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THE FLYWHEEL AS A CENTRIFUGAL ACCELERATOR

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FOREWORD

The proposal of the flywheel-operated circular track has stimulated a considerable amount of controversial questions. The initiation of basic studies has been made possible only by the farsightedness, competency, and tenacity of Lt Col H.H. Blackshear, USAF, MC. Encouragement was given by Dr. S.H. Crandall (MIT) who wrote a preliminary recommendation. Support was granted by the Office of Research Analysis, OAR, at Holloman AFB, by employing Dr. Raymond F. Askew (Auburn University, Alabama) on a stress analysis study. The actual workload rested with Dr. C.N. Gaylord and Dr. J.A. Friedericy and their staff (University of Virginia, Charlottesville) who attacked the new problems with enthusiasm and authority.

ABSTRACT

Subjected to investigation is a flywheel accelerator as a component of a 160 to 200-foot diameter circular track. The 22 spoke, box-construction flywheel could be made from commercially available steel plates. Based on optimal design conditions, the upper application limit, governed by the welding property of the material used, was found to be a test weight - load factor capacity of 230,000 pound - 300 g. The discussion, based on a linear dependence of flywheel weight, moment of inertia, power and cost on test weight, and cross-section of box members at constant radius and stress, shows that the lower application limit of the flywheel reaches far into the application range of proposed, arm-type centrifuges and that the flywheel is a logical necessity, if the test capacity of existing centrifuges needs to be exceeded.

PUBLICATION REVIEW

This Technical Documentary Report has been reviewed and is approved.

Hamilton H. Blackshear

HAMILTON H. BLACKSHEAR
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I. INTRODUCTION

Centrifugal accelerators, originally built as static gravitational generators, have experienced a vast development as astronautic or bioastronautic test facilities. The ever increasing test requirements have reached a point where the construction of advanced centrifuges exceeds the limit of economic sanction. The question arises whether the concept of a conventional centrifuge can be preserved or had better be replaced by a different design approach. The answer to this question can be found only on the solid ground of comparative design studies, including such factors as production cost, operation and maintenance cost, operational reliability and versatility, safety, usefulness and growth potential.

This paper is restricted to the discussion of a statically stressed flywheel as the prime mover of a proposed astronautic accelerator, called a circular track.

II. DESIGN CONCEPTS

A fictitious description of the circular track was published in 1960 (Ref. 1). The principle of this suggestion is illustrated by Figure 1. The test specimen, including all test equipment, accessories, and assemblies are supported by a circular track-riding sled, all together accounting for the total test weight to be accelerated. The drive of the sled is achieved by controlled transfer of stored rotary energy from the flywheel to the sled. The sled is decelerated by controlled energy transfer from the moving sled to the stationary track. A rotating truss beam, serving as the carrier of the test service lines, can be connected directly with the sled or can be omitted.

The design requirements of a centrifugal accelerator vary widely with the test objectives. Bioastronautic research, preflight and postflight checkout of manned or unmanned space capsules, and training of one astronaut or of operational space crews, all require different test procedures and a highly versatile test facility.

Extensive studies of several design approaches resulted in a preference for the central drive, arm type, conventional centrifuge (Ref. 2). Nevertheless, acknowledgement was made that "a flywheel can comprise the basic accelerator, but was not analyzed due to insufficient time and support."

