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FINAL ENGINEERING REPORT FOR THE

DART STABILIZATION SYSTEM
(Directional Automatic Realignment of
Trajectory)

Using The

SLIP LINE
Prepared under Navy, Bureau of Naval Weapons
Contract No. N600(19)59218
5 April 1963

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ABSTRACT

Any misalignment of the rocket thrust with the C.G. of a man and an ejection seat causes the seat to rotate. This rotation causes the rocket thrust to change direction, thereby changing the trajectory of the seat. The man may not be recovered at low altitudes. Furthermore this rotation cannot be controlled by drogue chutes except at high speeds. At low or zero speeds the seat can be at any attitude or the drogue chute can be wrapped around the seat when the man separates from the seat, very possibly fouling his parachute.

The Slip Line System stabilizes the seat during rocket burning and corrects the trajectory. It incorporates a brake, a bridle on the bottom of the seat and line to be pulled through the brake after the seat has traveled a short distance. As long as the seat does not turn past the design angle during Slip Line action, the seat is corrected for all misalignments in both directions in proportion to the offset.

This report covers the development of a brake, the construction of a computer to find the brake pull time and length of pull, and the seat testing to optimize the corrections and test the system effectiveness.

Two preliminary tests were made with the Slip Line which was designed for a 1-inch maximum misalignment. These tests resulted in a maximum of 13 percent under-correction, with 1-inch misalignment. After adjustments two further tests gave about 7 percent under-correction. A test with 1.4-inch misalignment resulted in approximately 12 percent under-correction.

These errors in correction of seat turning rate can be easily taken care of with drogues smaller than the large drogues in use at present.

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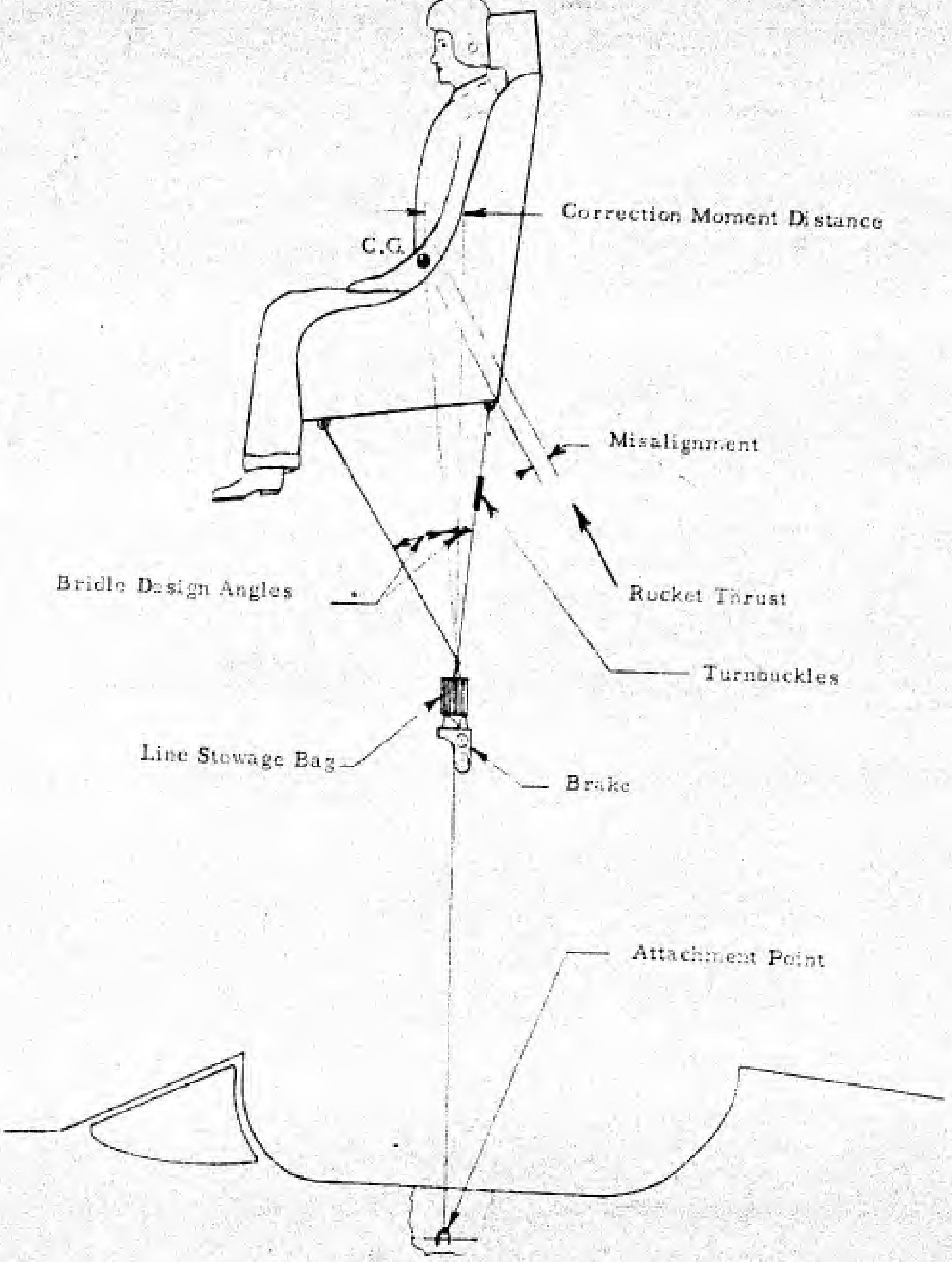


SLIP LINE SYSTEM

Figure 1

I. INTRODUCTION:

Whenever a seat or capsule is ejected from a plane by a rocket any misalignment of the center of gravity with the rocket thrust causes rotation or pitch of the seat. This rotation can be stopped at high plane speeds by a reasonably small drogue parachute. A large drogue chute is required at low plane speeds to stabilize the seat. This large drogue chute not only reduces the height of the trajectory, but also causes intolerable deceleration forces at very high speeds. At zero speed even a large drogue chute will not stop the rotation of the seat with a large misalignment.

