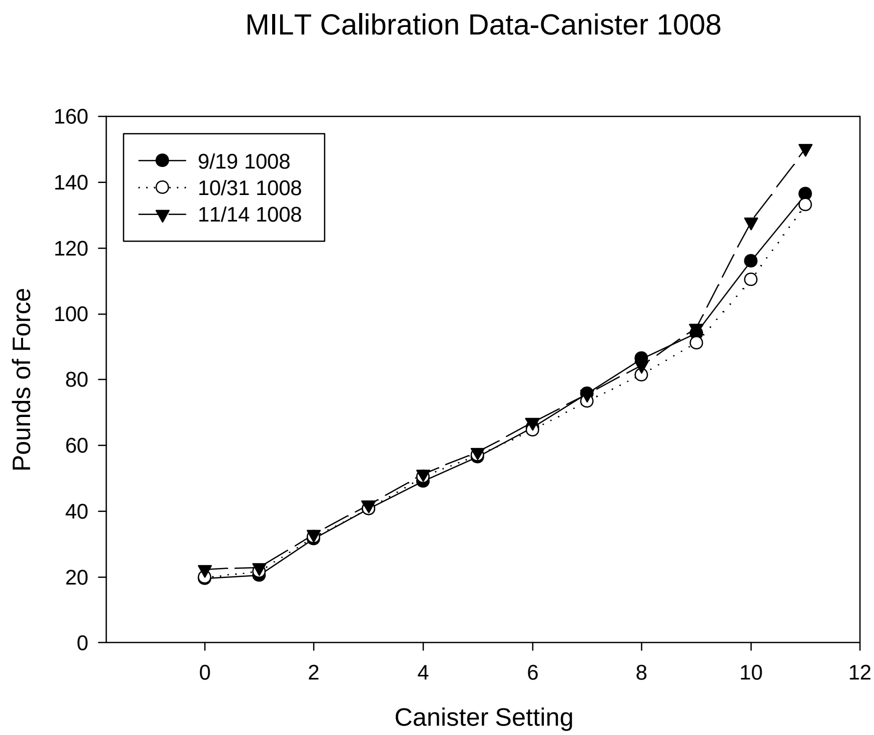

Figure 6. Calibration results for Canister 1008. The forces at canister markings 10 and 11 were increased when canister failure was imminent.

D. Failure of Canister 1008

As noted previously, Canister 1008 failed prior to the attainment of the 57,000-repetition goal for MILT. For approximately one week prior to this failure, Canister 1008 exhibited light scraping/brushing noises when used at the higher canister settings (>10). Over the course of the week prior to failure, the noise became more audible, and some subjects stated that they could feel a difference in the loading between the two canisters. The "failure" point of the canister occurred when a large (~12 inches) portion of the cord would no longer retract into the canister, and the loading difference between the two canisters was very pronounced. When opened and examined, it was determined that the uppermost flex pack in the canister had failed (Illustration 4). One of the elastic spokes had broken, and another was close to the breaking point. The “scraping” sound was caused when the flex pack stack moved off-center because of the unbalanced load. At this point, it is difficult to state with certainty what the predominant contributor to the failure was, i.e. was it the number of repetitions or the load settings? It might be possible for the exercise prescription for the crew to be altered in such a way as to extend the life of the canisters without an adverse impact on crew health. For example, if the number of repetitions on the device is the primary driver toward failure, the exercise sessions can be tailored for fewer repetitions per set, performed at higher loads.