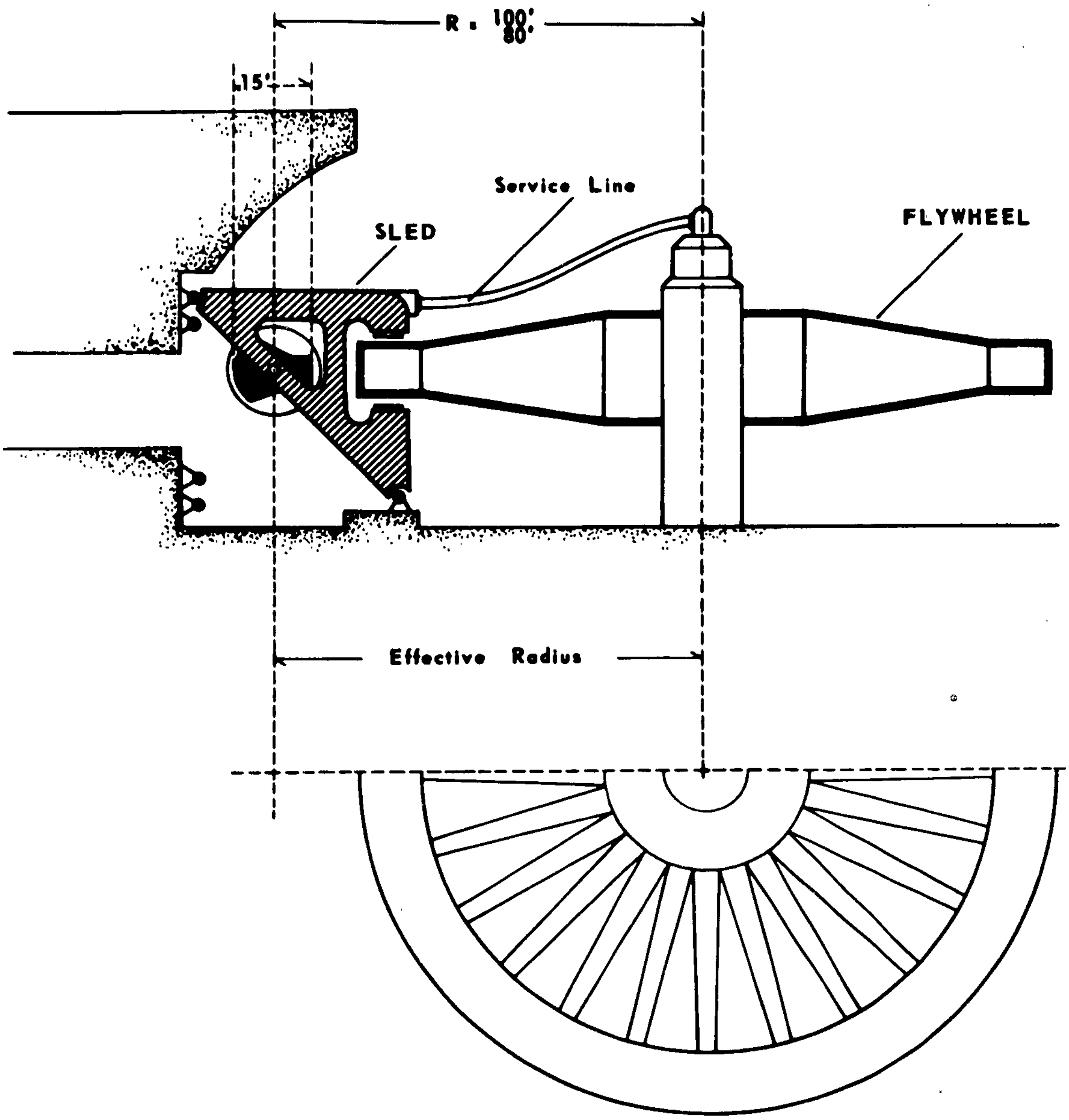

FIGURE 1. PRINCIPLE OF CIRCULAR TRACK

The 6571st Aeromedical Research Laboratory proposed the flywheel-operated circular track as early as February 1959, but a scientific treatment of this project was prevented by the lack of funds and personnel. However, preliminary in-house studies yielded enough evidence to recognize a statement on the superiority of any one type of centrifugal accelerators as a premature conclusion, as long as a comparison of equivalent studies of alternate designs was missing. A small contract was let to close this gap and the engineering report on the feasibility of a flywheel will soon be available (Ref. 3). A summarizing discussion of the main problems and findings is given in the following.

III. DESIGN FACTORS

The evaluation of alternate designs of this magnitude requires a feasibility study of each design and a comparison between them on the basis of well established performance requirements. This report discusses the flywheel only. Related problem areas of the circular track or of the conventional centrifuge are ventilated only to emphasize the need for further investigations.

To provide for the possibility of a design comparison, this chapter is divided into a discussion of the imponderables, the test requirements, the individual design factors, and the decisive design factors.

