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Rockets for Spin Recovery

R.D. Whipple

GRUMMAN AEROSPACE CORPORATION
Bethpage, NY 11714

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National Aeronautics and
Space Administration

Langley Research Center
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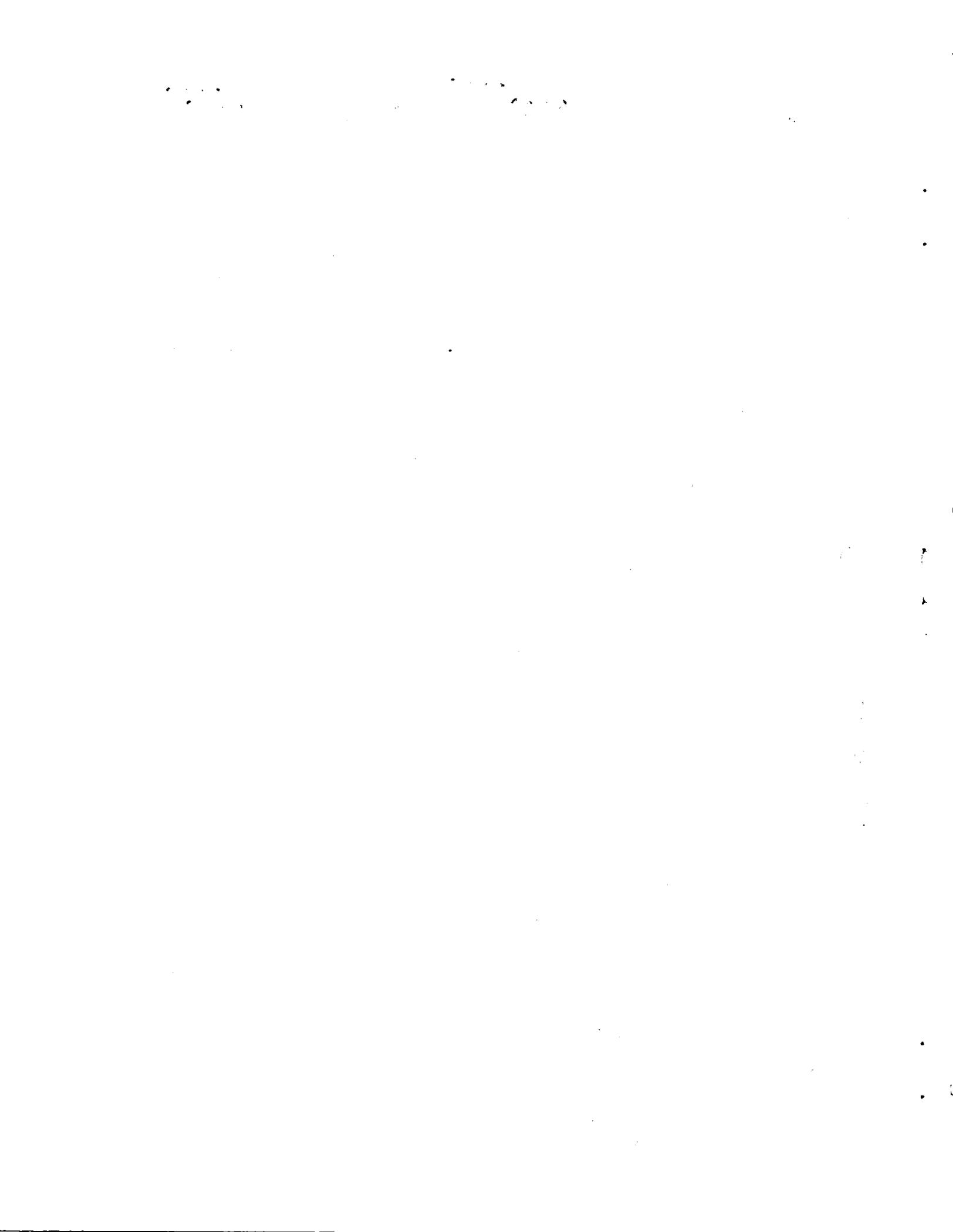
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List of Symbols and Abbreviations

Measurements were made in the U.S. Customary Units and converted to the International System of Units (SI).

AGARD	Advisory Group for Aerospace Research and Development	
b	wing span	m (ft)
c.g.	center of gravity	percent MAC
$\bar{c}$	wing mean aerodynamic chord	m (ft)
C_c	chordwise force coefficient	-
C_l	rolling moment coefficient	-
C_m	pitching moment coefficient	-
C_n	yawing moment coefficient	-
C_N	normal force coefficient	-
C_x	$- C_c$	-
C_y	side force coefficient	-
C_z	$- C_N$	-
E_s	spin energy factor	-
FFAR	folding fin aerial rocket	
FRL	Fuselage reference line	-
F_x	aerodynamic force component x body axis	(lb)
F_y	aerodynamic force component along y body axis	(lb)
F_z	aerodynamic force component along z body axis	(lb)
g	acceleration due to gravity	m/sec^2 (ft/sec^2)
GW	gross weight	kg (lb)
h	altitude	m (ft)
I	moment of inertia	kg-m^2 (slug-ft^2)
I_x, I_y, I_z	moments of inertia about the x, y and z body axes	kg-m^2 (slug-ft^2)
I_v	moment of inertia about the vertical axis	kg-m^2 (slug-ft^2)
I_{xz}	product of inertia	kg-m^2 (slug-ft^2)
i_s	stabilizer deflection	deg
JATO	Jet-Assisted Take-Off	-
L, M, N	aerodynamic moments about the x, y and z body axes	kg-m (ft-lb)

m	mass	kg	(slugs)

m   mass   kg   (slugs)

MAC   mean aerodynamic chord

NACA   National Advisory Committee for Aeronautics

NAKA   a 3.8 cm (1.5 inch) unguided armament rocket

NASA   National Aeronautics and Space Administration

p, q, r angular velocity components about the x, y and z body axes   deg/sec

S wing area m^2 (ft^2)

t time   seconds

u, v, w linear velocity components along x, y, and z body axes   m/sec   (ft/sec)

V free stream velocity   m/sec   (ft/sec)

V_R total linear velocity   m/sec   (ft/sec)

X, Y, Z airplane body axes

α angle of attack   deg

β angle of sideslip   deg

γ flight path angle   deg

Δ increment

δ deflection   deg

θ pitch angle   deg

ρ atmospheric density kg/m^3 $(slug/ft^3)$

σ tilt angle of rocket   deg

$\emptyset$ bank angle   deg

ψ yaw angle   deg

Ω angular velocity vector   rad/sec

Subcripts

aero   aerodynamic

e   Euler angle

o   oscillatory

r   rotational

$(\dot{\ })$ dot over a quantity represents the first derivative with respect to time

1.0 INTRODUCTION

A key feature of airplanes configured for high-angle-of-attack testing is the emergency spin recovery device.

Although departure from controlled flight was a common, if not predominant occurrence in the earliest days of aviation, the spin was not identified until sufficient altitudes had been achieved to sustain it. Certainly by 1912 the spin was known and the study of it came into being.

Since an airplane's ability to recover from a spin seemed unpredictable at best, auxiliary devices were developed to supplement any control deficiencies.

Anti-spin parachutes have been the most common system, attached variously to the tail, wing-tips, and recently, even to the nose of the aircraft. However, the potential effectiveness of the rocket has been recognized for a long time.

The rocket systems which have been investigated sporadically over the years have generally been found deficient in a number of ways.

The space effort has produced enormous advances in rocket technology and suggests that currently available systems may obviate the problems encountered earlier.

In light of this, this study was undertaken. A modern fighter configuration known to exhibit a flat spin mode was selected. A substantial aerodynamic data base at spinning attitudes was available as well as a computer code especially amenable to spin analysis.

Using these tools, an analytical study was made of the thrust requirements for a rocket spin recovery system for the subject configuration. These results were then applied to a preliminary systems study of rocket components appropriate to the problem.

Subsequent spin tunnel tests were run by NASA to evaluate the analytical results.
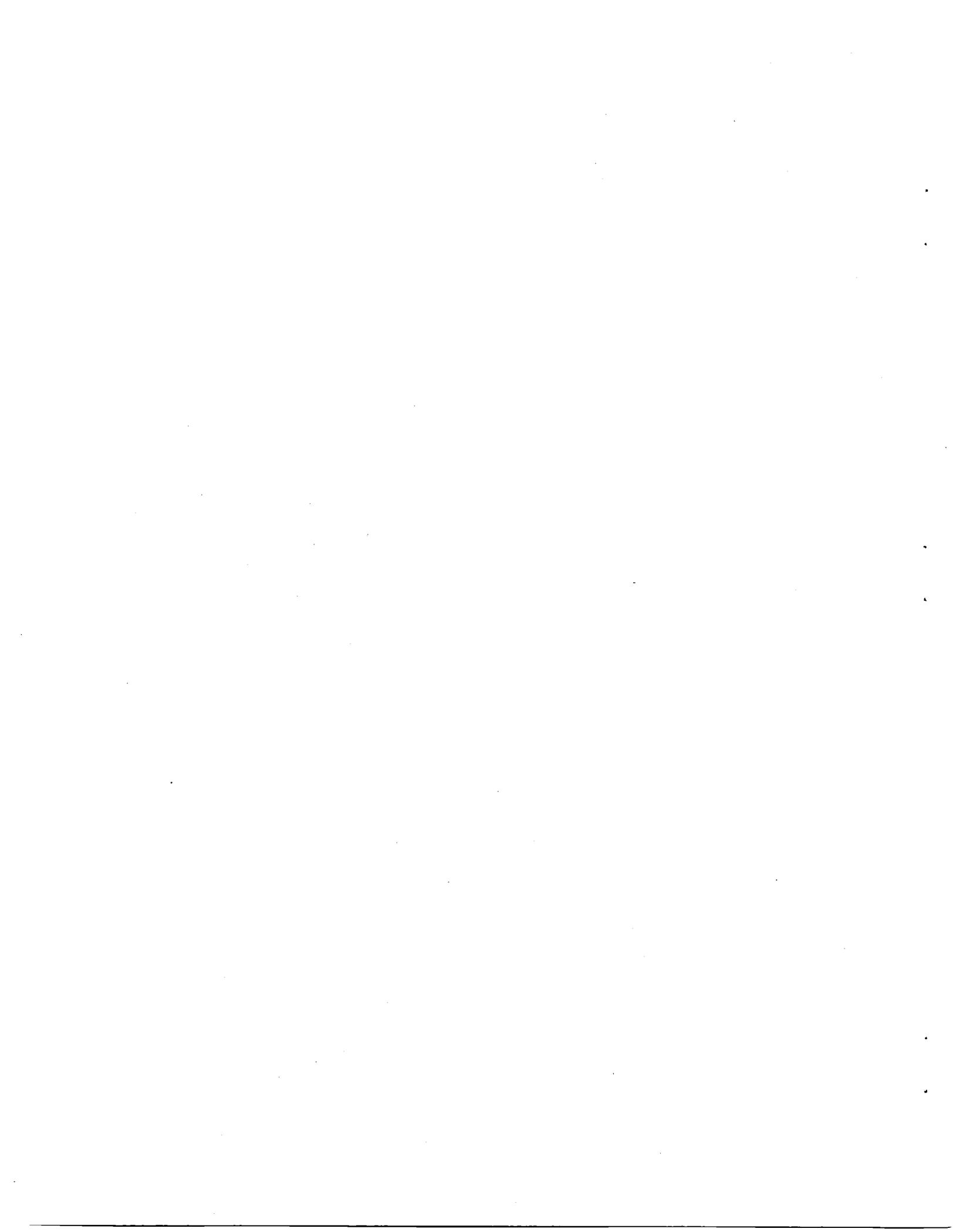
2.0   HISTORY

Anyone familiar with the existing literature on airplane spinning
has no doubt noticed, amidst numerous treatments of the anti-spin
parachute as an emergency spin recovery device, an occasional
reference to the use of rockets for this purpose. As a starting
point for this study, a survey was undertaken to identify as
completely as possible the previous work done for rockets.

The following discussion represents a chronological history of
the results and conclusions obtained by various investigators
using analytical techniques, wind tunnel tests and flight
evaluations.

2.1   SURVEY OF THE LITERATURE

In 1938, a series of flight tests was performed in Germany to
evaluate the effectiveness of a rocket for spin recovery.
(Reference 1)

For safety reasons, the FW56 type airplane was used because it
was known to be recoverable should the test system prove inadequate.
A tail-mounted rocket was fired in pitch or in yaw against pro-spin
controls. Full recovery was not a sine qua non - it was considered
beneficial if the rockets only served to change the spin to a more
easily recoverable mode.

The authors state the objective of the tests was to clarify the
relative usefulness of pitch rockets versus yaw rockets.

Preliminary tests were performed in a second FW56 airplane with
jettisonable weights to evaluate the increased inertial efects
and c.g. change of the proposed rocket installation on the basic
spinning characteristics of the configuration.

The maximum available thrust used was 100 Kg and was not
sufficient to produce complete recovery in the yaw mode.
However, it was predicted that "slightly" larger thrust
would do so. Interestingly, the authors express complete

surprise that the application of thrust to produce nose-down pitching moments not only fails to generate recovery, but, in fact increases the resultant angular velocity.

The spin chute was apparently unknown or, at best, not considered "proven" in Germany at that time, because the comment is made that ". . . . no flight tests exist concerning another expedient (i.e. recovery system) that would offer 100 percent safety. . ."

In England, howvever, the spin chute was certainly recognized and a crude installation, "one of the earliest cases", was employed for the spinning trials of the Spitfire which was introduced into service in 1938. (Reference 2)

R. Gross refers to the use of spin chutes, presumably in the Unites States, "as far back as 1942" (Reference 3)

Interest in rocket recoveries in the United States seems to have appeared in 1949 with an NACA report by Neihouse (Reference 4). Spin tunnel tests were performed on a P-47 model using wing-tip mounted rockets to provide a yawing moment. These tests were successful, but the author emphasized the preliminary nature of the results and called for full scale research.

Some time later a conference was held at the United States Air Force Air Material Command on "Use of Rockets for Spin Recovery". As a result of this conference North American Aviation, Inc. was given a contract to conduct flight tests of a rocket system in 1952. (Reference 5)

The authors note that spin recovery parachute sizes were becoming excessive and the feasibility of alternatives should be investigated.

The test vehicle selected was a T-28A airplane whose spin characteristics were considered well understood. Rocket thrust was provided by wing-tip mounted JATO bottles with a rated thrust of 363 Kg (800 pounds).

Only the effect of applied yawing moment was evaluated in this first program. For the T-28, the location of the spin axis was 2.4 meters ahead and 1.5 meters lateral of the c.g. Tests showed that the yawing moment applied about the spin axis was significant, rather than the moment about the airplane Z body axis.

Some discrepancies between predicted and observed recovery characteristics were encountered because pro-spin controls were maintained while the airplane angle of attack decreased into the unstalled region. During that time the ailerons were able to generate large rolling moments.

Discussion is made concerning the eccentricity of the spin axis and its effects on which wing-tip rockets should be fired.

In summary, the flight program demonstrated that rockets applying a yawing moment were effective in terminating a spin against pro-spin controls for a wing-loaded straight-winged airplane. Recommendations included further flight research using an airplane of the jet fighter class, such as the F-86.

This project entered a Phase II in late 1952. The rocket pack was relocated from wing tips to the aft fuselage to change the inertia yawing moment to a more negative value. (References 11 and 23). The author notes "that it is not absolutely necessary that the emergency recovery device . . . stop the spin completely", placing the aircraft in an aerodynamically recoverable mode was deemed sufficient.

