REPRINTED FROM THE PROCEEDING
OF THE SKYLAB LIFE SCIENCES SYMPOSIUM
AUGUST 27 - 29, 1974
LYNDON B. JOHNSON SPACE CENTER

Physiological Mass Measurement in Skylab 373-386

PHYSIOLOGICAL MASS MEASUREMENTS IN SKYLAB

William E. Thornton, M.D., and Col. J. Ord, M.D., U.S.A.F. M.C.*†

ABSTRACT

One of the first changes noted in man following space flight was a loss in weight. To study the mechanism of such changes during flight, intake/output balance studies and measurements of crew mass were required. These measurements depended on the availability of nongravimetric mass-measurement devices. Such devices were flown and successful operation was demonstrated for the first time during Skylab missions. Electronically timed spring/mass oscillators were used to routinely determine all crew food residue and fecal masses to accuracies of a few grams. Daily body mass measurements were made with errors of a small fraction of a pound.

Two general patterns of body mass loss, usually mixed, were apparent. The first is a more or less continuous loss beginning before flight with an increase in rate of loss during flight. A second pattern is indicated by relative stability except for a small loss during the first few days of weightlessness with a reciprocal gain during the first few days after flight. Interpretation was complicated by heat stresses, changing exercise, and increased food as the missions progressed. However, the following observations are consistent with the data: a surprisingly high metabolic cost occurred on the mission; a metabolic loss was present in all crewmen except the Skylab 4 Commander; and a small fluid loss, on the order of a liter, appears to occur during the initial few days of weightlessness followed by a reciprocal change on return to normal gravity. This latter loss is small and self-limited, and appears to be the only obligatory loss with other losses seen to date being primarily metabolic.

INTRODUCTION

I would like to thank you for this opportunity of telling you about our medical experiments on Skylab, some of the things we discovered, and a few we did not. Many of you in the audience have worked directly or indirectly on these experiments and made these results possible.

---

*Astronaut Scientist, National Aeronautics and Space Administration - Lyndon B. Johnson Space Center, Houston, Texas

†Hospital Commander, Scott Air Force Base

Some of us and some of you, have waited quite a while for these results; in the case of this experiment almost eight years. Nine years ago while working on the Manned Orbiting Laboratory Project at the Aerospace Medical Division of the Air Force, we concluded that one of the first priorities in space medical research was to determine the cause and time course of the weight loss which always seemed to accompany space flight. It was obvious to us and to many others that a carefully controlled intake/output study with accurate daily mass measurements in-flight would be required. At that time, the insurmountable problem to such a study was the lack of an instrument for nongravimetric mass measurement. The first priority, then, was development of a mass measurement device which did *not* depend on weight. Development was started and by 1966 I had built protypes of the instruments flown on Skylab.

As time went on, the Manned Orbiting Laboratory program had an unfortunate end, we had mass measuring devices, and Nasa had a planned in-flight balance study without a mass measuring device so we formed a joint effort which was implemented on Skylab. This morning, I will describe the methods used to measure mass in weightlessness since this technique had not been used before, and then, as time allows, I will discuss the results obtained, results which affect many other experiments and future planning.

Gravimetric mass determination or weighting is such a simple and accurate process that no other methods have been developed or really needed since the Egyptians began using balances 5000 or more years ago. The only practical alternative to gravimetric attraction is some determination of the mass' inertial property. The method chosen to do this in 1965, and not necessarily the present method of choice, was the spring-mass oscillator constrained to linear motion.

PROCEDURE

Figure 1 is a schematic of the method. A sample mass is placed between two springs and constrained to linear motion in the longitudianl axes of the springs. If the mass is displaced from its rest postion X_0 to a new position X and released, it will undergo essentially undamped natural ocillation at a frequency given by the well known relationship shown. If this period of oscillation is accurately measured by a high resolution timer, mass may be calculated. Rather than attempt a calculation based on machine quantities such as spring rates, a calibration which would have inevitable errors from gravitational effects, an in-flight calibration using precision masses was done.

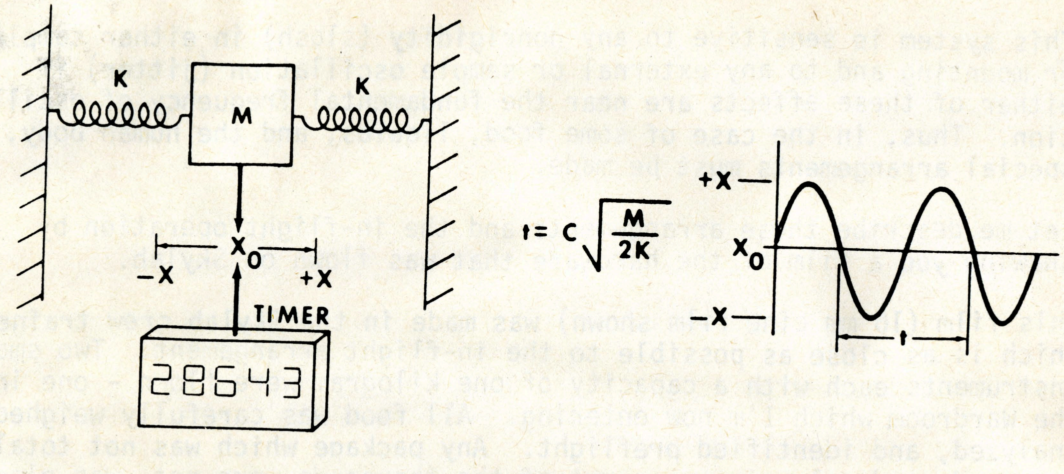

Figure 1. Schematic of Spring/Mass Oscillator and its motion.