A. Imponderables

The designer can select the basic design parameters of angular velocity (coriolis acceleration), circumferential velocity (air drag), and radius (acceleration gradient) in the limits of their fixed dependence on the required acceleration level, as illustrated by Figure 2. It is here where the controversy starts and usually ends with a compromise. The final choice of the test weight and acceleration level automatically involves other considerations such as need, usefulness, and gain of a specific design, which are less accessible to a numeric evaluation, and thus are a peculiarity of controversial test philosophies such as:

1. Ground testing versus flight testing
2. Unmanned versus manned spacecraft
3. Threshold versus performance testing
4. Individual versus group testing
5. Component versus composite testing
6. Separated versus composite testing
7. Isolated versus consecutive testing.

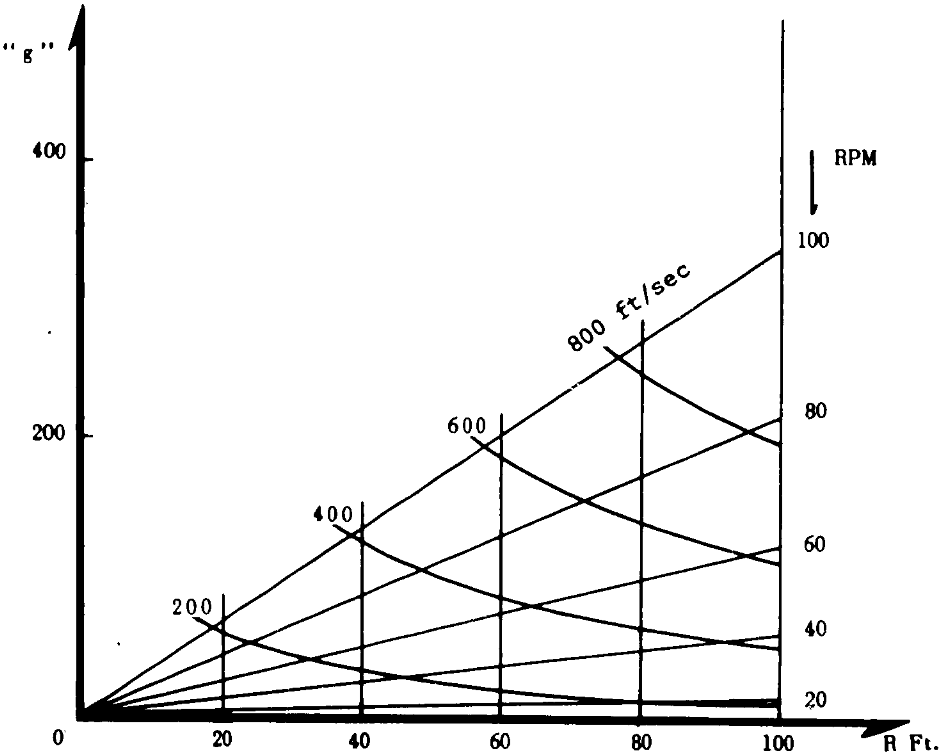

FIGURE 2. BASIC DESIGN PARAMETERS

No attempt is made at this time to elaborate on the pros and cons of the different test philosophies. The final decision on the design requirements, however, should be governed by the need to secure by testing rather than by a dispute of the need per se. This is to say that testing under actual performance conditions has always been the only valid resource of empirical science.

B. Test Requirements

Disregarding the usefulness of special purpose designs, identical design requirements should be chosen for the sake of a fair comparison of alternate devices. A parametric study of thus established common significance design factors will then provide the cognition of definite design limitations.

1. Radial Acceleration Gradient and Coriolis Acceleration

The radial acceleration gradient becomes meaningless when a point mass specimen is under consideration, and becomes important when spacious test specimens are tested. Figure 3 illustrates the magnitude of the radial acceleration gradient in percent per foot, relative to any radius. The plotting of the steep slope of this diagram in the radius range of less than 10 foot is somewhat bizarre, for spacious specimens would hardly make use of small accelerators. The change of the radial acceleration gradient is considerably large in the radius range of existing centrifuges, i.e., from 20 to 50 feet and becomes negligible beyond 80 foot.

The coriolis acceleration ($a_c = 2 v_r w$) is experienced by radially moving test specimens or components thereof. The general trend of the dependency of the coriolis acceleration on the radius is illustrated in Figure 3. Essentially, this dependency is governed by the term $1/\sqrt{R}$ and it can be seen that significant gains in the repression of the coriolis effect cannot be expected for radii beyond 100 feet, while considerable increase of the coriolis acceleration will occur with decreasing radius.

