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MALTON – ONTARIO

TECHNICAL DEPARTMENT (Aircraft)

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ARROW 2A ZERO LENGTH LAUNCH INVESTIGATION

PREPARED BY W.U. Shaw DATE October 1958.

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CONTENTS

1. SUMMARY

An investigation has been made of a zero length launching method for the Arrow.

The method adopted consists of mounting two JATO Type 121 Units under the wings, the take-off being accomplished from a ramp supporting the aircraft by means of its undercarriage.

The general configuration of the aircraft, method of mounting the booster units, arrangement of the ramps, and method of ejecting the boosters, are shown on the attached drawings.

A preliminary study of the dynamic characteristics of the launch has been made (Ref. Report No. 72/Stab/45). This study included effects of malalignment of thrust, variation of c.g. position, and effects of temperature. The report indicates the importance of c.g. position tolerance in particular, as well as booster thrust axis alignment. The maximum acceptable tolerance for the former is of the order of ± 1 inch and for the latter, 15 minutes of arc.

Examination of loads and stresses indicated that some modifications would be required in the vicinity of the booster attachment points to the wing, but these do not appear to be of a serious nature.

2. INTRODUCTION

2.1 A request has been made that the company investigate the feasibility of a method of launching the Arrow to flying speed without the use of any ground run. It was assumed in this study that the zero launch operation would be required to be located at any point in the country and would be set up on a 24 hour "at the ready" basis.

2.2 The purpose of this report is to present the results of this investigation. The reasons for the equipment selected and its adaptation to the Arrow are discussed. Modifications that would be required to the airframe and controls are pointed out. Mention is made of necessary ground ancillary equipment. Finally, the analysis of dynamic characteristics and the limitations to thrust and weight tolerances are summarized.

2.3 In order that this investigation would envelop possible future developments of the Arrow, it has been based on the 2A version - the design study of which showed an A.U.W. of 76,750 lb. (Ref. Report No. 72/Stab/45), compared to the A.U.W. of 65,200 lb. of the Arrow 2. Adding 11,450 lb. for the rocket units and attachments gives a maximum launching weight of 88,200 lb.

2.4 A zero length launch requires a thrust, in addition to that provided by the engines, sufficient to provide an aircraft trajectory of at least 10° in elevation. This additional thrust must also be of sufficient magnitude and duration to ensure flight speed in the shortest possible time consistent with the acceleration tolerances imposed by the airframe and crew.

Assuming a flight speed of 170 knots and a constant acceleration of 3g:

$$\text{duration of launch} \quad t = \frac{170 \times 1.689}{3 \times 32.16} = 2.977 \text{ secs.}$$

$$\text{distance of launch} \quad S = \frac{170 \times 1.689}{2}(2.977) = 426.5 \text{ ft.}$$

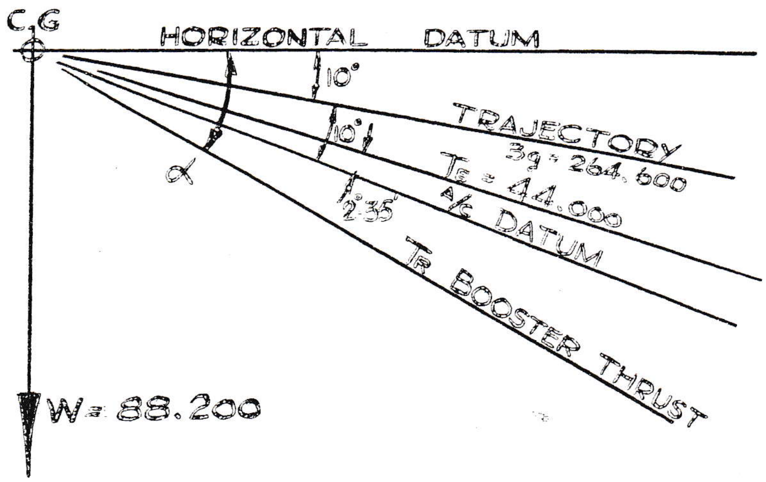
Higher accelerations would produce a launch of reduced duration and distance but are not recommended on account of crew and airframe limitations.

The launching distance under 3g acceleration therefore would indicate that a thrust booster be used which is an integral part of the aircraft, though it may be jettisoned at the end of the launch.

Hence, this investigation concerned itself with the adaptation of rocket boosters for the zero-launch operation.

An approximate value for the rocket thrust required can be obtained by considering the forces involved, neglecting moments and aerodynamic loads.

2.4 (Continued)



Engine Thrust Assumed = 44,000 Lb. = T_E

Gross Weight of Aircraft = 88,200 Lb.

Balance Vertical Forces:

$$88{,}200 + 264{,}600 \sin 10^\circ - 44{,}000 \sin 17^\circ 25' - T_R \sin \alpha = 0$$

$$88{,}200 + 45{,}900 - 13{,}160 - T_R \sin \alpha = 0$$

$$T_R \sin \alpha = 120{,}946$$

Balance Horizontal Forces:

$$264{,}600 \cos 10^\circ - 44{,}000 \cos 17^\circ 25' - T_R \cos \alpha = 0$$

$$260{,}060 - 42{,}000 - T_R \cos \alpha = 0$$

$$T_R \cos \alpha = 218{,}000$$

$$\tan \alpha = .5555$$

$$\alpha = 29^\circ 2'$$

$$\sin \alpha = .48532$$

$$T_R = 249{,}000$$

2.5 Examination of the airframe structure revealed that it would be extremely unlikely that such a single thrust could economically be applied. It was resolved, therefore, to use two rocket boosters, mounted symmetrically to the lower side of the wing.

