POSSIBLE BIOMEDICAL APPLICATIONS AND LIMITATIONS OF A VARIABLE-FORCE CENTRIFUGE ON THE LUNAR SURFACE: A RESEARCH TOOL AND AN ENABLING RESOURCE

N93-17458

Keith L. Cowing
American Institute of Biological Sciences
730 11th Street N.W.
Washington DC 20001

Centrifuges will continue to serve as a valuable research tool in gaining an understanding of the biological significance of the inertial acceleration due to gravity. Space- and possibly lunar-based centrifuges will play a significant and enabling role with regard to the human component of future lunar and martian exploration, both as a means of accessing potential health and performance risks and as a means of alleviating these risks. Lunar-based centrifuges could be particularly useful as part of a program of physiologic countermeasures designed to alleviate the physical deconditioning that may result from prolonged exposure to a ⅙-g environment. Centrifuges on the lunar surface could also be used as part of a high-fidelity simulation of a trip to Mars. Other uses could include crew readaptation to 1 g, waste separation, materials processing, optical mirror production in situ *on the Moon, and laboratory specimen separation.*

HUMANS AND GRAVITY LEVELS OF LESS THAN 1 *g*

Spaceflight removes living organisms from the *only* environmental factor whose strength and direction have remained constant throughout life's tenure on Earth: gravity (*Gordon and Chen,* 1970; *Halstead,* 1987; *Pestov and Gerathewohl,* 1975; *Parfyonov,* 1983; *NASA Office of Space Science and Applications,* 1987). Living organisms exhibit a wide range of sensitivities to a variably perceptible gravitational/accelerative vector. This range of responses is seen both between individual species and among various physiologic systems within individual organisms (*Pestov and Gerathewohl,* 1975; *NASA Office of Space Science and Applications,* 1987; *Fuller et al.,* 1987; *Schopf,* 1988).

Of particular interest to the human exploration of the Moon (and eventually Mars and other planets) is the effect of prolonged exposure both to weightlessness (or, more accurately, the accelerative unloading that occurs upon exposure to a microgravity environment) during cislunar transit and to gravitational levels greater than microgravity but less than 1 *g* (hypogravity) upon a planetary surface (*Nicogossian and Parker,* 1982; *Ride,* 1987).

Current knowledge regarding the effects of prolonged exposure to microgravity has a temporal limit in the 326-day exposure of one cosmonaut (*Schneider et al.,* 1988) and that of two other cosmonauts who spent 365 days in orbit aboard the MIR space station (*Covault,* 1988). The data regarding shorter exposures to microgravity (on the order of days or weeks), while greater in quantity, still leave us with more questions than answers (*Schneider et al.,* 1988; *Covault,* 1988). In the matter of prolonged exposure to lunar gravity, the data are limited to that gained from the exposure of 14 individuals with a maximum exposure (during the Apollo 17 mission) of 2 individuals to 75 hr on the lunar surface, of which 22.1 hr were spent in extravehicular activity (EVA) (*Pestov and Gerathewohl,* 1975; *Nicogossian and Parker,* 1982; *NASA Johnson Space Center,* 1973).

While the physiological aspects of microgravity exposure have been only partially investigated, even less is known about the gravitational regime that lies between microgravity and 1 *g* (*NASA Office of Space Science and Applications,* 1987; *Fuller et al.,* 1987; *Schopf et al.,* 1988; *Nicogossian and Parker,* 1982; *Schneider et al.,* 1988). Significant questions remain as to what exposure times and level(s) of gravity or other forms of inertial acceleration are necessary for the maintenance of normal physiologic activity (*Schopf et al.,* 1988; *Schneider et al.,* 1988; *National Research Council,* 1987a; *Smith et al.,* 1986). In the course of further research it may be discovered that some activities such as neurovestibular function adapt readily to ⅙ *g* and remain pliant enough to allow full readaptation to 1 *g*. Other activities such as bone mineral homeostasis, muscle function and maintenance, and cardiovascular function may be found to maladapt to ⅙ *g* and may not completely readapt once an astronaut returned to a 1-*g* environment.