For the wing-loaded configuration a 45 degree tilt of the wing-tip rocket was employed to compare a pro-spin rolling component with an anti-spin rolling moment component. Incomplete data

suggests that for the 363 Kg thrust unit the 45 degree inclination providing both rolling and yawing recovery moments was less effective than a pure yawing moment orientation.

In all these tests, the JATO unit was equipped with a pilot-controlled blow-out plug so that rocket thrust could be terminated at any time.

In 1954 NACA published a comparison of model and full-scale results for spin recoveries using wing tip rockets (Reference 6) based on these T-28 flight tests. The data show the model spinning at 7 to 10 degrees lower angle of attack than the airplane and, on the average, recovering a fraction of a turn quicker. The conclusion drawn is that there is good correlation between model and airplane for these tests.

In 1955, NACA published spin tunnel results for two Chance Vought airplanes which included the sizing of rockets for emergency spin recovery (References 7, 8).

For the F7U-3, yaw rockets and roll rockets were tested for both erect and inverted spins. Mounted on the wing tips, these rockets generated approximately 3000 Kg-meters (22,200 ft-lbs) of recovery moment (full scale). Model results turns for recovery:

	Yaw Rocket	Roll Rocket
Erect	$\frac{1}{4}$-3/4	1-1$\frac{1}{2}$
Inverted	3/4-1$\frac{1}{2}$	1 3/4

An interesting comment suggests that "a rocket that is too large may be just as bad for recovery as one that is too small" and calls for a means for the pilot to terminate the thrust at will.

The roll rockets were not considered attractive because of adverse gyrations produced during recovery.

Model tests of the XF8U-1 erect spins were conducted in
a similar manner, but various rocket locations were used
(wing-tip and fuselage installation) enabling some variat-
ions in recovery yawing moments. Roll rockets were limited
to the wing tip locations

Yawing Moment (kg-m)	Recovery Turns
2785	Unsatisfactory
3140	$2\frac{1}{4}$-$2\frac{1}{2}$
5630	1-$1\frac{1}{2}$
6030	$\frac{1}{2}$-$1\frac{1}{2}$
9420	$\frac{1}{2}$*
*Resulted in opposite spin	

No quantitative results were presented for the roll rockets
but it was noted that a "sufficient rolling moment may be
effective".

In about 1956, the next known flight application was again
employed by North American for the F-100D spin evaluation
(Reference 9). This installation consisted of a 200 Kg
(440 pound) package of 122 one and one-half inch NAKA
armament rockets mounted under each wing. Each rocket was
capable of 180 Kg (400 pounds) thrust for 0.6 seconds
duration. Thus the average thrust and duration could be
predetermined by setting the firing sequence. A yaw rate
sensor prohibited firing unless yaw rate was greater than
15 degrees per second. In Reference 29, it is noted that
these rocket packages had negligible aerodynamic effects.
The inertia changes were comparable to those produced by
fuel consumption.

In 1957 Neihouse et al published a comprehensive summary of spin research. They briefly note that model tests are necessary to determine rocket force requirements. (Reference 35)

North American maintained a high-level of capability with rocket systems during this time period. The T2J employed wing-mounted rockets firing in yaw (i.e. fore and aft thrusting). A rocket package was also planned for the F-107 program.

Rocket recovery sizes were determined for the FJ-4 airplane as part of the normal spin tunnel series. (Reference 28) Wing-mounted yaw rockets were used on this airplane also.

For the A3J airplane, the spin tunnel specified the rocket sizing requirements. The airplane installation consisted of 42 2.75-inch nose-mounted rockets (21 firing left, 21 right) automatically operated by an independent yaw rate gyro which determined the proper direction and also terminated the firing sequence when yaw rate dropped below 20 degrees per second. There was also a pilot-operated manual control. Each rocket was rated at approximately 320 Kg (700 pounds) thrust for 1.6 seconds. Firing in sets of four, 1270 Kg thrust was available for nine seconds.

Ground tests were conducted and on one occasion, two rockets inadvertently "cooked off" due to improper insulation. The rocket installation was a back-up to the spin chute. Although the chute was used twice during testing, the rockets were never needed.

When the Grumman Aircraft Engineering Corporation began building the A2F-1 (later redesignated the A-6A), a typical in-house study was instituted to determine the best emergency spin recovery device (Reference 25). After

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discussing tail-mounted parachutes, wing-mounted parachutes, pitch rockets, yaw rockets, jettisoning wing stores, and the use of slats, flaps, and/or landing gear, the author simply notes that tail-mounted chutes are most commonly used, that wing-tip mounted chutes are less desirable, and that comparison of yaw rockets "is difficult to present because rockets have not yet been tested to the extent that parachutes have in the field of spin recovery".

The A-6 spin tunnel test report, not published until 1964, (Reference 10) discussed the size of wing-mounted yaw rockets required for that configuration. For a 9000 Kg-m (65000 foot-pound) yawing moment, satisfactory recoveries were realized when the thrust vector "was tilted as much as or more than the inclination of the principal axis". The maximum tilt tested was ten degrees off the FRL.

Based on these spin tunnel tests, and the excessive structural reinforcement required to withstand the anticipated opening shock loads of a spin chute, in 1961 the company submitted a proposal to the Navy to install an anti-spin rocket installation. (Reference 32)

This system consisted of one hundred fifty-four 2.75-inch "Mighty Mouse" rockets located as follows:

> 14 forward thrusting in each wing pylon
>
> 14 aft thrusting in each wing pylon
>
> 21 each side thrusting in the aft fuselage

They were capable of providing 13350 Kg-m (96,500 foot-pounds) of yawing moment for 10.5 seconds. Lights were provided for cockpit checks of system readiness. The system could be operated either manually or automatically.

However, citing a "lack of experience with rocket spin recovery systems", the Navy rejected the proposal and an anti-spin parachute system was implemented.

In 1964, NASA published a study (Reference 12) which attempted to determine recovery moment requirements analytically using wind-tunnel data. A spin-energy factor was derived based on the kinetic energy of spin rotation. Yawing moments required for recovery were shown to be related to this factor. Rolling moments required for recovery were a function of this factor and also Ix.

In 1965, the Russians published an update (Reference 17) of an earlier flight test manual (Reference 18). In this volume it is noted that prior to spin testing, an anti-spin device - either anti-spin rocket or anti-spin parachute - is fitted to the test aircraft.

Reference 22 is apparently another translation of this work. However, this version contains a drawing of yaw rockets mounted on a delta-wing airplane and notes that the thrust can be employed acting vertically (roll) or horizontally (yaw) and that the horizontal arrangement is most commonly used in practice. An interesting photograph on the same page shows an interior view of either the Langley Spin Tunnel, or a remarkable exact copy.

A 1967 publication devoted to stall and spin alone by Kotik a sole author (Reference 19) states that the aerodynamic recovery methods are sufficient for modern aircraft recovery. However, for future aircraft which may be developed that "differ basically in their design and equipment" - canards being given as one example, the author indicates that special anti-spin devices such as parachutes or rockets may be necessary.

Another spin tunnel report (Reference 13) published in 1969 addressed the sizing of rockets for emergency spin recovery. The OV-10A airplane is a twin-boom configuration and therefore has no mounting-place for a tail chute.

The original test series was for a 9.1 m (30 foot) wing span airplane. Tilting the wing-tip rocket vector angle from 0 (parallel to body axis) to 10 degrees (parallel to X principal axis) produced no appreciable change in results. The final requirement was for a yawing moment of 2580 Kg-m (18670 foot-pounds) for 9.5 seconds.

It is noted that the rocket must provide a sufficient yawing moment and also must provide the moment for a long as rotation is present. That is, the total impulse does not sufficiently define the rocket requirement.

In 1970, a follow-up report was published (Reference 14) for a modified version of the airplane with a 12.2 m (40 foot) span. The modification produced no noticeable adverse effect on the spin and recovery characteristics. However, the rocket size requirement was increased to 3820 Kg-m (27,600 foot-pounds) for at least 4.5 seconds.

These spin tunnel tests were preliminary to an actual flight program. The North American Rockwell Corporation employed wing-tip mounted rockets as the emergency spin recovery system for spin tests of the OV-10A. The Naval Air Test Center report published in 1970 (Reference 15) describes the system as consisting of four 2.75-inch diameter rockets installed in each wing-tip. These rockets were FFAR type rated at 340 Kg (750 pounds) thrust each. Mass effects of the rocket installation was compensated for by keeping wing fuel tanks empty.

By firing in pairs at a 1.5 second interval, nearly 4150 Kg-m of recovery yawing moment could be generated by each pair. The system could be armed manually or by a signal from a rate gyro.

In the manual mode, the pilot determined the spin direction. The rockets were fired manually but firing was inhibited unless yaw rate exceeded 30 degrees per second.

The contractor demonstrated the effectiveness of the anti-spin rockets by recovering from a developed spin. The two pairs of rockets fired at angles of attack of 32 and 43 degrees respectively, and yaw rate of 112 and 76 degrees per second respectively. Zero yaw rate was achieved in slightly over two seconds from initial firing or 3/4 of an azimuth turn.

In 1972, a critical-flight-testing handbook for pilots discussed spin testing. (Reference 16). The authors list five desirable characteristics for an emergency spin recovery device (in addition to effectiveness)

1. Simplicity
2. Reliability
3. Armed only for test maneuvers
4. Pilot check-out capability
5. Minimal effect on basic airplane spin characteristics

Although it is observed that "rocket systems may be designed to produce yaw, pitch and roll or any desired combination of these", rockets are deemed less desirable than parachutes because of the following design problems:

1. Two systems are required - - one for right and one for left spins unless thrust vectoring is used.

2. The design must automatically preclude the possibility of firing the wrong system and must also provide a manual override for the automatic system.

3. High reliability is required for the rocket and the electrical system which activates it.

4. The rocket thrust duration must be controlled either automatically or by the pilot to avoid overcontrolling during recovery.

5. The installation should not appreciably change the external contour of the airplane.

6. The device should be capable of correcting for inadvertent spin reversals and secondary spins on recovery.

7. Appreciable objectionable mass changes may be encountered from rocket fuel consumption.

8. Storage and handling procedures for rockets can be quite complex.

A NASA publication the same year devoted to spin-recovery parachute systems (Reference 20) briefly addressed rockets. It was essentially a summary of NASA spin work and the rocket was viewed as less attractive than parachutes for the following reasons:

1. a direction sensor is required

2. thrust duration is limited

3. too-long and too-short firings would be problems

4. the rocket is a "one-shot" system

5. two installations are necessary for wing-tip systems

However, a list of advantages was also included:

1. definite, known yawing moment is applied

2. not affected by aircraft wake

3. jettison after use not required

4. structural beef-up only needed to withstand forces produced by the rockets

General considerations of rocket systems discussed in this report are:

1. The installation should not significantly alter the aerodynamic and/or inertia characteristics of the airplane.

2. The rocket thrust should be aligned as closely as possible with the principal axis of the airplane.

3. Thrust and duration parameters should be determined in the Langley spin tunnel. A value of total impulse does not sufficiently define the requirements.

In 1973 some results of rocket studies in the French spin tunnel were presented. (Reference 27)

At an AGARD meeting in 1975, some work on spin rockets performed in the French spin tunnel at Lille was presented. (Reference 21) The test articles were models of light, general-aviation-type aircraft.

The range of rocket parameters tested was 80 to 100 percent of gross weight for about two seconds to 2 to 3 percent of gross weight for about six seconds.

The results are discussed in terms of axis of applied thrust - pure pitch, roll, and yaw.

A summary formulation of rocket effectiveness given as thrust required in pitch to roll to yaw is 15 to 6 to 1.

The authors allude to flight tests using a fixed-duration solid-fueled rocket. The problem of excessive firing times leading to spin reversals was solved by decreasing the length of the moment arm, thus decreasing the yawing moment generated by the fixed-thrust rocket.

Pitch rocket:	Thrust	Duration	Recovery
	50 percent GW	4 seconds	satisfactory
	80 percent GW	2 seconds	satisfactory
Roll rocket: (raising outer wing)[1]	10 percent GW	5-6 second	3 turns
	20 percent GW	shorter	better
	15 percent GW is required		
Yaw rocket:	2 percent GW	7 seconds	5-6 turns
	5 percent GW	4-6 seconds	2-3 turns
	12 percent GW	4 seconds	1-2 turns

NOTE 1 - Roll rocket to raise the inner wing requires triple the
thrust to obtain recovery. It also produces severe
post-recovery gyrations. Too small a thrust applied
in this manner worsens the spin, i.e. makes it flatter.

In extrapolating their conclusions to military aircraft, a
caveat is introduced concerning "rough" (i.e. oscillatory)
spins. That is, the appropriate direction of the thrust
vector is not evident.

At the time this report is being prepared, the NASA Langley
Research Center is conducting a flight program using hydrogen
peroxide fueled thrusters for spin research on a Beech Sundowner
aircraft. (Reference 26)

3.0   ANALYTICAL STUDY

3.1   COMPUTER PROGRAM

The six-degree-of-freedom digital computer program used in this study was developed under NASA contract NASl-13578 and is reported in References 30 and 31. The assumptions and limitations of the technique are discussed in those documents.

The equations of motion and associated formulas used in this program are presented in Appendix A.

The unique feature of this mathematical formulation is that the aerodynamic forces and moments acting on the spinning aircraft due to steady rotational flow (obtained from measured rotation balance data) are included and the dynamic derivatives are restricted to the oscillatory component of the total angular rates. Details of this treatment are given in Reference 12.

3.1.1   Aerodynamic Model

The aerodynamic model used in this study represents a current fighter aircraft configuration. The data base is derived from conventional static and forced-oscillation wind-tunnel data, as well as rotation-balance data and is presented in Appendix C of Reference 31.

The aircraft configuration data employed are given in Table I.

3.2   COMPUTATION STRATEGY

The rotary-balance data was measured at a maximum $\Omega b/2V$ of .3045. For the full-scale airplane computation this represents a maximum rotation rate of about 175 degrees per second. This value was therefore used for the initial yaw rate.

The lowest pitch angle for which rotation-balance data was measured was 55 degrees.

In Reference 31. It is noted that "while the post-stall and and spin entry motions were not well-predicted, the developed

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TABLE I. AIRCRAFT CONFIGURATIONS

GROSS WEIGHT	21,800 kg	(48,000 LB)
I_x	88,100 kg-m^2	(65,000 SLUG-FT^2)
I_y	307,800 kg-m^2	(227,000 SLUG-FT^2)
I_z	379,600 kg-m^2	(280,000 SLUG-FT^2)
I_{xz}	−3820 kg-m^2	(−2820 SLUG-FT^2)
WING AREA	52.5 m^2	(565 FT^2)
WING SPAN.....................	19.5 m	(64 FT)
MEAN AERODYNAMIC CHORD	3 m	(9.8 FT)
CENTER-OF-GRAVITY.............	14% MAC	
WING SWEEP....................	22 DEG	
STORE LOADING	CLEAN	
I.Y.M.P........................	−0.0264	

R80-1274-001(T)

spinning motion and the initial phases of the spin recovery
motion were reasonably well-predicted". Also, "the phases of
motion which were not well predicted were the flight regions for
which rotary aerodynamic characteristics had to be assumed".

Due to these factors and the desire to avoid unnecessarily long
computer runs, no attempt was made to fly into the flat spin.
At time = 0, the initial condictions given in Table II were
input and the run started in a fully-developed flat spin.

