Human Tolerance to Multistage Rocket Acceleration Curves

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IN THE course of its flight, the occupants of a passenger-carrying rocket are subjected to accelerations differing substantially from that normally experienced. The use of a human centrifuge capable of high peak acceleration and rate of change of acceleration allows us to duplicate sufficiently closely the acceleration curves of a rocket and to determine their effect on human beings in advance of actual flight. If rocket performance and the limitations of human tolerance are closely matched, it would probably be advisable to make individual tests for each rocket design. Alternatively, if it can be shown that normal tolerance is in excess of that required by any foreseeable rocket design, the design problems themselves and those of passenger selection are greatly simplified. In addition, the possibilities of emergency corrective action being undertaken during flight can be investigated. The present paper shows that a very large proportion of feasible rocket designs impose no undue strain on the passengers.

Except for the high, short duration, accelerations that can be imposed by booster rockets, a rocket designed to leave the earth's surface and take up a circular orbit outside the atmosphere will probably present the various acceleration stresses in their most acute form. From this it follows that acceleration programs that simulate the performance of such escape rockets provide useful criteria for test purposes.

Engineering limitations of a fundamental nature require an escape rocket to consist of several steps, each being fired successively. Such a rocket will undergo subjective acceleration that approximates to a series of hyperbolic increases with time separated by discontinuous decreases.[3]

THEORETICAL PREDICTIONS

In predicting the acceleration curves of an escape rocket it will considerably simplify the analysis if we can show that to a rough approximation:

1. The characteristic velocities (*i.e.*, the velocities the rockets would be capable of attaining in a vacuum and in the absence of a gravitational field) of all rockets considered are equal.
2. The constituent steps contribute equally to the overall characteristic velocity of the rocket.
3. The initial accelerations of corresponding steps of various rockets are equal.
4. The effective exhaust velocity of

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a rocket varies, if at all, only slightly and in a similar manner for all rockets.

TABLE I. DATA FOR ENTERING VARIOUS CIRCUMTERRESTRIAL CIRCULAR ORBITS VIA THE SYNERGY CURVE FROM THE EARTH'S SURFACE.

Height of Orbit	Period of Orbit	Velocity in Orbit	Initial Thrust	Final Thrust	Total Thrust	Transit Time
0 km.	1 hr. 25.5 min.	7.95 km./sec.	7.95 km./sec.		7.95 km./sec.	0
224 km.	1½ hr.	7.82 km./sec.	8.02 km./sec.	0.067 km./sec.	8.09 km./sec.	44 min.
1,620 km.	2 hr.	7.10 km./sec.	8.39 km./sec.	0.412 km./sec.	8.80 km./sec.	51 min.
4,100 km.	3 hr.	6.20 km./sec.	8.84 km./sec.	0.807 km./sec.	9.65 km./sec.	1 hr. 5 min.

Although the above considerations hold to a fair degree of accuracy, two further considerations that complicate matters are: (1) the number of steps of the rocket is not, unfortunately, fixed but may be three, four or five, with a strong probability of three; and (2) the exhaust velocity is not fixed but may vary between approximately 2.5 and 4 km. sec.

We shall now discuss these six conditions very briefly and then try and show how they affect the result.

There are adequate reasons for supposing that a rocket will be required to enter a circular orbit round the earth instead of acting as a "one shot" escape rocket. Although the power requirements, and the ratio of the initial to the final velocity increments, vary with the orbit selected, for practical orbits the variation is not large, as is shown in Table I. After making the rather large allowance necessary to offset the gravitational and atmospheric losses we can say with some confidence that we require a rocket having a characteristic velocity in the range from 10 to 11 km./sec.

If we make the simplifying assumption that all steps of the rocket have the same structural factor (mass without propellant divided by the mass with propellant, both without payload) we can show that under certain conditions that bear some resemblance to the actual conditions the mass ratios (mass with propellant divided by mass without propellant, both with payload) of the individual steps should be equal for maximum overall efficiency of the rocket. If the exhaust velocity is constant, it then follows that the characteristic velocities of all the steps are equal. They are, of course, given by $V_{cn}=V_c/N$ where N is the number of steps.

The initial subjective acceleration of any rocket at takeoff will be of the order of two *g*. At values much higher than this the decrease in gravitational losses, which are obviously infinite at a subjective acceleration of one *g* and decrease progressively for higher accelerations, is more than offset by the increase in structural and motor mass, and vice versa for values much lower than two *g*. The initial acceleration of subsequent stages will probably be of the same order or a little less, although the rigorous lower limit of one *g* does not apply in these cases; their lower acceleration limit is fixed by the requirement that they expand fuel at as low an altitude as possible, because a minimum potential energy should be imparted to the fuel for high efficiency, but increase velocity fast enough to prevent their falling into the atmosphere. Once again the optimum initial acceleration lies within rather narrow limits.

