System Design Costs and Considerations as a Function of Maintaining Space Crew Physical Fitness

I. STREIMER, PH.D., A. J. GETZKIN, PH.D., AND B. WENDROW, PH.D.

The engineering costs imposed by exercise programs upon space system design are detailed. The implications of their impact upon future systems are discussed and the possibilities of the utilization of pharmacological techniques alone or in conjunction with exercise programs as maintainers of space crew physical fitness are surveyed.

AN INCREASING AMOUNT of concern has been expressed about system requirements for weight, power and volume arising from problems attendant to the maintenance of human health during prolonged exposure to zero gravity.[2,15,18] This concern, in part engendered by phenomena observed in space flight[16,19] and in part from simulation studies[3,4,12] or clinical observations of bedridden patients,[6,7] has focussed upon the necessity of preventing, among other effects, cardiovascular decompensation and loss of skeletal calcium.

To date the primary techniques advocated to offset these anticipated deleterious effects have been the utilization of varying types of mandatory exercise programs. A body of experimental evidence is available which indicates that, in simulation studies, exercise programs may diminish or prevent the onset of adverse effects with respect to cardiovascular output characteristics.[3,4,12] Conversely, reports issued about the Russian cosmonaut flights cast grave doubts upon the efficacy of exercise programs as maintainers of cardiac output capability in those exposed to zero gravity.[16,19]

A secondary concern of equal importance arises from the possibility of loss of skeletal calcium during prolonged exposure to zero gravity. The characteristics of bone as a linear reactant to physical stressors have been experimentally demonstrated,[11] and as yet the applicability and efficacy of exercise programs to the prevention of calcium mobilization and decalcification phenomena have not been validated. Although the results of one experimental animal study do appear somewhat promising,[10] the Russian reports again cast strong doubts on the feasibility of the exercise approach in the solution of this problem.

If, for the sake of this discussion, it is assumed that exercise programs will maintain humans exposed to

From North American Aviation, Space and Information Systems Division, and San Fernando Valley State College.

zero gravity for extended time periods in desired physical condition, two considerations must be recognized which can alter current system design sizing concepts. The first consideration arises from the determination of the amounts of exercise required per man-day while the second is concerned with the constancy of the exercise requirements as a function of increasing elapsed mission time.

To emphasize the importance of these considerations upon system design we may arbitrarily divide system logistics requirements into the categories of fixed and variable expendables. Fixed expendables are primarily propellants and may be designated as those materials requisite to all phases of vehicle flight. Variable expendables are largely determined by life support requirements and may be markedly influenced by alterations in exercise requirements per man-day. It is also apparent that despite the title, "fixed" expendables requirements will vary in some positively correlated manner with variable expendables requirements, increasing as a function of increased system size and weight.

To further illustrate the problem a group of almost identical missions may be assumed which differ from each other only with respect to the amounts of exercise required per man-day. It will be assumed that these exercise requirements vary from a minimum of zero hours to a maximum of two hours per man-day in discrete increments of one-half hour. For the purposes of simplification it is assumed that increases in oxygen consumption correlate linearly with increases in exercise requirements, and that the exercise level selected—2000 BTU/hr performed in 15 minute sessions—will not exceed crew members' aerobic capacity, thus eliminating the calculation of increases in oxygen consumption during recovery periods. Although this last assumption is unlikely it simplifies all calculations and minimizes the adverse effects of the exercise program on overall system requirements. During all other crew activities a mean energy expenditure of 500 BTU/hr has been assumed.

In the illustrations that follow it is assumed that variable expendables requirements, e.g., food intake, carbon dioxide and BTU outputs, etc., increase as oxygen consumption increases and the illustrative data are calculated from projected state-of-the-art values which least penalize the systems. The utilization of state-of-the-art values derived from techniques of carbon dioxide removal, water reclamation, oxygen storage, etc., which are believed to be optimal in nature, results in the imposition of minimum power/weight factor penalties in system expendables calculations. Variable expendables calculations are predicated upon a respiratory quotient of 0.85, an operator efficiency of 21 per cent and the production of 20 BTU per liter of oxygen consumed. A power/weight factor of 500 pounds per kilowatt has also been assumed.

