ACES-II Seat Roller Study: Findings of Detrimental Friction under High Windblast or Adverse Flight Conditions

Analytical findings of an intrinsic, restraining, high-friction response from the ACES-II Ejection Seat's legacy "seat roller" (a dry metal wheel on a shaft), when subjected to high loads (such as ejections at high speeds or with an aircraft yaw angle). Recommendations are made for improvement.

12 Aug 2015

Sean P. Stapf
Ejection Seat and Rocketry Analyst
Bldg. 423, Bay C-310
1201 Edward H. White II Street
45th Space Wing, Safety Engineering
Patrick Air Force Base, Florida 32925
321-494-5130

DISTRIBUTION STATEMENT A:
Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE *(DD-MM-YYYY)* 12-08-2015	**2. REPORT TYPE** Technical Report	**3. DATES COVERED** *(From - To)* Jan 2013 - Aug 2015
4. TITLE AND SUBTITLE ACES-II Seat Roller Study: Findings of Detrimental Friction under High Windblast or Adverse Flight Conditions		**5a. CONTRACT NUMBER** N/A **5b. GRANT NUMBER** N/A **5c. PROGRAM ELEMENT NUMBER** N/A
6. AUTHOR(S) Stapf, Sean P.		**5d. PROJECT NUMBER** N/A **5e. TASK NUMBER** N/A **5f. WORK UNIT NUMBER** N/A
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 45th Space Wing Safety Engineering (45th SW/SE) 1201 Edward H. White II Street Patrick AFB, FL		**8. PERFORMING ORGANIZATION REPORT NUMBER** TR45SW-SE-2015-001
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) HQ AFSEC/SEFE 9700 G Ave SE Kirtland AFB, NM 87117		**10. SPONSOR/MONITOR'S ACRONYM(S)** AFSEC **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** N/A

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A:
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Recommendations are made with some urgency, as safety improvements would be anticipated for ejections throughout the USAF fleet, and next-generation ejection seats – which also need these upgrades - are currently in development.

14. ABSTRACT
Analytical findings of an intrinsic, detrimental high-friction response of the ACES-II Ejection Seat's legacy "seat roller" (six metal wheels on six dry metal shafts) when subject to high loads (such as windblast from a 600 KEAS ejection, or adverse aircraft conditions of yaw or roll rate). Verification and validation is provided through 6-DOF mechanical-dynamics simulations, "classical" hand calculations, comparison against the F-16 "Aviano Mishap" data, comparison against sled tests (110E-A1 of 2012; F-16 at 600 KEAS, with forward 5th percentile and aft 95th percentile manikins), and theoretical discussion of the dynamic mechanical relations. Two recommendations are made, (1) Replace the current ACES-II seat rollers with modern industrial “cam rollers” (or similar load-rated roll-and-thrust bearing wheel system), and (2) insure that no future ejection seat system (such as an "ACES 5", "Mk 16", or other) with limited-energy propulsion (such as a propellant charge) is fielded to the fleet without a seat-to-aircraft release system that maintains a friction coefficient below 0.01 under normal (X-axis) loads of 10000 lbf and lateral (Y-axis) loads of 1500 lbf.

15. SUBJECT TERMS
ACES-II, Ejection, Seat, Cam, Roller, Bearing, Friction, CKU-5, Rocket, Catapult, ROCAT

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Sean P. Stapf
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)* 321-494-5130
U	U	U	UU	47	

Standard Form 298 (Rev. 8/98) Prescribed by ANSI Std. Z39.18

FOREWORD

Review of these findings and the supporting analysis has been made, and concurrence with the conclusions and recommendations is given.

PAUL ROSATI
Chief, Risk Analysis (SELR), 45th Space Wing

PETER CADDEN
Chief, Flight Analysis (SELF), 45th Space Wing

CURT BOTTS
Chief, Launch Safety (SEL), 45th Space Wing

HOWARD SCHINDZIELORZ
Chief Safety Engineer (SED)
45th Space Wing
Patrick AFB, FL

ACKNOWLEDGMENTS

This collection of information is a product of numerous stewards over many years, among them…

- Mark Ruddell – Kirtland AFB, for oversight of, and insights to, the numerous functions of the system, the historical data and coupled behaviors, and the entire investigative process.

- "Big John" Messina – Hill AFB, for technical guidance and insights, with on-point hands-on wisdom into the ACES-II seat after it has been through real-life events.

- Michael Breeze – Tinker AFB, for providing hardware insights and documents.

- Timothy Gross – Holloman AFB, for providing supportive data from high-speed sled tests.

- Craig Wheeler (retired) – Naval Surface Warfare Center, Indian Head, Maryland, for technical insights into sled tests, the CKU-5 ROCAT function, and the overall mechanical-dynamic-ballistic-aerodynamic relations involved in the ACES-II seat function.

- Tom Ilkka – Naval Surface Warfare Center, Indian Head, Maryland, for technical insights into the CKU-5 ROCAT functions, hardware, propellant formulations, test methods, and interaction of numerous minute dynamic, ballistic, thermal, mechanical, structural, and manufacturing conditions within a CKU-5 ROCAT.

- The current management (signatories, included), and predecessors, within the 45th Space Wing which have steadily supported the overall mission of the Air Force by supporting Air Force Safety Investigation Boards and related support analyses – including this one.