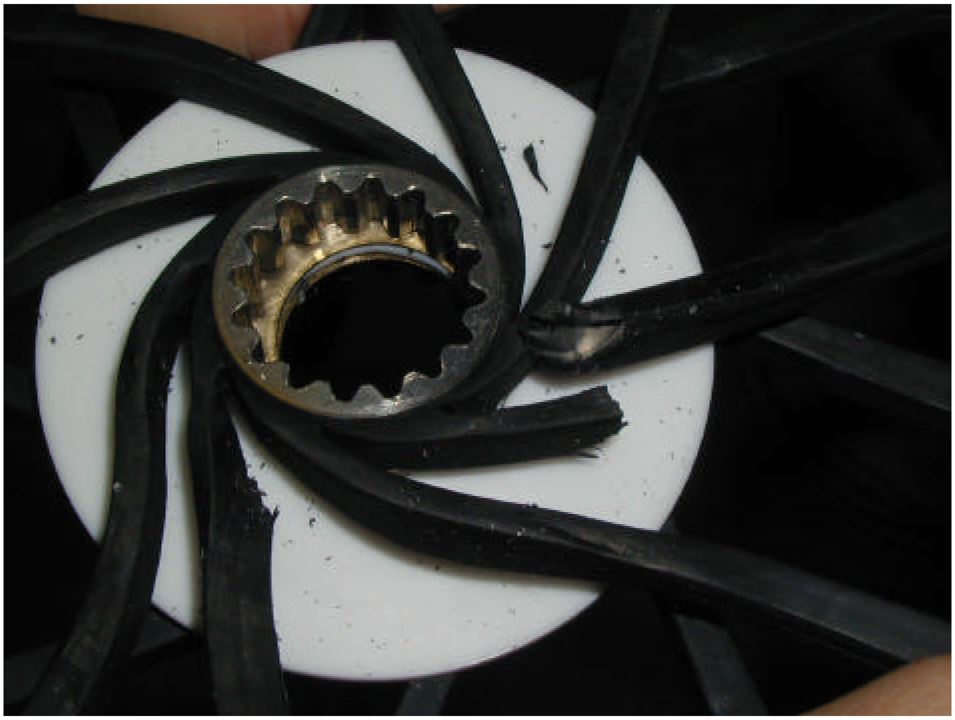

Illustration 4. Flex pack failure. Note the broken elastic “spoke” and fraying of another.

The MILT continued, using Canister 1007 only, after the failure. Use of a single canister would be a contingency operation on orbit, but would cause the users to lose the capacity to perform two (squats and heel-raises) of the three “core” countermeasure exercises.

E. Comments Regarding iRED Use

All subjects were given the opportunity to provide comments regarding the iRED device. The universal comment was that the subjects liked the device and thought it would be a good addition to the exercise countermeasures for ISS. However, there were also some concerns that were voiced. The major concern expressed by the astronaut participants evaluated was that it is cumbersome to switch between one exercise and another, particularly when going from exercises requiring the harness to exercises using the long bar. The necessity of adjusting the extension straps to different settings for each exercise and vary the number of extension clips between exercises was also a concern in terms of time required. The amount of time scheduled for resistance exercise during flight is only 60 minutes, and time spent on configuration changes results in loss of time to perform exercise. The subjects recognized that these limitations were due to using the iRED as a "one machine does all/fits all" device, and suggested that the exercise sessions for ISS be planned in such a way as to minimize the setup time when changing from one exercise to another.

A few of the subjects experienced minor discomforts during, or due to, iRED exercise. During the overhead (military) press, which is performed in the seated position, the amount of clearance for the arms was minimal for larger subjects and resulted in these subjects having to concentrate on keeping their elbows in close to their side. This felt unnatural and reduced the amount of force that could be exerted during this exercise. The iRED cords tended to rub against the upper arms (deltoid area) during the shoulder press, which caused minor abrasions for some subjects. The Velcro on the hand attachment sometimes scratched the subjects in the wrist area; rotating the handle so the Velcro did not rub against the skin alleviated this problem. Very rarely, the clips which attached the long bar to the iRED cord would apparently fail on the first repetition of an exercise. This was caused when a subject did not completely attach the clip thus; the attachment ring was not fully closed and the bar could detach from the cord. Another problem, experienced by three subjects, was an apparent minor over-use injury induced by performance of the biceps curls using the iRED long-bar attachment. Of these subjects, two were relative novices to weight training, but one was an experienced lifter. This injury, which was nicknamed "iRED elbow," was a soreness that occurred in the medial epicondyle region of the elbow. We hypothesize rotational torque of the forearm, induced by using the long-bar attachment for biceps curls, produced connective tissue (tendon or tendon sheath) inflammation in the medial epicondyle area. For all three subjects, discontinuance of curls for approximately 2 weeks resolved the pain. Use of the separate handles, instead of the long bar, to perform single-arm curls may have prevented this problem.

Another concern regarding use of the iRED is that the loading range is not optimal for conducting all resistance exercises. For example, the lowest weight possible using a single iRED canister is approximately 20 lb (at setting "0"). This weight is too high for most individuals to perform exercises such as the frontal raise and triceps kickbacks. Forty pounds (20 lb × 2 canisters) is also too high of a load for many individuals to use two canisters when performing curls, upright rows, and shoulder presses. Use of two canisters for these exercises is preferable because it simplifies the configuration changes needed to use the device. It is easier for the subjects when all long-bar exercises are performed using two canisters because they do not have to change the setup of the iRED from a single-canister configuration to a two-canister configuration between different exercises, such as from biceps curls to dead lifts. Also, the loading at the upper end of the range of iRED (150 lb per canister) is not sufficient in a one gravitational environment to support the squat and heel-raise exercises for many individuals. This will be even more problematic on ISS, because the crew will not have their body weight to lift against as a component of the core exercises. Bungee augmentation, that is the use of bungee cords connected between the iRED mounting plate and the exercise attachment point to increase the load capability of the iRED, was used for subjects who exceeded the 150-lb-per-canister load limitation of the iRED. (Approximately ½ of the iRED exercise study subject group required bungee augmentation for the heel raises, and ¼ needed bungee augmentation for their high-level (83% load) training days for the squat). It is anticipated that these proportions will be higher for crewmembers on ISS because of the microgravity environment. Use of the bungee augmentation is helpful but is not an optimal solution, particularly for the squat exercise, which involves a large range of motion because, at the beginning of the range of motion, the bungee cords are slack and do not provide additional force.