This report covers the development of a brake and Slip Line System to stabilize the seat at zero or low plane speed with minimum loss in rocket impulse. The Slip Line corrects the seat position during rocket burning; therby correcting the trajectory close to that of a seat with no misalignment. The correction in trajectory will more than make up for the loss in height due to the Slip Line if the C.G. is approximately 0.3-inch or more below the thrust line. However, it should be pointed out that the impulse lost due to a drogue large enough for low plane speeds is more than that lost due to the Slip Line.

At high plane speeds the drogue chute will completely over-ride the effect of the Slip Line.

While the Slip Line System could be applied to any ejection seat the A4D seat was selected as requiring the Slip Line most urgently. The A4D seat in use at the present has no drogue chute. Therefore, it was felt that the drogue size could be assumed since the Slip Line should be used with a drogue.

Two 24-inch dia. drogue chutes will take care of errors in pitch in the Slip Line corrections at zero or low plane speeds while giving very reasonable deceleration forces at high speed.

II. PRINCIPLES:

The basic principle of the Slip Line System is that as the seat turns a pull by the Slip Line will give a correcting moment in proportion to the angular displacement from a no-misalignment position. This proportion holds closely up to the design angle of the bridle. (Figure 1) If the seat turns past the design angle the other bridle

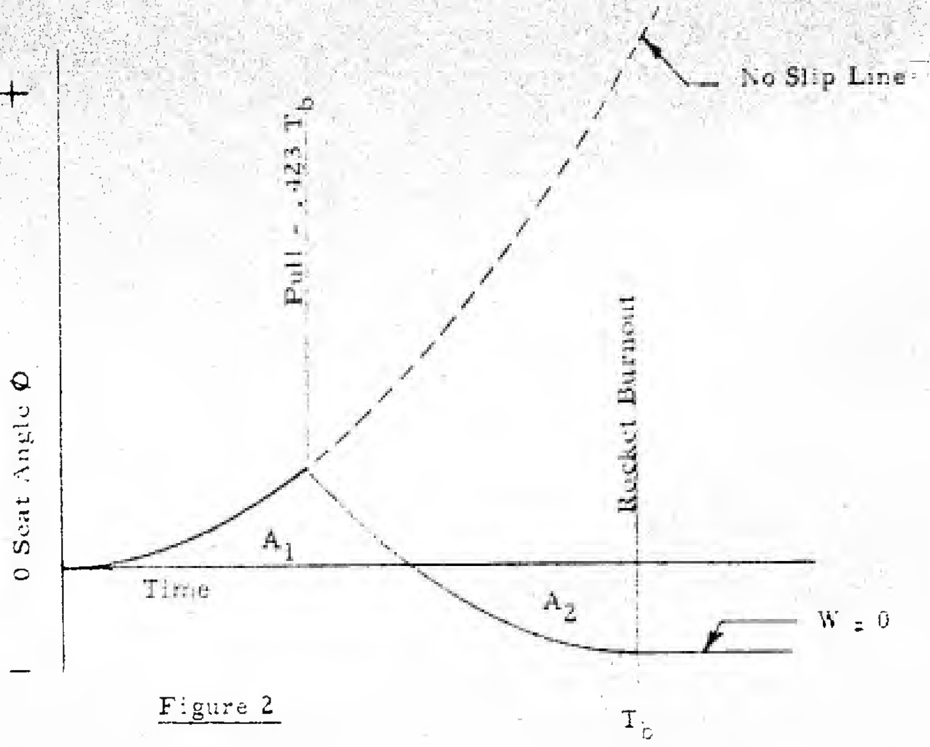


Figure 2

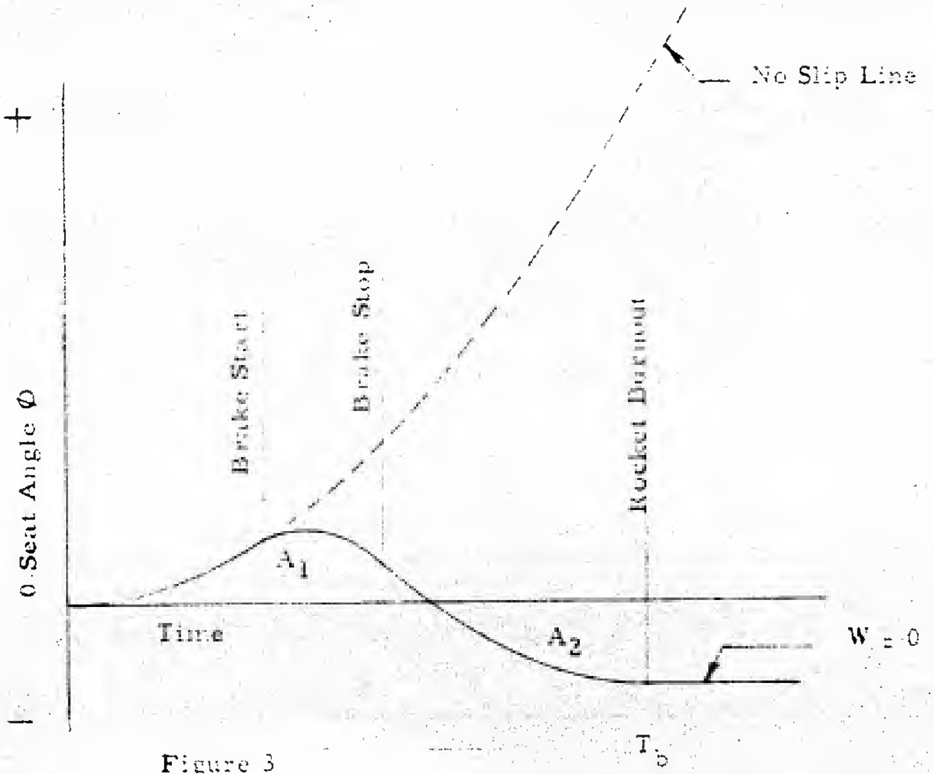


Figure 3

II. PRINCIPLES: - Continued

goes slack, and the correcting moment goes up less than proportional. It is necessary, therefore, to design for some maximum misalignment. Any greater misalignment will be corrected less than 100 percent.

In order to correct seat rotation with a minimum brake impulse, it is necessary to wait until the seat has turned a maximum and pull with a large force for a short time interval. However, this turning during rocket burning changes the thrust direction and, therefore, the trajectory.

On the other hand if the Slip Line impulse is applied earlier the trajectory can be made similar to that of the seat with no C. G. misalignment. To accomplish this the correction must be made at time .423 T_b, where T_b is the burning time. It is assumed here that the rocket thrust is constant during burning time. In Figure 2, Area A_1, is equal to Area A_2.

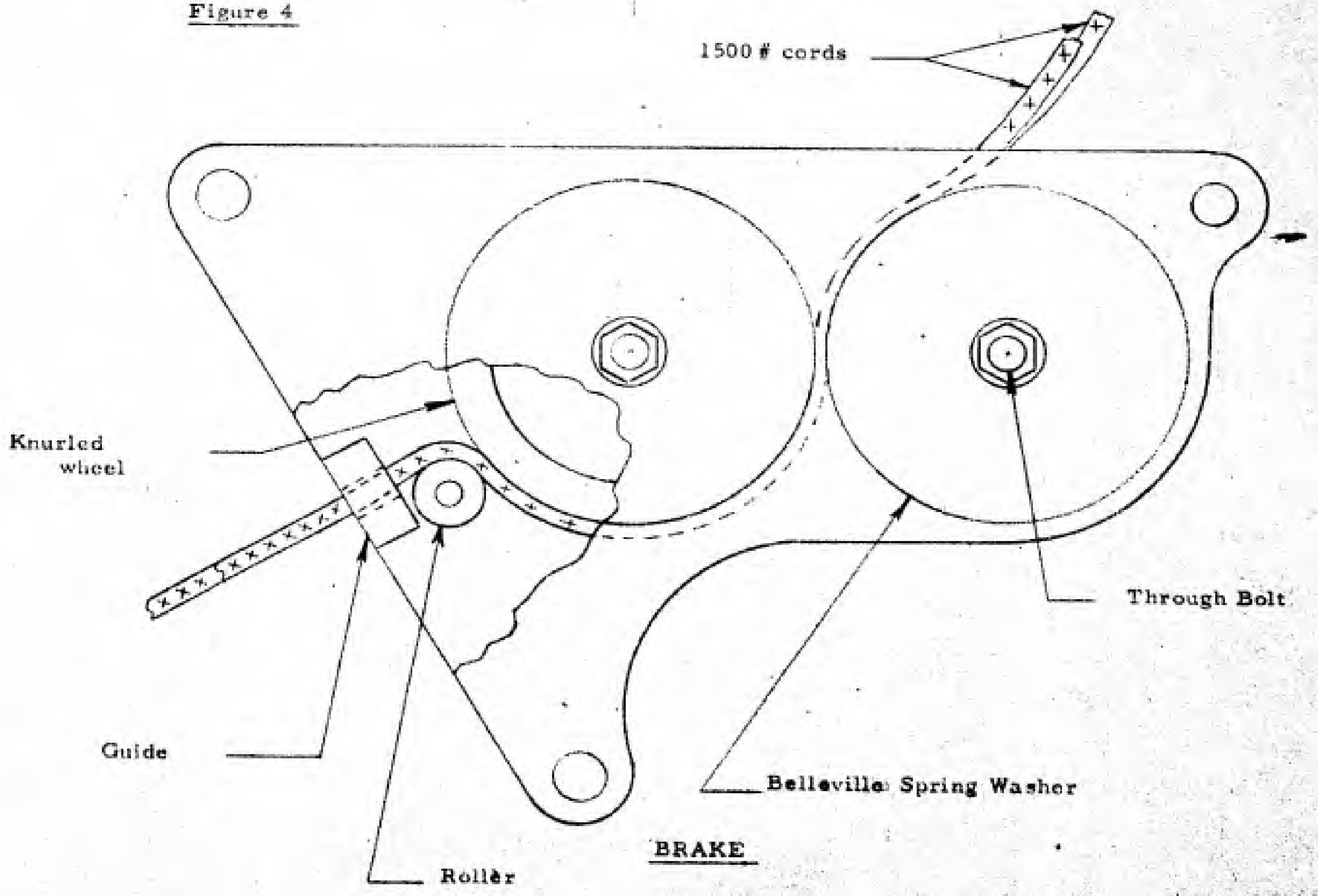
Obviously the brake impulse (brake force times pull time) cannot be made instantaneously. Therefore, the seat angle versus time will appear as in Figure 3. The longer the pull time the greater the angle change during the pull and the more difficult it is to get an optimum correction ($A_1 = A_2$).

This angle change during the pull increases the necessary brake impulse.