TABLE OF CONTENTS

FOREWORD....3
ACKNOWLEDGMENTS....3
TABLE of CONTENTS....5
TABLE of FIGURES....5
NOMENCLATURE....7
EXECUTIVE SUMMARY....8
ABSTRACT....9
BACKGROUND....10
APPROACH....16
RESULTS....19
RESULT SET #1 (ADAMS 6-DOF Design Study): 20
RESULT SET #2 (Sled Test Data; Apparent ~2-9g Loss Due to Friction): 21
RESULT SET #3 (Hand-Calculation Example & Verification): 24
RESULT SET #4 (Logic Discussion & Verification): 25
CONCLUSIONS....31
RECOMMENDATIONS....31
AFTERWORD....33
APPENDICES....34
Ref-1, APPENDIX A: PRELIMINARY "FAULT TREE" for "ARTIFACT #1"....35
Ref-1, APPENDIX B: PRE-RESOLUTION OF SOME FAULT-TREE ITEMS for ARTIFACT #1 39

TABLE OF FIGURES

Figure 1 – Summary of "Low-g" Artifact and Its Severity Increase with Loads on Seat Rollers.... 11
Figure 2 – Hand-Calculation of Aerodynamics on a Man-Seat Emerging at 7100ft-msl & 600kt 12
Figure 3 – Prior Graph from Reference-1: Mishap Artifact #1 (Apparent "Low-g" Region).... 13
Figure 4 – Recap of Artifact #2; Apparent Man-Seat Yaw of ~90deg plus Drogue Chute Delay 14
Figure 5 – Sled Test Example of Windblast Emergence (Between Elbow and Head Height).... 15
Figure 6 – Diagram of Current ACES-II Seat Roller Design, Installation, and Use 16
Figure 7 – Images of some Typical Cam Rollers and Bearings 17
Figure 8 – Joint AF/Navy ADAMS Ejection Trajectory Model (Developed/Maintained since 1995).... 18
Figure 9 – ADAMS-Predicted ACES-II Seat Roller Loads (Fx) at Two Friction Coefficients.... 19
Figure 10 – ADAMS-Predicted ACES-II Tail Clearance and Apogee at Two Friction Coefficients.... 20
Figure 11 – Results from ADAMS Design Study of Seat Roller/Rail Friction Coefficients 20
Figure 12 – Superposition of ADAMS Design Study with Aviano Seat Accelerations.... 21
Figure 13 – Sled Test Indication of Seat-Rail Friction (at "Straight and Level" Conditions).... 23
Figure 14 – Hand Calculation Supporting Conclusion of Causal ACES-II Seat Roller Friction.... 24
Figure 15 – Results from ADAMS Design Study: Friction Can Drive Roller Loads Above 10,000bf .. 26
Figure 16 – Illustration of Recommended "Cam Roller" to Replace Current ACES-II Seat Rollers 32
Figure 17 – Example of a Deviation Analysis; Aerodynamic Helmet on Pitot Tube (from ADAMS).... 39
Figure 18 – Proof of DRS Accuracy; Mostly Complies w/ Lightweight Sled Test Instrumentation.... 40
Figure 19 – Proof of DRS Accuracy; Mostly Complies w/ Heavyweight Sled Test Instrumentation 41
Figure 20 – Illustration of the Discussed "Time Shift", Cosmetically Fixes Artifact #1 & #2.... 42
Figure 21 – Proof that Seat Flexure Didn't Cause Artifact #1 (Manikin Chest Accel Agrees w/ DRS).. 43
Figure 22 – Acceleration Report of Aircraft for 90sec Prior To Ejection (at ~2.3g) 44
Figure 23 – Example of Potential Seat/Rail Mechanical Dynamics Analysis.... 45