Figure 2 is a plot showing a calibration record chosen at random from one of the small or specimen mass measuring devices used on Skylab and it simply shows that it follows the theoretical curve reasonably well. It really was chosen at random for linearity is usually approximately 0.1 percent and normally no points can be found off the curve. With care and by using a modified calibration curve, accuracy of 0.01 percent, or better, can be obtained with solid masses.

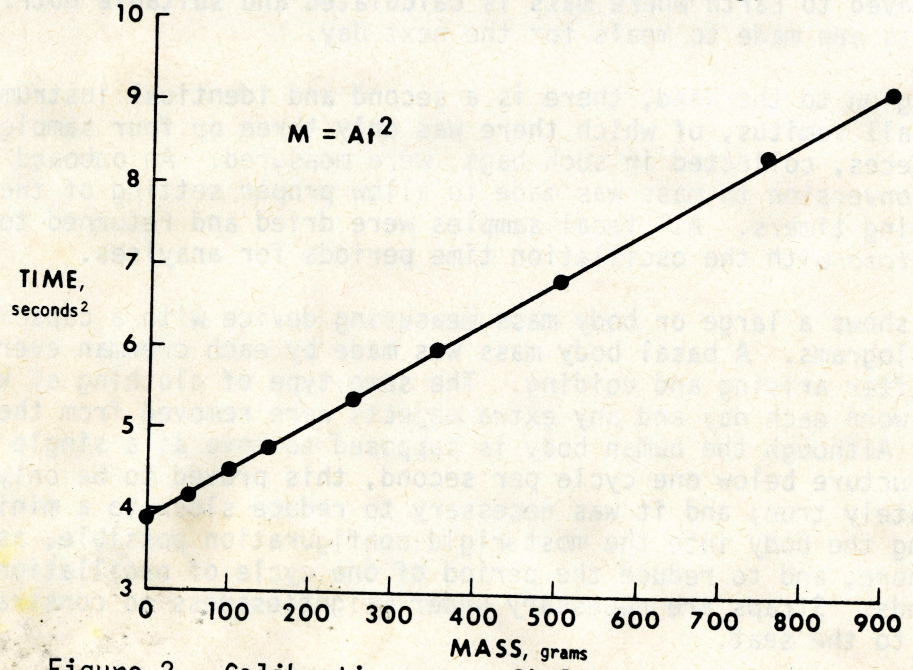

Figure 2. Calibration curve Skylab 2 small mass measuring device, mission day-9.

This system is sensitive to any nonrigidity (slosh) in either sample or mounting and to any external or sample oscillation (jitter) if either of these effects are near the fundamental frequency of oscillation. Thus, in the case of some food, liquids, and the human body, special arrangements must be made.

Let me describe these arrangements and the in-flight operation by showing you a film of the hardware that was flown on Skylab.

This film (16 mm ciné film shown) was made in the Skylab crew trainer which is as close as possible to the in-flight arrangement. Two small instruments each with a capacity of one kilogram were flown - one in the Wardroom which I'm now entering. All food was carefully weighed, analyzed, and identified preflight. Any package which was not totally consumed, and only six or so out of the thousands were not, was placed in the device shown here, and measured.

This is the oscillating specimen tray, and the perforated elastic sheet holds the food package to it. Operation consists of turning the counter on, adjusting it to, and rotating and holding the lever which successively unlocks, displaces, and then releases the specimen tray.

The time for three periods of oscillation is then registered by the opto-electronic counter to 10 seconds. This time is recorded and voice relayed to Earth where mass is calculated and suitable nutritional adjustments are made to meals for the next day.

Now moving on to the Head, there is a second and identical instrument on which all vomitus, of which there was only three or four samples, and all feces, collected in such bags, were measured. An onboard graphic conversion to mass was made to allow proper setting of the fecal drying timers. All fecal samples were dried and returned to Earth *in toto* with the oscillation time periods for anaylses.

Figure 3 shows a large or body mass measuring device with a capacity of 100 kilograms. A basal body mass was made by each crewman every morning after arising and voiding. The same type of clothing of known mass was worn each day and any extra objects were removed from the pockets. Although the human body is supposed to move as a single rigid structure below one cycle per second, this proved to be only approximately true; and it was necessary to reduce slosh to a minimum by folding the body into the most rigid configuration possible, as you see here, and to reduce the period of one cycle of oscillation to two seconds. Straps are necessary under weightlessness to constrain the body to the seat.