The brake pull force must be less than the vertical component of the rocket thrust if the pilot is to avoid zero vertical G's and thus possibly change his position for the remainder of the rocket burning time. Therefore, a compromise force should be used on the order of 800 to 1000 lbs. maximum if the vertical component of the rocket force is 1500 to 1800 lbs.

In reality the start of pull can be changed 15 to 20 percent without hurting the trajectory appreciably so long as the Slip Line length and brake force are also changed to the correct values. With a given start of pull any percent error of the Slip Line length will introduce the same percent error in rotation correction. Also any error in the brake impulse will introduce slightly less than the same percent error in rotation correction.

Figure 4



BRAKE

II. PRINCIPLES: - Continued

Ideally the seat bridle confluence point must be located approximately below the C.G. so that with no C.G. misalignment the seat will not receive a correcting moment. It is desirable from at least two stand points to adjust the bridle confluence point to give a rearward* seat rotation. First, the drogues can correct for a higher backward rotation than forward rotation. Second, the forward C.G. misalignment would hurt the trajectory height; therefore, an over-correction toward the back would help this trajectory especially when the plane also is pitched forward.

The vertical component of the rocket force will cause seat roll if there is lateral misalignment of the C.G. with the rocket thrust. Since the roll moment will be in proportion to the thrust, and the correction will be in proportion to the roll angle, the roll will be corrected with the same percent accuracy as the pitch as long as the design angle of the bridle is not exceeded.

III. BRAKE DEVELOPMENT AND DESCRIPTION:

Two brakes were designed, built and modified, using Johns-Manville Style 160 flat brake lining. Two 1500 lb. tensile strength nylon cords were each wrapped around two knurled wheels. Guides were used to feed the cords between idler rollers and the first wheels (See Figure 4). Brake lining 1/16 inch thick was cemented to two side plates and a 1/8 inch thick piece of brake lining was used between the sets of wheels. The latter piece was held in place by pins and allowed to "float" between the wheels. Belleville spring washers were used with through bolts to apply force between the brake lining and the sides of the wheels.

Force is transmitted from the cords to the wheels by the wrap of the cords on the wheels, the compression between the idler and the first wheel and the compression between the two wheels. Most of the force is transmitted by the wraps so that the amount of compression is not critical.

* The direction of seat rotation is referred to by the direction the man's head moves with respect to the rest of his body.

III. BRAKE DEVELOPMENT AND DESCRIPTION: - Continued

Brake testing was accomplished first by using a tensile tester. Later tests were made on a runway using a truck with a pick-up hook on the rear bumper. A loop in a cable from the Slip Line was picked up by the hook on the truck at about 55 mph or 80 feet per sec. (The approximate speed at the beginning of pull). An oscillograph was used with a load cell to record the pull force versus time, from which miximum force, average pull, pull time and impulse could be calculated.

The first brake was a heavy experimental model. It was found that the cord was weakened as it was being pulled over the knurled wheels. To avoid a high peak force necessary to overcome static friction and to accelerate the wheels, a release was incorporated in the brake to allow the braking force to be applied after the cord started through the brake. It became apparent that the brake release complicated the design of the brake and would not work satisfactorily with nylon cord between the seat and the brake due to the stretch.

Rather, than increase the number of cords or use the brake release and therefore increase the weight of the brake, it was decided to go to a lower brake force, since this would not penalize the correction or brake impulse appreciably.

The average braking force was reduced to about 500 lbs. and the maximum braking force which the cord would tolerate was determined to be approximately 800 lbs. average force. A total of fifteen runway tests were made with this brake. The free ends of the Slip Line cords were stowed in a nylon cloth bag with nine pockets on each side.

A second and final brake was made with a weight of 1.9 lbs. This brake was similar to the first except for the plates. This brake was tested twenty-one times on the runway. The maximum capability was again approximately 800 lbs. average force. The peak force with 800 lbs. average force was a maximum of approximately 1400 lbs. The average force was reduced to 500 lbs. to give a safety factor. To reduce the peak force of static friction one wheel was started before the other. With an average force of 500 lbs. the peak force is 800 to 900 lbs. If both sets of wheels were started together a peak of 1100 lbs. would result.

Several sizes and arrangements of Belleville spring washers were experimented with. One washer with 100 lbs. capacity ± 7 lbs. was used on each through bolt in the final brake tests and the seat tests. The brake lining

III. BRAKE DEVELOPMENT AND DESCRIPTION: - Continued

has a coefficient of friction of .56 ± 10 percent over a temperature range from 300 deg. F. to 1000 deg. F. The brake temperature before its operation will not vary more than ± 100 deg. F. from an average, and the brake temperature rise would be the same for each use, (about 75 deg. with time for dissipating the heat within the wheel rims), therefore the coefficient should not vary more than 3 to 5 percent in the brake.

Due to differences in coefficients of friction, differences in line stretch and differences in truck speed, a maximum error in impulse was estimated to be approximately ± 10 percent. Although the spring washers were, according to the manufactuer, accurate to ± 7 percent, it was found that the tensile tester was valuable in setting up the brake. In general the tensile tester reading was a relative indication of the average brake force, although not the same value. The washer deflections were adjusted to give the same tensile tester reading to obtain the 10 percent maximum error.

IV. ANALOGUE COMPUTER:

The analogue computer was designed to use slotted cards fed across contact points to control three variables, rocket thrust, Slip Line pull and drogue chute pull.

A synchroneous motor moves the card at one inch per second. By varying the length and starting point of each slot each variable is controlled.

The contacts control electrical solenoids which in turn release weights to simulate either the rocket, the Slip Line or the drogue chute. The weights act on a flywheel which is free to rotate on low friction bearings. The flywheel represents the inertia of the seat in pitch except it is 100 times the inertia of the seat compared to the weights. Since the angular displacement is proportional to the torque and the time squared, the model seat rotates through the same angle as the real seat but the time of action is increased by a factor of ten.