2.6 The economics of choosing an existing booster for which performance and reliability were known, led to the selection of JATO Unit 121, Type 405-130000 X226A1. This booster is used on Snark and the characteristics are as follows:-

Weight per Booster		= 5,125 Lbs.
Thrust	at 77°F	= 132,000 Lbs.
	at 120°F	= 143,500 Lbs.
	at -65°F	= 101,500 Lbs.
Burning Time	at 77°F	= 3.72 seconds
	at 120°F	= 3.45 seconds
	at -65°F	= 4.55 seconds

2.7 It should be pointed out that figures given for -65°F temperature are extrapolated, whereas it is recommended that the booster be stored and fired at a minimum environmental temperature of -20°F. Improved propellants may extend this temperature to lower limits.

2.8 The tolerances on thrust and burn-out time for this booster are not exactly known and further information on latest data would be required for confirmation. It can be assumed that, as propellants are being continuously developed, the tolerances would be sufficiently close to minimize adverse effects when using two boosters.

3.0 DESCRIPTION OF BOOSTER APPLICATION

3.1 One JATO Unit, Type 405-130000 X226A1 is disposed on each wing, each being mounted beneath the main box spar, and attached to the wing structure by three struts. The forward strut which is rigidly attached to the booster, is pinned to a wing fitting at the juncture of the main spar and rib no. 4. Two rear struts, each pinned to the booster near the aft end, pick up on fittings at the juncture of the rear spar at ribs number 4 and 5.

The bodies of the JATO units are substantially parallel to the aircraft datum whereas the axis of the booster nozzles are oriented so that the thrust line projected passes almost, but not quite, through the aircraft gross centre of gravity. They meet, of course, at the plane of symmetry and hence lateral components cancel each other. The intersection on the vertical and fore and aft co-ordinates is such as to produce the desired trajectory, this positive mal-alignment being necessary to balance engine thrust moments about the c.g.

3.2 Both boosters must be jettisoned at the point of burn-out. Investigation of jettisoning by free release showed that powerful pitch-up aerodynamic forces were present, which would cause interference with the aft under surface of the wing and result in damage. Hence, positive downward ejection of the boosters is provided.

Each booster strut is locked into its fitting on the wing by means of a hook lever. The three levers are connected to a single operating source on the top centre of the rocket by means of rods and bellcranks. The gas operated jacks for jettisoning are located in the front and rear inner struts. Gas pipes connect these jacks with the same operating source servicing the release levers. The operating source consists of a cartridge, manifolded to a gas jack which operates the release levers. At the instant of this release gas is fed to the ejection jacks which propel the booster downward clear of the wing. It is proposed to proportion the ejection loads produced by the jacks in such a manner that a pitching moment is applied to the booster during ejection, forcing the nose down to a position where the free air stream will cause it to have further negative pitching.

3.3 Firing of the boosters is accomplished simultaneously by a pilot's actuating button or switch.

4.0 AIRCRAFT ATTITUDE

A trajectory of 10 degrees was considered the minimum to provide adequate clearance for the launch. At the same time a minimum trajectory requires minimum boost thrust and reduces the time to controllable flight speed. Ten degrees was chosen in consideration of these two characteristics.

At the period in the launch at which controllable flight speed is reached, or at the slightly higher speed at which burn-out of the boosters occurs, it is desirable that the incidence of the aircraft be the normal one for that speed. This provides a smooth transition from boosted launch to normal climb and obviates a sudden demand on the pilot to correct for incidence, at a time when he is probably correcting for other deviations.

Combining the trajectory with the incidence gives a 20° attitude for the aircraft datum and this applies to the static position on the ramps. The aircraft is supported on three ramps, one for each undercarriage. Due to the 20° datum angle, it is necessary to raise the main undercarriage above the ground to avoid interference of the rear of the jet pipes with the ground.

The aircraft is winched up onto the ramps, the main wheels are locked to prevent roll-back, and the nose gear then elevated to give the desired datum angle. The nosewheels must be locked to the ramp during elevation and subsequently because the c.g. normal to the ground passes very close to the main gear fulcrum point.

4.0 (Continued)

At the instant of firing the boosters, all locks between aircraft and ramps are released and the nose gear ramp is quickly lowered to allow the rear bottom fuselage to clear on take-off.

5.0 MODIFICATION TO AIRFRAME

Consideration of the reactions induced in the airframe by booster thrust and acceleration, and the manner in which they are distributed through the main wing torsion box, indicates that no serious problem regarding the structure exists. The preliminary findings are as follows:-

5.1 Rib 4

A redesign is probably necessary to incorporate additional web material and flange material to diffuse the fore and aft booster thrust loads into the skins over a considerable chordwise length. If the rib be made capable of distributing the loadings to the skin over its whole length, no skin thickening would be necessary.

5.2 Front Spar

Local redesign likely required to suit booster strut pick-up fitting just outboard of rib 4.

5.3 Rear Spar

Local strengthening between ribs 7 and 4 in the form of increased web thickness and flange sizes is indicated to accommodate local moment and differential shear loads applied by the rear mounting points.

5.4 Rib 6

There is a possibility that modification is required from the rear spar to the centre spar aft to provide a balance path for loads from rear outboard fitting.

5.5 Skins

A possible increase in thickness aft of the centre spar aft between ribs 4 and 6 to accommodate local differential shears between the aft mounting points.

5.6 Fuselage Sidewalls

Possible increase in skin gauge below rib 4 to longeron to carry that portion of thrust loads which is reacted by fuselage inertias.

5.7 Deflections

Analysis indicates the following wing deflections under launching conditions:-

5.7 (Continued)

a. Forward pick-up point downward deflection = 0.12 inch

b. Rear inboard pick-up point downward deflection = 0.41 inch

c. Rear outboard pick-up point downward deflection = 1.80 inch

This results in a nose up movement of the booster thrust axis of about 0.36 degrees due to wing deflections only. Some angular movement nose outboard will accompany this deflection and will be of the same order.