CENTRIFUGES AS RESEARCH TOOLS

Identifying the physiologic threshold(s) of gravitational loading sensitivity, the character and course of response, perturbation, adaptation, and the development of countermeasures requires the capability to expose humans and other species to variable levels of inertial acceleration. The effects of gravity must also be able to be removed as a variable in order to identify the involvement of other spaceflight factors (e.g., radiation, vehicle disturbances, and environmental contaminants) in observed phenomena (*NASA Office of Space Science and Applications,* 1987; *Fuller et al.,* 1987; *Schopf et al.,* 1988; *Schneider et al.,* 1988; *National Research Council,* 1987a). There are three ways to do this: (1) conduct research on a planet with the desired gravity level (impractical and, in the case of humans, unethical and potentially hazardous); (2) place specimens in a spacecraft and then accelerate them in a linear trajectory at a constant velocity (impractical and prohibitively expensive); or (3) use centrifugation. Centrifuges have been, and will continue to be, the favored means of producing an "artificial" gravity inasmuch as they can provide a practically available substitute in space for the level of inertial acceleration due to gravity experienced upon the Earth's surface, with the added capability to expose organisms to hypogravity environments, which are not possible to produce upon the Earth's surface (*Fuller et al.,* 1987).

To date, only small-radius centrifuges have been flown on far too few occasions as on-orbit controls, e.g., on the German D-1 Spacelab Mission (STS 61-A) (*Fuller et al.,* 1987; *Schopf et al.,* 1988; *Schneider et al.,* 1988; *National Research Council,* 1987a; *Mesland,* 1988). This will change dramatically with the advent of a 2.5-m centrifuge aboard space station *Freedom.* A variety of centrifuges will soon be available that will allow specimens up to the size of a rhesus monkey to be exposed to variable levels of artificial gravity (*NASA Office of Space Science and Applications,* 1987; *Schopf et al.,* 1988; *Schneider et al.,* 1988; *NASA Ames Research Center,* 1986; *NASA,* 1987). The capability to provide prolonged exposure of humans to variable levels of artificial gravity will have to wait until much larger radii centrifuges become available (*Schopf et al.,* 1988; *Schneider et al.,* 1988; *National Research Council,* 1987a; *Healy et al.,* 1988; *Sanford et al.,* 1988; *Burton,* 1988). One such facility, the proposed Variable Gravity Research Facility (VGRF), would be a tethered vehicle with a radius of 100 m or more, capable of exposing humans to various levels of artificial gravity for prolonged periods of time. Research aboard such a VGRF or other facility equipped with large-radii centrifuges would make it possible to identify the effects of long-term lunar (and martian) gravity and would allow countermeasures to be developed before humans return to the Moon or explore Mars (*Schopf et al.,* 1988; *Schneider et al.,* 1988; *National Research Council,* 1987a; *Healy et al.,* 1988; *Sanford et al.,* 1988; *Lemke,* 1988; *National Commission on Space,* 1986).

CENTRIFUGES AS COUNTERMEASURES AGAINST PHYSICAL DECONDITIONING

Centrifuges may have a second role in addition to their importance as a research tool, that of a countermeasure to lessen or eliminate the deleterious effects of prolonged exposure to microgravity and hypogravity (*Fuller et al.,* 1987; *Schopf et al.,* 1988; *Schneider et al.,* 1988; *Healy et al.,* 1988; *Sanford et al.,* 1988; *Nicogossian and McCormack,* 1987). Having such a countermeasure available in Earth orbit or on the Moon may serve as an enabling factor that greatly extends the otherwise limited ability of humans to work for long periods on the lunar surface. Two possible approaches that might be taken are (1) intermittent exposure to 1 *g* (or higher levels) for short periods, which might be sufficient to eliminate or reduce deconditioning to a manageable level, or (2) continuous exposure at 1 *g* or less, which may also produce the same effect (*Lemke,* 1988). Before either approach can be implemented a number of questions need to be answered.

1. What thresholds exist at which gravity directs or influences different physiologic functions? In other words, what levels of centrifugation might be needed (e.g., 0.5 *g*, 1 *g*, or more than 1 *g*) to counteract deconditioning (*Burton,* 1988)?
2. What exposure times (e.g., occasional periods of prolonged centrifugation vs. intermittent, acute exposures; *Burton,* 1988) produce the desired counteractions to deconditioning?
3. What gravity gradients, force vectors, coriolis forces, and cross-coupled accelerations would be acceptable to humans, and what countermeasures (e.g., exercise, nutritional supplements, pharmacological agents) might need to be used in conjunction with centrifugation (*Pestov and Gerathewohl,* 1975; *NASA Office of Space Science and Applications,* 1987; *Fuller et al.,* 1987; *Schopf et al.,* 1988; *Nicogossian and Parker,* 1982; *Ride,* 1987; *Schneider et al.,* 1988; *Healy et al.,* 1988; *Sanford et al.,* 1988; *Nicogossian and McCormack,* 1987)?