REFERENCES

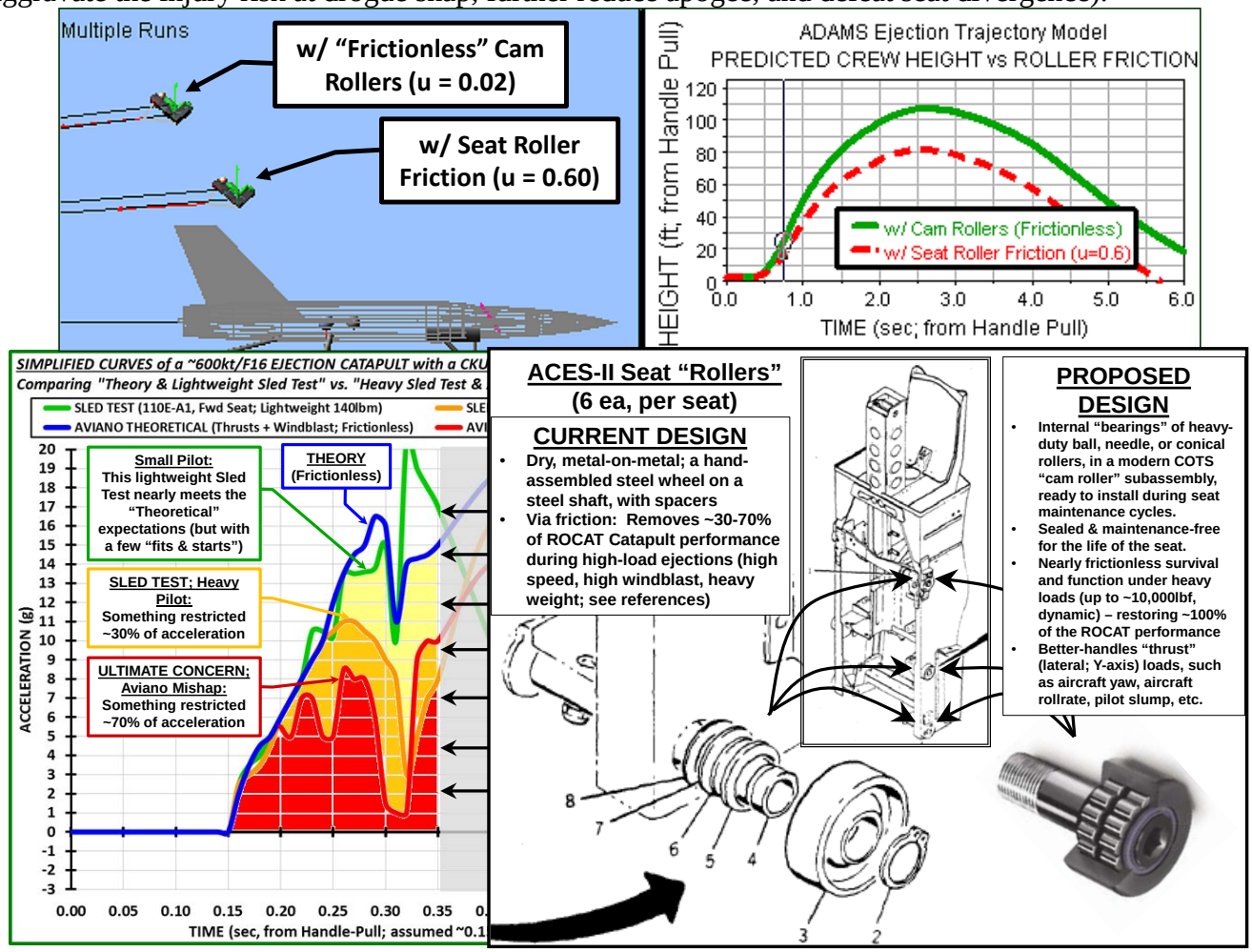
1) "Ejection Simulation Report" Summary Report of the Provided Input, Assumptions, Results, and Recommendations for the Ejection Trajectory Simulation of the F-16 Aircraft near Aviano AFB, 28 January 2013, delivered to Mark Ruddell, AFSEC, authored by Sean Stapf, 45th Space Wing, Safety Engineering, 11 April 2013.

NOMENCLATURE

45th SW/SELR = 45th Space Wing, Safety Engineering Launch Risk Group, Patrick AFB
6-DOF = Six degrees of freedom (rotation around, and translation along, three perpendicular axes)
ACES-II = Advanced Concept Ejection Seat, version two (primarily the "Air Force seat", since 1970's)
ADAMS = Automatic Dynamic Analysis of Mechanical Systems (6-DOF software, MSC Corporation)
AEPS = Aircrew Escape Propulsion Systems
AIB = Air Force Accident Investigation Board
AMRDEC SAFE = U. S. Army Aviation & Missile Research, Development and Engineering Center, Safe Access File Exchange
AoA = Angle of Attack; the angle between the long-axis of a body and its airspeed directional vector
Booster = solid propellant grain in the catapult of a ROCAT
Catapult = the telescopic tube phase that lifts the ACES-II ejection seat within the cockpit
Cg = center of gravity (from distribution of mass)
CLAZ (g) = Manikin Chest Linear Accelerometer reading in the Z axis, measuring in g's
COTS = Commercial Off-The-Shelf (generally: publicly-available retail products)
Cp = center of pressure (from distribution of aerodynamic forces)
DOF = Degrees of Freedom (see "6-DOF")
DRI = Dynamic Response Index (individual X, Y, and Z-axis prediction of crew injury)
DRS = Digital Recovery Sequencer (electronic "black box" on the back starboard of ACES-II seats)
ft-agl = feet above ground level
ft-msl = feet above mean sea level
g = One earth gravity; a measure of translational acceleration (each "g" being 32.174 feet/s^2)
ICET = Acronym for aircraft airspeed adjustment order; "Indicated, Calibrated, Equivalent, True"
KIAS = Knots Indicated Airspeed (aircraft-dependent interpretation of speed, as displayed on gage)
KCAS = Knots Calibrated (or Corrected) Airspeed; adjustment to IAS, based on aircraft-dependent pitot position, AoA, side-slip, Mach, etc.
KEAS = Knots Equivalent (or Effective) Airspeed; adjusted for air density (altitude, Mach, etc)
KTAS = Knots True Airspeed (actual translation rate relative to air; ground-speed, in zero wind)
kt = knot
lbf = pounds of force (=1 lbm x 1g)
lbm = pounds of mass (=1/32.174 of a slug)
MDRC = Multi-Axial Dynamic Response Criteria (0-1 scaled collation of individual-axis DRI)
ROCAT = Rocket Catapult ejection propulsion system
SBLAZ (g) = Seat Back Linear Accelerometer reading in the Z axis, measuring in g's
SIB = Air Force Safety Investigation Board
Start Switch = ACES-II trigger near the top of rails which, following handle-pull, canopy removal, and most of the catapult phase of the CKU-5 ROCAT, will begin a sequencer to drive recovery timing.
Sustainer = rocket phase of a ROCAT
X = axis of the man-seat system which is aimed "forward" (positive), and perpendicular to Z-axis
Y = axis of the man-seat system which is aimed "laterally" (port-starboard; positive port)
Z = axis of the man-seat system which is aimed "spinally" ("up the seat rails"; positive up)