During the MILT, the pins that attach the heel-raise block to the iRED mounting plate became unusable over time. This was due to bending of the pins with repeated usage. The iRED engineering team assessed this problem and plans to change the material of the pins to a harder metal and to shorten the pins. This should reduce the tendency for the pins to bend. The pins can be removed/replaced on orbit; therefore, flying a spare set of pins with the device may be an option worthy of consideration. Another minor issue was that the nut used on the hinge of the shoulder harness front stabilizing bar tended to detach. This happened three times over the course of the MILT. A better method of affixing this nut to the harness should be investigated. Finally, the Velcro on some of the accessories, most notably the extension clips, came off slowly over time. A summary of the issues associated with iRED use is contained in Table 7.

Table 7. Summary of iRED Issues During the MILT

Issue	Frequency	Proposed Resolution
Canister failure prior to 57 K repetitions	N/A	1 – Continue development of more robust resistive exercise device 2 – Replace iRED canisters every ISS Increment 3 – Fly a backup set of canisters in case of premature canister failure 4 – Investigate use of different elastic polymer material for flex packs 5 – Exercise prescription may be modified to allow for few repetitions performed during flight
Cumbersome and time-consuming to switch accessories between exercises, became less bothersome with experience	Every exercise session	1 – Training 2 – Plan exercise sessions in manner to minimize changing of accessories
Lack of clearance for shoulder press	Shoulder press exercise	Use separate hand handles rather than long bar for this exercise
Velcro on hand handles scratch wrist	Shoulder press exercise with handles	Rotate handle so that side without Velcro is side that contacts wrist
Apparent clip failure	Rare	Train crew to visually confirm that clip is completely closed prior to initiating exercise
“iRED Elbow” – overuse injury	3 of 32 subjects only on curl exercise	1 – Use handles rather than long bar for curls 2 – If pain is detected in elbow area, discontinue curl exercise for at least 2 weeks

Issue	Frequency	Proposed Resolution
Loading range is limited	Common to all subjects	1 – Use single canister to perform certain low-resistance exercises 2 – Use bungee augmentation for heel raises and squats for subjects who can exceed 300 lb 3 – This issue needs to be addressed in next-generation resistance exercise devices
Heel block pins bent	At about 30 K reps, heel block became unusable	1 – Shorten pins 2 – Use stronger material for pins
Nut which affixed shoulder harness stabilizing bar comes off	3 times in 57 K reps	1 - Investigate methods of better affixing nut to harness 2 – Consider making nut captive to shoulder harness

IV. CONCLUSIONS

The major finding of the iRED MILT evaluation was that one canister of the device failed prior to the attainment of the testing goal. This points to the need for continued development of a more robust system. In the interim, it is recommended that: 1) the iRED canisters should be replaced every ISS Increment, and 2) a spare set of canisters should be flown to “back up” the prime flight canisters in case of premature canister failure on orbit. The failure of Canister 1008 was at the 87% complete point of a 3-person ISS Increment, while Canister 1007 lasted past the 100% complete mark. The “core” exercise capability loss due to the failure of one canister could be partially compensated by use of the bungee-based contingency resistance exercise system and the remaining functional canister. The exercise prescriptions for crew members may be written in such a way as to reduce the number of total repetitions applied to the iRED device during flight. However, from a crew health maintenance and safety perspective, this is not a desirable option because the exercises would be conducted at higher resistance loads and may increase the potential for an over-use injury. In addition, it is uncertain if the trade-off, which would involve using higher loads, would increase the iRED life span.

With regard to iRED operations, the comments received regarding the device were overwhelmingly positive; however, it will be important to plan the exercise sessions to minimize setup and reconfiguration time. Hardware problems were discovered during the evaluation. Minor problems, such as the bending of the heel-raise pins, should be easily solvable. The failure of the flex pack material is more problematic, and may only be resolved by changing the characteristics/materials of the elastic polymer. The MILT provided valuable insight into the long-term use of iRED, and provides a compelling case for the need for utilizing long-term man-in-the-loop testing for evaluation of all exercise devices targeted for use on board ISS.

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13. ABSTRACT *(Maximum 200 words)*
The Interim Resistance Exercise Device (iRED), developed for the International Space Station (ISS), was evaluated using human subjects for a "Man-In-The-Loop Test" (MILT). Thirty-two human subjects exercised using the iRED in a test that was conducted over a 63-working-day period. The subjects performed the same exercises that will be used on board ISS, and the iRED operating constraints that are to be used on ISS were followed. In addition, eight of the subjects were astronauts who volunteered to be in the evaluation in order to become familiar with the iRED and provide a critique of the device. The MILT was scheduled to last for 57,000 exercise repetitions on the iRED. This number of repetitions was agreed to as a number typical of that expected during a 3-person, 17-week ISS Increment. One of the canisters of the iRED failed at the 49,683-repetition mark (87.1% of targeted goal). The remaining canister was operated using the plan for operations if one canister fails during flight (contingency operations). This canister remained functional past the 57,000-repetition mark. This report details the results of the iRED MILT, and lists specific recommendations regarding both operation of the iRED and future resistance exercise device development.

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