After ten seconds, the rocket system was fired while pro-spin
controls were maintained. Therefore, at rocket initiation, the
airplane was in a flat spin at an average angle of attack of
approximately 83 degrees, yawing at 168 degrees per second.
A mild roll oscillation of ± 15 degrees was present. This
correlates quite well with the developed spin characteristics
of this configuration observed in both the spin tunnel (Reference
36) and also in a flight test accident (Reference 24).

TABLE II. INITIAL CONDITIONS

ANGLE OF ATTACK	81.63 DEG
ANGLE OF SIDESLIP	−3.15 DEG
FLIGHT PATH ANGLE	−60.1 DEG
ALTITUDE	10,670 m (35,000 FT)
VELOCITY	98 m/SEC (320.9 FT/SEC)
PITCH RATE	1.98 DEG/SEC
ROLL RATE	15.5 DEG/SEC
YAW RATE	174 DEG/SEC
BANK ANGLE	2.8 DEG
HEADING ANGLE	0 DEG
HORIZONTAL STABILIZER	−5 DEG
DIFFERENTIAL STABILIZER	7 DEG
RUDDER	−30 DEG

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The two or two and one quarter turn recovery has traditionally been used as the criterion for acceptability. Considering the large mass of this airplane and the extremely high rotation rates, along with the rather low sink rate, it has been felt that a good case can be made to accept recoveries of four turns.

Requiring faster recoveries results in very high rocket thrust levels. Earlier analytical studies on this aircraft indicated that reducing the recovery requirement from 2 to 3 turns would decrease the necessary yawing moment by 24 percent.

Therefore, for most of the runs in this study, a ten-second rocket burst was used, being considered reasonable and practical.

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When pro-spin control inputs were maintained throughout the run, the computation would often generate extremely severe post-recovery gyrations after low angles of attack were attained. An analogous phenomenon is frequently seen in the spin tunnel where the model recovers from the spin and then careens wildly into the net. Large excursions in sideslip would greatly exceed the existing data matrix. It was found that neutralizing the rudder and differential tail after the yaw rate had decreased below 50 degrees per second had negligible effect on the time to recovery, but resulted in much more realistic aircraft behavior and a more consistent set of computational results.

For these calculations, recoveries were defined as yaw rate or angle of attack reaching zero.

3.3   RESULTS

Yawing moment has been found to be the primary recovery mechanism in nearly all studies to date. When rolling moments were used, the thrust levels required were generally significantly higher. Therefore yawing moments were investigated first.

Rather large thrust values were found necessary. A 1270 Kg (2800 pound) rocket firing for ten seconds was able to recover the configuration. Four different rocket locations are appropriate to generate yawing moments. These are:

1) nose installation

2) tail installation

3) one wing tip

4) two wing tips

For the computational scheme used, it was found that the rocket location has negligible effect on the results. Application of the same total yawing moment for the same length of time of time effected the same recovery trajectory.

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Pure pitch inputs were looked at briefly. Thrust levels in excess of 2270 Kg (5000 pounds) were unable to produce even a tendency toward recovery, so no further effort was expended along these lines.

Pure roll inputs were tried and found to be unexpectedly effective. The moment required was in the same sense as "rolling into the spin", i.e. a positive rolling moment required for a right spin. A 1180 Kg (2600 pound) wing-tip rocket (or a 590 Kg (1300 pound) rocket on each wing-tip) firing for ten seconds would produce recoveries.

Previous work has sometimes shown an improvement in recovery if yaw rockets were tilted to introduce some rolling moment. Therefore, the entire spectrum of tilt angle (σ) was investigated from σ = 0 degrees (pure yaw) to σ = 90 degrees, (pure roll).

A σ of 45 degrees was found to be optimum. Figure 1 shows the thrust required to produce zero yaw rate as a function of tilt angle σ. A rocket thus oriented was able to effect recovery for a ten second firing with a thrust of only 740 Kg (1630 pounds). Because of the dramatic and unanticipated effectiveness of this tilted thrust vector, an extensive series of runs was made for a large matrix of thrusts and tilt angles in an attempt to gain a better understanding of the phenomenon.

Using minimum yaw rate attained for a ten-second firing as the indicator of effectiveness, the results are shown in Figures 2 and 3.

Figure 4 shows the minimum yaw rate attained as a function of firing duration for a series of rocket thrusts varying from 450 Kg (1000 pounds) to 1140 Kg (2500 pounds) at a tilt angle of 45 degrees. For the higher thrust levels the slopes of the curves, yaw "deceleration" in a sense,

are quite steep. However, at 510 Kg and less, additional
duration of firing does not provide any further decrease
in yaw rate. In fact, for these runs yaw rate increased
again while the rocket continued to fire.
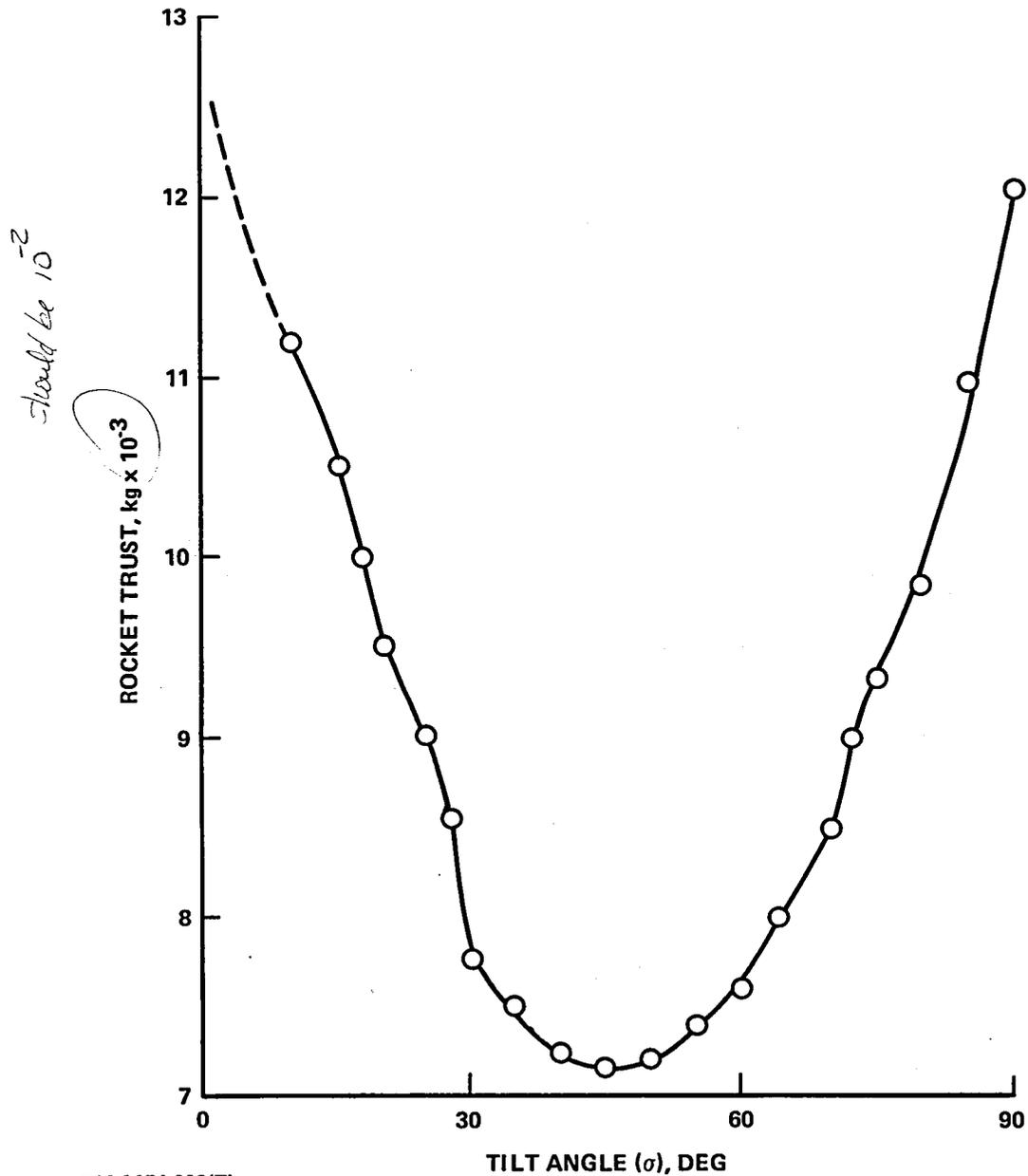
Figure 1. Rocket Thrust Required for Zero Yaw Rate as a Function of Tilt Angle σ
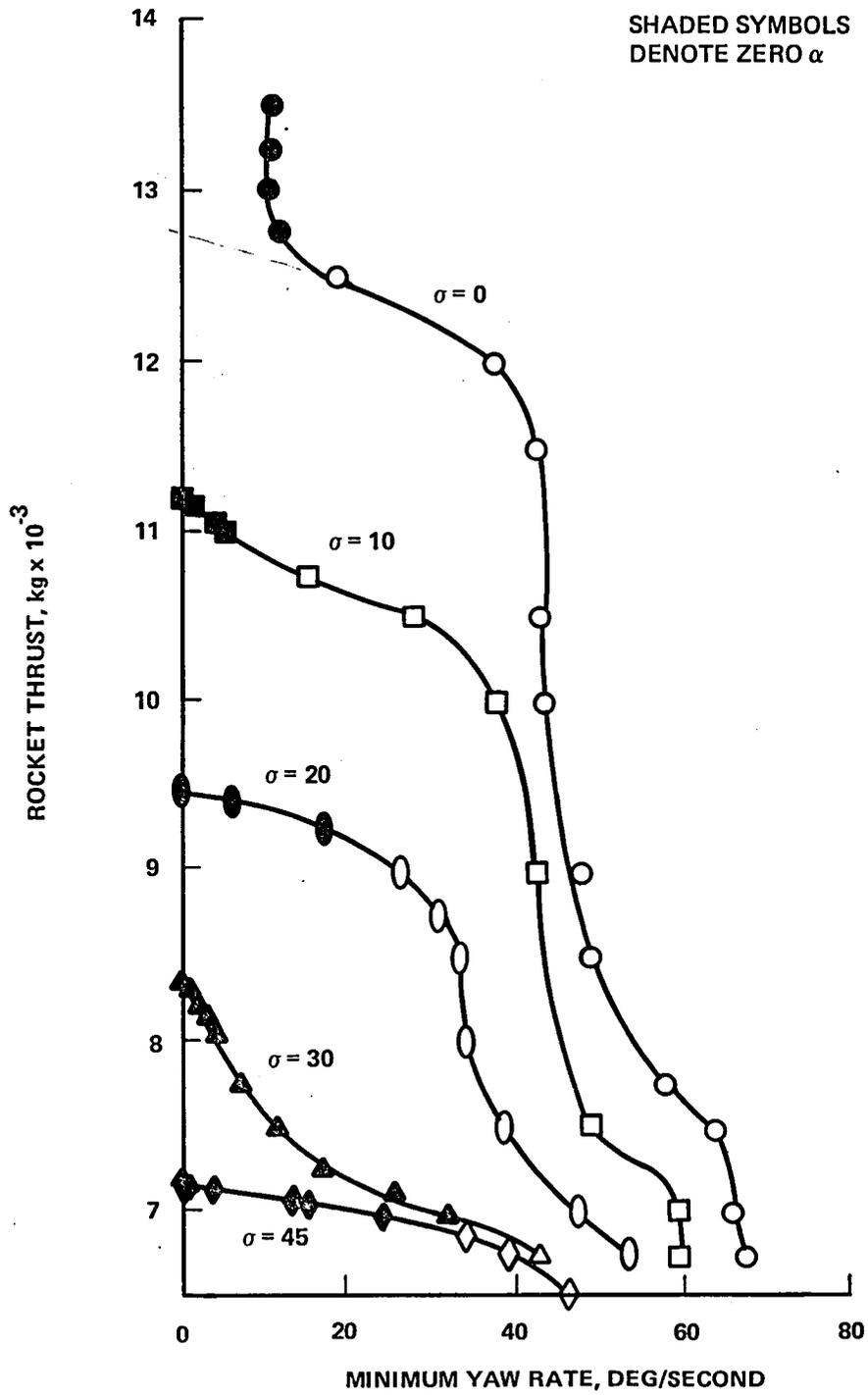
Figure 2. Rocket Thrust Vs Minimum Yaw Rate for σ = 0 to 45 Degrees (10-Second Firing)
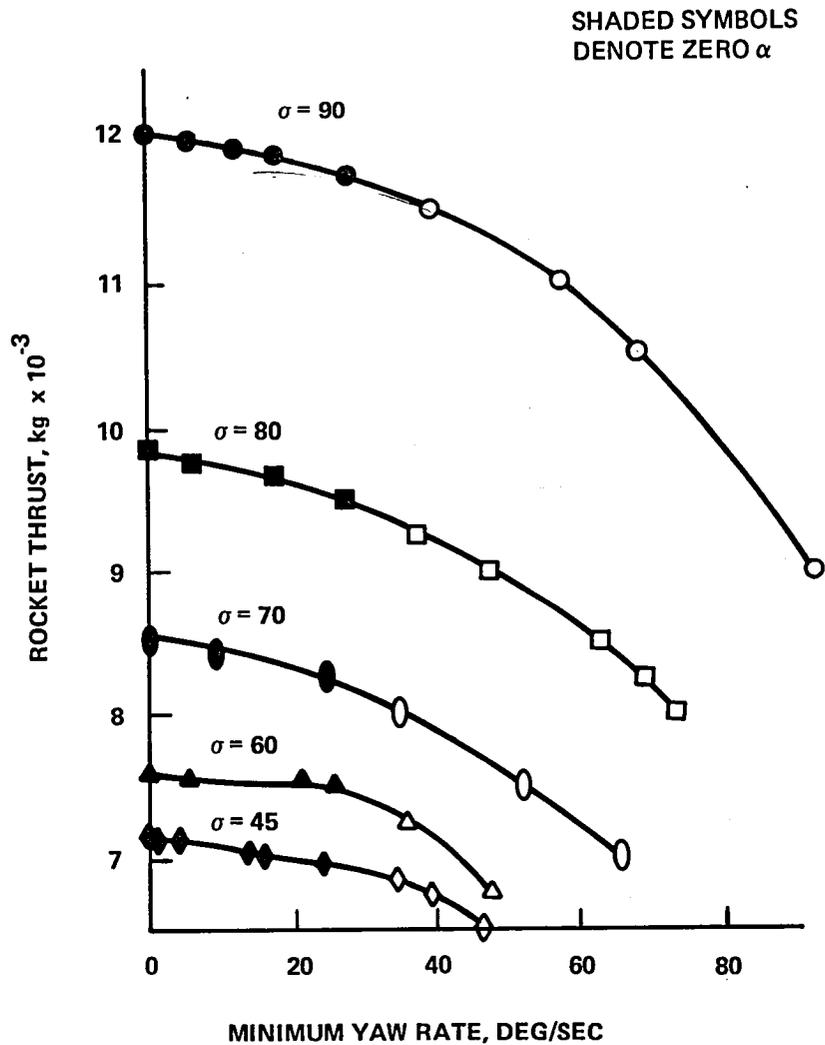
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R80-1274-010(T)

Figure 3. Rocket Thrust Vs Minimum Yaw Rate for σ = 45 to 90 Degrees (10-Second Firing)

A comparison of the yaw rate time histories for tilt angles
of 0, 45 and 90 degrees at three different thrust levels is
shown in Figure 5. It can be seen that the roll rocket is
consistently the least effective. The yaw rocket and 45
degree rocket are initially of nearly the same effectivity,
however, at approximately 100 degrees per second yaw rate,
the 45 degree configuration suddenly gains in performance
according to this particular calculation.