The first decision the designer is confronted with is to determine the significance of the radial acceleration gradient and of the coriolis acceleration with regard to the anticipated use of the planned test facility.

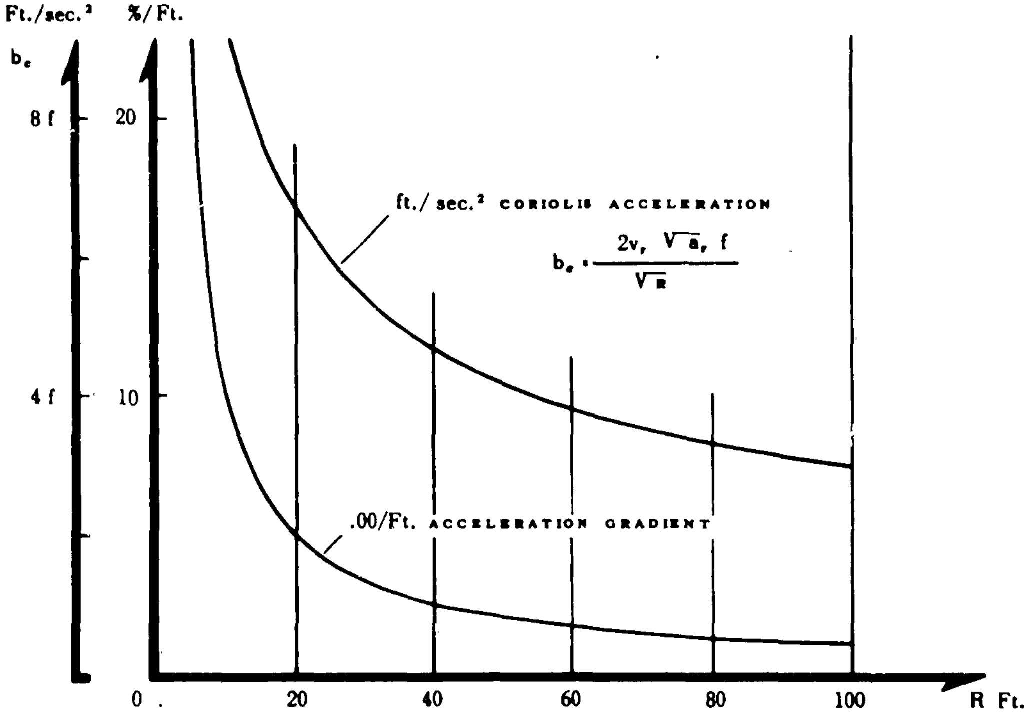

FIGURE 3. RADIAL ACCELERATION GRADIENT AND CORIOLIS EFFECT

2. Acceleration Level and Time History

Technological test objectives usually endeavor to establish the yield or failure limits, while human testing is restricted to the threshold of reversible damage, which in most cases is unknown. From a general point of view, the capacity of a centrifugal accelerator should cover the possible space-flight profiles (Fig. 4), and all superimposed acceleration patterns resulting from oscillation, buffeting, vibration, and noise.

Based on "normal" manned space-flight procedures, the acceleration level could be restricted to 12 g or less, save impact. "Faulty" or fictitious return from outer space could, at the most, result in a 90-degree re-entry with escape velocity into the earth's atmosphere. This would require a bell-shaped test profile with a peak acceleration of 320 g, arrived at in 5 seconds. The acceptance of one of these limits as a design requirement depends on the chosen test philosophy. The choice of any acceleration level between these limits is a compromise.

The multi-stage launch profile is characterized by having a rather abrupt drop in acceleration between stages. The flywheel is the only mechanical accelerator capable of reproducing a realistic launch profile.

3. Test Weight and Load Factor

The weight requirements of astronautic testing have become increasingly demanding, but a calculated limit of 23,500 pounds is dictated by the capacity of conventional centrifuges (Ref. 2). On Page 10 of this reference it is stated that one has "to accept reduced onset, capsule space and weight --- to attain the 100 radial g requirement -- by means of practical power requirements," 50,000 HP that is.

This test weight limit of 23,500 pounds includes only 200 to 500 pounds of the actual test specimen with the weight difference accounting for the necessary test equipment, such as support structure, gimbal system, and accessories to generate the environmental test conditions. To imagine that an error of 200 pounds in designing of the equipment weight of 23,000 pounds could eliminate the test specimen altogether (for otherwise unchanged test requirements) illuminates the unfeasibility of such a design.