The subsystem illustrations selected are believed to be both major factors in expendables requirements calculations and representative of the anticipated changes. In the interest of simplicity it is assumed that daily exercise requirements remain constant throughout the duration of the mission. If exercise requirements of 0.0, 0.5, 1.0, 1.5 and 2.0 hours per man-day are assumed, the following system equipment or power costs may be derived. Tabular documentation of these requirements are shown in Tables I-VII.

TABLE I. SUPER CRITICAL OXYGEN STORAGE

		Exercise Hours per Man-Day				
		0	0.5	1.0	1.5	2.0
3 Man 30-Days	Lbs. O_2 Day	5.52	5.87	6.22	6.58	6.94
	Total O_2-Lbs	166	176.2	186.5	197.5	208.1
	Storage System-Lbs	59	62	66	71	75
	Power Penalty-Lbs	11.3	12.2	13.0	13.6	14.5
	Total Weight-Lbs	236.3	250.4	265.5	282.1	297.6
3 Man 90-Days	Lbs O_2 Day	5.52	5.87	6.22	6.58	6.94
	Total O_2-Lbs	498	529	560	593	624
	Storage System-Lbs	177	186	195	212	220
	Power Penalty-Lbs	11.3	12.2	13.0	13.6	14.5
	Total Weight-Lbs	686.3	727.2	768.0	818.6	858.5
6 Man 90-Days	Lbs O_2 Day	5.52	5.87	6.22	6.58	6.94
	Total O_2-Lbs	996	1058	1120	1186	1248
	Storage System-Lbs	354	382	400	432	452
	Power Penalty-Lbs	23	24.7	25.8	27.2	29.0
	Total Weight-Lbs	1373	1465	1546	1645	1729
6 Man 90-Days	Lbs O_2 Day	5.52	5.87	6.22	6.58	6.94
	Total O_2 Lbs	1992	2116	2240	2372	2496
	Storage System-Lbs	708	764	800	864	904
	Power Penalty-Lbs	23	25	26	27	29
	Total Weight-Lbs	2723	2905	3066	3263	3429

TABLE II. CARBON DIOXIDE REMOVAL VIA MOLECULAR SIEVE

		Exercise Hours per Man-Day				
		0	0.5	1.0	1.5	2.0
3 Man 30-Days	CO_2-Lbs/Day	6.45	6.86	7.25	7.70	8.12
	Mol. Sieve Fixed Wt. Lbs	27	28.7	30.3	32.2	34
	Expendables-Lbs	4.3	4.6	4.8	5.0	5.2
	Power Penalty-Lbs	39	41	42	45	46
	Total Wt.-Lbs	70	75	77	82	85
3 Man 90-Days	CO_2-Lbs/Day	6.45	6.86	7.25	7.70	8.12
	Mol. Sieve Fixed Wt. Lbs	27	28.7	30.3	32.2	34
	Expendables-Lbs	13	14	14	15	16
	Power Penalty-Lbs	39	41	42	45	46
	Total Wt.-Lbs	79	84	86	92	96
6 Man 90-Days	CO_2Lbs/Day	12.90	13.72	14.5	15.4	16.24
	Mol. Sieve Fixed Wt. Lbs.	45	48	51	54	57
	Expendables-Lbs	25	26	28	29	30
	Power Penalty-Lbs	72	76	81	86	90
	Total Wt.-Lbs	142	150	160	169	177
6 Man 180-Days	CO_2Lbs/Day	12.9	13.72	14.5	15.4	16.24
	Mol. Sieve Fixed Wt. Lbs	45	48	51	54	57
	Expendables-Lbs	50	52	56	58	60
	Power Penalty-Lbs	72	76	81	86	90
	Total Wt.-Lbs	167	176	188	198	207

TABLE III. METABOLIC INCREMENT DUE TO EXERCISE

Hours Exercise per day	Mean BTU per Hour Increase 3 Men	6 Men
0		
0.5	95.7	191.4
1.0	191.4	382.8
1.5	287.1	574.2
2.0	382.8	765.6

The implications of these analyses are important but certainly foremost is that the maintenance of man's well being during space flight by means of exercise programs may impose severe penalties upon system design. In view of the projected system cost increases it seems appropriate at this time to examine the applicability of another technique, basically pharmaceutical in nature, to the solution of this problem.