EXECUTIVE SUMMARY

The six wheels ("seat rollers") on the ACES-II ejection seat have been found to intrinsically create a high friction response to windblast or adverse aircraft yaw/roll, restraining the man-seat on the aircraft rail during high-speed ejections. This high friction response – when combined with modern changes to the ejection system (arm and leg restraints, heavier pilots, and a regressive CKU-5C ROCAT catapult thrust) – further compromises the safety margin in recovery from high-speed ejections. Without correction, high-speed ejections are expected to continue to exhibit faulty spinal accelerations (a ~30-70% loss in catapult acceleration, which reduces apogee, tail clearance, and drogue chute clearance) and seat-structure failures (wheel loss, which may precipitate detrimental man-seat yaw or roll, which can aggravate the injury risk at drogue snap, further reduce apogee, and defeat seat divergence).



The proposed correction is a rapid retrofit program to replace the current ACES-II's "dry metal wheel on a shaft" design with a modern "cam roller" (lifetime-sealed, high-duty, lateral-thrust tolerant roller bearings). An insightful team may find roller integrations which exploit existing seat hardware (holes, shafts, brackets, etc.), require no machining modifications to the ACES-II seat (only removal of the old wheel, shaft, etc), and minimal additional fittings and tools, such that the retrofit can be performed during routine seat maintenance in fewer than two man-hours per seat, with less than $1,000 per seat in hardware costs, and adding less than 10 pounds of mass per seat.

In a limited retrofit scenario: The upper set (pair) of rollers may be the lowest priority to replace, as those rollers exit the rail before the full, leveraged windblast burdens the bottom set of rollers.

ABSTRACT

Following the SIB investigation of the fatal "Aviano Mishap" (F-16 ejection of 28 January 2013; AFSAS 128823), two anomalous artifacts remained unresolved, as itemized in the "Ejection Simulation Report" of 11 April 2013, from this office. First, a dramatic loss (~30-70%) in spinal acceleration occurred during seat travel near the top of the seat rails ("Artifact #1: Low-G Period at Top of Rails"). Second, the man-seat was apparently perturbed to 90-deg yaw (as shown by lateral windblast g-load) prior to correction by the drogue chute (which also appeared delayed; "Artifact #2: 0.1-sec Delayed Drogue Chute Inflation"). For Artifact #1, an informal fault tree was developed, partially resolved, and included in the report.

Over the subsequent two years – as available – exploration of both artifacts continued, particularly Artifact #1 (low-g period at top of rails). Working one theory via the fault tree branch, "3.1: Lost Energy; Seat Rail & Roller Mechanics" (which captures anomalies from rail or seat or roller flexure, failure, binding, skidding, or other imperfect motion) - design studies were performed to test the credibility of seat roller friction being strong enough to cause an ACES-II seat to experience Artifact #1's 30-70% low-g period at top of seat rails. Additionally, the current seat roller hardware was reviewed, as well as anecdotal reports of seat roller performance (or failure) in fleet ejections and sled tests – as well as hand-calculations to verify results of the 6-DOF ADAMS Design Study simulations.

Results appear conclusive: The current ACES-II seat roller design (a steel wheel on a dry metal shaft) is not only capable, but predicted to produce such a large frictional response in high-load/high-windblast ejections that it explains the Aviano Mishap's "Artifact #1" (a ~30-70% low man-seat acceleration), and may explain Artifact #2 (0.1-sec delayed drogue chute, due to tail impact, and the 90-deg man-seat yaw, due to wheel failure on the rail). Further: These friction responses become exponential (onset of friction slows seat motion, increasing dwell time on rail in the windblast, which increases rock-back of man-seat against rail, which increases loads on the seat roller and thus the restraining friction response, etc.). Even more severe performance losses are possible (up to 100% loss of the CKU-5 ROCAT catapult acceleration – zero acceleration – as seen on several data points from the Aviano Mishap. Hand-calculations remind that a 0.6 friction coefficient with a 6,000 lbf windblast causes a ~3,600 lbf frictional response - more than neutralizing a 3,500 lbf CKU-5 ROCAT catapult. Further, years of investigations (and sled track tests) have found occasional "flats" ground on the wheels after high-speed ejections, confirming high friction is occurring – and consistent with the now-normal expectations at high speed sled tests of sub-theoretical man-seat accelerations and apogees. Further: This additional load vector (friction; Z-axis, from X- and/or Y- loads) can contribute to overload and structural failure (as has been anecdotally observed by investigators; high-speed ejections missing wheels – including the Aviano and recent B-1 Mishap). This structural failure may also explain the Aviano Mishap's observed man-seat yaw (as the seat ascended the rail asymmetrically from a lost wheel). Therefore, this single dysfunction (roller friction) may contribute to several artifacts (~30-70% low-g egress, delayed drogue chute inflation if tail collision occurs, and injury-aggravation from correcting a man-seat yaw). These findings aggregate to the conclusion that the current ACES-II seat includes a detrimental legacy artifact; a high frictional resistance in the seat rollers which threatens the safety of high-speed ejections. The trend also appears emergent; while the ACES-II Seat Rollers "have been around for 40 years" – the possibility of a "perfect storm" has not; latent friction combines with modern limb restraints, pilot weight overages, and the CKU-5C catapult thrust profile which regresses near the top of seat rails. Recommendations are made to exchange the current "dry metal wheel on a shaft" design with a modern "cam roller" during future seat maintenance cycles – as well as prevent future concept-seats from being approved without a 10,000 lbf normal load friction coefficient below 0.01.