The weight representing the rocket pulls on a cord wrapped around a drum at the center of the flywheel. The effective inertia of the flywheel and the misalignment are changed by changing the weight.

IV. ANALOGUE COMPUTER: -Continued

The Slip Line is represented by a weight pulling on a bridle under the model seat which is attached to the flywheel. This weight must be changed for each inertia of the seat or each different Slip Line pull force.

Although the drogue force decays rapidly as the seat velocity goes down and its angle of pull changes, it is represented by a constant force over a relatively short time at an average angle.

An indexing pin to release the flywheel is operated by a solenoid through a relay. The relay is controlled by a fourth contact. The same relay connects power to the first three solenoids as well as energizing the indexing pin when the card is inserted between the contacts. The first three solenoids cannot be energized until a card is inserted and the fourth contact broken. The indexing pin is released and the flywheel free to rotate until the card clears the contacts.

The computer is used either to check calculations or to solve seat problems by trial and error. A card is cut for the proper rocket burning time and the Slip Line slot is lengthened until the optimum correction is obtained.

The drogue is used to find the minimum size drogue that will position the seat during free flight or the maximum error in the Slip Line the drogue will correct.

The chief limitation of the computer is that the rocket is assumed to have a constant thrust. Also any change in the direction of the rocket thrust or any aerodynamic forces must be neglected; effects of tip-off of seat at end of catapult cannot be fed in; and effects of trajectory curvature are not simulated. For this reason the computer cannot be substituted for actual seat tests. These aspects are discussed under the Seat Testing.

V. SEAT TESTING:

The set up for testing the ejection seats consisted mainly of a static stand with guide rails and a socket to receive the catapult and absorb its thrust.

V. SEAT TESTING: - Continued

P6M seats were used as test vehicles. The weight and moment of inertia of an A4D seat was duplicated using P6M seats with steel weights bolted to the seats. The weights were arranged so that 5 percentile, 50 percentile, and 95 percentile men could be duplicated.

A system was made to find the rocket burnout distance. This included an inertia switch to sense the thrust drop-off at burnout, a switch and static line to arm the inertia switch after rocket ignition, a line cutter with a plunger operated by an electrical squib, a battery and a pull-out line. The pull-out line was tied to the test stand and was played out as the seat went up. The line was cut at burn-out and the length measured and recorded.

The rocket and catapult motor was disassembled, and a jig was made to locate the center of gravity of the seat and weights accurately with respect to the center line of the rocket thrust.

A twenty-foot ballistically projected parachute was mounted to deploy to the side. The deployment was initiated by a timer which in turn was started by a static line during catapult travel. After two tests the 20-foot diameter parachute was replaced with a 24-foot diameter reserve parachute to reduce the rate of descent.

To fire the catapult an electrical squib and a charge of black powder were used to supply pressure to the catapult initiator. The squib was fired with a 12-volt automobile battery from a distance of 250 feet.

A seat bridle was made using 3/32 inch aircraft cable with two (2) turnbuckles. (See Figure 1) The bridle was attached to the seat with eyebolts. Two cable clamps were used to hold the confluence point of the bridle.

The first two seat tests were made with seats simulating the 5 percentile man in the A4D seat, but with no Slip Line. The line cutter was used to obtain burnout distance. The first seat had the C.G. aligned with the thrust. The second seat had a misalignment of 3/16 inch tending to turn the seat backward.