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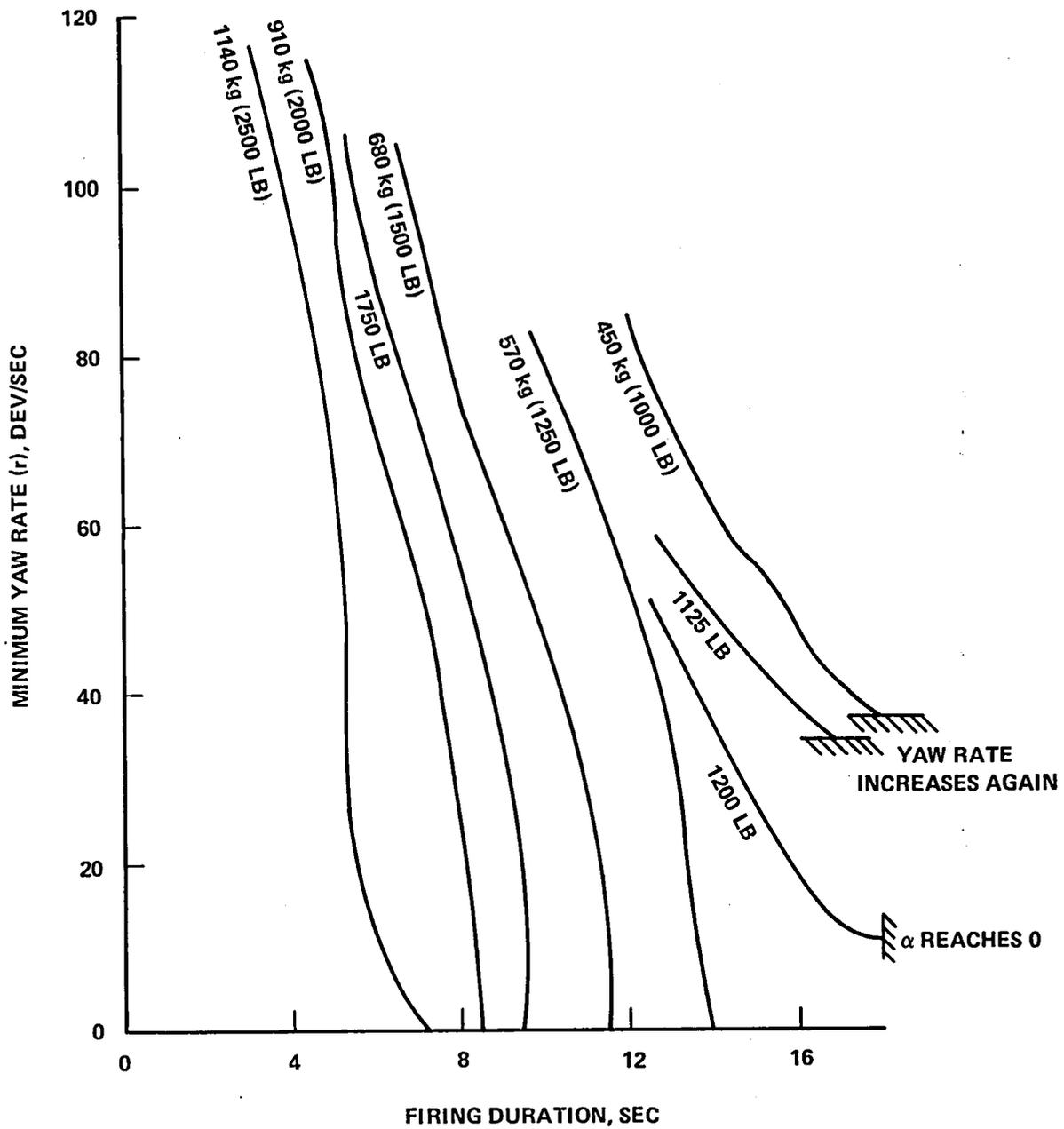
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Figure 4. Minimum Yaw Rate as a Function of Rocket Firing Duration, σ = 45 Degrees
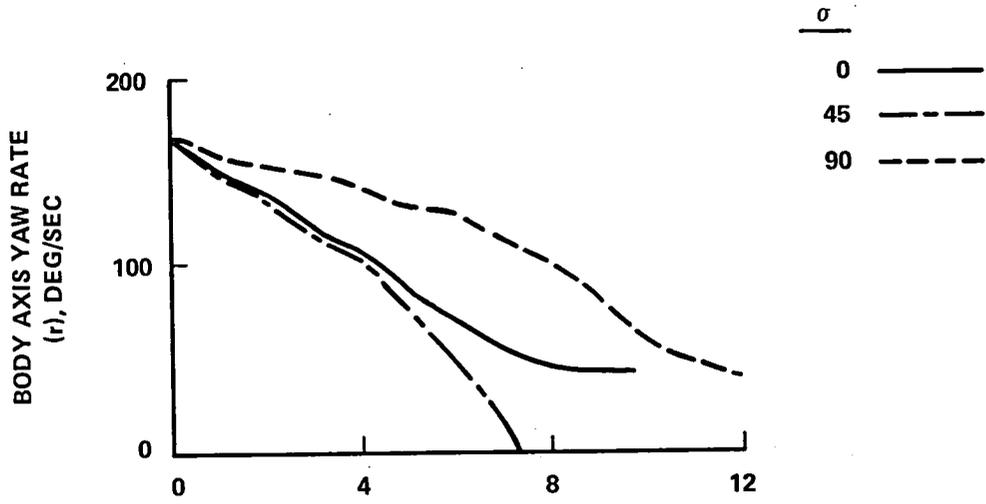
A. 1140 kg THRUST (2500 LB) 10 SEC
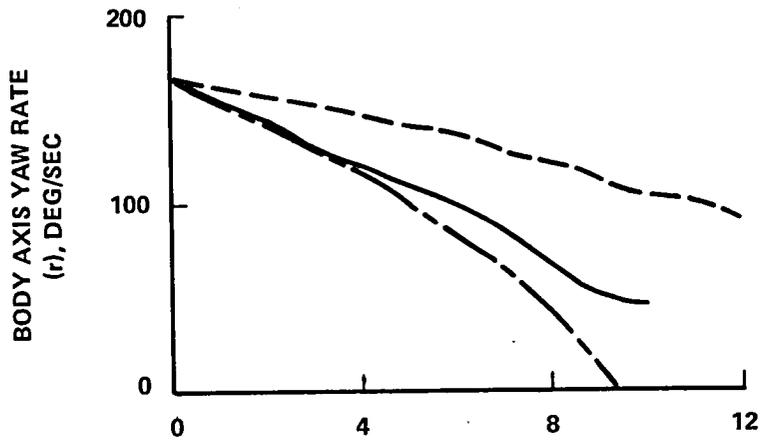
B. 910 kg THRUST (2000 LB) 10 SEC
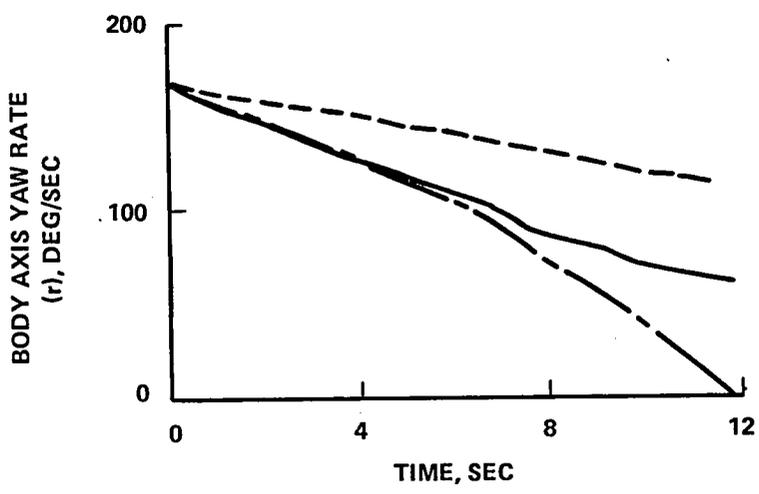
C. 750 kg THRUST (1650 LB) 10 SEC

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Figure 5. Yaw Rate Time Histories

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3.4   COMPARISON WITH EARLIER METHODS

The determination of required rocket thrust levels for the spin recovery task may be made experimentally or analytically, to various degrees of sophistication.

Dynamically-scaled model tests in the spin tunnel are generally regarded as the definitive experimental method for making this assessment and numerous examples are cited in the referenced material.

One early analytical method using simple momentum considerations for predicting the required anti-spin yawing moment was developed by Farmer as reported in Reference 5. A more sophisticated technique is treated in Reference 12, which also examines the roll rocket thrust requirements.

It is of interest to compare these relatively simple techniques with the results obtained using the six-degree-of-freedom program in order to estimate the benefits obtained for the more costly and time-consuming methods.

Method I

Aircraft momentum $= I\Omega$

where

$$I = I_z \cos^2 \theta + IxSIN^2 \theta$$

For the subject configuration

$I_x = 88100$ Kg-m^2 (65000 Slug-ft^2)

$I_z = 379600$ Kg-m^2 (280000 Slug-ft^2)

$\theta = -7$ degrees

$I = 372900$ Kg-m^2 (276807 Slug-ft^2)

should be 375 271.

$\Omega = 3.03$ rad/sec

Momentum $= 1137100 \dfrac{\text{Kg-m}^2\text{-rad}}{\text{Sec}}$ ($838725 \dfrac{\text{Slug-ft}^2\text{-rad}}{\text{Sec}}$)

$$\text{Rocket thrust} = \frac{I\Omega}{h\ t\ \cos\theta}$$

where h = moment arm = 9.75 m (32 feet)

t = time to recover = 10 seconds

Thrust = 1200 Kg (2640 pound) yaw rocket

From Figure 1 it is seen that the prediction is reasonably close to the values obtained from the computer, but a little too small for complete recovery.

Method II

Using the method detailed in Reference 12, the rocket sizing computation for subject aircraft follows:

The moment of inertia (I_v) about a vertical axis:

Assume $\theta e = 0$ on the average

$$Iv = \sin^2\theta e\ Ix + \cos^2\theta e\ Iz + \sin 2\theta e\ Ixz$$

For $\theta e = -7$ degrees ($\alpha = 83$ degrees)

$Ix = 88100$ Kg-m^2 (65000 Slug-ft^2)

$Iz = 379600$ Kg-m^2 (280000 Slug-ft^2)

$Ixz = -3820$ Kg-m^2 (-2820 Slug-ft^2)

$Iv = 376220$ Kg-m^2 (277490 Slug-ft^2)

The spin energy factor is:

$$Es = \frac{\frac{1}{2}Iv\Omega^2}{\frac{1}{2}\rho V_R^2 Sb}$$

Using values of parameters at time of rocket firing:

$Iv = 376220$ Kg-m^2 (277490 Slug-ft^2)

$\Omega = 3.03$ rad/sec

$\rho = .376$ Kg/m^3 (.0007285 Slug/ft^3) For 10360m (34000 feet)

$V_R = 96$ m/sec (316 ft/sec)   Es = 1.042

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Using the Loading II ($IYMP = -.0394$) data on Figure 21, of Ref. 12:

$$\Delta C_n = .105$$

For the subject configuration, $C_n = 17750$ Kg-m (128322 ft-lb)

Therefore a wing tip yaw rocket of 1820 Kg (4010 lb) thrust is predicted to produce a $2\frac{1}{4}$ turn recovery. As a check, a test run on the computer made for this condition produced a two-turn recovery in seven seconds. This would be termed a good correlation.

It is necessary to expand upon this method a bit in order to correlate with the ten-second firings, used in this study. This thrust determination was extrapolated using a simple constant total impluse ratio, thus giving a 1280 Kg (2807 pound) rocket thrust required for ten seconds. This gives very good correlation with the value obtained by extrapolating the $\sigma = 0$ curve shown in Figure 2.

For a rocket fired in roll, from Figure 22 of Reference 12,

$$\Delta C_1 = .14$$
$$C_1 = 23660 \text{ Kg-m } (171096 \text{ ft-lb})$$

a rocket of 2425 Kg (5347 lb) thrust fired in roll is predicted to produce a $2\frac{1}{4}$ turn recovery.

A test run made for this condition achieved a recovery in 1.9 turns (4.9 seconds)

The extrapolation to the ten-second firing yields a 1188 Kg (2620 pound) thrust requirement. This is in remarkably good agreement with the 1184 Kg (2610 pound) value shown in Figure 2. 3

The simple methods, therefore, are seen to yield rather good approximations to the results obtained from the computer code. For any preliminary calculations, particularly with an appropriate "safety factor" added on, the simple methods appear to be entirely adequate.
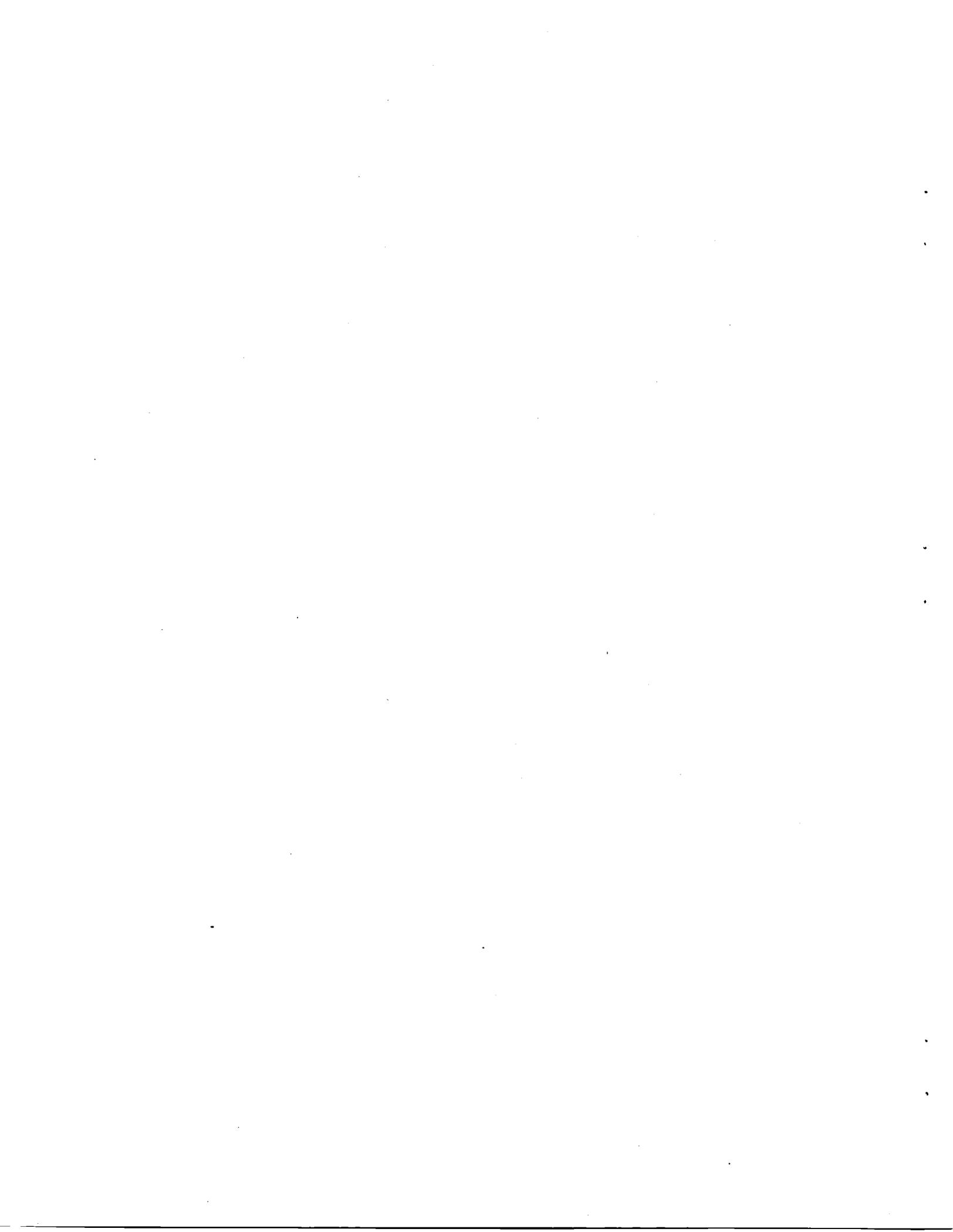
4.0   EXPERIMENTAL STUDY

4.1   SPIN TUNNEL TESTS

The analytical study produced certain unanticipated results
with regard to the effects of thrust vectoring, so a short
series of spin tunnel tests was conducted to evaluate these
effects and assess the degree of correlation with the
computations.