BACKGROUND

With the advent of modern electronics mounted on the ACES-II seat (including three-axis seat-back accelerometers with onboard digital recording) – insights into the last 6-10 years of ejections have been increased, and allowed discovery of several nuances in the egress - particularly in "high speed" ejections (~450 to 600+ KEAS).

The Ejection Trajectory Study of the F-16 "Aviano Mishap" of 2013 (see Reference (1)) identified two anomalies which had been anecdotally noted on several prior ejections and sled tests – particularly under the heavy loads of a high windblast (high speeds, low altitudes, large torso area, etc). These anomalies are labeled in Reference (1) as,

- "Artifact #1: Low-G Period at Top of Rails"
- "Artifact #2: 0.1-sec Delayed Drogue Chute Inflation"

Details of Artifact #1 appear to erode the ejection, and may have contributed to Artifact #2:

- Artifact #1, Primary Concern: As shown in Figure 1, the Aviano ejection seat exhibited what appeared to be ~30-50% lower seat acceleration than comparable sled tests, during motion of the ACES-II seat along the top ~1-2 feet of the seat rail – presumably resulting in slower egress speeds and lower heights above the ground and aircraft tail. This seat acceleration is also ~70% lower than "theory" (F=ma, with expected forces of thrust and windblast), as well as compared to the "static test stand" (performance of which measures the CKU-5 ROCAT against an assumed "frictionless" motion of the man-seat up the rails, via a Teflon or greased "slug" on a test-track). A higher-resolution graph (from Reference (1)) of the Aviano Mishap's seat acceleration is shown in Figure 3, which includes several data points that suggest the man-seat was even arrested to a near-zero acceleration (or slightly negative) near the top of the rails.

- Artifact #2; Possible Cause and Injury-Aggravation from Artifact #1: While Artifact #2's "0.1 sec delay" in Drogue Chute correction may be unrelated and within standard deviations – or may be due to a drogue-tail interference (from Artifact #1) – the fact that the man-seat had rotated 90 degrees in yaw prior to chute inflation indicates two topics: First, this yaw rotation magnifies the violence and injury risk of this late correction, as the man-seat is "snapped back" violently to zero-yaw as the drogue chute fills. Second, the apparent early initiation of man-seat yaw (Y-axis g-load curve tracing back to rail departure, as shown on Figure 4) - suggests that a man-seat yaw perturbation may have occurred early enough to have been caused by seat-rail interaction. (Recall: the man-seat is aerodynamically unstable, so it will try to rotationally accelerate around the "pirouette" Z-axis – i.e. to "face backwards" – if any yaw perturbation occurs before the drogue chute stabilizes). Theoretically tracking back to the "first failure": Rather than three independent anomalies (low seat g's, delayed drogue chute inflation, and a high seat yaw), the possibility exists that all three misfortunes were caused by one initial mechanical malfunction at the rails (the seat rollers grinding against windblast and aircraft yaw, then tearing off).

All three anomalies (30-70% low acceleration, a 0.1-second delayed drogue chute, and a 90-deg yaw) presumably eroded the safety margin of recovery, and suggest an opportunity for improved performance by correction of only one item (the seat roller design).