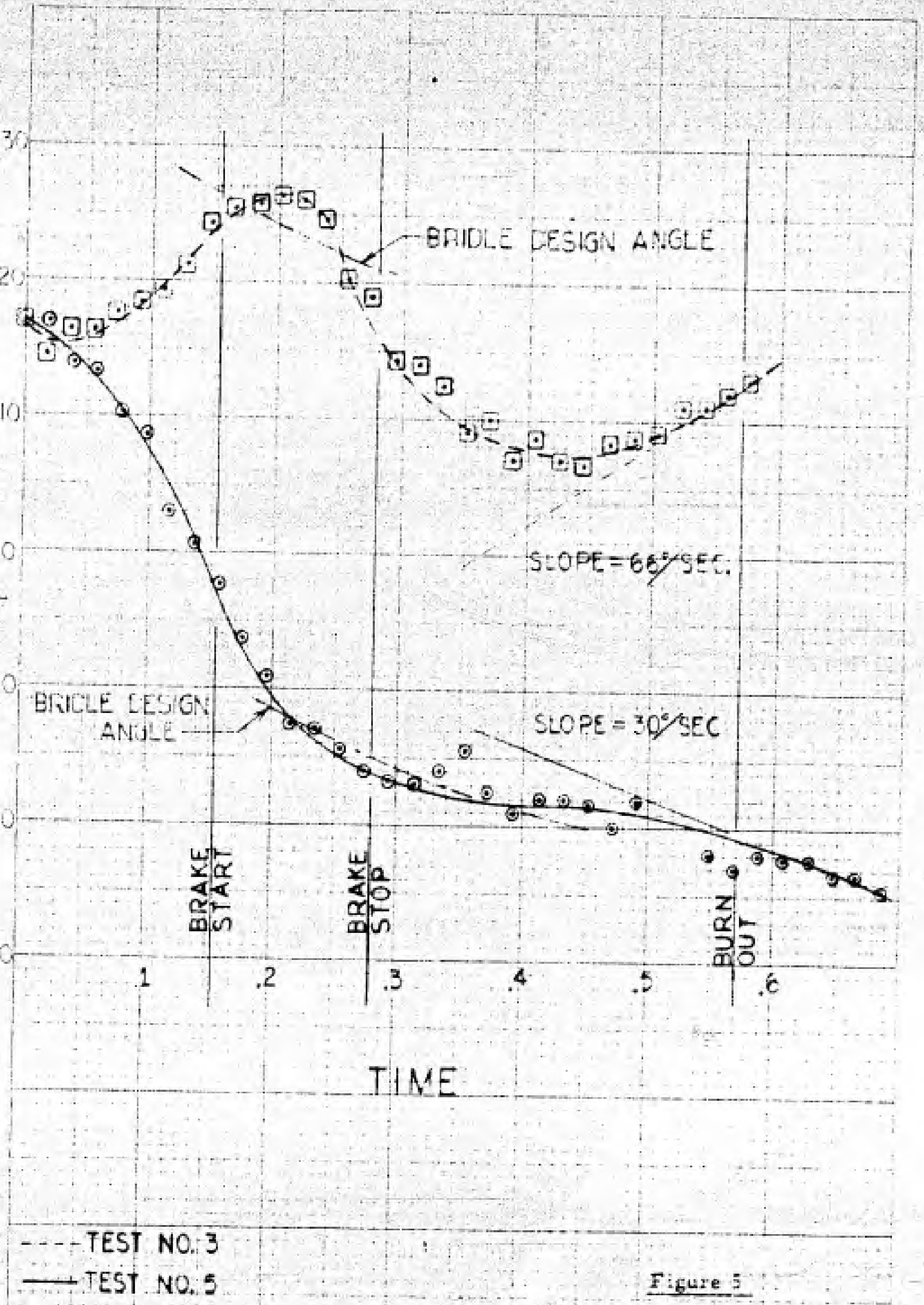

30
20
10
0
-10
-20
-30
Φ
.1
.2
.3
.4
.5
.6
TIME
BRIDLE DESIGN ANGLE
BRIDLE DESIGN ANGLE
SLOPE = 66°/SEC.
SLOPE = 30°/SEC
BRAKE START
BRAKE STOP
BURN OUT
- - - - TEST NO. 3
—— TEST NO. 5

Figure 5

V. SEAT TESTING: - Continued

Camera coverage was made and the trajectories and seat attitudes studied. It was learned from these studies that the seat had an initial forward tipoff and that later during rocket burning the seat rotation very nearly stopped.

The forward tipoff is caused by the rocket thrust which has built up before the seat guides clear the rails. During the time the last guide is in the rails and after the next to last guide has cleared the rails a forward angular velocity is imposed on the seat. This changes the seat attitude during the Slip Line pull.

From the first two tests (Table No. 1, Test No. 1 and 2) information was obtained to design a seat bridle and obtain the brake pull distance.

Two preliminary tests were made with the same Slip Line System and no drogue chute. These tests, and those following, were made simulating a 50 percentile man in an A4D seat. In test No. 3 the seat had a 1-inch C.G. misalignment tending to turn it backward. The rate at burnout was 66 deg. per sec. under-corrected. Test No. 5 was made with the C.G. misalignment tending to tip the seat forward. The rate at burnout was 30 deg. per sec. under-corrected. Test No. 4 was the same as Test No. 3, but without the Slip Line. The turning rate at burnout was 525 deg. per sec.

With the results of tests No. 3 and No. 5, it was possible to determine if either the Slip Line bridle angle, the brake impulse or the distance at which the brake starts to pull should be changed. From Figure 5 it can be seen that in both tests the seat was under-corrected, that the bridle design angle was exceeded and that the pull should start sooner. Even though the tests indicate that the bridle confluence point should have been changed, it was not changed because it is desirable to over-correct for forward pitch, and to under-correct for backward pitch.

Changes were then made in the Slip Line and two tests were attempted to find if further changes were necessary. Two 18-inch dia. drogue chutes were attached to be picked up from the ground. A release latch was installed just behind the C.G. to reduce the moment turning the seat backward when the velocity is high. When the seat turns backward the latch releases and the drogue bridle operates.