Research aboard space station *Freedom,* and later aboard a potential VGRF-like facility, should provide information as to the course and character of any deconditioning that may occur after prolonged exposure to variable gravity levels such as $1/6$ *g*. If it is determined that chronic exposure to $1/6$ *g* does have deleterious consequences that can be ameliorated by centrifugation, the question then arises as to what centrifugation capabilities need to be provided.

LIMITATIONS TO THE USE OF CENTRIFUGES WITH HUMANS

A number of potentially undesirable factors that result from centrifugation need to be taken into account when considering the use of centrifugation as a countermeasure. The biological effects of "artificial" gravity produced by centrifugation, while indeed similar to those experienced by organisms undergoing constant linear acceleration on a planetary body or within a spacecraft, also differ in many significant ways. Organisms undergoing centrifugation experience a constant change in their direction without a change in their rate of motion, as opposed to what occurs within a planetary gravitational field where an organism experiences a change in its motion without a change in direction (*Fuller et al.,* 1987; *Smith,* 1975). The size of a centrifuge must be carefully considered when large animals such as humans are concerned. As the radius of a centrifuge is decreased, the rate at which it must rotate to maintain a given force at its rim must be increased. The smaller the radius, the more pronounced the gravity gradient from its axis of rotation outward to its rim becomes. For upright humans with their feet on the inside of a centrifuge's rim, a gradient will always exist with the greatest force felt at the subjects' feet and the least force felt at their heads. Again, the smaller the centrifuge radius, the more pronounced and troublesome the gradient becomes (*Fuller et al.,* 1987; *Smith,* 1975; *Graybiel,* 1975). If a centrifuge is to be designed to mimic the accelerations experienced by a human on a planetary surface (where a gravity gradient, while present, is infinitesimally small and probably not detectable), then the radius must be extremely large. Such would be the case in a facility like the proposed VGRF (*Lemke,* 1988).

There are, however, other factors to be considered when designing a centrifuge for human use. Troublesome problems arise when humans are exposed to radial acceleration: coriolis forces. If a person were to attempt to move tangentially or radially in a linear fashion (i.e., walk) within the rotating environment of a centrifuge, they would experience a force (depending upon whether they were walking with or against the rotation of the centrifuge) that would cause them to tend to veer off at an angle to the straight line that they would otherwise expect to travel. The slower the rate of rotation, the less of a problem this becomes. Coriolis effects could be expected to affect all crew movements within a centrifuge (*Nicogossian and McCormack,* 1987; *Graybiel,* 1975).

A more severe problem would arise if a person attempted angular motions, most notably moving his head out of the axis of the centrifuge's rotation. The angular acceleration of the centrifuge becomes cross coupled with that produced by head movement and often leads to motion sickness (*Nicogossian and McCormack,* 1987). The faster a centrifuge rotates, the more severe these effects become. It is uncertain at present if humans can adapt to such vestibular perturbations (*Nicogossian and McCormack,* 1987; *Graybiel,* 1975). This problem is also an argument for reducing the rotation rate as much as possible, which, if significant gravity levels are desired, requires large-radii centrifuges.

If it is deemed necessary to expose humans to frequent centrifugation to counteract microgravity- or hypogravity-induced deconditioning, then it will be important to minimize the effects of gravity gradients, coriolis forces, and cross-coupled angular accelerations, especially if the persons within the centrifuge need the freedom to move and work. As such, an extremely long radius (100 m or more) at low rotation rates (1 rpm) would be required (*Lemke,* 1988; *Nicogossian and McCormack,* 1987). Such is the case with a facility like the proposed VGRF or a large, rotating interplanetary spacecraft (*Schneider et al.,* 1988). If deconditioning from chronic exposure to $1/6\,g$ can only be treated with continual centrifugation (which would make human presence on the lunar surface impractical), the other preventative or therapeutic countermeasures will need to be developed such as pharmacological agents, dietary supplements, or exercise regimens.