In contrast, the testing of an actual, man supporting space capsule under the environmental conditions of space flight can easily result in an estimated total weight of 230,000 pounds

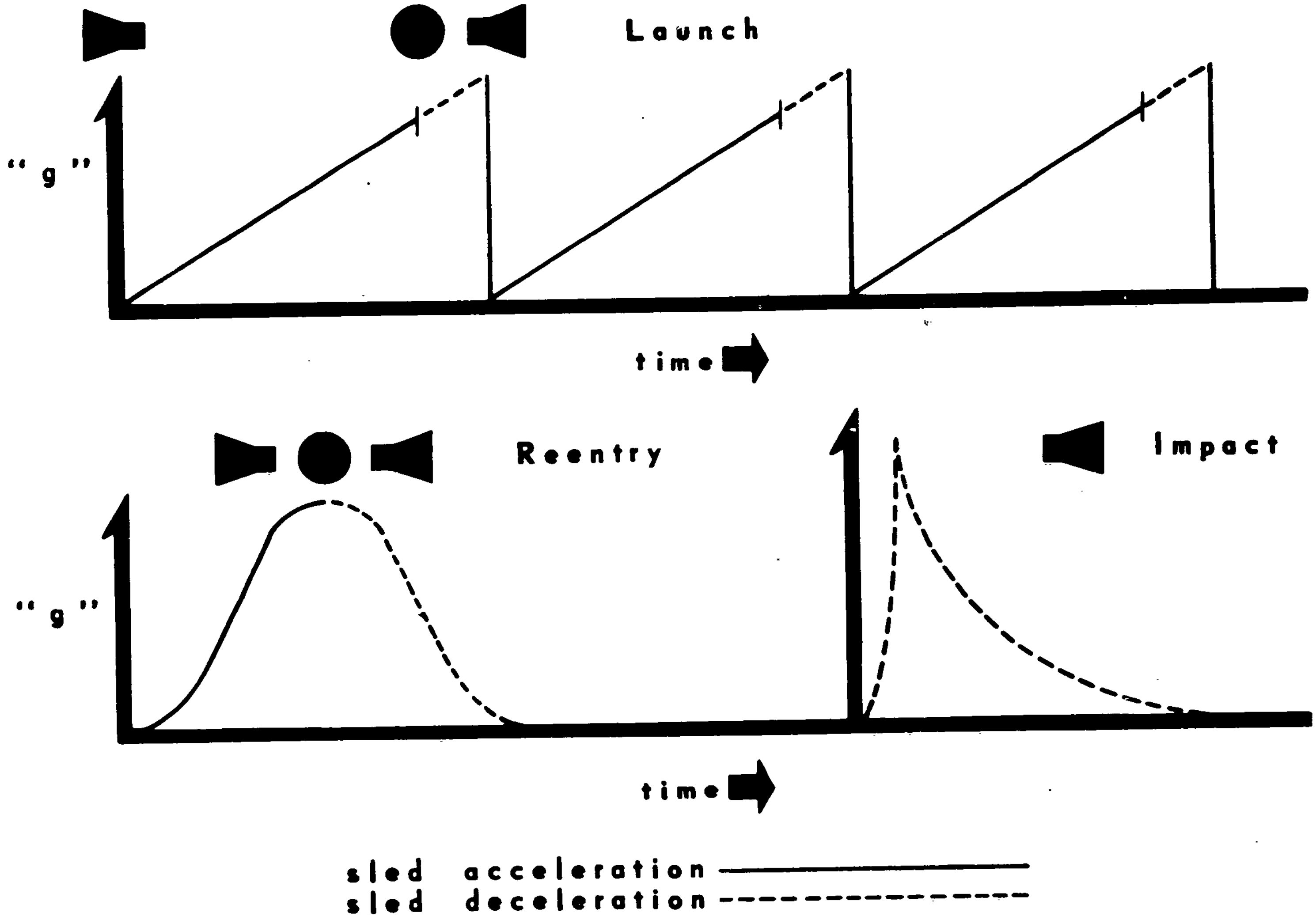

FIGURE 4. ACCELERATION PROFILES

being considered as a reasonable limit of a parametric study rather than a definite design requirement. A test facility of this wide test range would not only permit the preflight and postflight checkout, but also would increase the training output by a factor of 30 by use of ten 3-men mockup capsules compared with the presently applied one man - one capsule training procedure.