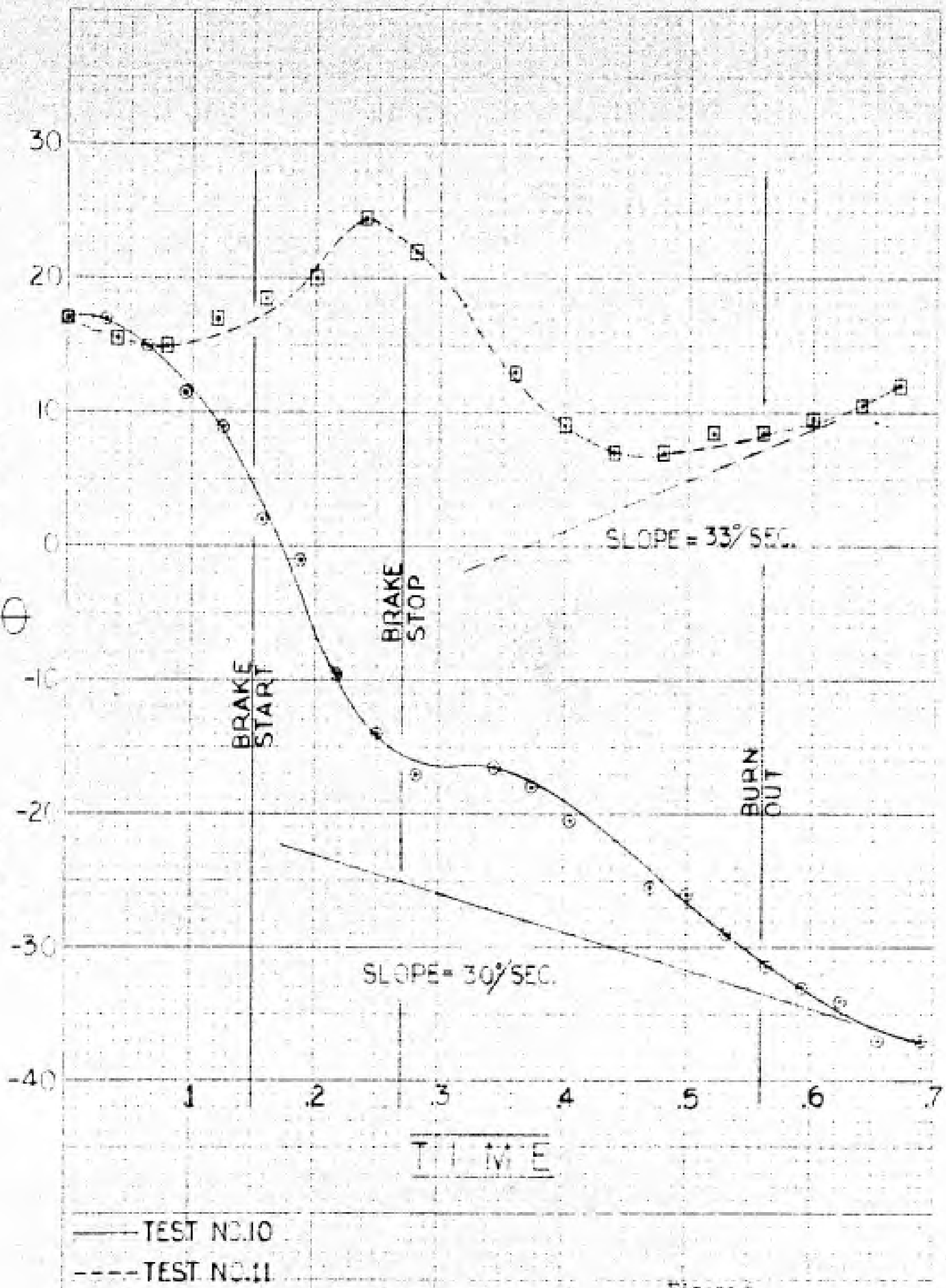

30
20
10
0
-10
-20
-30
-40
Φ
BRAKE START
BRAKE STOP
BURN OUT
SLOPE = 33°/SEC.
SLOPE = 30°/SEC.
.1
.2
.3
.4
.5
.6
.7
TIME
TEST NO.10
TEST NO.11

Figure 6

V. SEAT TESTING: - Continued

In test No. 6 the drogues were picked up, but they swung into the rocket blast. The chutes were then stowed in bags and static lines used to deploy the drogues just before burnout. Test No. 7 used this system; however, a turnbuckle damaged in test No. 6 broke and the bridle cables, which had a very small safety factor and had been weakened by repeated use, also failed. The Slip Line was not effective because of the bridle failure. The rotation at burnout was 480 deg. per sec., approximately the same as test No. 4 except in the opposite direction. The trajectory height was low and the recovery chute barely had time to open.

The seat bridle was replaced with 1/8-inch cable and a single cable clamp at the confluence point. Test No. 8 was a repeat of test No. 7. The brake over-corrected the seat approximately 70 deg. per sec., however, the drogues imparted a large additional rearward rotation rate. Part of this rate was due to the drogues getting into the rocket blast just before the rocket had lost its thrust. An additional rotational rate was apparently introduced during deployment of the drogue with the static lines. Although the drogues stopped the rearward rotation of the seat, it had turned further backward than was desirable.

The 18-inch dia. drogues were replaced with 24-inch dia. drogue chutes since the 18-inch dia. drogues did not appear adequate to turn the seat back, stop the rotation, and correct the seat position. For test No. 9 the drogues were deployed correctly, however, the Slip Line seat cables were not clamped securely at the confluence point. The bridle slipped so that the full correction was not obtained. The drogues did not stop the rotation of the seat until it had made one turn.

The drogues were tied with break cords to sheet metal plates on the sides of the seat. The bridle was clamped and swaged and tests No. 10 and No. 11 were run. Test No. 10 had a 1-inch offset tending to turn the seat forward, the angular velocity at burnout was 33 deg. per sec. under-corrected. The drogues slowly turned the seat backward.

Test No. 11 was made with 1-inch misalignment tending to turn the seat backward. The Slip Line again under-corrected 30 deg. per sec. The brake did not give its full impulse partly because of wear from repeated tests. The drogues stopped the pitch rotation, but the seat yawed. From tests No. 10 and No. 11 (See Figure 6) it was seen that the bridle angle should be changed. This was changed slightly

V. SEAT TESTING: - Continued

toward the rear of the seat. Test No. 12 was made with approximately the same brake impulse as before, but with 1.4-inch misalignment forward. The seat had 75 deg. per sec. rotation at burnout under-corrected as would be expected. The drogue chutes stopped the forward rotation and turned the seat backward. The seat yawed as in test No. 10.

Test No. 13 was the same 1.4-inch misalignment as test No. 12, but with no Slip Line System. The rotational rate at burnout was approximately 660 deg. per sec. The rocket was still burning well after the thrust direction had turned vertically downward. The trajectory height was so low that the recovery chute did not have time to open. Table I, summarizes the seat tests.

VI. CONCLUSIONS AND RECOMMENDATIONS:

The brake alone weighs under 2 lbs. (1.9 lbs.). The cost of producing it in quantity in its present design would be about $100. The bridle and lines would add somewhat to both the weight and cost.

The brake and line stowage has proven very reliable. No failures of this system occurred with the final design except with a maximum capability test.