If the same propellant mixture is used for all steps of the rocket, the exhaust velocity will be constant except in the initial portion of the orbit. Here the external air pressure will reduce the exhaust velocity by about 20 per cent. We assume here that a constant expansion ratio and pressure are used in the motors and also that it is not worthwhile equipping the final steps with a higher performance but more expensive propellant mixture. The reduction of the overall characteristic velocity of the rocket owing to the initial low exhaust velocity is allowed for under atmospheric losses.

Limitations of a fundamental character suggest that in the foreseeable future orbital rockets will be chemically propelled step-rockets having an exhaust velocity of 4 km./sec. or less. For a given structural ratio and exhaust velocity there is a minimum possible number of steps for a rocket that is required to give some specific characteristic velocity. Neglecting the possibility of entirely revolutionary engineering techniques, this lower limit will be three for the present case. Although more steps mean more efficiency, the rapid increase of complexity that accompanies an increase in the number of steps makes it probable that three will be the number used, with a rapidly decreasing possibility of four and five. The last figure can safely be taken to be a maximum.

Although the value of the exhaust velocity is of fundamental importance in the overall design of a rocket, from our point of view we are concerned only with its effect on the acceleration curve; the higher the exhaust velocity the smaller the variation in acceleration. "Dense" propellants, which involve relatively low structural mass, will have exhaust velocities within the limits of 2.5 and a little over 3 km./sec.; "light" propellants may have exhaust velocities as high as 4 km./sec. We may take specimen exhaust velocities of 3 and 4 km./sec as being representative of the two classes.

We will assume from the above consideration that the rocket we are concerned with will have a characteristic velocity of 11 km./sec, will consist of three or four steps, and will have an exhaust velocity of 3 or 4 km./sec, this value being reduced by 20 per cent for the initial part of the orbit. We will also assume an initial subjective acceleration of two *g* for the first stage and 1.7 *g* for the remaining steps.

If M is the initial mass of the step under consideration plus its payload, and a mass *m* of propellant is being burnt away every second, the acceleration at time *t* seconds after the step begins to fire is given by:

$$a = \frac{m}{M}\left(\frac{v_e}{1 - \frac{mt}{M}}\right)$$

If the exhaust velocity (v_e) is constant, the acceleration curve is therefore a hyperbola.

Because we have already fixed the value of the initial acceleration (a_1) and v_e is known, the value of $\frac{m}{M}$ is determined from the equation:

$$a_1 = \frac{m}{M} v_e$$

The ratio of the initial (a_1) to the final (a_2) acceleration of a step is determined by the mass ratio of the step (r_n) and the ratio, often unity, of the exhaust velocities:

$$\frac{a_2}{a_1} = \frac{V_{e2}}{V_{e1}} r_n$$

and from r_n we also obtain τ, the total time of firing:

$$\tau = \frac{M}{m} \left(1 - \frac{1}{r_n}\right)$$

r_n itself is obtained from the known characteristic velocity of the complete rocket (v_c) and the known number of steps (N):

$$r_n = e^{\frac{V_c}{N v_e}} \quad \text{or} \quad \frac{V_c}{N} = v_e \log_e r_n$$

Figure 1 shows the variation of the individual step mass ratios (r_n), and hence of the over-all variation of acceleration (see third equation) with varying exhaust velocity for three, four, and five-step rockets having a characteristic velocity of 11 km./sec. It is obvious that the variation in acceleration decreases rapidly as the exhaust veloc-

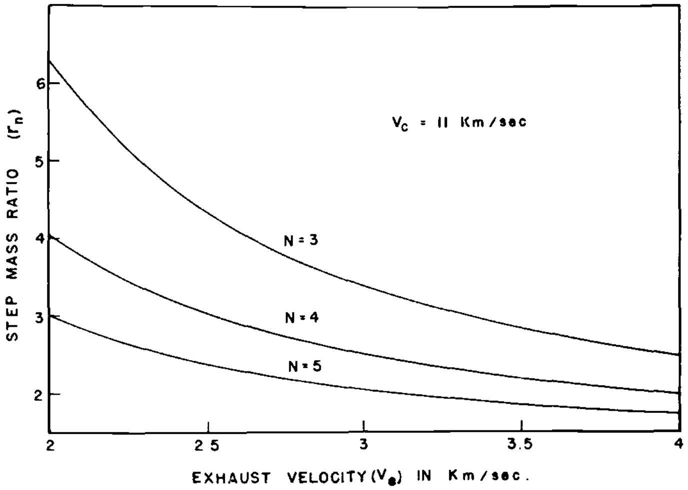

Fig. 1. The effect of changes in exhaust velocity on the mass ratios of the individual steps of three-four- and five-step rockets capable of taking up a stable orbit round the earth.