It has been emphasized that the test requirements per se are highly vulnerable from the view of the test philosophy, but once the need to satisfy a specific set of test requirements is agreed upon, the design itself is a purely technical task. The subject of this basic study is to find a feasible flywheel for a set of test requirements representing the anticipated needs of long range planning. From this view the following design specifications are assumed:

a. 100 foot radius, to minimize the radial acceleration gradient and coriolis effect

b. 300 g acceleration level, generated in 5 seconds, to provide the possibility of testing up to 90-degree re-entry profiles

c. Means to produce abrupt acceleration decay

d. 230,000-pound total assembly weight, to provide for testing of actual space capsules or training of operational crews

C. Individual Design Factors

Based on the requirements established by the anticipated test objectives, the individual design characteristics of a flywheel accelerator have been investigated. A preliminary report on the current studies has been completed, limited to a static stress analysis (Ref. 3). The results are evaluated for general information on the design of a flywheel with a radius between 80 and 100 foot, composed of a box-type flywheel rim and 22 box-type spokes, made out of commercial T-1 and Hy-80 steel (U.S. Steel Corporation).

The diagram of the flywheel design factors (Fig. 5), was arrived at by one single plot of the computed dependencies, reported in Reference 3. The square framed data represent an 80-foot radius, the circle framed data a 100-foot radius flywheel. This single plot represents a flywheel (80 and 100 foot) of optimal geometric configuration to satisfy the maximal test