CENTRIFUGES AS PART OF A LUNAR HEALTH MAINTENANCE CAPABILITY

It has been suggested, based upon microgravity- and hypergravity- (where gravity is $>1\,g$) based research that exercise and pharmacological countermeasures, combined with intermittent exposure to gravity levels approaching $1\,g$ (or more), may suffice to reduce problems such as bone loss and muscle atrophy to tolerable levels (*Lemke,* 1988; *Nicogossian and McCormack,* 1987). Such exposures can be provided with much smaller centrifuges (radii of several meters) rotating at higher rates (10 rpm or more) (*Nicogossian and Parker,* 1982). The use of small centrifuges would be feasible if it could be shown that the troublesome effects of gravity gradients, coriolis forces, and cross-coupled angular accelerations can be controlled. This could be accomplished by limiting exposures to periods of the day when physical activity could be minimized. This could be done during periodic rest periods or even during sleep. Evidence exists from human experiments within a ground-based, 2-m, rapidly rotating (23.2 rpm) centrifuge that sleeping (and moving while asleep) does not produce any noticeable or unpleasant side effects (*Graybiel,* 1975).

Centrifuges may therefore need to be incorporated into the design of the earliest long-term outposts on the Moon. Crews could be assigned specific "centrifuge time" during breaks in their work cycle or be required to spend a certain number of sleep periods under centrifugation (*Burton,* 1988). As with all medical treatments, a wide range of responses can exist between individuals. Frequent monitoring of crew health would be needed to determine the effectiveness of centrifugation as well as other possible adjunct countermeasures.

Living on the Moon will undoubtedly lead to crew members developing new instincts unique to living in a $1/6$-g environment. This was clearly evident with regard to the peculiar gait adopted by the Apollo astronauts as they worked on the lunar surface (*Pestov and Gerathewohl,* 1975). Learned behaviors acquired from long periods on the Moon such as those acquired from surface EVAs and other activities, e.g., the moving of large pieces of equipment, might be difficult to unlearn and therefore potentially hazardous once an astronaut returned to Earth. Humans have been shown to readapt to terrestrial conditions very quickly after short-term exposures to microgravity. As microgravity exposure times increase, the time needed for readaptation increases. This may also prove true with regard to extended stays on the lunar surface. Lunar-based centrifuges could also be used to help crew members readapt their motor skills to 1-g conditions before returning to Earth, thus reducing the possible time needed to readapt to terrestrial conditions after their return. Such a readaptive capability would probably require the construction of much larger centrifuges to minimize the deleterious characteristics inherent in the smaller centrifuges that might be used as part of deconditioning countermeasures. While this concern should be considered, it would probably not need to be implemented at the onset of lunar base operations, that is, at least until tours of duty became extremely long. From a logistical point of view, it may turn out to be more practical for crew members to spend some time aboard a successor to the proposed VGRF in low Earth orbit before returning to Earth rather than in a large (and no doubt expensive) centrifuge on the Moon.

USE OF A LUNAR-BASED CENTRIFUGE IN A SIMULATED MARS MISSION

Planning both the human and hardware components of any Mars mission will undoubtedly be preceded by extensive simulations (*Ride,* 1987; *Schneider et al.,* 1988). Another use for a lunar-based centrifuge could be as part of a high-fidelity simulated mission to Mars. A possible scenario might be as follows: Astronauts would spend a simulated outbound trip aboard a VGRF-like facility outfitted with a large-radius centrifuge to simulate an artificial-gravity-equipped Mars spacecraft. Crews would be transferred to lunar orbit where they would be subjected to a lunar descent with a high-gravity profile similar to that expected when landing on Mars. Crews would then be housed in a lunar-based facility containing a centrifuge capable of being spun up to the equivalent of $0.38\,g$, wherein the crew would sleep and perform other activities not requiring substantial movement. The facility would have a coupling that could be despun to allow the crew to perform EVAs on the lunar surface with spacesuits and equipment weighted down to allow crews to experience a close approximation of the work loads that would accompany surface activity on Mars at $0.38\,g$. Activities within the lunar facility requiring significant movement would likewise be performed with appropriately weighted garments. Such a simulation would be faced with the obvious human factor constraints imposed by living within a centrifuge on a planetary surface and those associated with wearing weighted garments, and would most likely find the greatest applicability with the simulation of relatively short stay times associated with so-called Mars "Sprint" missions. The return portion of the trip could be conducted in a similar manner with crews spending additional time aboard a VGRF. Such a simulation would allow a thorough evaluation of human health and performance issues such as the need to transfer to and from an artificial gravity environment, experience transient microgravity, tolerate high-gravity accelerations after prolonged spaceflight, and perform surface activity at $0.38\,g$. Suggesting such a simulated mission presumes the existence of a vigorous program of lunar exploration with an already established infrastructure, one that is designed to incorporate evolutionary explorative activities and therefore capable of being substantially augmented for an activity of this nature (*Ride,* 1987; *National Commission on Space,* 1986).