The runway tests on the brake showed a maximum variation in the brake impulse of ± 10 percent. The seat test records indicated a ± 25 percent variation. The brake had been used many times and became worn, however, there is some question as to the validity of the oscillograph results due to the rocket blast. Also, the results of the seat tests indicate much less variation.

While the Slip Line System was designed for a maximum misalignment of 1-inch, it was 88 percent effective for 1.4-inch. Corrections can be made for larger misalignments; however, larger losses of impulse will be experienced. It is therefore recommended that the correction be designed for only 2/3 of the maximum possible misalignment and rely on the drogue chute to help take care of the larger misalignment.

While the Slip Line correction for a given seat can be calculated or solved on the computer closely, it is recommended that several seat tests be made in pairs such as tests, No. 3 and No. 5, or No. 10 and No. 11

TABLE I

Test No.	Misalignment	Angular Velocity at Burn-out	Percent Correction	Slip Line Impulse	Percent Impulse Lost To Slip Line	Remarks
1	0	---	---	---	---	Preliminary Test Slip Line Not Used.
2	3/16" bk wd.	---	---	---	---	Preliminary Test Slip Line Not Used.
3	1" bk wd	66°/sec.	87.4%	75#sec	5.8%	Slip Line Under-Corrected.
4	1" bk wd.	525°/sec.	---	---	---	Slip Line Not Used.
5	1" fwd.	30°/sec.	94.3%	---	---	Slip Line Under-Corrected.
6	1" fwd.	---	---	---	---	Drogues were ripped off by rocket blast.
7	1" fwd.	480°/sec.	---	---	---	Seat Bridle Failed.
8	1" fwd.	70°/sec.	114.6%	106.3#sec.	8.1%	Drogues went into blast. Slip Line Over-corrected.
9	1" fwd.	---	---	---	---	Seat bridle clamp slipped. Slip Line Under-corrected.
10	1" fwd.	30°/sec.	93.7%	70	5.4	Slip Line Under-corrected.
11	1" bk wd	33°/sec.	93.1%	54.6	4.2	Slip Line Under-corrected.
12	1.4" fwd.	75°/sec.	88.6%	---	---	Slip Line Under-corrected.
13	1.4" fwd.	660°/sec.	---	---	---	Slip Line Not Used.

VI. CONCLUSIONS AND RECOMMENDATIONS: - Continued

to obtain the optimum Slip Line corrections. Unless complete catapult and rocket information is available, it is also necessary to make a seat test with no misalignment, with full camera coverage and no Slip Line. This test would be analyzed to determine information for the first pair of tests above.

Two 18-inch dia. drogue chutes should theoretically control the seat. However, with the rate of turning introduced by aerodynamic forces, and the decay of the drogue force, the small drogues were marginal. The 24-inch dia. drogues while controlling pitch allowed the seat to yaw near the peak of the trajectory. Different drogue bridles or larger drogues are recommended.

A latch close to the C. G. is recommended with small drogues to avoid high rearward turning rates.

It can be seen from the test results (Table I) that the Slip Line was very effective in tests No. 10, No. 11, and No. 12, while reducing the vertical impulse about 5 percent. Also in the tests No. 3 and No. 5 small drogue chutes would have taken care of the error in the Slip Line correction.

However, it should be pointed out that due to a higher rocket thrust in the first part of burning and a lower catapult velocity than was assumed, the Slip Line pull was started later than ideally it should have been.

For tests No. 10, and No. 11 and No. 12, the start of pull was earlier and the trajectory improved; the correction still was not ideal. If more rocket or catapult data were available or more tests possible the trajectory could be corrected to near perfect each time with different C.G. misalignments. If the plane is pitching nose down close to the water it would be ideal to over-correct forward pitch while under-correcting backward pitch. Furthermore the drogue chutes can handle more error backward than forward and the seat must turn backward before the drogues stop its rotation. It is recommended, therefore, that the bridle be arranged to over-correct forward pitch.

VI. CONCLUSIONS: - Continued

The bridle is designed to correct a C.G. misalignment along a line perpendicular to the line of thrust. Any displacement parallel to the thrust will cause an error in the correction. A reasonable maximum parallel deviation would be 3/4 inch. This would cause a maximum error of 4-1/2 percent in the correction.

The Slip Line is designed for a 50 percentile man. If the assumption is made that the moment of inertia is proportional to the total weight, a maximum error of approximately 7 percent is introduced when a 5 percentile or 95 percentile man is in the seat.

The average weight force would vary as much as ± 10 percent for temperature extremes of -65 deg. F. to 165 deg. F., thus the seat will experience higher angular and linear accelerations for higher temperatures and lower accelerations for lower temperatures. The moment arm for the Slip Line restoring moment is approximately independent of the average rocket force, while the brake pull time is approximately inversely proportional to the linear acceleration, giving a resultant correcting impulse that is theoretically in error by about 0.3 times the rocket force error or about 3 percent maximum.

With two 24-inch dia. drogues which were used in testing, an error of 25 percent in the Slip Line correction will be taken care of for a 1-inch misalignment at zero plane speed and zero altitude. If a 4-1/2 percent error is allowed to overcome maximum error due to C.G. displacement parallel to thrust, if 3 percent is allowed to overcome maximum error resulting from temperature variations, and if 7 percent is allowed to overcome errors introduced by 5 percentile or 95 percentile pilots, then a 10 percent error in brake impulse would be acceptable even for the highly unlikely situation where all errors occurred simultaneously in the same direction.

Any plane speed would increase the maximum permissible Slip Line error. At stall speed, for instance, the drogues would allow at least a 50 percent error total. In addition, a drogue 5 feet in dia. would permit at least a 50 percent error in the Slip Line correction at zero plane speed with a 1-inch misalignment.