Deflections of the booster struts and the booster body will be additional to the above.

It is submitted that these deflections can be catered for with regard to mal-alignment by presetting the booster thrust axes to cancel deflections while under thrust loads.

As pointed out elsewhere, the problem of thrust mal-alignment is alleviated to some degree by maintaining a very close tolerance on a standard c.g. position for the aircraft.

6.0 GROUND SUPPORT EQUIPMENT

Minimum ground support equipment will include the following:-

6.1 Main gear and nose gear ramps, together with tie downs, winching gear and nose elevating and release gear.

6.2 Temperature control of boosters, missiles and radar. This may be accomplished by a unit heater supplying controlled temperature air to the units, or by surrounding the aircraft with an insulated hangar, the air and contents of the hangar being maintained at the required temperature by means of a heating unit and controls.

6.3 Equipment for handling the booster units on the base, capable of raising them to a position for coupling to the aircraft. Also required are booster alignment tools for aligning the booster thrust to within required tolerances.

6.4 Ground starting equipment for the main engines.

6.5 Ground crew and flight crew quarters.

6.6 An insulated hangar for the aircraft. This is required to be as small and as light as possible and be of prefabricated construction. It must be possible to transport the panels of which it is assembled to the site by whatever transport is specified for this operation. Volume and surface area must be a minimum to keep the environmental heating or cooling load as low as possible. It is not considered possible to

6.6 (Continued)

"fire" the aircraft out of the hangar even though both ends be open. The energies of engine efflux and booster efflux would be sufficient to demolish a light structure. Hence, it is proposed to move the hangar sideways out of the damage zone. This requires that one side be removed, which can be done by folding the side accordian fashion and moving it sideways with the hangar. Provision would be necessary to remove any ancillary equipment contained in the hangar at the same time, either sideways with the hangar or to some other protected area.

6.7 It is presumed that facilities exist for fuelling the aircraft, or would be provided. This does not necessarily involve the launching procedure under discussion.

7.0 WEIGHT ANALYSIS

Weight of Arrow 2A with drop tank	81,000
Less Weight of drop tank and fuel	4,250
	76,750
Plus 2 JATO Boosters	10,250
Plus Booster Struts and Gear	1,000
Plus Mods. to Aircraft	200
Total Gross Weight	88,200 lbs.

8.0 DYNAMIC CHARACTERISTICS

A preliminary investigation has been done for the zero-length launch, the results are described in Avro Report No. 72/Stab/45.

8.1 In this report, the trajectory and time histories of the incidence, pitch angle, accelerations, speed, yawing and rolling moments, rates of yaw and roll etc. have been worked out for standard conditions and for non-standard conditions. The latter include effects of temperature, of mal-alignment of thrust axes and movements of centre of gravity. Effects of pilot control or damping system were not considered.

8.2 Although the final design may differ in geometry, weight, etc. from that assumed in the analysis, and hence, the responses will differ, the acceptable tolerances of boost alignment and c.g. position estimated in the report give a representative range of values to be expected and emphasize their importance.

8.3 This investigation indicated that the maximum acceptable tolerances of c.g. positions and booster thrust mal-alignment should be:

8.3.1 Aircraft Centre of Gravity

Longitudinal	± 0.5% M.A.C. = ± 1.8 inch
Lateral	± 1.0 inch
Vertical	± 1.0 inch

8.3.2 Booster thrust axes mal-alignment: 15 minutes of arc.

8.4 These tolerances produce deviations in the flight envelope as shown on Figures 1, 2, 3, and 4. Further details may be found in Avro Report 72/Stab/45.

8.5 Combining the responses due to geometric mal-alignment with those due to the maximum temperature range, will produce responses which are somewhat wider in spread than for each one separately. A very rough estimate may be made by combining them additively as shown in the above reference.

8.6 The booster thrust alignment tolerance of 15 minutes will be difficult to meet. This alignment is aggravated somewhat by random gas mal-alignment of the booster, a quantity unpredictable except by statistics.

8.7 Report 72/Stab/45 shows that for pitching and yawing responses produced by thrust mal-alignment, a thrust mal-alignment of 15 minutes is equivalent to a c.g. movement of 0.8 inch. Hence, a tighter tolerance on c.g. movement would allow an increase in thrust mal-alignment, e.g. if the tolerance on c.g. is fixed at ± 0.25 inch, thrust mal-alignment may be increased to approximately ± $0^{\circ}30'$.

8.8 A consideration of the responses shows up two critical points:-

a. After 3 seconds, height gained may be as low as 18 ft.

b. Incidence may be 19.5°

These indicate the significance of mal-alignment and the c.g. position.

8.9 Figure 3 shows that at 2 seconds from zero, the air speed is 108 knots and at three seconds, it is 165 knots. Hence, up to 2 seconds, controls will be ineffective and from 2 to 3 seconds, control will increase rapidly. This allows the pilot to correct to a great extent for the deviations calculated, starting at approximately the 2 second point. Hence, it is submitted that the calculated envelope of responses, as shown on the graphs, may be modified from a divergent trend to a converging value and by the time burn-out occurs, normal attitude and climb will be attained.

9.0 CONCLUSIONS

The comments outlined in the previous section are confirmed to a certain extent by Reference 1, where an F-100D airplane was launched by the aid of a single booster of similar size as that proposed for the Arrow. During the simulator training programme, quote "It was learned, for instance, that booster thrust misalignments up to 1.5 inches in any direction could be safely handled".