The same timer and timing arrangement is used as those on the Small Mass Measurement Devices. After strapping in, the seat is unlocked and cocked by the large handle. The timer is turned on and the device is adjusted to zero. One takes a breath, holds it to avoid "jitter" and then releases the seat to oscillate by means of a trigger on the hand bar. After three cycles of timing has has been completed, the period is recorded and returned to Earth where mass is calculated.

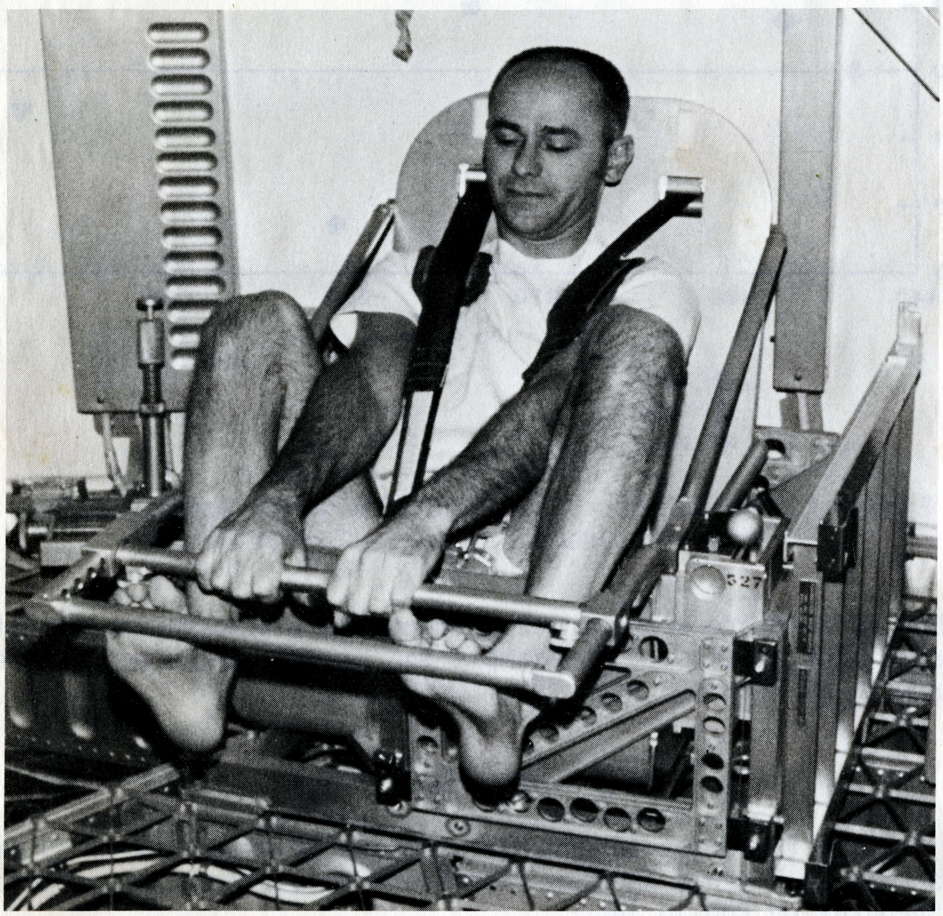

Figure 3. In-flight photo of Skylab 3 Commander making daily body mass measurement. "Chair" oscillates along back-to-front axis of subject. Timer is at the subject's left and the forward elastic flexure pivots may be seen (diagonal braced lightened frame).

Figure 4 is a record of the total *uncorrected* deviations of the Specimen Mass Measuring Device in the Head at the 50-gram calibration point. These points were taken over three missions as shown. Without going further into the engineering aspects, maximum error for food and vomitus samples, was less than three grams. Repeatability of body mass measurements was ±0.1 pounds, and absolute accuracy was between +1/4 and +1.0 pounds and probably nearer +1/4 pounds.