An existing dynamically-scaled model of the subject airplane
was modified for the tests by mounting a pressurized freon
container on the dorsal area. The gas was ducted to the wing
tips by flexible tubing. The tubing was crimped until thrust
was commanded by a radio signal.

The freon system appears to be capable of producing repeatable
thrust levels. Some typical calibration runs of this system are
shown in Figure 6.
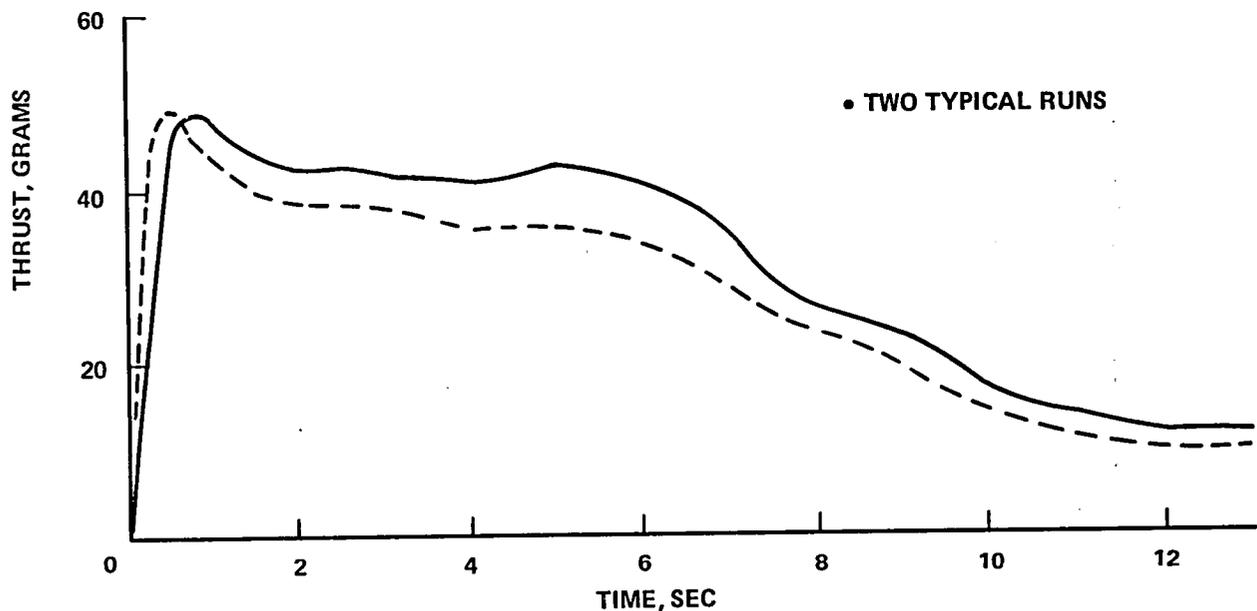
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Figure 6. Thrust Characteristics of Freon Reaction System

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The mass and inertial characteristics of the model with freon
devices installed (scaled to full-size aircraft values) compared
to the parameters used in the analytical study are shown in
Table III.

**TABLE III. - COMPARISON OF SPIN TUNNEL MODEL AND COMPUTER MODEL MASS
AND DIMENSIONAL CHARACTERISTICS**

PARAMETER	SPIN TUNNEL	COMPUTER
WEIGHT, kg	18,660	21,800
1_x, kg-m^2	88,500	88,100
1_y, kg-m^2	298,700	307,800
1_z, kg-m^2	373,700	379,600
cg, % MAC	22	14
Y DIST, m	9.6	9.4
h_o, m	9,140	10,670
SCALE	1/36	1

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The tests were performed by launching the model into the tunnel
with full pro-spin controls. After a short time, when the fully-
developed spin had become relatively stabilized, a remote-control
radio command released the freon gas to the wing-tip nozzles.
These nozzles were adjustable to obtain desired tilt angles (σ).

4.2   DISCUSSION OF RESULTS

A brief check was made using the spin tunnel values in a computer
run. The only significant parameter change was found to be moving
the center-of-gravity aft. This resulted in an approximately five
percent reduction in spin rate at rocket firing. Recovery
characteristics were not appreciably changed.
The results of the spin tunnel tests are presented in Table IV.
A number of significant discrepancies are immediately evident.

TABLE IV. - SPIN TUNNEL RESULTS

FULL-SCALE THRUST		TILT ANGLE σ, DEG	TURNS FOR RECOVERY
kg	lb		
840	1850	0	4½, 12, 7½
840	1850	90	>25
840	1850	-45	>25
840	1850	45	7 3/4, 11 3/4
1680	3700	0	4¼, 3 3/4, 3¼, 3¼
1680	3700	90	>20, >20, >20
1680	3700	45	4½, 4

NOTES: A) ROLL WITH, YAW WITH
B) LEFT NOZZLE ONLY FIRING DURING FIRST TURN
C) LEFT NOZZLE ONLY FIRING DURING FIRST 1-3/4 TURNS

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The inadequacy of pure rolling moment for recovery shows the most apparent lack of correlation. In the computational results, slightly more than 1180kg (2600 pounds) thrust would produce a zero yaw rate recovery. In the spin tunnel, thrust equivalent to 1680kg (3700 pounds) was totally insufficient.

In both situations a very flat spin at essentially zero bank angle is exhibited (the computed spin has a roll oscillation that is not noticeable in the spin tunnel). When thrust is applied (roll into the spin), the computation produces a bank angle change, inner-wing-down, followed by decreasing yaw rate and subsequent recovery.

The spin tunnel model, however, shows an inner-wing-down change followed by a slight increase in yaw rate. This mode persists until termination of thrust, at which time the model reverts to the original spin mode.

The most obvious possible source of error in this case is the aerodynamic data package. On page 21 of Reference 30 the authors indicate problems in precisely this area.

Therefore, it is felt that the discrepancies in roll rocket effectiveness observed between the spin tunnel model and the computed trajectories are due to an inadequate data base. A consistent set of data for both positive and negative sideslip angles is required.

These deficiencies in the roll axis suggest that problems may well exist for any computation incorporating a rolling moment recovery component. For example, the analytical study showed a large effect due to vectoring the rocket thrust, with an optimum tilt angle of 45 degrees being established.

Although the interpretation of spin tunnel results is based upon trends observed in large numbers of tests, the few runs shown suggest that the $\sigma = 45$ degees cases exhibit slightly poorer recoveries than the $\sigma = 0$ runs. That is, the beneficial effect of a rolling moment component seen in the computation was not observed in the tunnel.

No tests were run for $0 < \sigma < 45$. For certain earlier configurations (see Literature Survey) a slight tilt angle was found to be helpful. Some of these tests indicated that a σ equal to the principal axis might be optimum. For this study, the subject airplane's principal axis is less than two degrees below the longitudinal body axis, so such an effect would probably not be seen in tunnel tests.

Recoveries by pure yawing moment ($\sigma = 0^{\circ}$) showed the best correlation between the spin tunnel and the computer runs. Even in these, however, the spin tunnel model required on the order of 25 percent higher thrust levels. Here too, the aerodynamic data base must be scrutinized. In Reference 31 the author notes that correlation for the final phase of the recovery motion was "relatively poor." He advocates measuring rotational flow effects to lower angles of attack, at least near $\alpha = 30$ degrees.

Another potential source of discrepancies is the experimental thrust
mechanism. Although the measured thrust, as shown in Figure 14,
appears to be acceptably repeatable, these calibrations were not
performed with the apparatus installed on the model. In two test
runs, one of the nozzles did not begin firing immediately upon
activation.

Therefore, it is possible that the thrust levels achieved in the
spin tunnel were less than anticipated.

For future work with the freon system, it would be advisable to
perform some calibration tests with the mechanism installed on the
model.

5.0 SYSTEMS STUDY

5.1 GENERAL CONSIDERATIONS

In the Survey of the Literature, it was seen that the spin recovery rocket concept has been studied and tested on many occasions during the past forty years. Certain characteristics have surfaced as highly desirable for such installations and a number of problem areas were identified.

While the feasibility of spin recovery rockets in general can be considered demonstrated at this time, these systems have obviously not come into extensive use for military, or other aircraft testing. Anti-spin parachutes have seen much more widespread use, so there must be some serious deficiencies associated with rocket systems.

Rocket technology has made enormous advancements during the United States space program. It would be instructive to look at the systems requirements for anti-spin rockets to determine whether or not the problems encountered in the past can be obviated by this new technology.

Thrust Levels - in the past, sufficiency of thrust levels was often cited as a problem (much less frequently, excessive thrust was mentioned). Today's technology eliminates this difficulty. A rocket motor can be designed to virtually any thrust level desired. More practically, the problem becomes one of finding an existing motor with the required rating, in order to avoid development costs. The accuracy with which a rocket's thrust can be established far exceeds the tolerance required for airplane spin recovery. Throttleable rockets exist, but this level of sophistication does not seem warranted for this application at this time. It would, perhaps, be informative to analyze an advanced system capable of programming thrust as a function of selected spin parameters, such as yaw rate, etc.

Thrust Duration - Two aspects of firing duration must come under consideration. First, using the theoretical concept of momentum, the rocket impulse (defined as thrust multiplied by duration) is the significant parameter. Equivalent results are obtained for constant impulse. For the airplane spin recovery application this has been found not to be the case - for a given configuration there appear to be minimum thrust levels that cannot be compensated for by increased duration. Secondly, achieving sufficiently long firing times is not particularly difficult for liquid rocket systems. In current usage, typical firing times are much longer than needed for spin applications. Addition of fuel tankage is not limited by the rocket motor and there is no requirement that fuel storage be immediately adjacent to the motor. Most importantly, the ability to terminate thrust at will is an inherent feature of liquid rockets.

Restart Capability - For three foreseeable situations a restart capability might be required. - 1) premature termination of thrust before the airplane is fully recovered, 2) a second spin entry during post-recovery maneuvering, or 3) a spin in the opposite direction from "over recovery". A multiple restart function is provided in virtually all liquid rocket systems and the number of allowable restarts is much higher than would be required for airplane application.

Angular Rate Interlock - Some sensor must be provided to determine spin direction (in case of pilot disorientation) in order to inhibit firing in the wrong direction; to initiate automatic firing, if desired; and to provide automatic arming, firing and shut-off thresholds, if desired. This type of sensor is an integral part of the avionics suit of all modern military aircraft. Test aircraft invariably have additional rate sensing, so this requirement is easily met today.

Inertial and Center of Gravity Effects - The mass of these modern liquid rocket motors is negligible compared to the airplane. Large quantities of fuel could conceivably produce inertial effects,

however, the technique of distributing rocket fuel storage at various locations in the airplane could be employed to minimize such effects.

Solid rockets, of course, are less flexible in this regard. The fuel mass, of necessity, is concentrated at the motor.

Aerodynamic Effects - As discussed under inertial effects, the small size of these units should entail negligible effects on the aerodynamic characteristics of the basic configuration. In fact, for many installations, no deviations whatever in the aircraft's external contours would be required. Where there are surface changes, wind tunnel tests might be required to assess the effects. However, the problems associated with high angle of attack tunnel tests are well known, so flight evaluations are also required. Areas to be flight tested for aerodynamic effects should be the stall and post-stall regimes, spin modes, recovery characteristics and transonic departures.

Inadvertent "cook-off" of adjacent rockets - this has occurred due to clustering of small rockets. One or two large rockets, especially liquid-type would not be expected to have this difficulty.

Storage and Handling - rocket fuels present various levels of hazard which must be considered. Solid fuels are generally easier to deal with, but even many liquids can be pre-packaged to minimize difficulties. Table V lists the relative toxicity of some liquid propellants. Because of the danger through contact, ingestion, or respiration, protective clothing is recommended.

Typical additional safety measures for ground handling have included isolated, environmentally-controlled storage, with separate areas for fuel and oxidizers, using specially-designed materials and equipment.

Much of this could be left to the propellant vendors with pre-packaged components being delivered to the airplane test facility.

TABLE V. TYPICAL PROPELLANT CHARACTERISTICS

FUEL/OXIDIZER	FORMULA	TOXICITY	BOILING POINT, $^\circ$F
HYDRAZINE	N_2H_4	MEDIUM	236.3
MONOMETHYL HYDRAZINE MMH	CN_2H_6	MEDIUM	189.5
UNSYMMETRICAL DIMETHYL HYDRAZINE UDMH	$C_2N_2H_8$	MEDIUM	146
N_2H_4 - UDMH (50%-50%)		MEDIUM	158
NITROGEN TETROXIDE NTO	N_2O_4	HIGH	70.1

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5.2   FUELS

5.2.1   Solid Fuels

Solid fuel rockets have been used frequently in the past, often
in the form of artillery type rockets. Solids offer distinct
advantages in terms of ease of storage and handling. A persua-
sive case could be made for a solid rocket for spin recovery
purposes for airplane tests:

    a) of short duration

    b) with normal aerodynamic recovery anticipated

    c) with a suitable mounting location available away
        from engine inlets.

    d) with relatively small impulse required.

The solid fuels become less attractive when the test vehicle
is likely to be subjected to extensive vibrations and forces
over a significant period of time, or when frequent rocket
firings are anticipated, or, when a restart capability is
needed, or in cases in which particulate matter from the
rocket exhaust is likely to enter engine inlets, or when
a large impulse is required. Large impulse solid rockets
are available, of course, but their size and weight make them
undesireable for many installations, such as wing-tips.

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Therefore solid fuel rockets are not further considered for
this application.

5.2.2   Liquid Fuels

Several basic types of liquid-fuel rockets are being manufact-
ured, each having certain innate advantages and disadvantages.
Table VI lists a number of typical liquid rocket motors.

TABLE VI. - TYPICAL LIQUID ROCKET MOTORS

MANUFACTURER	DESIGNATION	FUEL	OXIDIZER	THRUST, kg	LENGTH, cm	DIAMETER, cm	WEIGHT, kg
ROCKET RESEARCH	XMR-86A	N_2H_4	-	680	38	15	-
MARQUARDT	R-40A	MMH	N_2O_4	680	48	27	11
HAMILTON-STANDARD	REA 36-1	N_2H_4	-	1360	41	23	17
HAMILTON-STANDARD	REA 30-3	N_2H_4	-	730	30	14	7
HAMILTON-STANDARD	REA 300	N_2H_4	-	450	26	15	11
AEROJET		N_2H_4	-	730	23	15	7
MARQUARDT	R-5B	N_2H_4-UDMH	N_2O_4	800	98	43	32
ROCKETDYNE		UDMH	N_2O_4	1360	102	51	18
TRW	DELTA V	N_2H_4	N_2O_4	1360	86	40	-
AEROJET	AJ 10-131	UDMH-N_2H_4	N_2O_4	1000	140	58	-

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Hydrogen Peroxide is currently being used in a number of
applications. The NASA Langley program described in Reference
26 employs this fuel. It has the advantages of ease of storage
and handling. The major limitation at this time is the lack of
motors of sufficient thrust for the subject application.