"Proper control techniques were developed on the simulator for handling rates of change of control effectiveness that take place during the launch. During the first two seconds all controls are relatively ineffective, but by the time booster burn-out occurs, they are very effective indeed. Thus, too great a pitch control correction early in the boosted portions of the launch could very easily result in an over-control condition a second or two later".

From his descriptions of the actual launch, quote, "For the normal launch, from the very first shot, it was evident that ZEL accelerations forces do not have the surprise effect that identical forces experienced on the steam catapult have. (note:- ZEL refers to zero launch). With ZEL, I felt that I was flying the airplane off the launcher with no apparent time required for recovery from the initial jolt".

10. REFERENCES

1. Making Like a Missile - A.W. Blackburn
   From Flying Safety, September 1958 - U.S.A.F.

2. Weight and Balance Problems of "Zero-Length" Launching, W.J. Griffey, Project Weight Engineer - G.L. Martin Co. - May 1954.

3. Zero Length Launch - 72/Stab/45
   D.L. Martin - Avro Aircraft Limited.

4. Artillery and Aircraft Rockets - CIT-VM-1 - W.A. Fowler

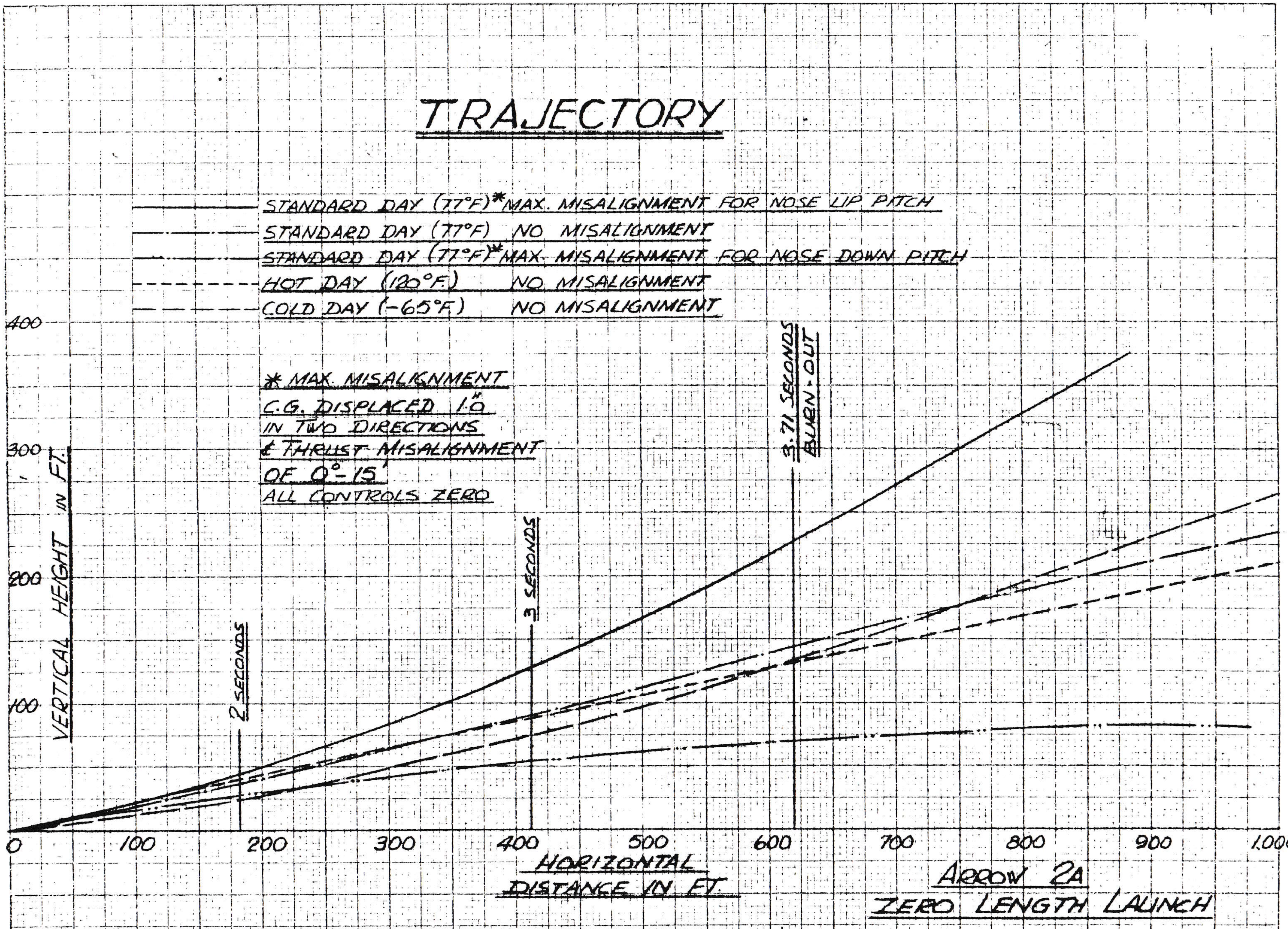
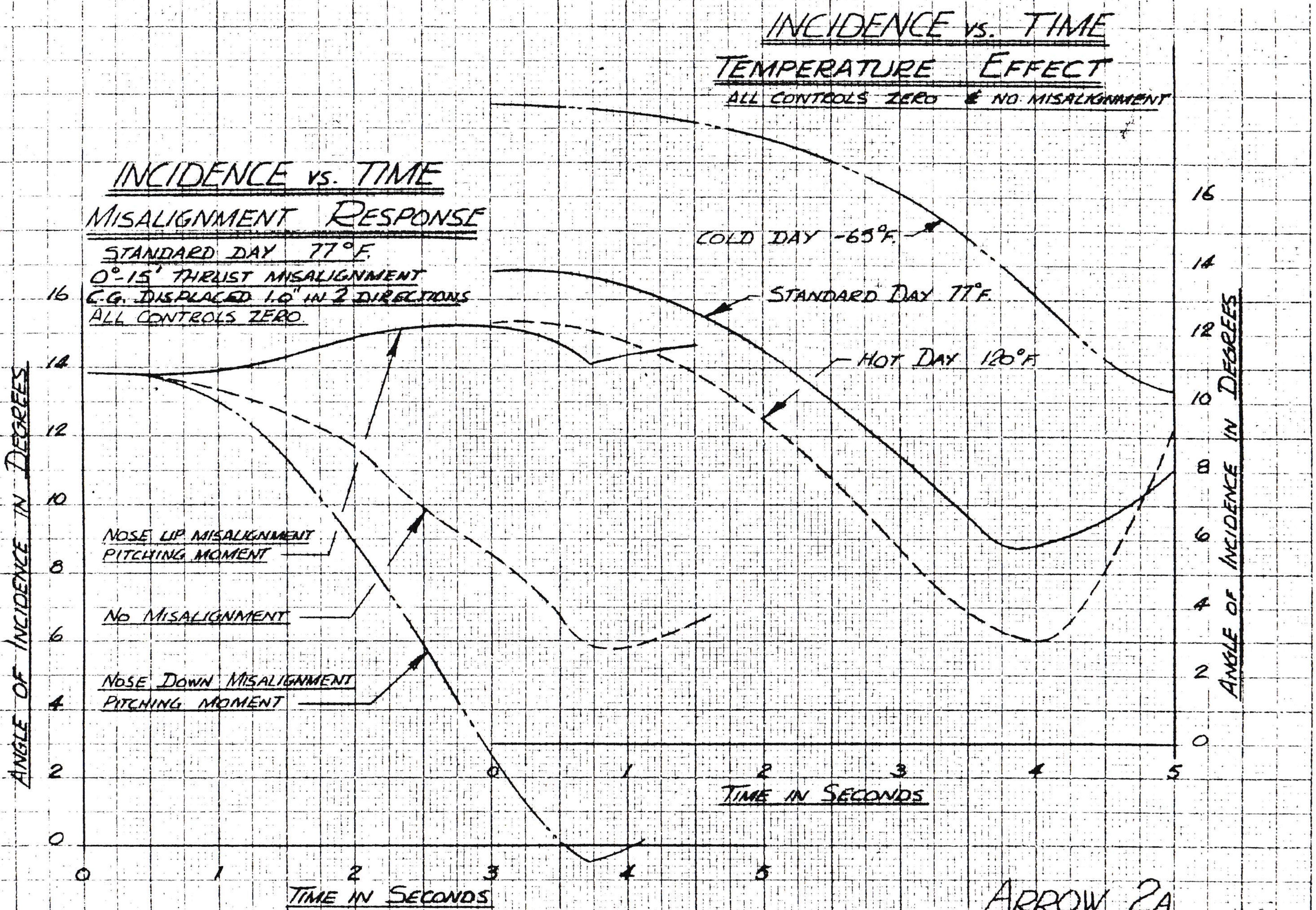
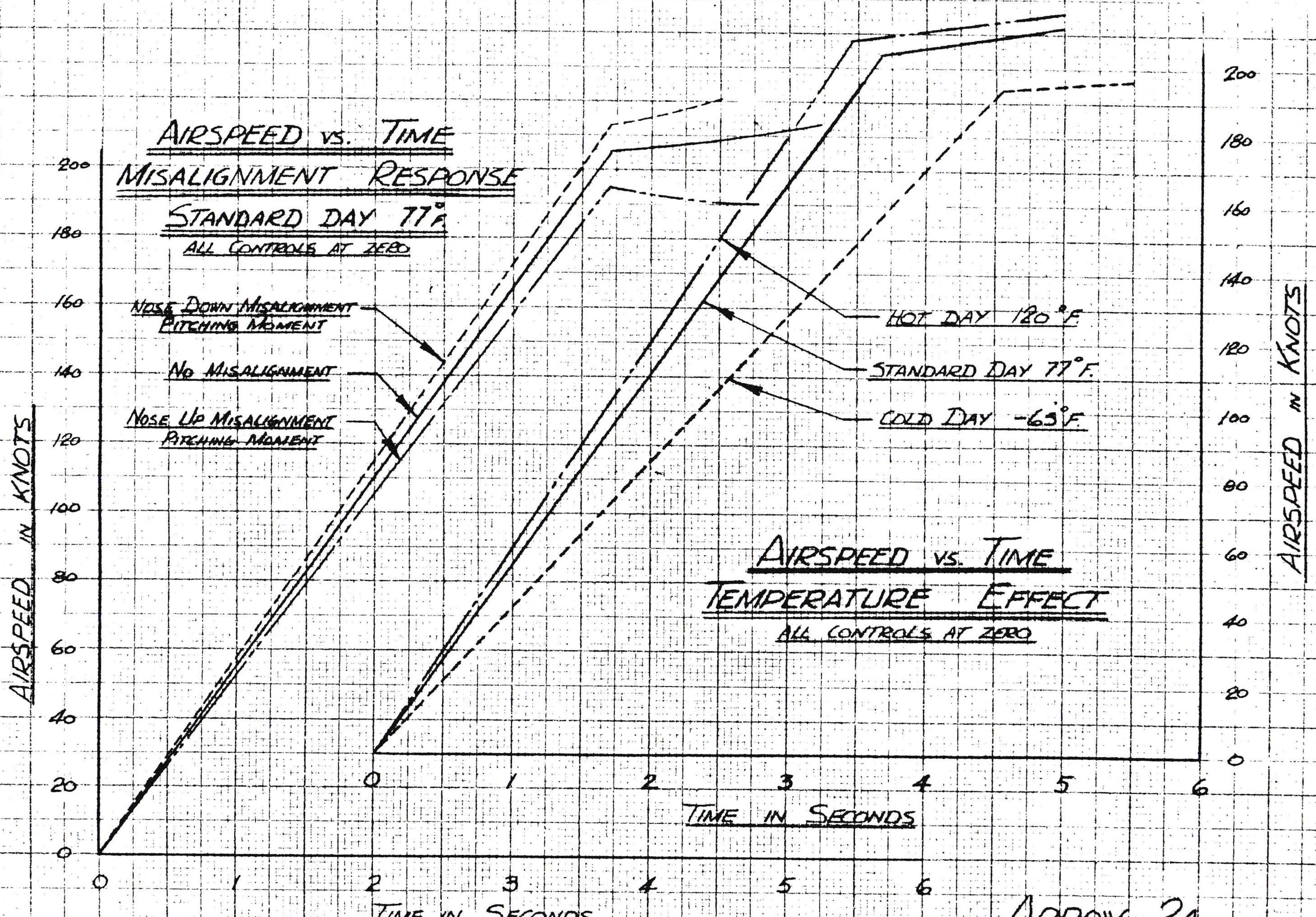