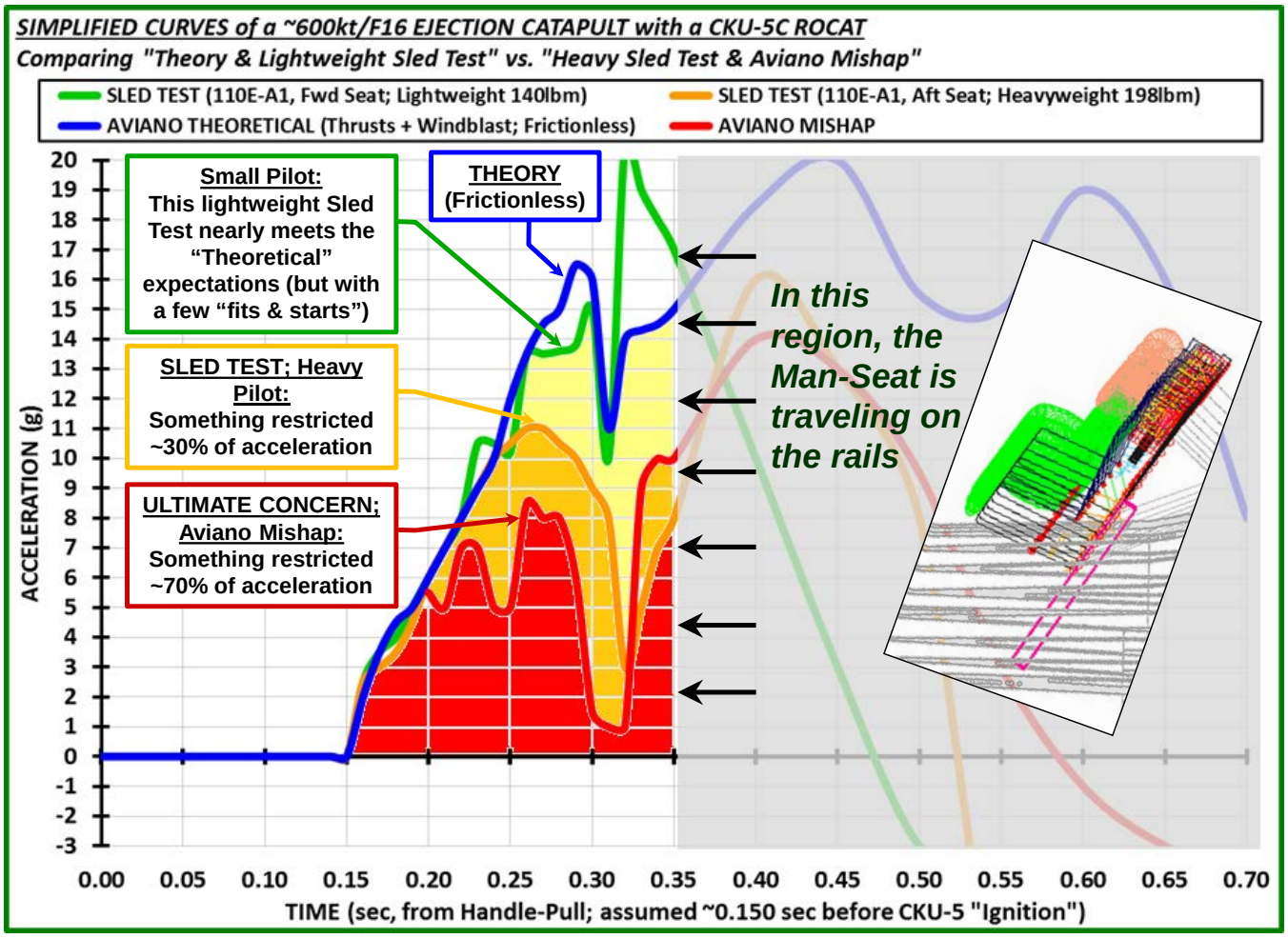


Figure 1 – Summary of "Low-g" Artifact and Its Severity Increase with Loads on Seat Rollers

The certainty of Artifact #1 (low-g period at top of rails) was increased by the expectation that – at these high speeds (~600 knots) – windblast should have been "getting underneath the seat" and increasing the spinal acceleration. Theoretically (Figure 1 - blue line; frictionless rollers), windblast should superimpose on the CKU-5 ROCAT's catapult and sustainer spinal vectors, particularly in the "leaned back" aircraft rail (34-deg, vs. 17-deg) and exposed man-seat (no windscreen) of the F-16 aircraft. Figure 2 confirms this wind-assist via hand calculations. Rough expectations then sum the catapult thrust (~3500 lbf; ~10g) with the windblast "getting under the seat" (~6.7g, as shown in Figure 2) for a sum of 16.7g. Thus, a hand-calculated expectation of a high-speed F-16 ejection would be a spinal acceleration peaking at ~15-20g during catapult phase, and the specific hand calculation (~16.7g) also matches the peak theoretical (frictionless) 6-DOF ADAMS model prediction (Figure 1; blue line).

As shown in Figures 1 and 3 (the red curves; spinal acceleration of the Aviano mishap); instead of finding this 15+g spinal acceleration during the Aviano's catapult phase, the investigation noted a "low g" performance; intermittent spinal acceleration, with a peak of only ~8g (instead of ~15-20g), and with regions down to ~0-1g. For perspective on the seat position (Displacement = Velocity x Time); recall that during a 50msec period (such as from 0.280sec to 0.330sec) – a man-seat traveling at ~40fps would traverse about 2 feet of the rail. So, this ~0-1g "low-g dropout" period was not a "brief transient" (as it may appear on a time-scale), but a long-stroke restraint or loss of thrust, occurring to the seat.

This contrast between the prediction (~15-20g) and observation (0-8g) drew the initial investigative concern – and in general; the finding that windblast caused a *decrease* in the man-seat's acceleration, rather than an increase, led to the logic of investigating friction (seat roller friction) as a potential cause of the restrained man-seat motion.

Subsequently, as the investigation narrowed to the seat-roller's frictional response to X-axis loads ("windblast"), the companion load (Y-axis; lateral, port-starboard seat loads – such as from ejecting during aircraft yaw or roll-rate) became another monitored fault path to detrimental restraint of the man-seat during ejection. For example: As shown in Figure 12, comparison between the ADAMS model (at zero yaw and roll-rate) and the Aviano incident suggests that this ejection experienced *more* of the frictional restraint (Z-axis) than would be expected for only an X-axis (windblast) burden. Consistently, the Aviano ejection was experiencing ~1-2g of *lateral* acceleration (presumably from a concurrent aircraft yaw angle and roll rate). Therefore, a validating finding would be to see the "straight and level" version of the Aviano ejection (a sled test at ~600KEAS) exhibit a lesser frictional loss (only ~30-50% loss, instead of ~50-70% loss) – and that lesser restraint would also match the medium-severe frictional responses predicted by the ADAMS model (set at zero yaw and roll). Confirmation of these findings began to be noticed when comparing Figure 1 (sled test curve; orange) against the ADAMS model prediction (Figure 12; light-blue to green curves; the expected range of friction coefficients; ~0.4-0.6).