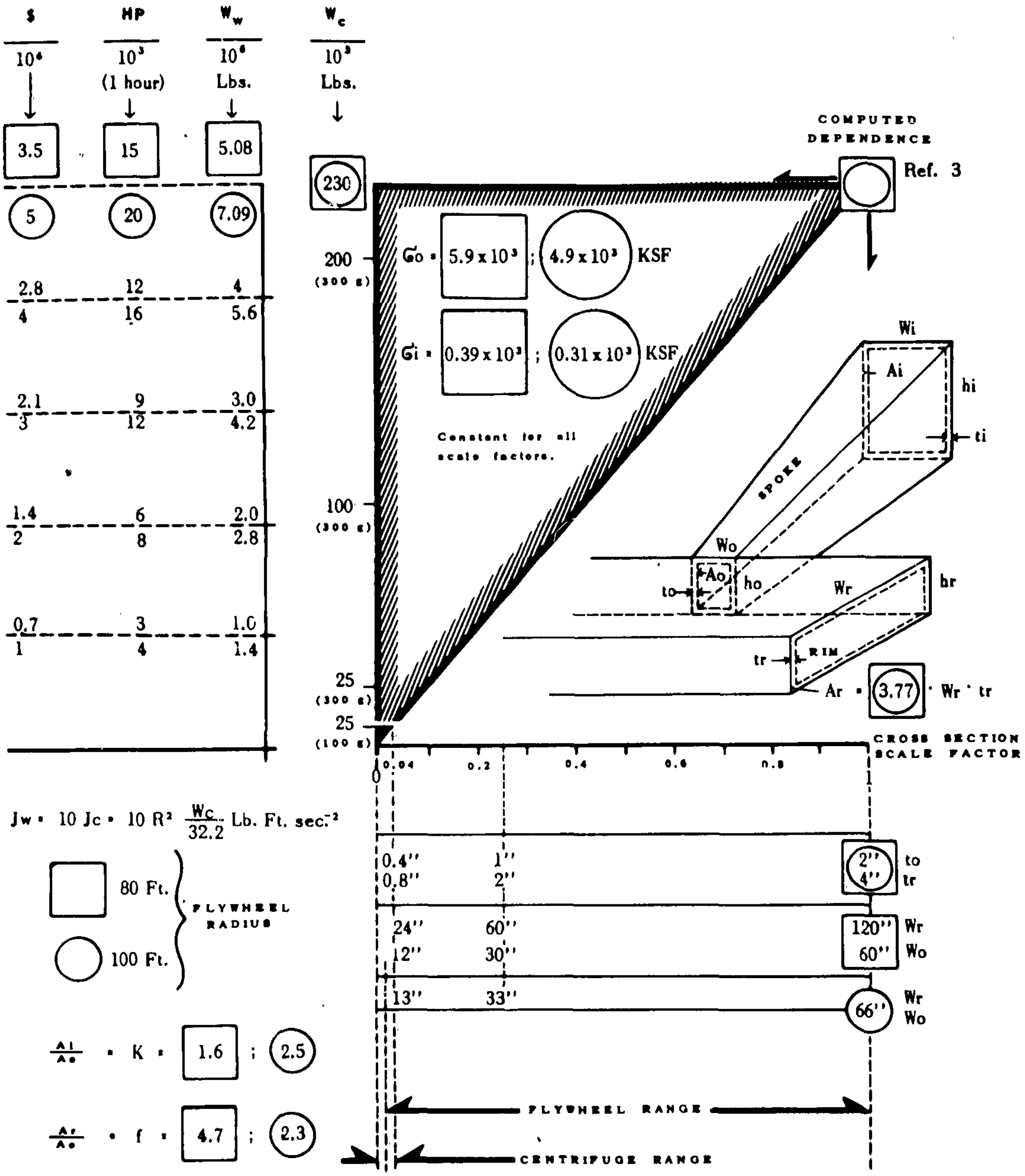

FIGURE 5. DIAGRAM OF FLYWHEEL DESIGN FACTORS

requirements of 230,000-pound test weight, 300 g load factor and $J_w/J_c = 10$ ratio of the moments of inertia of flywheel and total test weight.

The diagram, Figure 5, is based on the assumption of linear dependence of all design factors listed for constant flywheel radius and spoke stress. This assumption would have to be verified from case to case. For instance, the stress of the spokes remains constant for a certain range of wall thickness of the material used. The stress of the rim does not remain constant, but can be corrected for individual design. The power requirement would have to be corrected for losses by mechanical and aerodynamic drag. The considered load factor range of up to 300 g at 100-foot radius involves peripheral velocities of up to about 1000 ft/sec, resulting in tremendous air drag. For a 23,000-pound capsule at 100 g the drag requirements of still air are computed to be 14,000 HP (Ref. 2). Further consideration of the air drag is neglected in this report on the ground that equal test setup and conditions require equal means for both centrifuge and flywheel, to compensate for or to eliminate identical design difficulties.

The material cost of the flywheel varies linearly with the weight; the fabrication cost does not. However, for the purpose of an overall informatory survey of possible design trends, the chosen diagram might be acceptable.

1. Construction Limitation

It is essential to recognize that the design factors of the diagram are valid for a welded, box-type flywheel construction with the wall thickness t_o and t_r. Since Hy-80 (t_r) can be welded up to a wall thickness of 6 inches, and T-1 (t_o) up to 2 inches (Ref. 3), the applicability of the chosen construction would be limited by the wall thickness t_o of the spokes as the decisive design criterion. Designed to satisfy the maximal test weight requirements of 230,000 pound at 300 g as an upper limit, the lower limit of application of similar constructions can be estimated by the use of the diagram, based on the quoted linear dependencies.

At this point, it is of interest to venture on a comparison of a conventional, arm-type centrifuge with the data represented by the diagram. A parametric study on the centrifuge established that "between 20,000 and 25,000 pounds of gimbal assembly weight appears as a (upper) limit to be carried by a 100-foot arm at 100 g's" (Ref. 2, p22). Disregarding the individual design data of a conventional centrifuge such as moment of inertia, arm weight, power requirements and cost, the weight capacity limit (25,000 pounds, 100 g) of the centrifuge is plotted in the diagram, Figure 5. It is seen that a flywheel scale factor 0.04 satisfying the same test requirements, would have a spoke wall thickness of $t_o = 0.4$ inch. Provided the validity of all assumptions made, it could be concluded that the lower applicability limit of the chosen flywheel design deeply penetrates the applicability range of the comparable centrifuge (black sector). However, it should be kept in mind that this conclusion is based only on geometric design parameters and that economic considerations will dominate the final design selection.

The disproportion of the respective capacities of a centrifuge and a flywheel is tremendous and again reminds the designer of the primary significance of the test philosophy. If very low weight-load factor capacity is considered to satisfy the test objectives, a conventional centrifuge will do. If very high capacities are required, a flywheel will be imperative.