TRAJECTORY
STANDARD DAY (77°F)*MAX. MISALIGNMENT FOR NOSE UP PITCH
STANDARD DAY (77°F) NO MISALIGNMENT
STANDARD DAY (77°F)*MAX. MISALIGNMENT FOR NOSE DOWN PITCH
HOT DAY (120°F) NO MISALIGNMENT
COLD DAY (-65°F) NO MISALIGNMENT
* MAX. MISALIGNMENT
C.G. DISPLACED 1.0"
IN TWO DIRECTIONS
& THRUST MISALIGNMENT
OF 0°-15'
ALL CONTROLS ZERO
2 SECONDS
3 SECONDS
3.71 SECONDS
BURN-OUT
VERTICAL HEIGHT IN FT.
400
300
200
100
0
100
200
300
400
500
600
700
800
900
1,000
HORIZONTAL
DISTANCE IN FT.
ARROW 2A
ZERO LENGTH LAUNCH

FIG. 1



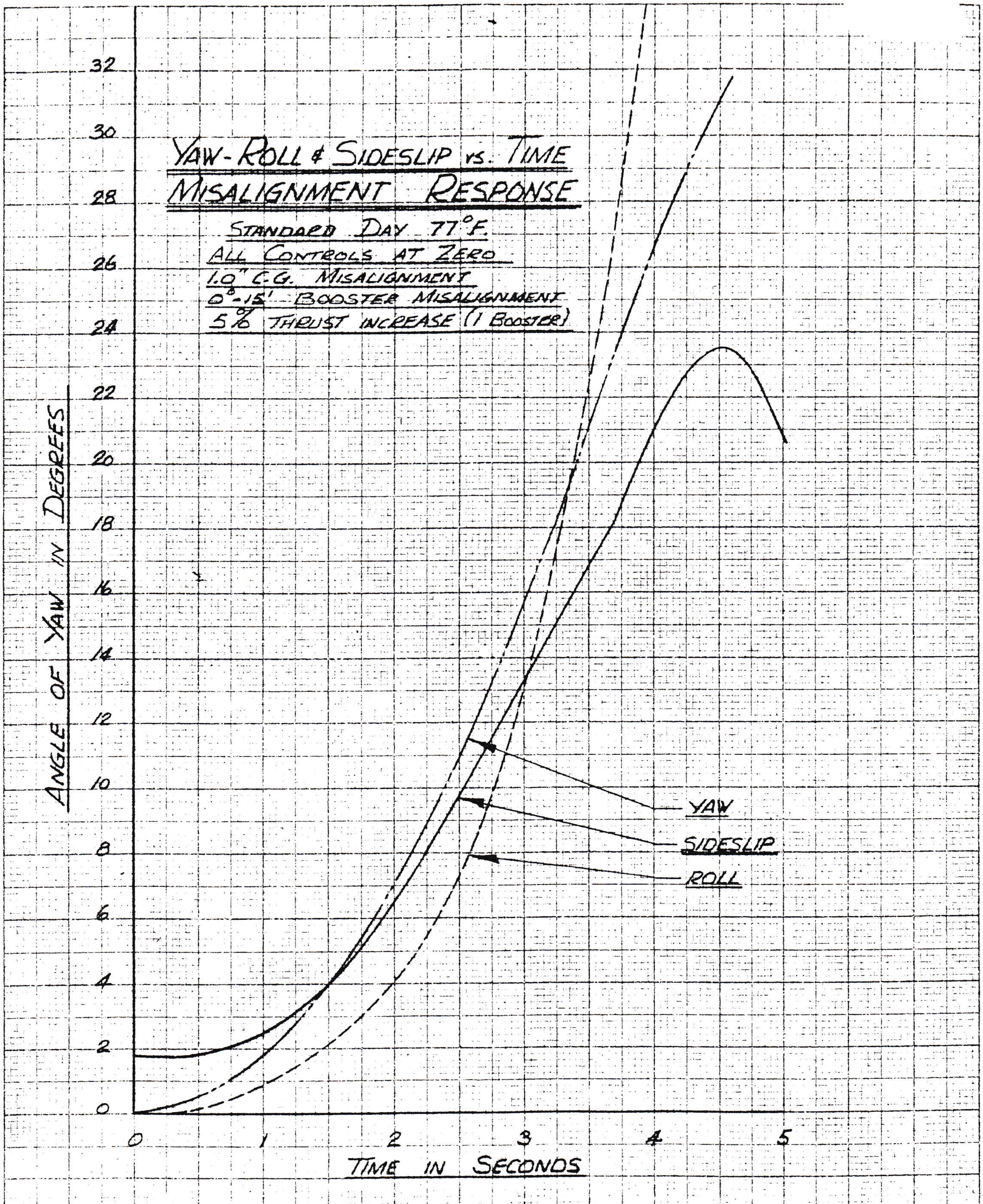
ARROW 2A
ZERO LENGTH LAUNCH

FIG. 2



ARROW 2A