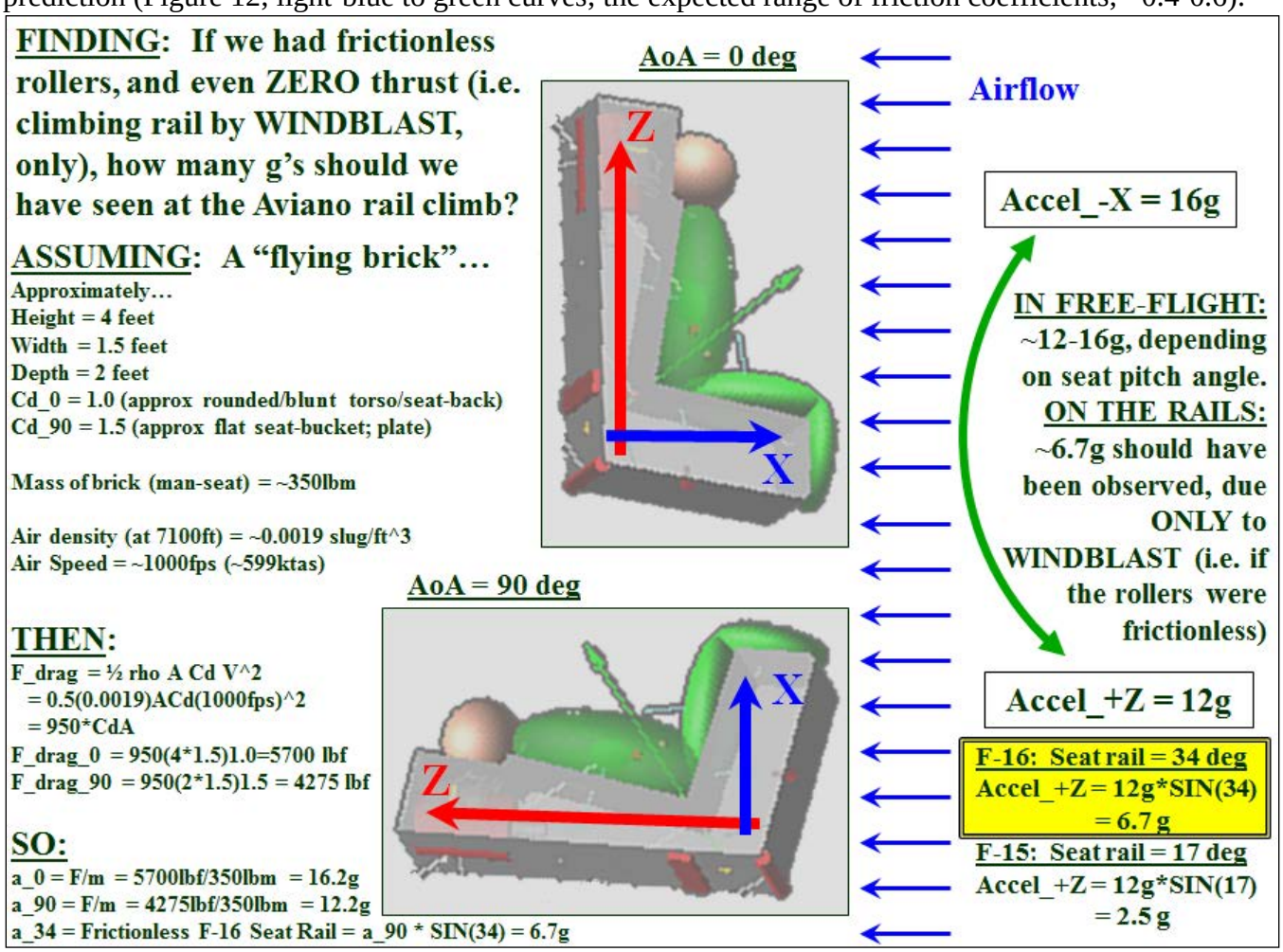


Figure 2 – Hand-Calculation of Aerodynamics on a Man-Seat Emerging at 7100ft-msl & 600kt