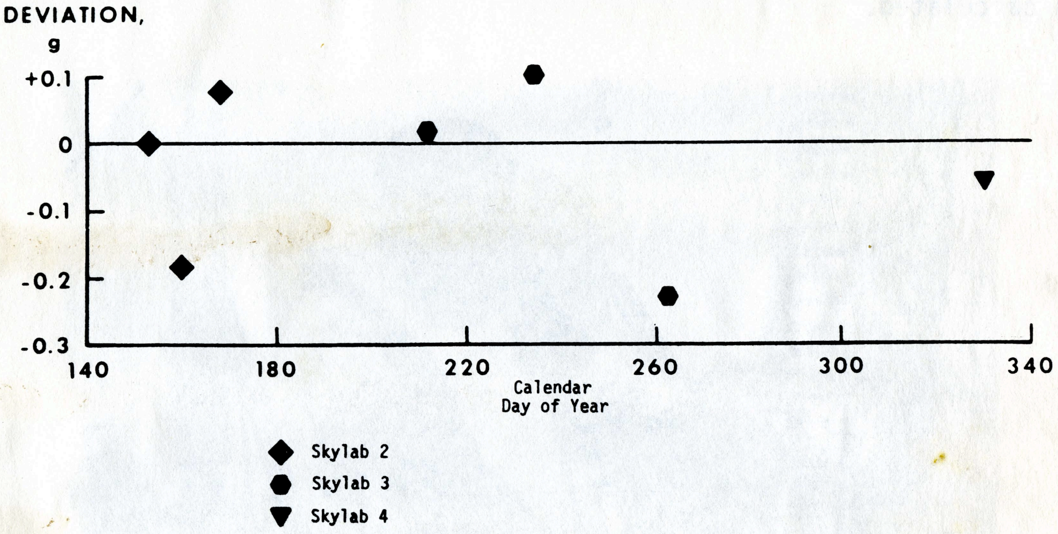

Figure 4. Variation in 50-gram calibration point, Small Mass Measurement Device - Skylab Mission

A number of hardware support measurements were made during the mission with excellent results: for example the 24-hour urine pools were measured to an accuracy of a few milliliters.

RATIONALE

Until Skylab, there was an unexplained loss of weight on every American and, so far as I know, Russian flight and in every astronaut except Alan Shepard* on Apollo 14.

There were three common theories to account for these losses:

° Under weightlessness, fluid was shifted from the lower portions of the body to the chest area where it was sensed as an excess and secreted by the kidneys in accord with the Gauer-Henry theory.

*Recent publication of data indicates a loss in this crewman also.

° At least a portion of the loss was sometimes thought to be metabolic since food quantities and opportunities to eat were frequently minimal.

° Under certain conditions there were periods of high physical activity with heat and other stresses which resulted in rapid loss..

A comment may be in order: One often thinks of daily weights as a highly variable measurement, as indeed they are unless carefully made. But if they are carefully made under basal conditions and if the subject is on a controlled diet, losses of a fraction of a pound per week become not only detectable but significant. While a few ounces loss or gain per week is normally of no importance, if they are continued for months, especially under conditions which can't be altered, they become significant indeed.

The slides (figs. 5 to 13) I will show now are the plots of Skylab crew body weights - preflight and postflight from experiment M071 and the inflight equivalent weights measured with the Body Mass Measurement Device. The data has been smoothed by taking a three-day sliding average. These plots cover the period that the crew were on the Skylab diet.

The plots shown in figures 5 and 6 are from the Commander and Pilot of Skylab 2. The Scientist Pilot (fig. 7) had a similar curve with a total loss between the previous two shown. The first few days' data was lost during vehicle repairs, and this was also a period of heat stress. One sees a loss which began with initiation of the diet and accelerated during the mission itself. The sharp dip inflight was coincident with extravehicular activity. Immediately postflight, there was a transient increase in weight followed by a plateau. The predominant loss pattern of the first manned Skylab flight is consistent with a simple metabolic deficit.

While the losses were easily sustained in this short mission they could not be tolerated on missions of long duration. Even the 3-1/2 pound loss of the Commander is significant in a small crewman who launched with a body fat of less than 10 percent.

On Skylab 3 both food and exercise were increased, and we see a different pattern. The Commander was relatively stable preflight, had a sharp loss for the first few days in flight, and another loss near the end. On recovery, there was the usual increase and plateau

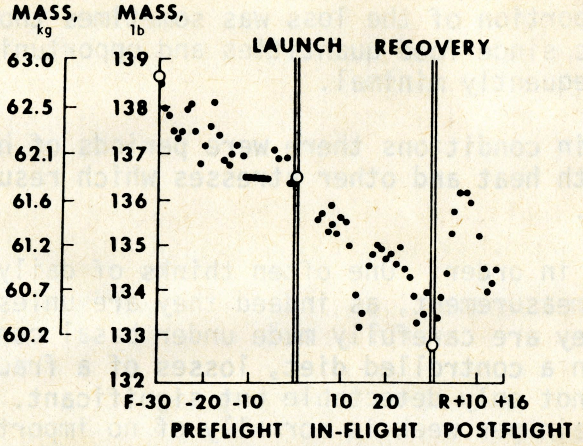

Figure 5. Body mass measurement of the Skylab 2 Commander.

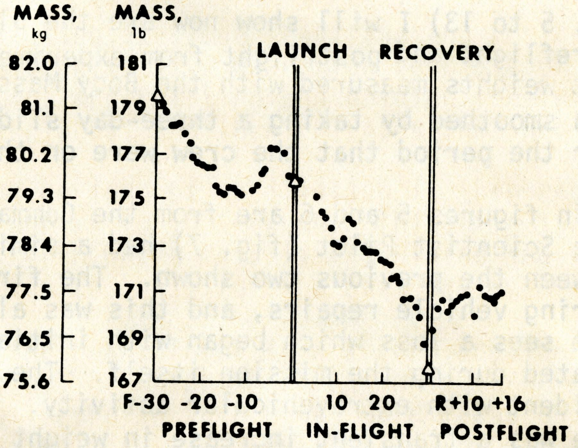

Figure 6. Body mass measurement of Skylab 2 Pilot.