The utilization of drugs may offer a far more economical approach to minimizing the increases in system cost presented in the foregoing illustrations. Additionally, drug therapy, if successful in alleviating or eliminating the anticipated symptoms resulting from exposure to prolonged weightlessness, could shed light upon the particular organs and systems which are affected by this unique environmental situation.

It has been theorized that cardiovascular decompensation due to weightlessness is in part manifested by abnormal pooling of body fluids in the extremities. Historically, similar clinical conditions have been treated by administration of specific drugs with great success. It is apparent that the cardiovascular effects reported may be alleviated by (1) increasing the efficiency of the heart as a pump, (2) increasing the muscular tone of the blood vessels or (3) a combination of the above processes. The common clinical condition, congestive heart failure, which usually involves circulatory incompetence, is characterized by the pumping of blood volumes which are inadequate for the needs of the body tissues. Such a condition may be accompanied by systemic manifestations, such as cardiac enlargement, edema and cyanosis, manifestations which, it may be noted, are theoretically attendant to the cardiac decompensation due to weightlessness. Treatment of congestive heart failure usually involves the administration of digitalis and certain other plant extracts containing the so-called cardiac glycosides, which tend to effect relatively normal cardiac competence. The primary effects of these drugs are to increase the force of systolic contraction, decrease heart size and lengthen the refractory period between contractions by direct

TABLE IV. SUBSYSTEM POWER INCREMENT DUE TO EXERCISE

Hours Exercise per day	Power Watts 3 Men	Power Watts 6 Men	BTU/hour 3 Men	BTU/hour 6 Men
0				
0.5	6.2	12.0	21	41
1.0	9.4	24.0	32	82
1.5	16.6	36.0	57	123
2.0	20.4	48.0	70	164

TABLE V. INCREMENTAL RADIATOR PARAMETERS DUE TO EXERCISE

Hours Exercise per day	BTU/hour 3 Men	BTU/hour 6 Men	Area, ft.² 3 Men	Area, ft.² 6 Men	Weight-Lbs 3 Men	Weight-Lbs 6 Men
0						
0.5	111	221	2.2	4.4	1.1	2.2
1.0	212	442	4.2	8.8	2.1	4.4
1.5	337	683	6.7	13.6	3.3	6.8
2.0	440	904	8.8	18.1	4.4	9.1

TABLE VI. FOOD REQUIREMENTS & STORAGE

Assumed: Freeze dried food, 6.0 Cal/gm, 30 lbs/ft³
: Wrapping = 0.0833 lbs of wrap/lb food
: Storage = 0.072 lbs of container/lb food
: Total Storage & Wrapping — 0.015 lbs/lb food

		Exercise Hours per Man-Day				
		0	0.5	1.0	1.5	2.0
3 Man 30-Days	Total O_2-Lbs	166	176.2	186.5	197.5	208.1
	Total Food-Lbs	94	99.8	105.8	112.0	118.1
	Total Wt-Lbs Wrap & Stor.	14.4	15.3	16.2	17.2	18.1
	Total Wt-Lbs Food + Wrap + Stor.	108.4	115.1	122.0	129.2	136.2
3 Man 90-Days	Total O_2 Lbs	498	529	560	593	624
	Total Food-Lbs	282	299.4	317.4	336.0	354.3
	Total Wt-Lbs Wrap & Stor.	43.2	45.9	48.6	51.6	54.3
	Total Wt-Lbs Food + Wrap + Stor.	331.2	345.3	366.0	387.6	408.6
6 Man 90-Days	Total O_2-Lbs	996	1058	1120	1186	1248
	Total Food-Lbs	564	598.8	634.8	672	708.6
	Total Wt-Lbs Wrap & Stor.	86.4	91.8	97.2	103.2	108.6
	Total Wt-Lbs Food + Wrap + Stor.	650.4	690.6	732.0	775.2	817.2
6 Man 180-Days	Total O_2-Lbs	1992	2116	2240	2372	2496
	Total Food-Lbs	1128	1197.6	1279.6	1344	1417.2
	Total Wt-Lbs Wrap & Stor.	172.8	193.6	194.4	206.4	217.2
	Total Wt-Lbs Food + Wrap + Stor.	1300.8	1391.2	1474.0	1550.4	1634.4