GRAVITATIONAL BIOLOGY RESEARCH ON THE MOON

Research into the physiological mechanisms whereby plants and animals sense and respond to gravity is a prime justification for the existence of space-based research facilities (*Halstead,* 1987; *Fuller et al.,* 1987; *Ride,* 1987; *Schneider et al.,* 1988; *National Research Council,* 1987a,b; *Smith and Fuller,* 1986; *Lemke,* 1988). Extensive research will continue to be performed in space before and, indeed, in preparation for the large-scale human exploration of the Moon and Mars (*Ride,* 1987; *Schneider et al.,* 1988; *National Commission on Space,* 1986). As lunar exploration in particular proceeds, there will be an ongoing need to build upon this body of knowledge by conducting additional basic and applied research, e.g., refining the effectiveness of human countermeasures and enhancing the growth of lunar food crops (*Galston et al.,* 1988). Such work will be done by researchers, many of whom will undoubtedly be located on the lunar surface themselves. As has been the case in microgravity-based research, centrifuges will be a useful tool on the Moon. There will, however, be some limitations to their use. The ubiquitous presence of the Moon's gravity will limit the gravitational forces available to levels above $\frac{1}{6}\,g$. In addition, lunar gravity will add a potentially unwanted acceleration vector to any specimen within a lunar-based centrifuge, unwanted in the sense that many of the biological processes studied by gravitational biologists are exquisitely sensitive to gravity and can only be studied under very low and precisely defined levels of gravity.

MATERIALS PROCESSING AND SEPARATION

Centrifuges also have potential applications outside biomedical research. One such application might be separating waste materials as part of a Closed Ecological Life Support System (CELSS). Another application will certainly be the use of ultracentrifuges in a clinical setting not unlike those currently used on Earth. Additional uses might be found in manufacturing, inasmuch as many manufacturing and refining processes rely upon the separation of materials of different densities (*Waldron,* 1988; *Schlichta,* 1988). Some processes, which may prove inefficient in a gravitational field of $\frac{1}{6}\,g$, may be enhanced by the use of centrifugation at levels equal to or above $1\,g$. A particularly important application might be found in the production of lunar-based construction materials (*Khalili,* 1985), cryogenic fuel production, and perhaps the casting of large optical mirrors for lunar-based telescopes (*Anderson,* 1988).

CONCLUDING REMARKS

Humans have been using centrifugation in various forms as a tool for a thousand centuries. It probably began with a nomadic hunter's use of a hand-operated centrifuge (known today in various forms as a slingshot, bolo, etc.) that she or he may have used to accelerate a projectile. As time progressed, centrifuge-based inventions such as the potter's wheel, spin-dry washing machines, and high-speed gas centrifugation for the isolation of fissionable U isotopes have appeared. Just as the slingshot helped to increase humanity's capability to wander across the surface of this planet, it seems befitting that the descendants of this ancient tool may allow latter-day human nomads to wander and thrive upon the surfaces of other planets.

REFERENCES

Anderson I. (1988) Angel sharpens the Vatican's vision of the heavens. *New Scientist,* May 5, 1988, p. 30.

Burton R. R. (1988) A human-use centrifuge for space stations: Proposed ground-based studies. *Aviat. Space Environ. Med., 59,* 579-582.

Covault C. (1988) Record Soviet manned space flight raises human endurance questions. *Aviat. Week Space Technol, 4.*

Diamandis P. H. (1988) The need for artificial gravity on the Moon (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century,* p. 71. Lunar and Planetary Institute, Houston.

Fuller C. A., Sulzman F. M., and Keefe J. R. (1987) Artificial gravity: The evolution of variable gravity research (abstract). In *Papers Presented to the 38th Congress of the International Astronautical Federation.* IAF-87-539.

Galston A. W., Vitousek P., and Hinkle C. R. (1988) Controlled Ecological Life Support System (CELSS). In *Exploring the Living Universe* (J. H. Bredt and M. Averner, eds.), pp. 112-123. NASA Life Sciences Strategic Planning Study Committee, Washington, DC.

Gordon S. A. and Chen M. J., eds. (1970) *Gravity and the Organism.* Univ. of Chicago, Chicago. 474 pp.

Graybiel A. (1975) Angular velocities, angular acceleration, and coriolis forces. In *Foundations of Space Biology and Medicine, Vol. 2* (J. P. Marbarger and P. V. Vasil'yev, eds.), pp. 247-304. NASA, Washington, DC.