2. Flywheel Weight

At it's upper application limit; an 80 or 100 foot radius flywheel would weigh approximately 5 or 7 million pounds respectively (Ref. 3); at the 25,000 pound, 100 g level, about 100,000 pounds (Fig. 5), which compares to 50,000 pounds of the conventional centrifuge of same test weight capacity.

3. Bearings

The asymmetrical mounting of an 80-foot radius flywheel (Fig. 1), to accommodate the asymmetrical loading of a 230,000 pound, 300 g, 5-second acceleration pattern would require a flywheel shaft diameter of 12.5 foot and would result in a power loss of 7,400 HP (Ref. 3). However, considerable simplification would result from the selection of a symmetrical bearing and symmetrical load arrangement.

The most unfavorable test conditions and arrangements would require 400 square feet of vertical (sled) slipper area, which also can be reduced considerably or even can be eliminated completely by symmetric test arrangement of two or more test capsules (Ref. 3), especially feasible in training of operational space crews.

4. Heat Transfer

The energy transfer from the rotating flywheel to the sled at rest at maximal test requirements results in 8 million BTU (Ref. 3). Considerable savings can be achieved by starting the test with an initial sled velocity.

D. Decisive Design Factors

No basic design difficulties are to be expected in the construction of the flywheel. The final decision on the design specifications will be governed by the availability of commercial power sources and the cost.

1. Power Requirements

The maximal test requirements (230,000 pound, 300 g, 5 second) of an 80 or 100 foot radius flywheel would need 51.4 or 65.6 million HP sec respectively (Ref. 3). This means that for charge times of 1 or 18 hours the power requirements to store a 100-foot radius flywheel with sufficient energy ($Jw = 10 J_c$) would be 18,000 HP or 1,000 HP respectively (disregarding mechanical and aerodynamic losses), which is well below the capacity of available electric power units.

On a comparable basis, a flywheel designed to operate a test weight of 25,000 pounds and 100 g at 100-foot radius would require 700 HP (Fig. 5), for one hour charge time while the conventional centrifuge operating the same test weight - load factor product would need 50,000 HP (Ref. 2).

It is obvious that besides pure numerical comparison other problem areas are involved such as gearing and operational flexibility on the one hand and air drag or mechanical friction on the other hand.

2. Cost

To start with the power requirements, a motor to satisfy the maximal test requirements, based on 1 or 18 hour charge time, would cost 3.6 or 0.2 million dollars respectively (Ref. 3). On a comparative basis, a 25,000-pound capacity conventional centrifuge would involve the motor cost of 10 million dollars, disregarding the additional development cost resulting from the unavailability of such a motor. The 25,000-pound capacity flywheel, charged in 1 hour, would involve a motor cost of $140,000.

The total cost of an 80 or 100-foot, maximal capacity flywheel, (including material and fabrication costs), was found to be $3.5 or 5 million respectively (Ref. 3). The low capacity flywheel would then cost about $500,000 (Fig. 5).

IV. CONCLUSIONS

All data of the compared accelerators are gained from an analysis of proposed facilities. With the implication that the controversy of centrifugal accelerators lies with the test philosophy, it can be stated that the designer will increasingly be attracted by the flywheel concept, the more the test requirements of test weight, load factor, and onset are increased.

In comparison with existing centrifuges a flywheel shows considerable advantages. For instance, let's take a centrifuge having a capacity of 5000 pounds and 40 g at a radius of 50 feet. Confronted with the low limit flywheel of the capacity of 25,000 pound, 300 g at 80-foot radius, the power requirements of this centrifuge based on 1 hour flywheel charge time, is $\frac{16,000}{2,000}$ times larger; in other words, for one-eighth motor (sales) cost, the flywheel could handle five times the test weight and eight times the load factor now achieved. For longer charge times of the flywheel, a comparison on the basis of power requirement and motor cost becomes grotesque.

A conclusive comparison between a centrifuge and a flywheel-operated circular track in the competitive test range up to the test weight-load factor capacity of 25,000 pounds at 100 g would need a more thorough design evaluation of the circular track. Based on identical test assembly, the total test weight of the circular track, increased by the weight of the sled, compared to the total test weight of the centrifuge is approximately 1.5:1. Further investigation of the flywheel concept would require inclusion of dynamic stress analysis, clutch and brake system, and track construction. Study continuation in this direction will proceed as dictated by funds available.

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