TABLE VII. SYSTEM WEIGHT CHANGES AS DERIVED FROM DAILY EXERCISE REQUIREMENTS

A = Super Critical Oxygen System, Total Weight (Table I)
B = Carbon Dioxide Removal System, Total Weight (Table II)
C = Incremental Radiator Parameters, Total Weight (Table V)
D — Food Requirements, Total Weight including Wrapping and Storage (Table VI)

		Exercise Hours				
		0	0.5	1.0	1.5	2.0
3 Man 30-Days	A	236.3	250.4	265.5	282.1	297.6
	B	70.0	75.0	77	82	85
	C	....	1.1	2.1	3.3	4.4
	D	108.4	115.1	122.0	129.2	136.2
	Total Wt.-Lbs	414.7	441.6	466.6	496.6	523.2
	Total Increment-Lbs	....	26.9	51.9	77.4	103.3
3 Man 90-Days	A	686.3	727.2	768.0	818.6	858.5
	B	79	84	86	92	96
	C	....	1.1	2.1	3.3	4.4
	D	331.2	345.3	366.0	387.6	408.6
	Total Wt.-Lbs	1096.5	1157.6	1222.1	1301.5	1367.5
	Total Increment-Lbs	....	61.1	125.6	205.0	271.0
6 Man 90-Days	A	1373	1465	1546	1645	1729
	B	142	150	160	169	177
	C	....	2.2	4.4	6.8	9.1
	D	650.4	690.6	732.0	775.2	817.2
	Total Wt.-Lbs	2165.4	2307.8	2442.4	2596.0	2732.3
	Total Increment-Lbs	....	142.4	277.0	430.6	566.9
6 Man 180-Days	A	2723	2905	3066	3263	3429
	B	167	176	188	198	207
	C	....	2.2	4.4	6.8	9.1
	D	1300.8	1391.2	1474.0	1550.4	1634.4
	Total Wt. Lbs	4190.8	4474.4	4732.4	5018.2	5279.5
	Total Increment-Lbs	....	283.6	541.6	827.4	1088.7

action on cardiac tissues. More important, the cardiac glycosides produce an increase in circulatory velocity because of the enhanced stroke volume with blood flow rates usually increased independently of any change in cardiac rate. The glycosides of digitalis are available individually and are orally administered to produce the specific cardiac effect required. Although the digitalis glycosides are usually used without significant untoward effects, it must be noted that their use may be counter-indicated in conditions associated with above normal serum calcium levels.[8] This last cautionary note becomes increasingly important in view of the calcium mobilization problems anticipated in space.

The sympathomimetic drugs evoke physiologic responses similar to those produced by the sympathetic adrenergic nerves and a great number of agents in this category are currently of therapeutic value. Although many drugs have a variety of profound effects, a number have been synthesized to produce rather specific clinical responses. Drugs such as phenylephrine show a strong vasopressor activity, yet do not stimulate the heart or central nervous system. This action has been employed in conditions which are evidenced by reduced cardiac output accompanied by hypotension and seems appropriate to complement the action of digitalis in correcting the cardiac condition resulting from weightlessness. Although most adrenergic pressor drugs are administered by injection, some of the newer agents are effective in oral application and would therefore be easily available to the crew members.

Symptoms identical to the clinically significant calcium mobilization associated with exposure to weightlessness have been observed in conditions resulting from hyperfunction of the parathyroid gland. In this condition, known as *osteitis fibrosa generalisata*, or von Recklinghausen's disease, excessive mobilization of calcium, excessive urinary excretion of calcium and phosphate, symptoms relating to bone resorption and urinary tract disorders, are observed.[5] Unfortunately there is no effective treatment for hyperparathyroidism except for surgical alteration of the gland so that recommendation of potential drug therapy to alleviate similar space conditions is not feasible at this time. Studies to further illucidate the role of the parathyroid gland in regulating the equilibrium of calcium have been reported[9] but extensive investigations into potential therapeutic forms are required before drugs are available to counteract calcium mobilization. The interesting reports by Ito and Aonuma[13,14] concerning the effect of parotid gland extract in reducing circulating calcium may provide a useful therapeutic agent in this regard.