It is noted that in an aircraft test application during the late
1950's and early 1960's, as fuel for a reaction control system
for extreme high altitude work with F-104 aircraft, this fuel
was considered hazardous. The NASA program (Reference 40)
experienced corrosion problems. As the catalyst deteriorated

over a period of time, raw hydrogen peroxide would leave the nozzles and penetrate even the slightest opening in the aircraft.

The Air Force program (Reference 41) was also troubled by corrosion. In addition, they experienced malfunctions due to trapped gases in fuel lines (in-flight bleeding required), residual hydogen peroxide after shut-down (purging system suggested) and iron oxide contamination. The authors state "... a hydrogen peroxide leak while airborne could result in loss of an aircraft."

Monpropellants such as hydrazine (N_2H_4) are seeing increased usage. (Reference 37) As with hydrogen peroxide, the degree of hazard perceived is decreasing as a longer history of familiarity and utilization is achieved. Although sufficiently high thrust levels appear to be achievable, present hardware yielding thrusts above 136 Kg (300 pounds) requires further development. Exhaust products of hydrazine are N_2, H_2 and NH_4. The effects of these substances on impingement areas is not considered a problem. Reference 38 lists an IR&D Monpropellant hydrazine engine which would be quite attractive for the military aircraft application. Rated at 1360 Kg (3000 pounds) thrust, this engine weighs 23 Kg (50 pounds) and is accommodated in a 20 cm (8 inch) diameter, 33 cm (13 inch) long envelope.

Hypergolic propellents have the property of spontaneous ignition when fuel and oxidizer come into contact. This characteristic has contributed to their being generally considered very hazardous materials. (Reference 33)

However, man-rated hypergolics have found acceptance in the Space Shuttle Program. (References 34 and 39)

The Shuttle's R-40A primary RCS thruster is rated at 400 Kg (870 lbf) and has been tested to 590 Kg (1300 pounds) thrust.

The manufacturer reports that "it is capable of providing a thrust well in excess of 725 Kg (1600 lbf)".

Having the desireable features of availability, compact size, light weight, liquid-fuel, man-rating; for the purposes of this study, the R-40A was chosen as the subject rocket engine. A configuration drawing is shown in Figure 7.

This engine uses monomethyl hydrazine (MMH) as the fuel and nitrogen tetroxide (N_2O_4) as the oxidizer. Shuttle specifications call for these engines to be reusable for a minimum of 100 missions and able to sustain 50,000 starts and 20,000 seconds of cumulative firings. Additionally, the yaw thrusters are anticipated to be used down to 13700 m (45,000 feet) altitude, so operation in the atmosphere has been considered.

MOUNTING FACE

23.1 CM
(9.1 IN.)
26.7 CM
(10.5 IN.)

14.5 CM
(5.7 IN.)

33 CM
(13 IN.)

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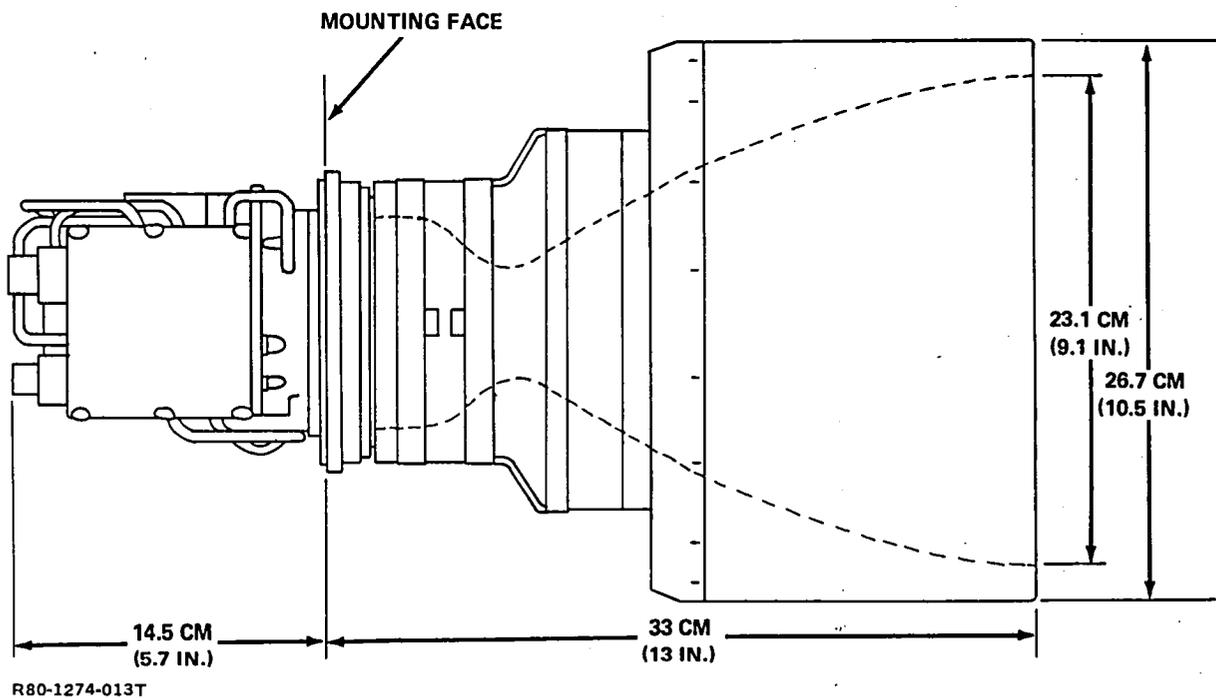
Figure 7. - R-40A Rocket Engine

The rocket exhaust for this system consists of CO, CO_2, H_2O, dissociated water amd minute amounts of NO_2 at temperatures of 4500 to 5000 degrees.

5.3 TYPES OF INSTALLATION

A number of possible installations have been roughly sized for the subject aircraft. Each installation consists of rocket motors, fuel tanks, oxidizer tanks, Helium tanks to pressurize the propellant tanks assuring positive expulsion under any "g" field, and associated plumbing.

The two basic types of installation are modular and custom. The modular systems are generally easier to design and package and, of course, are more readily attached and removed, simplifying restoration to the standard configuration. Jettison capability can be included if desired and remote fueling and servicing are possible. The custom arrangements provide greater packaging flexibility and can be better kept within normal airplane contrours.

Nose-mounted - nose-mounted rockets can provide significant yawing moments due to the large distance from the center-of-gravity. The radome area can accommodate four R-40 engines and the propellant tanks with no change to the airplane's normal contours. (Figures 8 and 9).

Wing-tip mounted - Wing tip installations can provide yawing moments, rolling moments, or combinations thereof. Presumably the units would be aligned longitudinally for normal flight and swivelled to a predetermined position for use.

Figure 10 shows a modular package suitable for a wing-tip installation (Figure 11). The size of this package compares favorably with the Sidewinder and Sparrow missiles.

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Figure 12 depicts a more compact custom installation for which the propellant tankage must be fitted into the wing itself. In this case only the small rocket motor itself need be mechanized to rotate if desired.
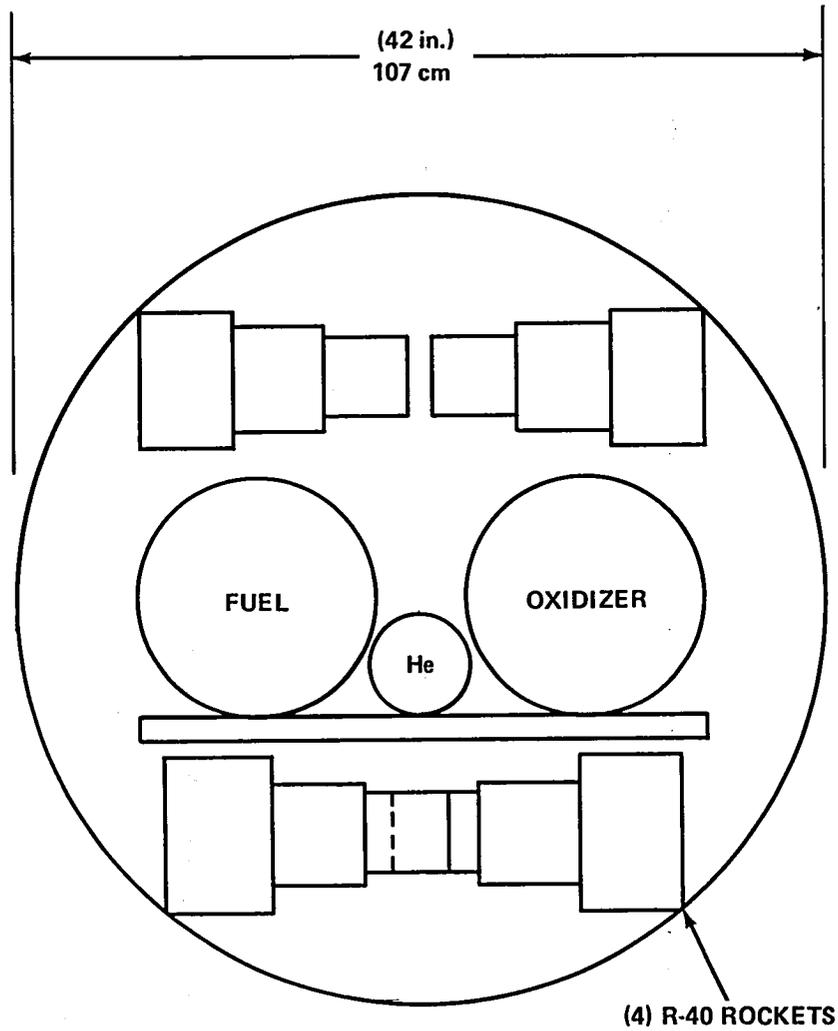
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Figure 8. Nose-Mounted Rocket Installation
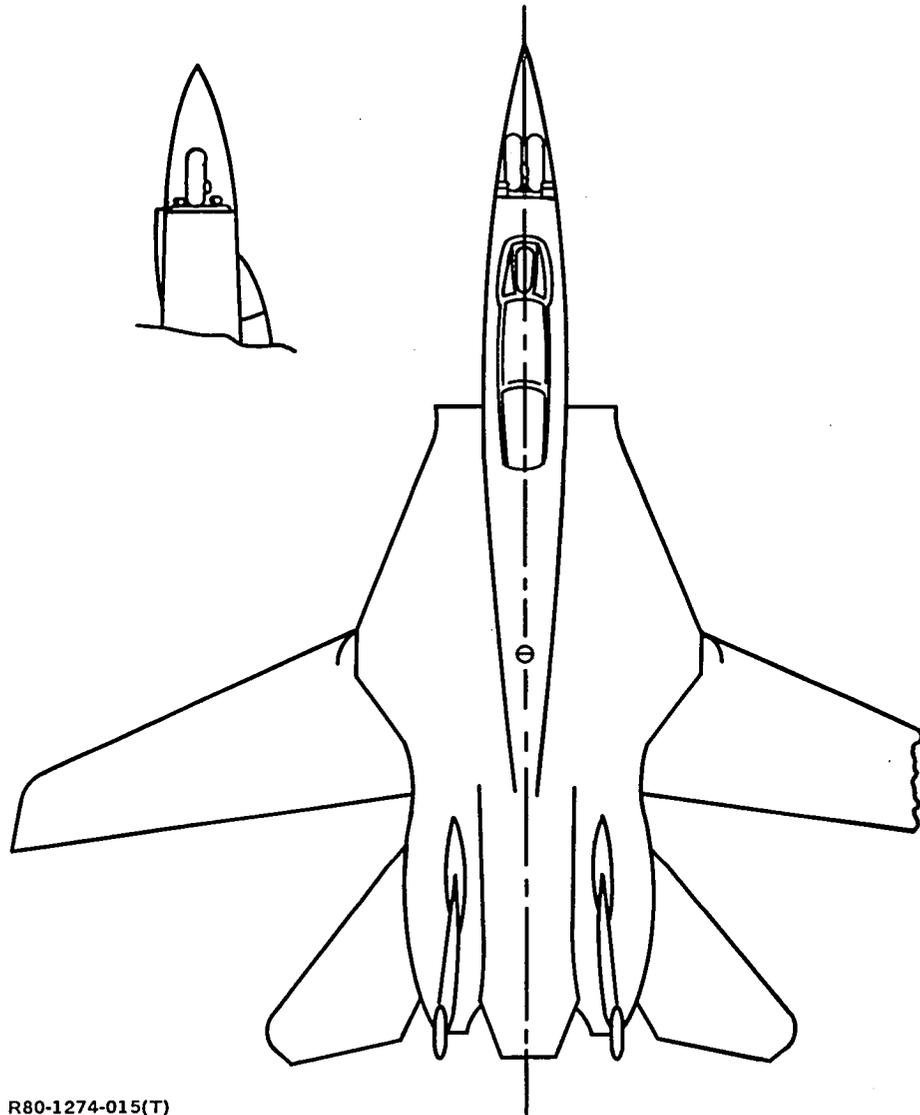
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Figure 9. Nose-Mounted Liquid Rocket Installed

SIZE COMPARISON	LENGTH	DIAMETER
PACKAGE	259	38
SIDEWINDER	287	13
SPARROW	366	20
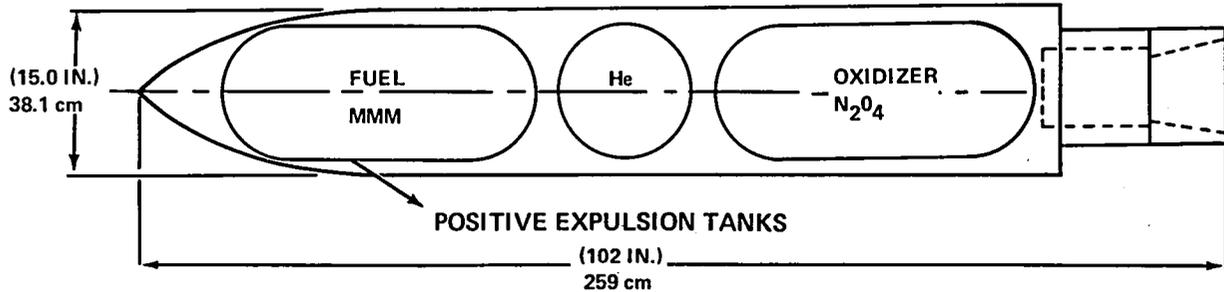
Figure 10. External Modular Package (Wing-Tip)

Pylon-mounted - Figure 13 is a large modular unit fitted within the dimensions of a typical 1135 liter (300 gallon) drop tank. While strictly applicable only to an airplane using this external store loading, (and obviously not for centerline carriage), it is noted that the external stores configuration is frequently the most critical. Also, the lateral displacement from the c.g. of the tank mountings is not usually very great. However, the large size permits clustering of engines and sufficient yawing moment is often achievable.

Tail-mounted systems - can generate yawing moments of similar magnitude to the nose installations. Rocket exhaust ingestion into engine inlets is not a problem, but the proximity to hot engine nozzles may require thermal insulation. An R-40 tail-mounted installation is not shown for the subject airplane, but in Appendix B a discussion is given of an interesting tail-mounted system originally proposed by the airframe contractor for flight test purposes (see Figure 14).