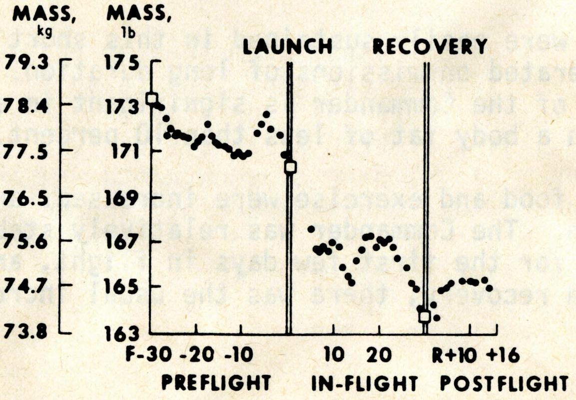

Figure 7. Body mass measurement of Skylab 2 Scientist Pilot.

or inflection point (fig. 8). The Pilot, had an almost identical curve (fig. 9). Remember, that these crewmen had nausea and were not eating properly the first few days, and that there was a period of increased activity, especially for the Pilot and Commander prior to entry. The Scientist Pilot had a sharp loss on exposure to weightlessness and a small continued loss in-flight consistent with a metabolic deficit and a typical recovery pattern (fig. 10). Here, I feel that we see two other loss mechanisms demonstrated.

From the time course of the losses and gains on orbital insertion and recovery, it seems reasonable to conclude that fluids are involved. This will be discussed further in a moment. At the same time, there are periods of increased stress, such as preparation for entry or extravehicular activity on Skylab 2 which temporarily exceed caloric intake.

On Skylab 4, food and exercise was again increased, and we have the second American astronaut in space who lost essentially no body mass in flight - the Commander (fig. 11). His profile shows a preflight gain, a small initial loss, and a postflight gain. His crewmen had losses similar to or smaller than the astronauts on Skylab 3 (figs. 12, 13).

At this point, we seem to have come full circle and have demonstrated that all three mechanisms originally proposed are operative. It would appear that the most significant on this mission was a simple metabolic loss. In further support of this, the average weight loss of all crewmen was plotted versus the normalized average caloric intake (fig. 14). The caloric data shown is the latest obtainable from the food section. Although the sample is small, the relationship seems clear, the three subjects off the "main line" relation were also the three crewmen with the smallest body fat -- all three well under 10 percent.

Caloric intake required for an extrapolated zero loss is extremely high indicating a surprisingly high in-flight metabolic cost.

It must be recognized that simply adding food to the diet is not the whole answer, for while this will assuage hunger and maintain mass, body muscle might be exchanged for fat. This closely related problem of exercise and conditioning will be discussed next.

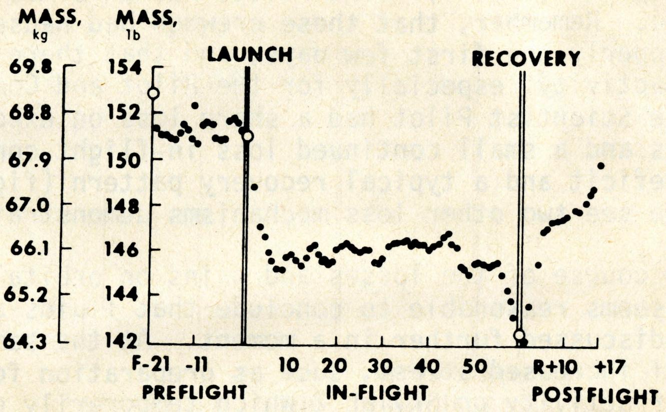

Figure 8. Body mass measurement of the Skylab 3 Commander.

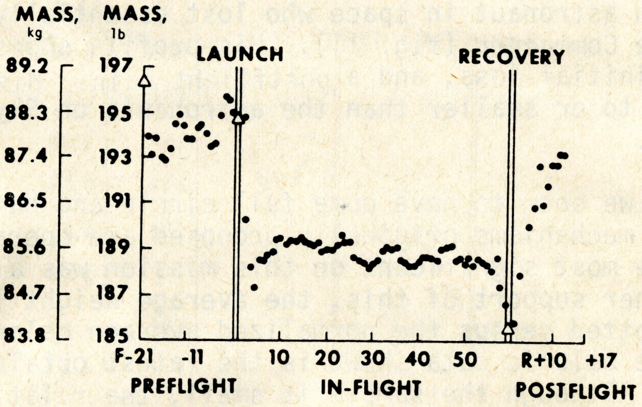

Figure 9. Body mass measurement of the Skylab 3 Pilot.