The paper has been primarily aimed at indicating system costs as a function of exercise programs designed to maintain the health of space crew members. It has been assumed that exercise programs will be effective, perhaps an unwarranted assumption in view of Russian cosmonaut experience. Even if exercise is effective its use will impose design costs of significant magnitudes upon future systems. It is not suggested at this time that any of the drugs mentioned are in themselves the panacea for the problem area. It is believed, however, that in view of the present uncertainty concerning the efficiency of exercise as a conditioning agent and the impact of its use on system design it may be rewarding to investigate the application of pharmaceutical agents alone or in combination with exercise programs.

The importance of any reduction in oxygen cost, and hence all expendables requirements, increases directly with the duration and man-days of future missions and thus looms ever larger as a factor in more sophisticated space programs.

REFERENCES

1. Aonuma, S.: Submaxillary Gland VIII—Serum Calcium—Level Decreasing Principle in the Equine Submaxillary Gland., *J. Pharm. Soc. Japan*, 12:199-208, 1956.
2. Bioastronautics Report, 3:486-487, 1964.
3. Birkhead, N. C., Issekutz, B., Blizzard, J. J. et al.: Circulatory and Metabolic Effects of Prolonged Inactivity. 35th Annual Scientific Meeting, Aerospace Medical Association, May 1964.
4. Brannon, E. W., Rockwood, C. A., Jr., and Potts, P.: The Influence of Specific Exercises in the Prevention of Debilitating Muscle-Skeletal Disorders; Implications in Physiological Conditioning for Prolonged Weightlessness. *Aerospace Med.*, 34:900-906, 1963.
5. Burns, E. and Whitehead, C. M.: Renal Complications of Hyperthyroidism. *J. of Urology*, 59, 664-673, 1948.
6. Dietrick, J. E., Whedon, M. D., and Shorr, E.: Effects of Immobilization Upon Various Metabolic and Physiological Functions of Normal Men. *Amer. J. Med.*, 4:3-37, 1948.
7. Dock, W.: The Evil Sequelae of Complete Bed Rest. *J. Amer. Med. Assoc.*, 125:1083, 1944.
8. Friedman, Mand Bine, R., Sr.: Observations Concerning Influence of Calcium Upon Actions of Digitalis Glycoside. *Amer. Heart Journal*, 35:984-989, 1948.
9. Gaillard, P. J. Talmage, R. V., and Budy, A. M., Editors: *The Parathyroid Gland: Ultra Structure Secretion and Function.*, Chicago: University of Chicago Press, 1965 (in press).
10. Geiser, M., and Trueta, J.: Muscle Action, Bone Rarefaction and Bone Formation. *J. Bone and Joint Surgery*, 48:282-311, 1958.
11. Glucksmann, A.: Studies on Bone Mechanisms *in Vitro*, II. The Role of Tension and Pressure in Chrondogenesis. *Anatomical Records*, 73:39, 39-55, 1939.
12. Grave, C., Mabry, J. E., and Stuhring, D. H.: Maintaining Cardiovascular Reflexes During Simulation of a Zero Gravity Effect: An Experimental Study. 35th Annual Scientific Meeting, Aerospace Medical Association, May 1964.
13. Ito, Y.: Biochemical Studies on Salivary Gland Hormones. *Endocrinologia Japonica*, 1: 1-50, 1954.
14. Ito, Y.: Parotin: A Salivary Gland Hormone. *Annals N.Y. Acad. Science*, 85: 228-301, 1960.
15. Jenkins, D.: Quoted in Missiles and Rockets, Jan. 6, 1964, p. 15.
16. Parin, V.: Fifth International Space Science Meeting, Florence, Italy, Quoted in *Los Angeles Times*, Section 1, p. 1, May 16, 1964.
17. Streimer, I., and Wendrow, B.: Effects of Variations in Operator Output Characteristics on Space Logistics. *Aerospace Med.*, 35: 1163-1166, 1964.
18. Streimer, I., and Wendrow, B.: The Implications of Space Crew Physical Fitness Maintenance to System Design. *J. Amer. Astronautical Society*, (1965) In press.
19. Wagner, B. M.: American Institute of Aeronautics and Astronautics, Washington, D.C., June 29, 1964. Quoted in *Los Angeles Times*, p. 1, Section F, June 30, 1964.