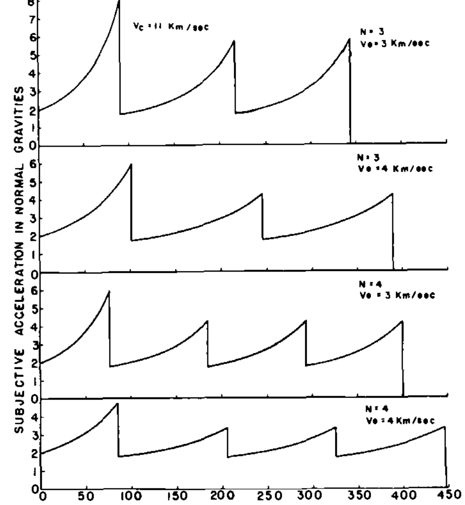

Fig. 2. Subjective acceleration against time for four multi-stage escape rockets. These acceleration curves formed the basis of the present series of tests.

ity and/or the number of steps increases.

This is further exemplified in Figure 2, which shows the acceleration curves for the four cases we have chosen as being most likely to correspond with actual conditions. These curves are calculated from the first equation except for the first step accelerations, which have been reduced by an amount varying linearly with time from 20 per cent at $t = 0$ to 0 at $t = \tau$. It is this correction that accounts for the steep rise of the first step curves.

HUMAN CENTRIFUGE STUDIES

Earlier calculations by Gauer and Haber[2] had indicated the very high and prolonged accelerations needed to attain the necessary velocity. In 1952 Ballinger[1] described human tolerance to such continuous accelerations and found, up to eight *g*, no serious complaints from a group of nine subjects. He used Gauer and Haber's table of constant accelerations necessary to attain escape velocity. They ranged from three *g* for ten minutes to ten *g* for approximately two minutes. In practice, due to the decreasing weight of the vehicle as the fuel is burned, the acceleration would not be uniform.[3] The question arose whether the constantly changing accelerations would cause symptoms or at least impair performance. It was known they would not prove intolerable if applied transverse to the body but there was no evidence whether a man would, for example, be able to perform a tracking task adequately during the rocket thrust and whether he could be expected to respond to a sudden emergency with an appropriate sequence of actions.

METHOD

The subject assumed the supine position on the floor of the centrifuge cab with his back raised at a 15° angle with the horizontal. Unlike the earlier tests conducted by Ballinger[1] his legs were raised at a 60° angle so that he was roughly in the conventional seated posture with respect to the line of flight. In a practical vehicle such a position would probably be necessitated by the limitations of cockpit space.

Suspended above and slightly forward of his head were two illuminated galvanometer dials, placed side by side and oriented so that one needle moved in the apparent vertical plane, the other in the horizontal. A short "joy" stick designed for wrist control was located on the cab floor to the right of the bed and was connected to two potentiometer shafts in such a way that vertical or horizontal control movements of the stick were reflected in corresponding movements of the galvanometer needles. An oscillograph was wired in series with each so that the movements of the pointer about the zero mark could be recorded (Figure 3). The output of a low frequency oscillator set at 0.083 c.p.s. was fed to each galvanometer pair to produce asynchronous, spontaneous deviations. The subject was directed to maintain the needles in the zero position by compensatory movements of his control stick. He was given a five minute familiarization period at 1 *g*, then a 4 *g* ride and finally a ten second 6 *g* ride prior to his test run. The test run consisted of the first three-stage acceleration curve of Figure 1 with peaks of 8, 5.8, and 5.8 *g* over a period of six minutes. The three-stage runs were preceded by a five minute practice period and a fifteen second control recording and were followed by a twenty second recording after the run.

viation produced by the oscillators was the same and a fair comparison of performance could be made.