ZERO LENGTH LAUNCH

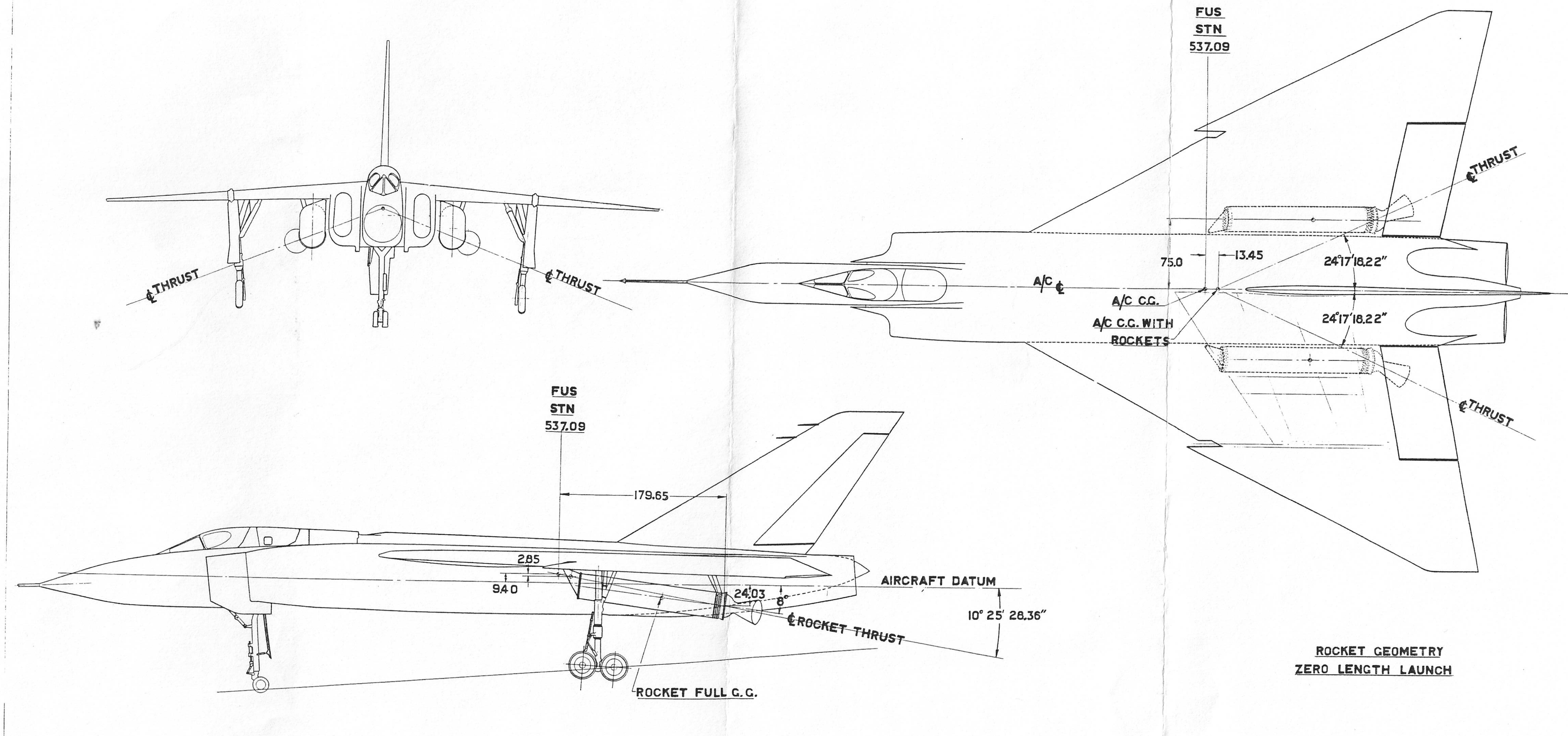
FIG. 3



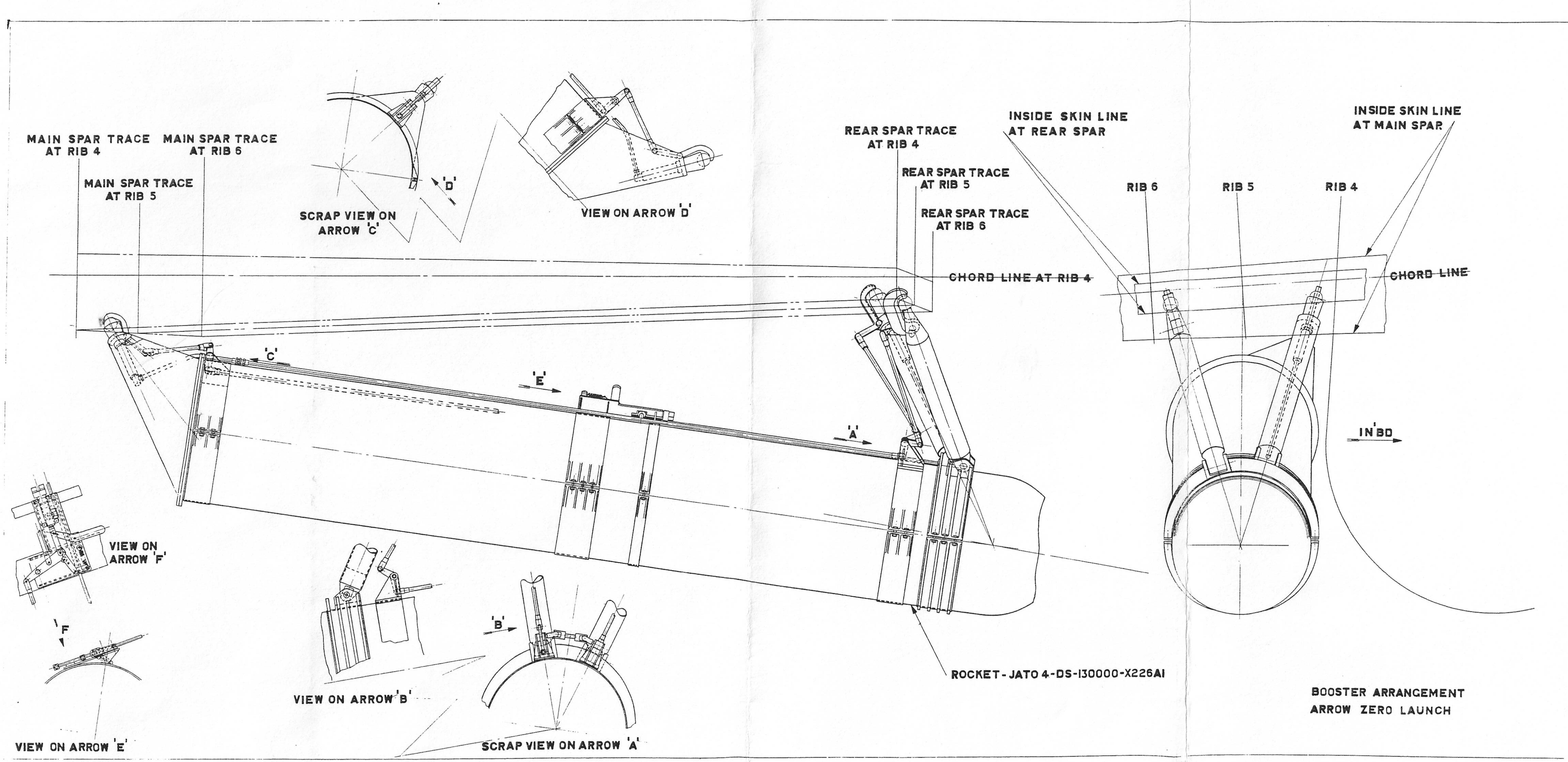
ARROW 2A

ZERO LENGTH LAUNCH

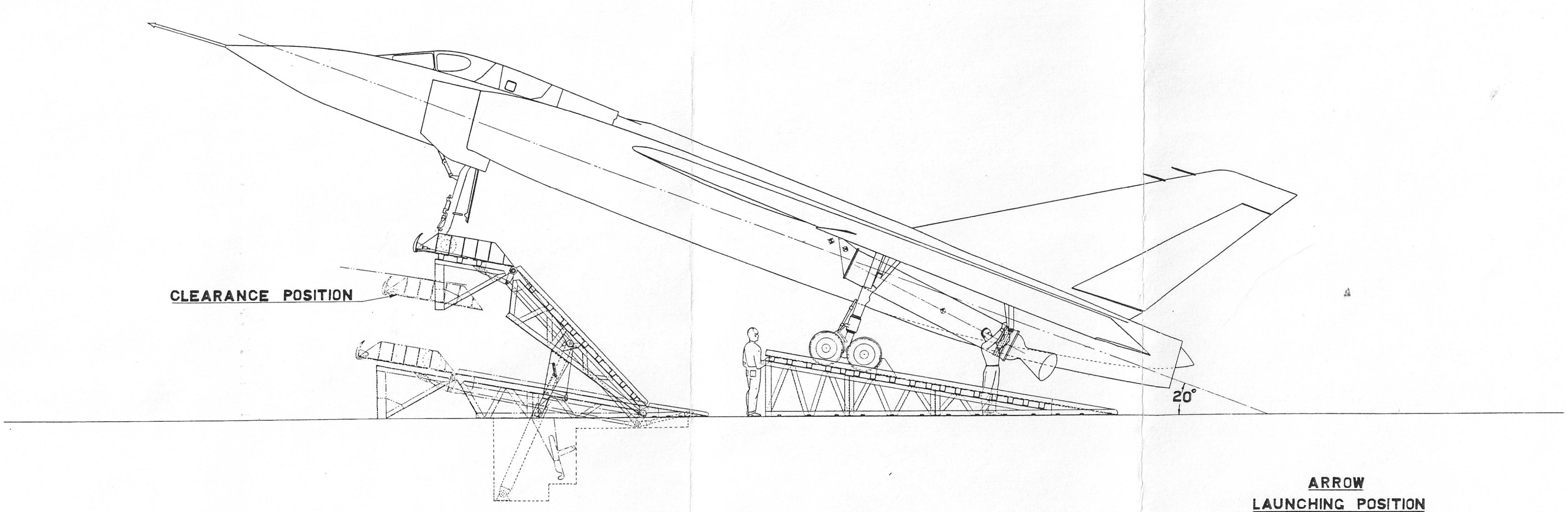
FIG. 4



ROCKET GEOMETRY
ZERO LENGTH LAUNCH



BOOSTER ARRANGEMENT
ARROW ZERO LAUNCH



ARROW
LAUNCHING POSITION
FOR ZERO LENGTH LAUNCH