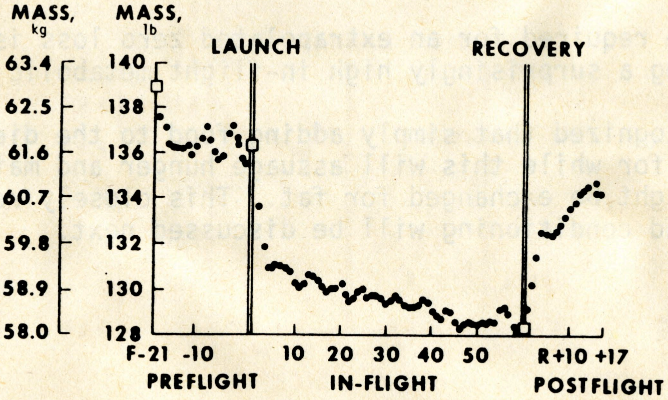

Figure 10. Body mass measurement of the Skylab 3 Scientist Pilot.

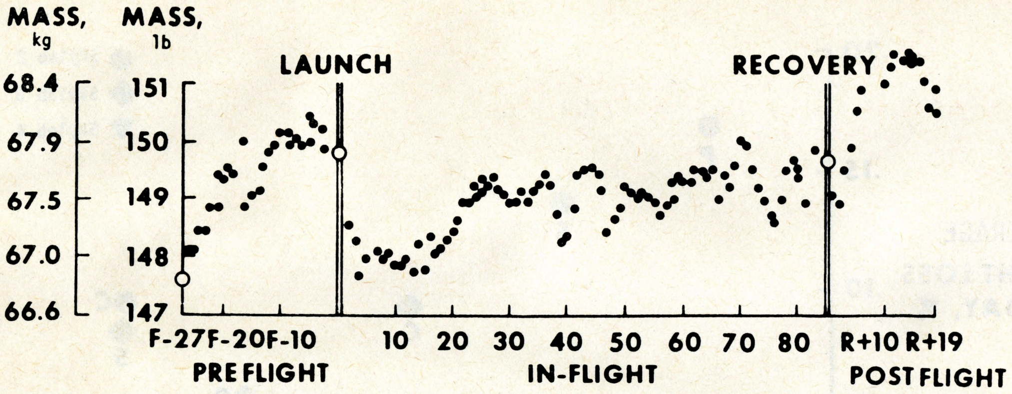

Figure 11. Body mass measurement of the Skylab 4 Commander.

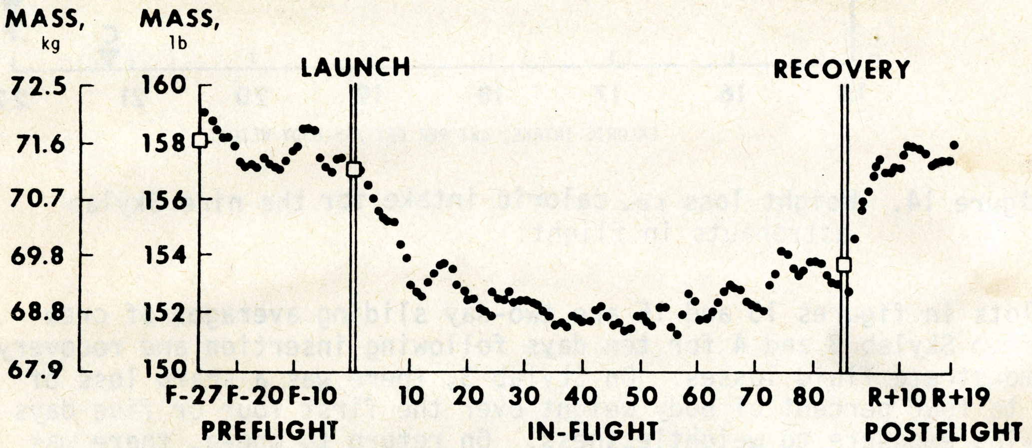

Figure 12. Body mass measurement of the Skylab 4 Scientist Pilot.

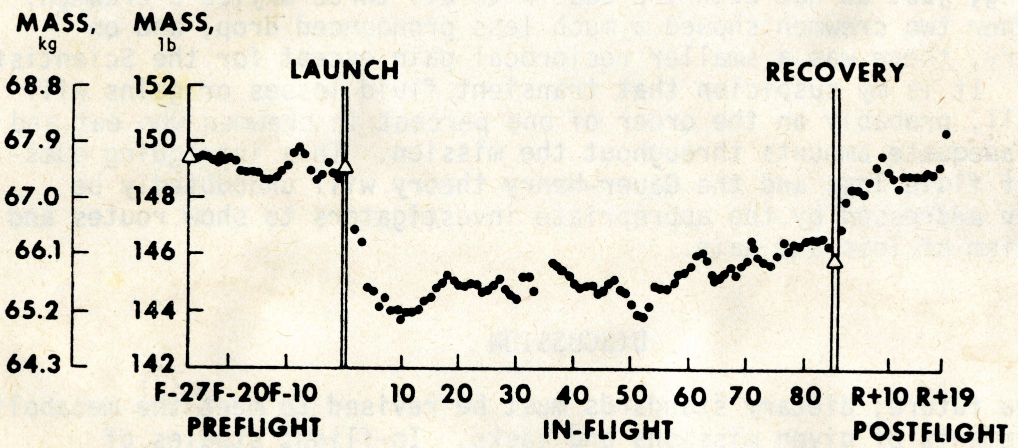

Figure 13. Body mass measurement of the Skylab 4 Pilot.