Halstead T. W., ed. (1987) *1986-87 NASA Space/Gravitational Biology Accomplishments.* NASA TM-89951.

Halstead T. W. and Dufour P. A., eds. (1986) *Biological and Medical Experiments on the Space Shuttle 1981-1985.* NASA Life Sciences Division, Washington, DC. 176 pp.

Healy B., DeCampli W., Robbins F. C., and Lockette W. (1988) Biomedical research. In *Exploring the Living Universe* (J. H. Bredt and M. Averner, eds.), pp. 40-52. NASA Life Sciences Strategic Planning Study Committee, Washington, DC.

Khalili E. N. (1985) Magma, ceramic, and fused adobe structures generated *in situ.* In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 399-403. Lunar and Planetary Institute, Houston.

Lemke L. (1988) VGRF technology overview and strawman design. Presentation to the Workshop on the Role of Life Science in the Variable Gravity Research Facility, NASA Ames Research Center, Moffett Field, California.

Mesland D. A. M., ed. (1988) *Biorack on Spacelab D-1.* ESA SP-1091. 182 pp.

NASA (1987) *Reference Mission Operation Analysis Document (RMOAD) for the Life Sciences Research Facilities (Revised).* NASA TM-89604. 289 pp.

NASA Ames Research Center (1986) *Life Science Research Objectives and Representative Experiments for the Space Station (Green Book).* Preliminary draft, Biological Research Project, NASA Ames Research Center, Life Science Division, Advanced Programs Office, Moffett Field, California.

NASA Johnson Space Center (1973) *Apollo 17 Preliminary Science Report.* NASA SP-330.

NASA Office of Space Science and Applications (1987) *Life Sciences Report.* NASA Office of Space Science and Applications, Life Sciences Division. 84 pp.

National Commission on Space (1986) *Pioneering the Space Frontier.* Bantam, New York. 214 pp.

National Research Council (1987a) *A Strategy for Space Biology and Medicine for the 1980's and 1990's.* National Research Council, Washington, DC. 196 pp.

National Research Council (1987b) *Report of the Committee on the Space Station.* National Academy Press, Washington, DC. 61 pp.

Nicogossian A. E. and McCormack P. D. (1987) Artificial gravity—a countermeasure for zero gravity. In *Papers Presented to the 38th Congress of the International Astronautical Federation.* IAF-87-533.

Nicogossian A. E. and Parker J. F. (1982) *Space Physiology and Medicine.* NASA SP-447.

Parfyonov G. P. (1983) Evolutionary and physiological adaptation to gravity. *Physiologist, 26,* S-57.

Pestov I. D. and Gerathewohl S. J. (1975) Weightlessness. In *Foundations of Space Biology and Medicine, Vol. 2* (J. P. Marbarger and P. V. Vasil'yev, eds.), pp. 305-354. NASA, Washington, DC.

Ride S. K. (1987) *Leadership and America's Future in Space; Report to the Administrator.* U.S. Govt. Printing Office, Washington, DC. 63 pp.

Sanford J. P., Huntoon C. L., Bennett I. L., and Linder B. J. (1988) Operational medicine. In *Exploring the Living Universe* (J. H. Bredt and M. Averner, eds.), pp. 91-100. NASA Life Sciences Strategic Planning Study Committee, Washington, DC.

Schlichta P. J. (1988) *Centrifugation Would Purify Mercuric Iodide.* JPL, Invention Report NPO 16737/6254. Jet Propulsion Laboratory, Pasadena. 4 pp.

Schneider W., Collins M., Carr G., Cowing K., Leveton L., and Hobish M. (1988) Flight programs. In *Exploring the Living Universe* (J. H. Bredt and M. Averner, eds.), pp. 154-170. NASA Life Sciences Strategic Planning Study Committee, Washington, DC.

Schopf W., Galston A., and Cowing K. (1988) Gravitational biology. In *Exploring the Living Universe* (J. H. Bredt and M. Averner, eds.), pp. 101-111. NASA Life Sciences Strategic Planning Study Committee, Washington, DC.

Smith A. H. (1975) Principles of gravitational biology. In *Foundations of Space Biology and Medicine, Vol. 2* (J. P. Marbarger and P.V. Vasil'yev, eds.), pp. 129-162. NASA, Washington, DC.

Smith A. H. and Fuller C. A., eds. (1986) *Space Station Centrifuge: A Requirement for Life Science Research.* 38 pp.

Waldron R. W. (1988) *Continuous Flow Centrifugal Separator.* MSC-21173, Rockwell, Houston. 5 pp.