SECTION A-A'

A'

A
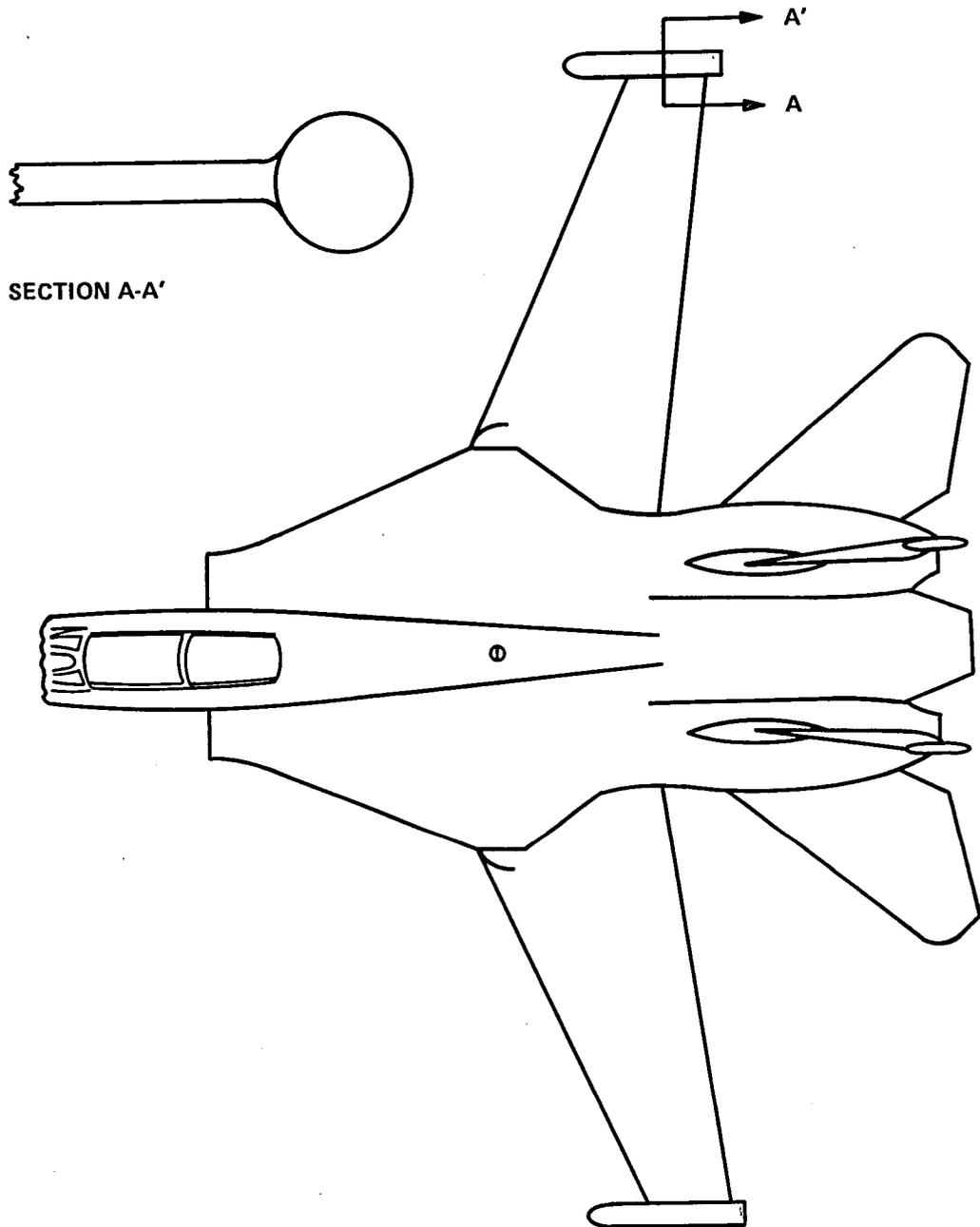
Figure 11. Wing-Tip Mounted Rockets

SECTION A-A'
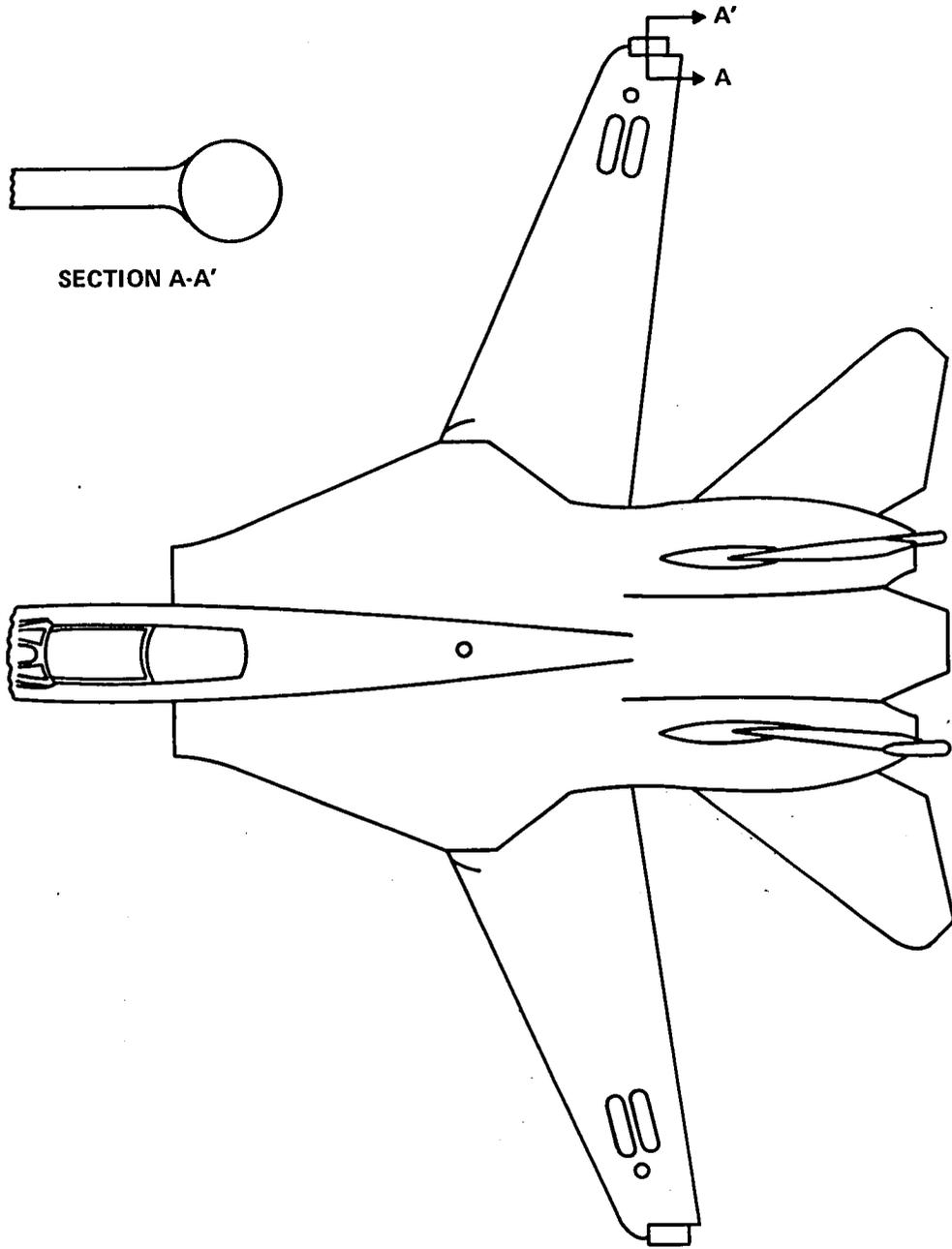
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Figure 12. Wing-Tip Mounted Rockets

1140 1
SIZE COMP (300 GAL) TANK
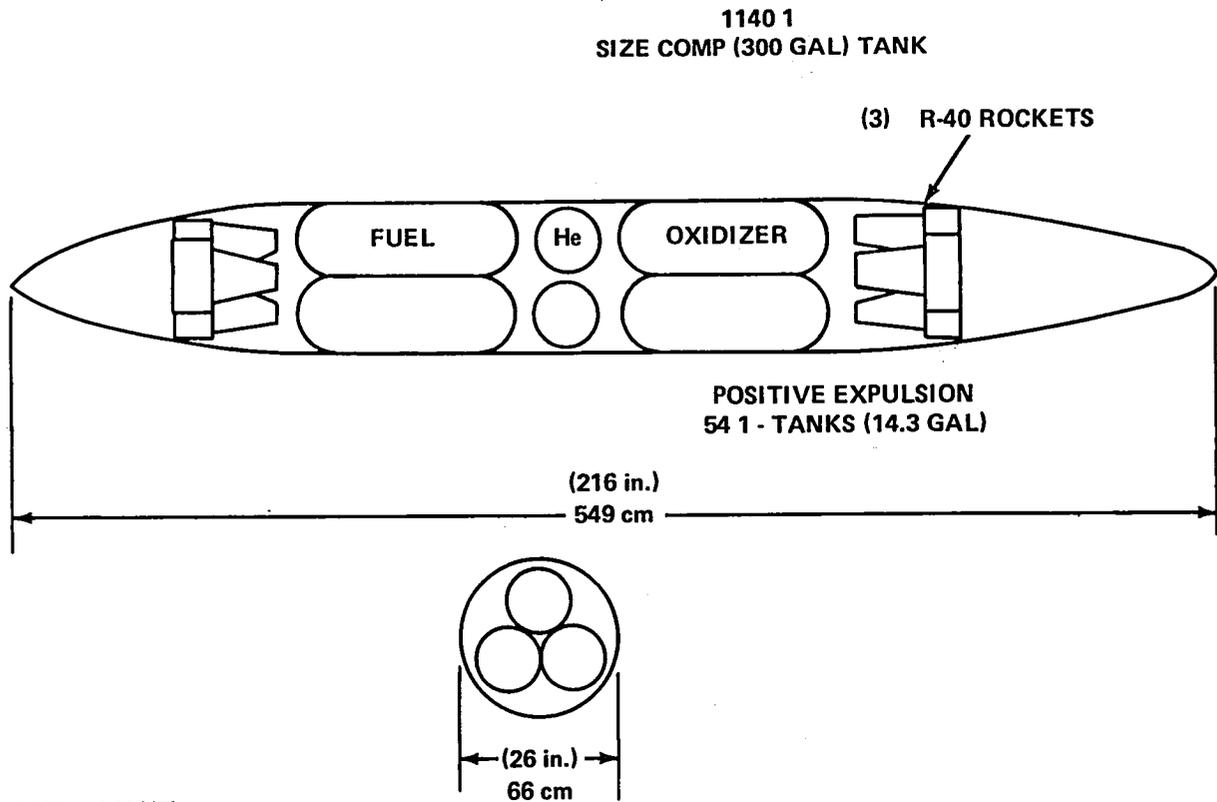
Figure 13. External Modular Package (Tank)

5.4 WEIGHT CONSIDERATIONS

The weight of rocket systems is in general quite satisfactory for the spin recovery application. For example, the nose-mounted system shown in Figures 7 and 8 would weigh less than 300 kg (650 lb).

An actual test airplane incorporated a tail-mounted spin chute system weighing nearly 400 kg (873 lb) complete. It must be noted, however, that nearly an equal amount of ballast was required in the nose to balance the airplane. These additional masses at the extremes of the longitudinal body axis resulted in a 10 percent increase in yaw inertia and a 15 percent increase in pitch inertia over the basic airplane.
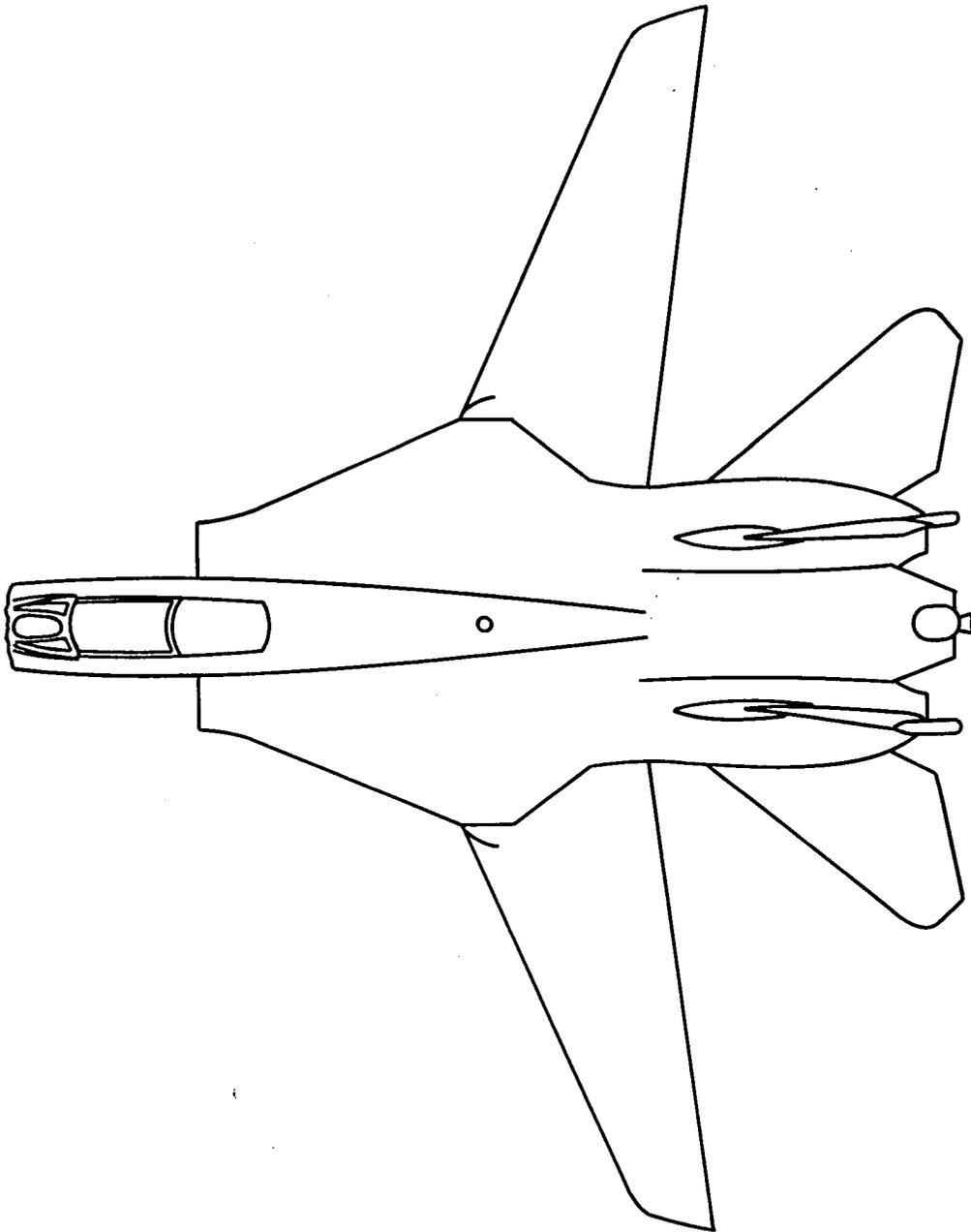
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Figure 14. Tail-Mounted, Swiveling, Solid-Fuel Rocket

Table VII gives a list of estimated component weights which can be used to roughly size systems.