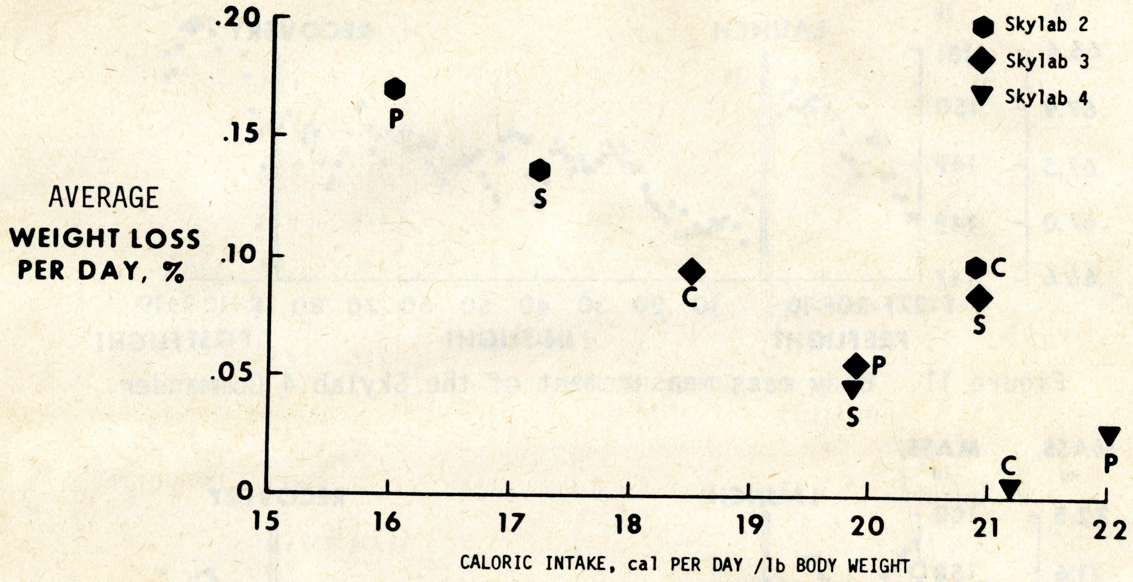

Figure 14. Weight loss *vs.* caloric intake for the nine Skylab astronauts in flight.

The plots in figures 15 and 16 are two-day sliding averages of crew mass from Skylab 3 and 4 for ten days following insertion and recovery to demonstrate fluid losses. On Skylab 3, there was a sharp loss of three to four percent of body weight over the first four or five days following exposure to weightlessness. On return to one-g, there was an approximate reciprocal gain. On Skylab 4, we see the same pattern in one crewman; the crewman who was nauseated and not eating and drinking, just as had been the case with all three Skylab 3 crewmen. The other two crewmen showed a much less pronounced drop, and on recovery, there was a smaller reciprocal gain except for the Scientist Pilot. It is my suspicion that transient fluid losses or gains will be small, probably on the order of one percent in crewmen who eat and drink adequate amounts throughout the mission. This intriguing question of fluid loss and the Gauer-Henry theory will undoubtedly be further addressed by the appropriate investigators to show routes and mechanism of loss and gain.

DISCUSSION

For the future; dietary standards must be revised to meet the metabolic requirements of given missions and tasks. In-flight studies of metabolic costs of realistic activities will allow better definition of overall requirements. The requirements on this mission with its