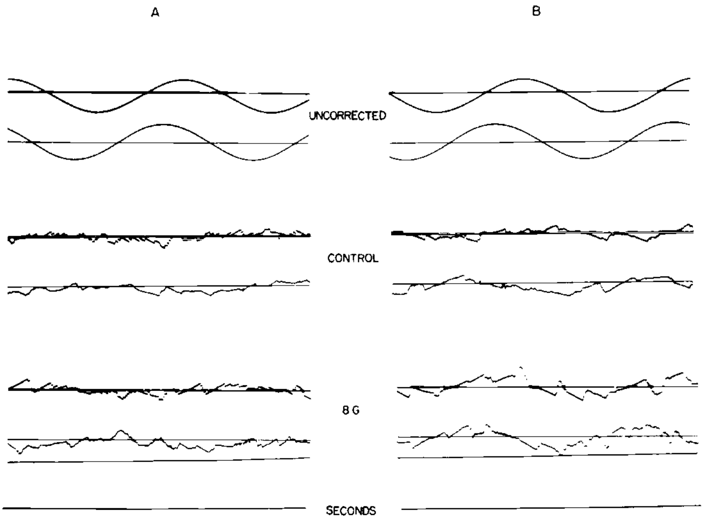

Fig. 3. Comparison of performance on two subjects, A and B, during three-stage rocket acceleration. The upper trace of each pair is the recording of the horizontal deviation, the lower one of vertical deviation.

ANALYSIS

For comparison of performance the total area above and below the zero reference line, circumscribed by the galvanometer tracing, was determined planimetrically. Because the amplitude of the recorded deviation is proportional to the angular deviation of the dial pointer, the area is a measure of cumulative error. Although performance in this test situation cannot be interpreted in terms of actual control of a rocket, the use of a control stick and the two indicators would suggest that this is a test of ability to hold a given orientation.

The duration of a single cycle of oscillation (12 seconds) was used as the length of selected samples. Thus for each sample the amount of de-

RESULTS

Subjective.—The nine subjects reported that the three-stage run was subjectively tolerable in the "legs-raised" position. There were about the same relative number of complaints of fullness in the chest and difficulty in breathing as in the former studies on extended supine position. No difficulty was experienced by any subject in making the wrist movements necessary for controlling the stick, nor was vision a serious problem, except during the later part of the deceleration phase. At this time vertical nystagmus usually occurred, which varied in severity from subject to subject. Vertigo was usually mild or absent. The hydrostatic effects of the legs-raised position will be considered elsewhere.

TABLE II. PERFORMANCE OF NINE SUBJECTS DURING VARIOUS PERIODS OF THE THREE-STAGE ROCKET ACCELERATION.

Values are in arbitrary units and refer to the areas of deviation from the zero reference trace. Letters A to H refer to the specific regions of the curve shown in Figure 4. Uncompensated areas were 45 vertical, 49 horizontal.

STAGE	A	B	C	D	E	F	G	H
	Control	To 8 g	From 8 g	To 5.8 g	From 5.8 g	To 5.8 g	From 5.8 g	Control
1 Vertical	28	26	27	23	29	25	31	20
Horizontal	21	24	30	16	21	20	18	19
2 Vertical	22	30	28	20	25	16	22	15
Horizontal	20	30	22	20	21	19	21	15
3 Vertical	12	15	16	16	15	15	21	14
Horizontal	13	19	26	19	19	18	27	18
4 Vertical	6	15	24	14	17	17	29	17
Horizontal	25	33	29	23	23	20	28	25
5 Vertical	13	19	18	15	17	16	27	16
Horizontal	14	22	13	18	17	22	25	14
6 Vertical	19	29	27	19	18	19	20	23
Horizontal	15	19	20	18	24	20	20	20
7 Vertical	13	25	33	24	28	28	42	29
Horizontal	22	33	29	27	23	20	43	16
8 Vertical	18	41	46	25	49	9	34	17
Horizontal	17	27	36	20	33	31	41	34
9 Vertical	27	37	60	35	54	——(No Record)——		
Horizontal	34	56	57	38	58			

Performance.—As expected, there was a great degree of individual variation in the effect of acceleration on performance. Inexperienced subjects showed a greater tendency toward deterioration under *g* than did those accustomed to the centrifuge. In general, performance deteriorated somewhat during acceleration, in a few cases rather negligibly (Fig. 3, A) and in a few seriously (Fig. 3, B). From an examination of the over-all results, there is good reason to believe that manual control can be depended on during three-stage accelerations of the type studied. Table II shows the areas of deviation for the nine subjects, lower values indicating better performance. Samples were taken during static conditions and during the run at points where severe and rapidly changing conditions would be expected to produce the most serious effects on performance (Fig. 4). It should be noted that for four of these subjects, (Numbers 2, 5, 8 and 9) this was the first exposure to a three-stage, 8 *g*, run, and for seven out of nine it was the first try at performance under such accelerations. Nevertheless deviation for many samples was less than the average control deviations of 17.6 vertical and 20.1 horizontal. Furthermore, while some subjects showed noticeable deterioration throughout the run, two subjects, Numbers 3 and 5, maintained their deviations at very close to average control levels in all cases where acceleration was increasing. The deterioration of these subjects during the descent from each peak acceleration was probably related to angular deceleration and its associated oculogyral effects. This was especially true of sample G where the angular deceleration was more severe than for samples C and E due to application of brakes in this last stage. Because in rocket take-off there will be no such angular decelerations, it is not anticipated that this noticeable decrement in performance will occur during burnout.