It appears reasonable that customized systems will be no worse, and, in fact, should be better than spin chute systems as far as mass and inertia changes.

TABLE VII. - ESTIMATED LIQUID ROCKET SYSTEM COMPONENT WEIGHTS

COMPONENT	WEIGHT
PROPELLANT TANKS	11 kg EACH (25 LB)
PROPELLANT WEIGHT	45-68 kg PER TANK (100-150 LB)
HELIUM TANKS	11-23 kg EACH (25-50 LB)
R-40 ENGINES	11 kg EACH (25 LB)
OTHER ENGINES	SEE TABLE IV
MODULE STRUCTURES:	
• 300-GALLON TANK SIZE	136 kg (300 LB)
• WING TIP SIZE	91 kg (200 LB)
ASSOCIATED "PLUMBING"	5 TO 10 % ADDITIONAL

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6.0   CONCLUSIONS AND RECOMMENDATIONS

6.1   CONCLUSIONS

1. The use of rocket devices for emergency spin recovery applications is feasible and offers a number of advantages over anti-spin parachute systems.

2. Suitable off-the-shelf hardware is available today, but initial development costs will probably be relatively high until a certain level of experience is achieved in this application.

3. Liquid-fuel rockets appear to offer the greatest promise, at this time, in terms of flexibility, availability and development potential.

4. Man-rated systems can be developed using hypergolic fuels.

5. For an initial assessment of thrust requirements for a yawing-moment rocket recovery system, the simple technique detailed in Reference 12 yields adequate results.

6. The NASA Langley vertical spin tunnel must still be considered the definitive tool for sizing rocket recovery systems.

6.2   RECOMMENDATIONS

1. Assessment of rockets for spin recovery on large-scale drop models would provide valuable information and experience at relatively low cost.

2. The freon-thruster system used in the spin tunnel should be further refined and developed for future applications.

APPENDIX A

EQUATIONS OF MOTION AND ASSOCIATED FORMULAS

The equations required to specify the translational and rotational motions of a rigid body moving through space are described in this appendix. The six degree of freedom differential equations representing linear and angular accelerations of a moving body axis system having its origin at the aircraft center of mass are:

$$\dot{u} = - g \sin \theta + vr - wq + \frac{\Sigma F_{x_{aero}}}{m}$$

$$\dot{v} = g \cos \theta_e \sin \phi_e + wp - ur + \frac{\Sigma F_{y_{aero}}}{m}$$

$$\dot{w} = g \cos \theta_e \cos \phi_e + uq - vp + \frac{\Sigma F_{z_{aero}}}{m}$$

$$\dot{p} = \frac{I_y - I_z}{I_x} qr + \frac{I_{xz}}{I_x} (\dot{r} + pq) + \frac{\Sigma L_{aero}}{I_x}$$

$$\dot{q} = \frac{I_z - I_x}{I_y} pr - \frac{I_{xz}}{I_y} (p^2 - r^2) + \frac{\Sigma M_{aero}}{I_y}$$

$$\dot{r} = \frac{I_x - I_y}{I_z} pq + \frac{I_{xz}}{I_z} (\dot{p} - qr) + \frac{\Sigma N_{aero}}{I_z}$$

In addition, the following formulas were used:

$$\alpha = \tan^{-1} \left(\frac{w}{u} \right)$$

$$\beta = \sin^{-1} \left(\frac{v}{V_R} \right)$$

$$V_R = \sqrt{u^2 + v^2 + w^2}$$

$$\Omega = \sqrt{p^2 + q^2 + r^2}$$

$$\text{Turns in spin} = \frac{\int \dot{\Psi}_e dt}{2\pi}$$

$$\dot{\Psi}_e = \frac{\dot{\emptyset}_e - p}{\sin \theta_e}$$

$$\emptyset_e = \sin^{-1}\left(\frac{\sin \emptyset}{\cos \theta_e}\right)$$

$$\dot{\theta}_e = q \cos \emptyset_e - r \sin \emptyset_e$$

$$\dot{\emptyset}_e = p + r \tan \theta_e \cos \emptyset_e + q \tan \theta_e \sin \emptyset_e$$

$$p = p_r + p_o$$

$$q = q_r + q_o$$

$$r = r_r + r_o$$

These total angular velocities (p, q, r) consist of steady rotation (p_r, q_r, r_r) components upon which oscillatory (p_o, q_o, and r_o) components are superimposed. These components are defined as follows:

$$p_r = -\dot{\Psi}_e \sin \theta_e \qquad\qquad p_o = \dot{\emptyset}_e$$

$$q_r = \dot{\Psi}_e \cos \theta_e \sin \emptyset_e \qquad q_o = \dot{\theta}_e \cos \emptyset_e$$

$$r_r = \dot{\Psi}_e \cos \theta_e \cos \emptyset_e \qquad r_o = \dot{\theta}_e \sin \emptyset_e$$

For the aerodynamic model, the following total derivatives were used:

$$C_N' = C_N + C_{N_q} \frac{q_o \bar{c}}{2V}$$

$$C_c' = C_c$$

$$C_y' = C_y + C_{y_{\delta_a}} \delta_a + C_{y_{\delta_R}} \delta_R + C_{y_{rot}} + C_{y_r} \frac{r_o b}{2V} + C_{y_p} \frac{p_o b}{2V}$$

$$C_l' = C_l + C_{l_{\delta_a}} \delta_a + C_{l_{\delta_R}} \delta_R + C_{l_{rot}} + C_{l_r} \frac{r_o b}{2V} + C_{l_p} \frac{p_o b}{2V}$$

$$C_n' = C_n + C_{n_{\delta_a}} \delta_a + C_{n_{\delta_R}} \delta_R + C_{n_{rot}} + C_{n_r} \frac{r_o b}{2V} + C_{n_p} \frac{p_o b}{2V}$$

$$C_m' = C_m + C_{m_q} \frac{q_o \bar{c}}{2V}$$

Note:

The values of $C_{Y_{rot}}$, $C_{\ell_{rot}}$ and $C_{n_{rot}}$ are obtained from rotary

balance data using the values of p_r, q_r and r_r to compute $\frac{\Omega b}{2V}$ as

$$\left(\frac{\Omega b}{2V} \right)^2 = p_r^2 + q_r^2 + r_r^2$$

APPENDIX B

PROPOSED FLIGHT TEST RECOVERY SYSTEM

When the subject aircraft was in the early stages of flight
development, an emergency spin recovery system was required
for the planned spin tests.

Because large chute sizes were anticipated with the associated
structural penalties, the contractor proposed a unique rocket
recovery system. Although quite different from the systems
considered in this study, a brief discussion of the proposed
installation is presented because of certain interesting
features.

Shown in Figure 14, the unit is a gimballed solid-fuel rocket
motor slaved to the aircraft's rudder pedals. In the event of
a spin, when the pilot commanded full rudder against, the rocket
would swivel 90 degrees, providing pure yawing moment against.
As the airplane recovered, the rudders would be neutralized and
the rocket aligned longitudinally, providing only forward force.
In the event of a spin reversal, opposite yawing moment would be
commanded as the rudder was reversed.

The proposed motor was a 17-inch elongated spherical motor, TE-M-
442-1, manufactured by the Thiokol Chemical Corporation, with a
rated thrust of 8700 pounds.

This system was not pursued by the contractor after discussions
with NASA Spin Tunnel personnel indicated that the idea was too
complex to be tested on the small spin tunnel model and NASA
would not endorse a rocket recovery system.

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15. Supplementary Notes

16. Abstract

The problem of providing an auxiliary means for an aircraft to effect recovery from spins, especially during testing, has typically been answered with the anti-spin parachute. However, the potential effectiveness of rockets for this purpose has been recognized for many years. The advances in rocket technology produced by the space effort suggest that currently available systems may obviate many of the problems encountered in earlier rocket systems. In light of this, this study was undertaken. A modern fighter configuration known to exhibit a flat spin mode was selected. An analytical study was made of the thrust requirements for a rocket spin recovery system for the subject configuration. These results were then applied to a preliminary systems study of rocket components appropriate to the problem. Subsequent spin tunnel tests were run by NASA to evaluate the analytical results.

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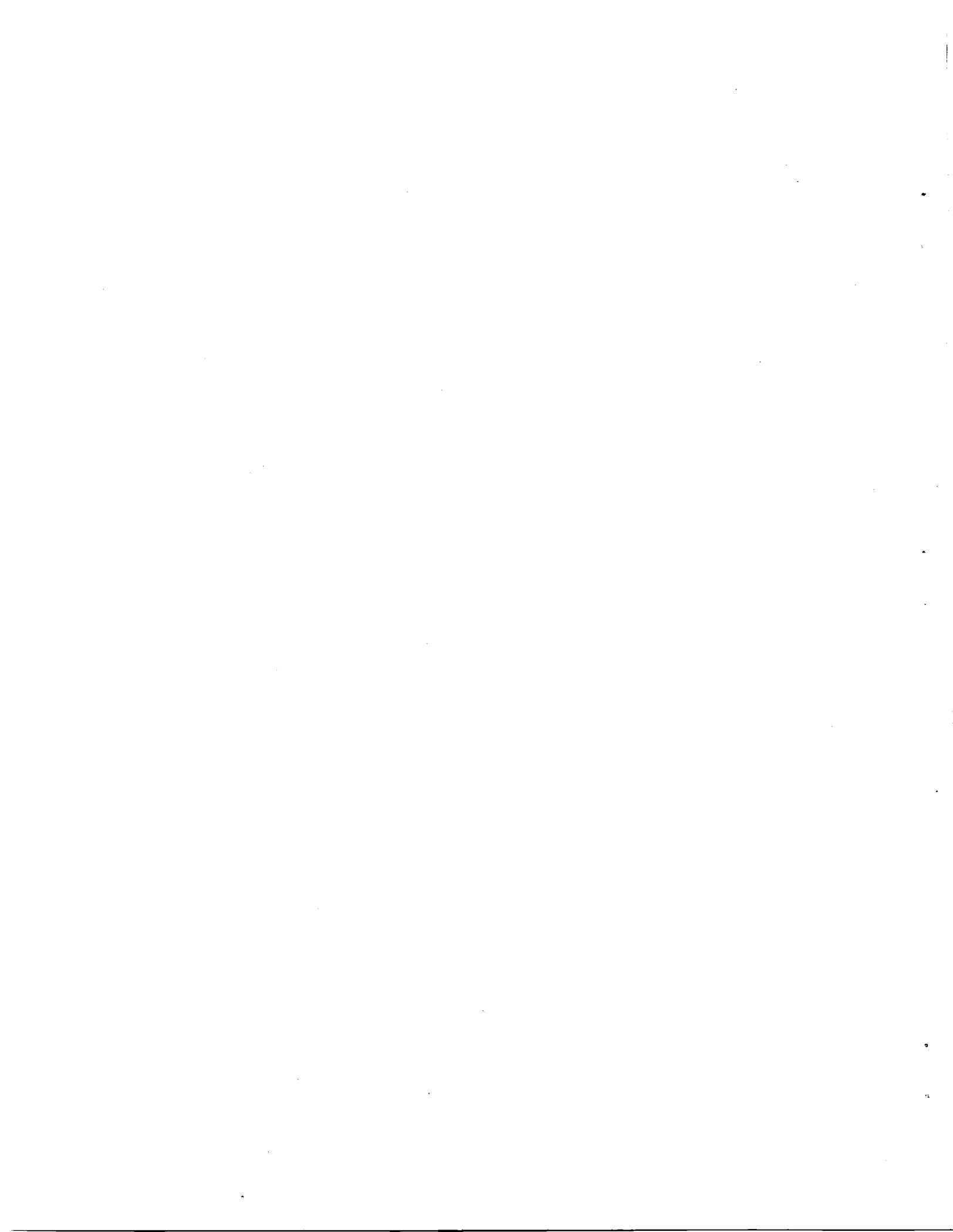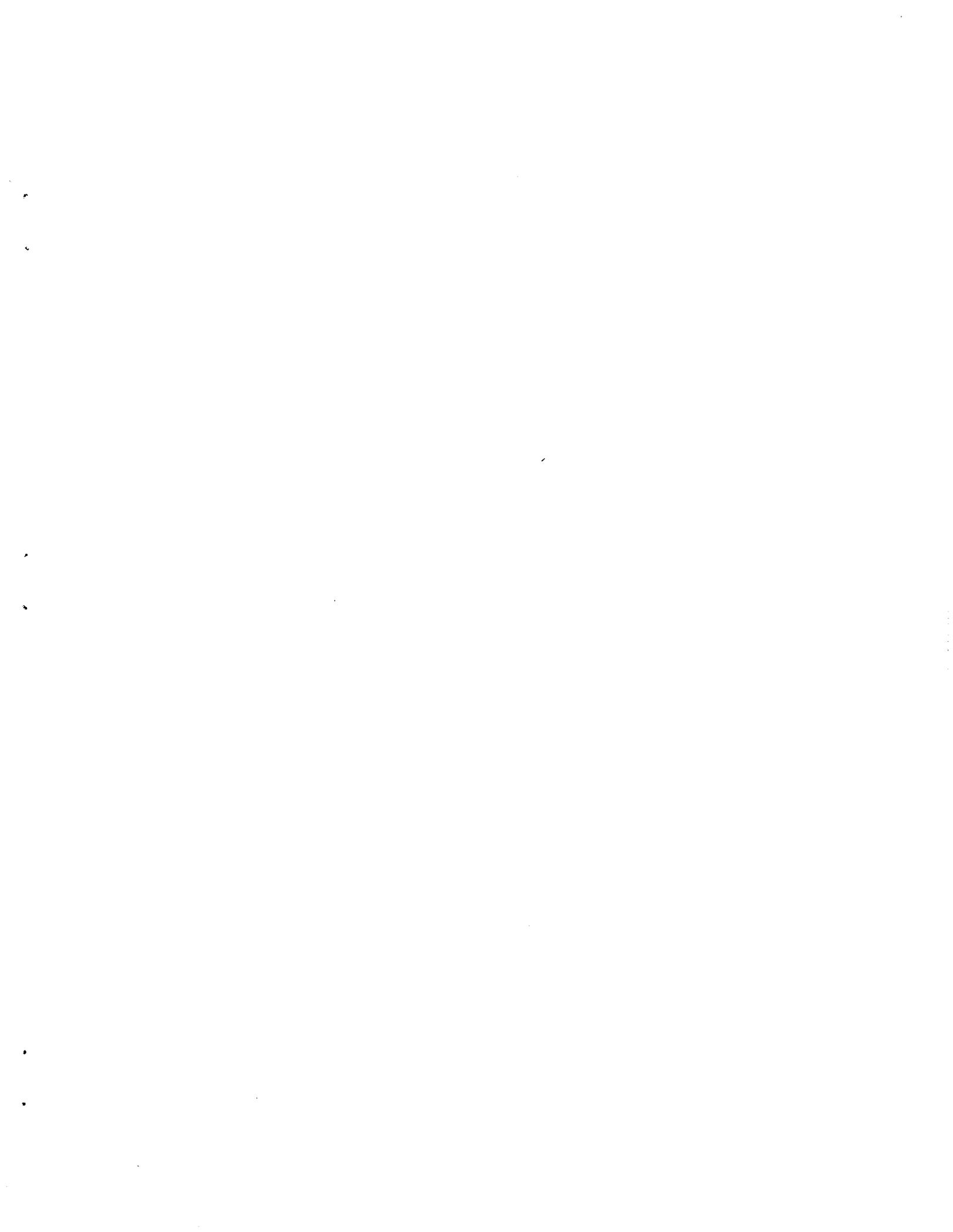
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