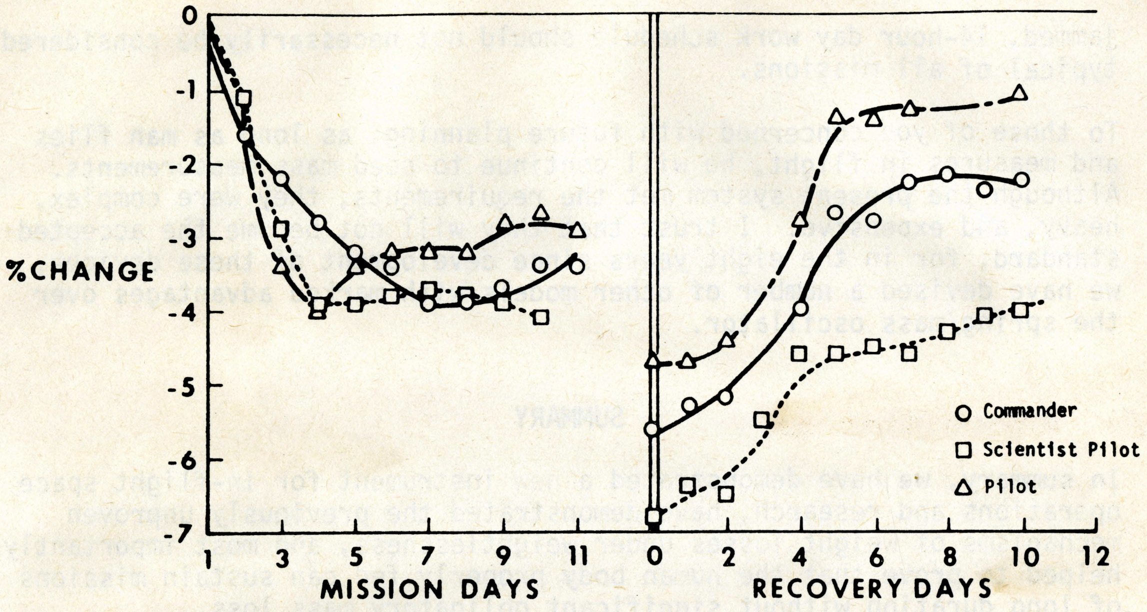

Figure 15. Body weight change Skylab 3 insertion and recovery.

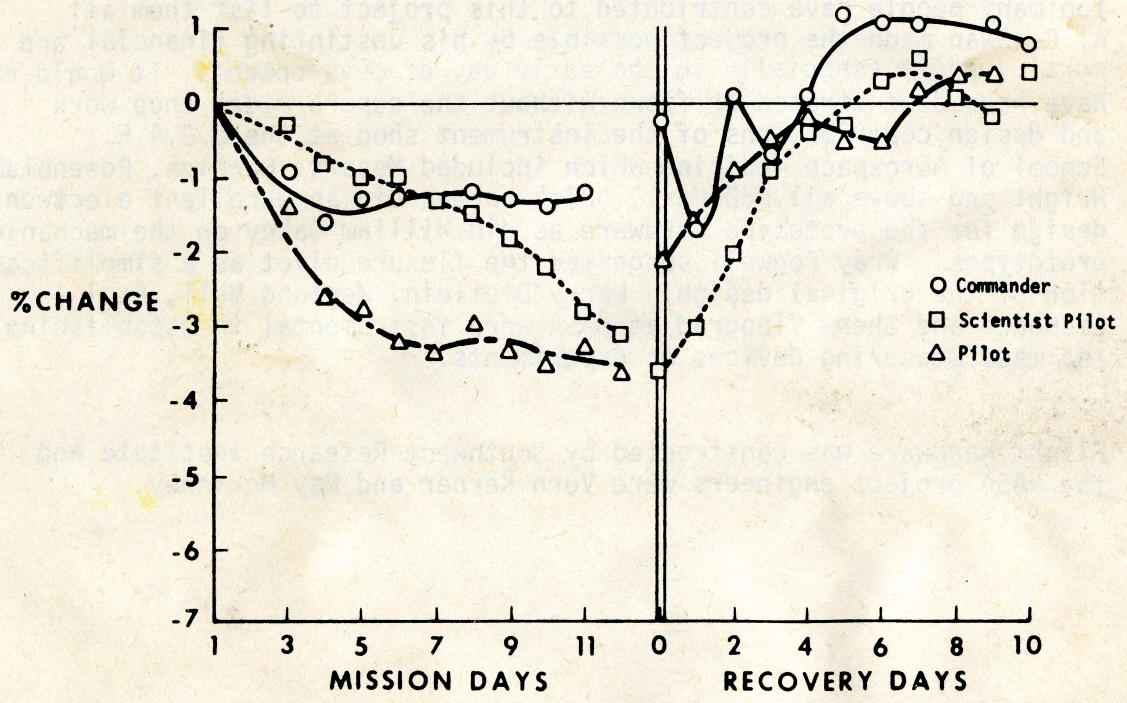

Figure 16. Body weight change Skylab 4 insertion and recovery.

jammed, 14-hour day work schedule should not necessarily be considered typical of all missions.

To those of you concerned with future planning; as long as man flies and measures in flight, he will continue to need mass measurements. Although the present system met the requirements, they were complex, heavy, and expensive. I trust that they will not become the accepted standard, for in the eight years since development of these devices, we have devised a number of other models with marked advantages over the spring/mass oscillator.

SUMMARY

In summary, we have demonstrated a new instrument for in-flight space operations and research, have demonstrated the previously unproven mechanisms of weight losses under weightlessness, and most importantly, helped to prove that the human body properly fed can sustain missions of long duration without significant obligatory mass loss.

ACKNOWLEDGEMENTS

Too many people have contributed to this project to list them all. A. G. Swan made the project possible by his unstinting financial and moral support especially in the early day of development. It would never have been demonstrated or flown without the superb model shop work and design contributions of the instrument shop at the U.S.A.F. School of Aerospace Medicine which included Messrs. Garbich, Rosenblum, Wright and above all McDougal. Dick Lorenz did an excellent electronic design for the prototype hardware as did William Oakey on the mechanical prototypes. Wray Fogwell suggested the flexure pivot as a simplification of the original design. Larry Dietlein, Weyland Hull, Paul LaChance and Sherm Vinograd at NASA were instrumental in establishing the mass measuring devices as experiments.

Flight hardware was constructed by Southwest Research Institute and the NASA project engineers were Vern Kerner and Ray McKinney.