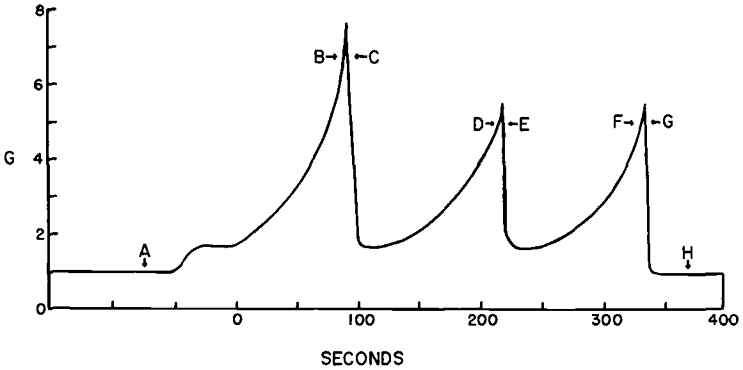

Fig. 4. Acceleration curve for three-stage rocket acceleration showing sampling points.

DISCUSSION

This preliminary study indicates that manual control of a three-stage rocket, vehicle is within the realm of possibility, especially if some small loss in control accuracy is acceptable. Throughout indoctrination on the centrifuge might be of value from the standpoint of familiarization with the sensations involved and the changes in control characteristics and to allay apprehension. We believe that the cause of some of the poor showings was as much a matter of alarm as of lack of practice under *g*. With two separate dials to monitor simultaneously, the subject must be able to concentrate on his task. Thus, in one case a marked deterioration in performance occurred when the subject was distracted from the tracking task by a transient but disturbing abdominal discomfort. On further runs when the pain had vanished, deterioration of performance during the acceleration was negligible.

We believe that the use of two separate indicator dials makes this test a more valid measure of performance than would a combined dial. The task of proper division of attention between the two indicators then becomes as important as is the proper coordination of the motor response. It was found that the subject, during moments of distraction, will continue to control one indicator while allowing the other to wander. As a test of the handicap imposed by divided attention, a subject was told to control only the horizontal dial and to ignore the other for a twenty second period. When told to control both meters, the deviation of his horizontal tracing was increased by 42 per cent. It is likewise interesting to note that while Subject 4 (Table II) did exceptionally well with his vertical pointer on the control and the 8 *g* sample, he performed poorly with the horizontal pointer, probably because of unevenly divided attention.

The extent to which the present preliminary studies duplicate the demands which would be put upon the operator of an intercontinental ballistic vehicle or orbiting rocket, both of which must very closely approach escape velocity to attain their objective, may be debated. The tests do establish, however, that a trained occupant of such a vehicle could be expected to do more than merely endure the accelerations while computers took over the task of adjusting it accurately to a predetermined course.

SUMMARY

Hyperbolic acceleration curves are derived for three or four stage rockets which could attain the 10 to 11 km./sec velocity necessary for establishment in a practical orbit round the earth.

A preliminary study has evaluated the capacity of nine subjects to perform a dual pursuit task while undergoing a typical series of curves.

Evidence is presented to indicate that select crewmen can be expected to assist in the control of such a vehicle during the critical acceleration phases of the flight.

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Helicopter Ambulance Service

Kenmore Mercy Hospital in Kenmore, New York, a suburb of Buffalo, is one of the two hospitals in the United States that now has helicopter emergency ambulance service. A temporary heliport, a 20-foot square wooden platform, has been constructed a few feet from the emergency entrance to the hospital. and a helicopter is on call any time of the day or night. . . . Physicians in this highly industrialized area of approximately a million people estimate that the helicopter will be used for at least eight to ten patients annually—perhaps a stricken sailor aboard a lake freighter miles from port or an expectant mother in a remote. snowbound farmhouse, or a wounded hunter along a wooded trail. . . .

Helicopter ambulance service was first established in the United States at a hospital in Santa Monica, Calif. Here a rooftop platform serves as a landing area, and helicopters are made available by rotorcraft firms in the Los Angeles area. Arrangements are now being made for the construction of a heliport in the Dallas-Fort Worth area.—*Public Health Reports,* 7:432, April 1955.