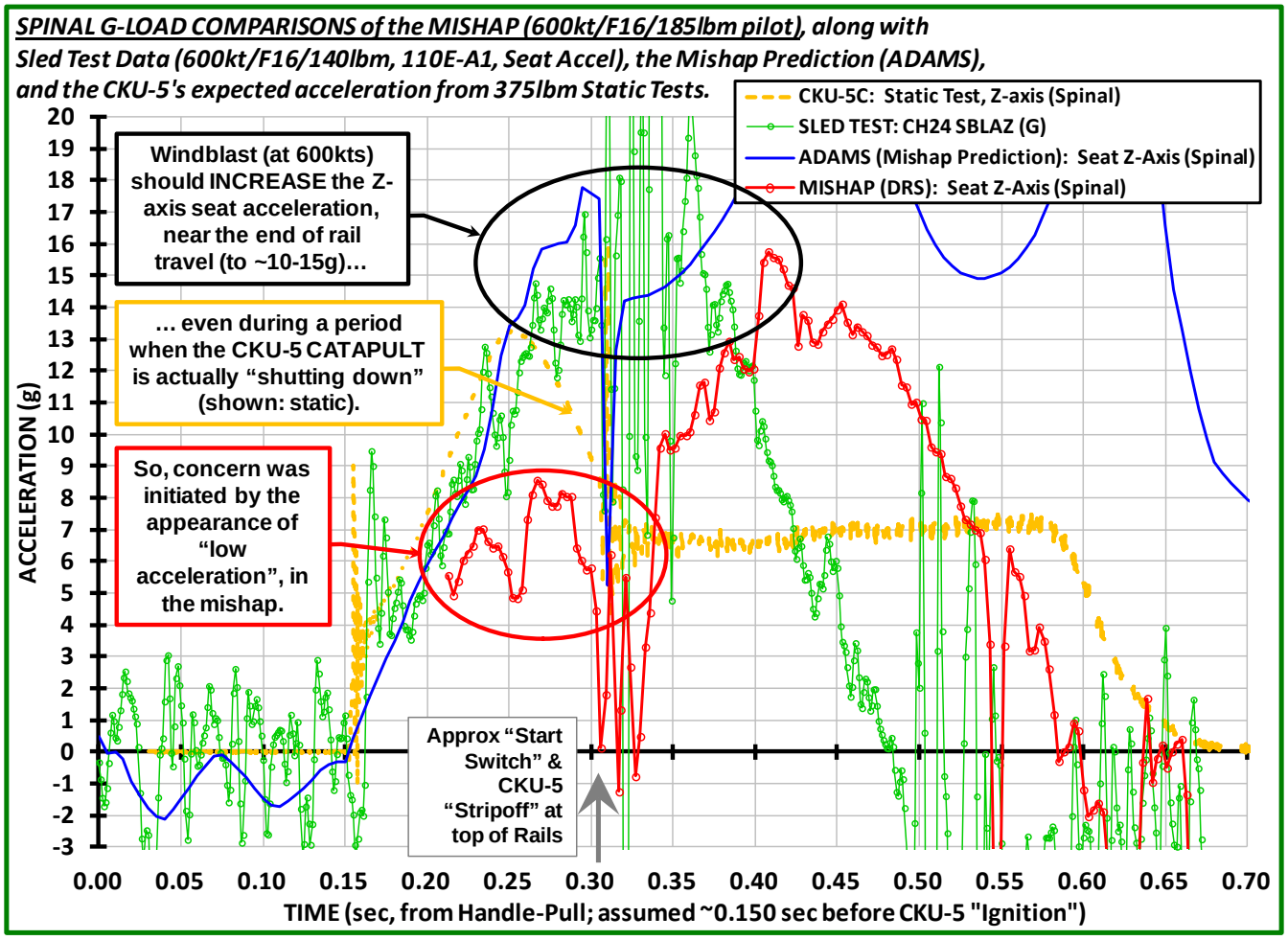
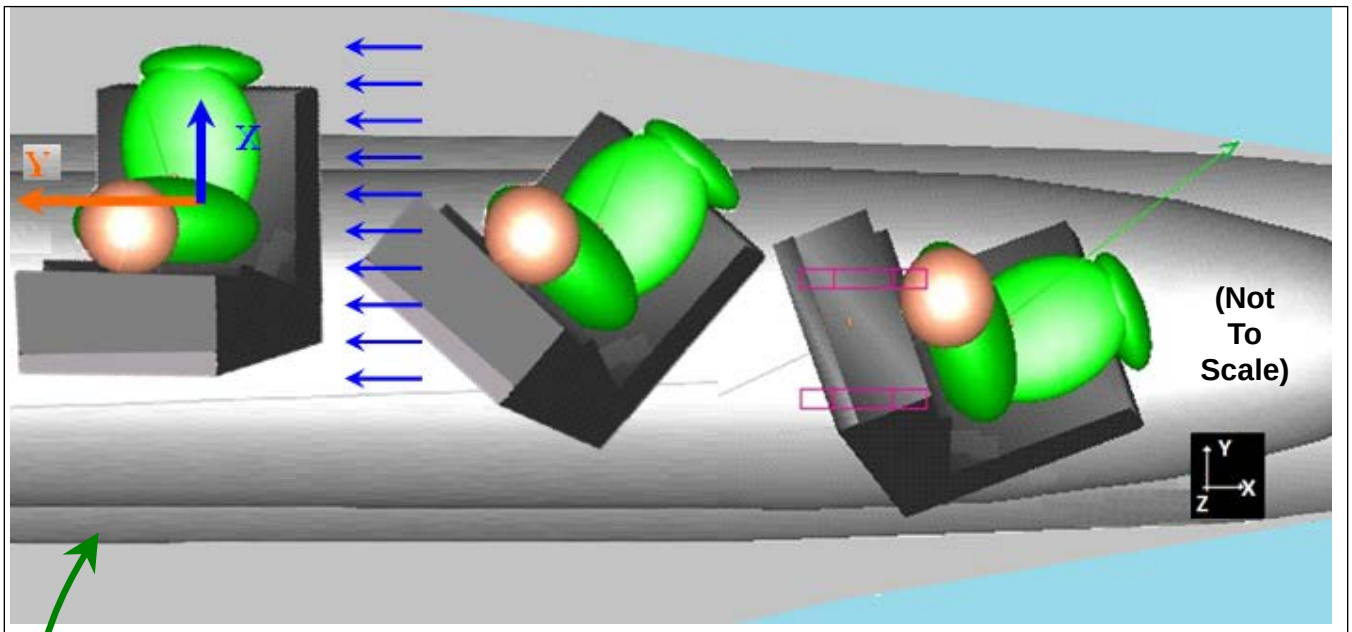
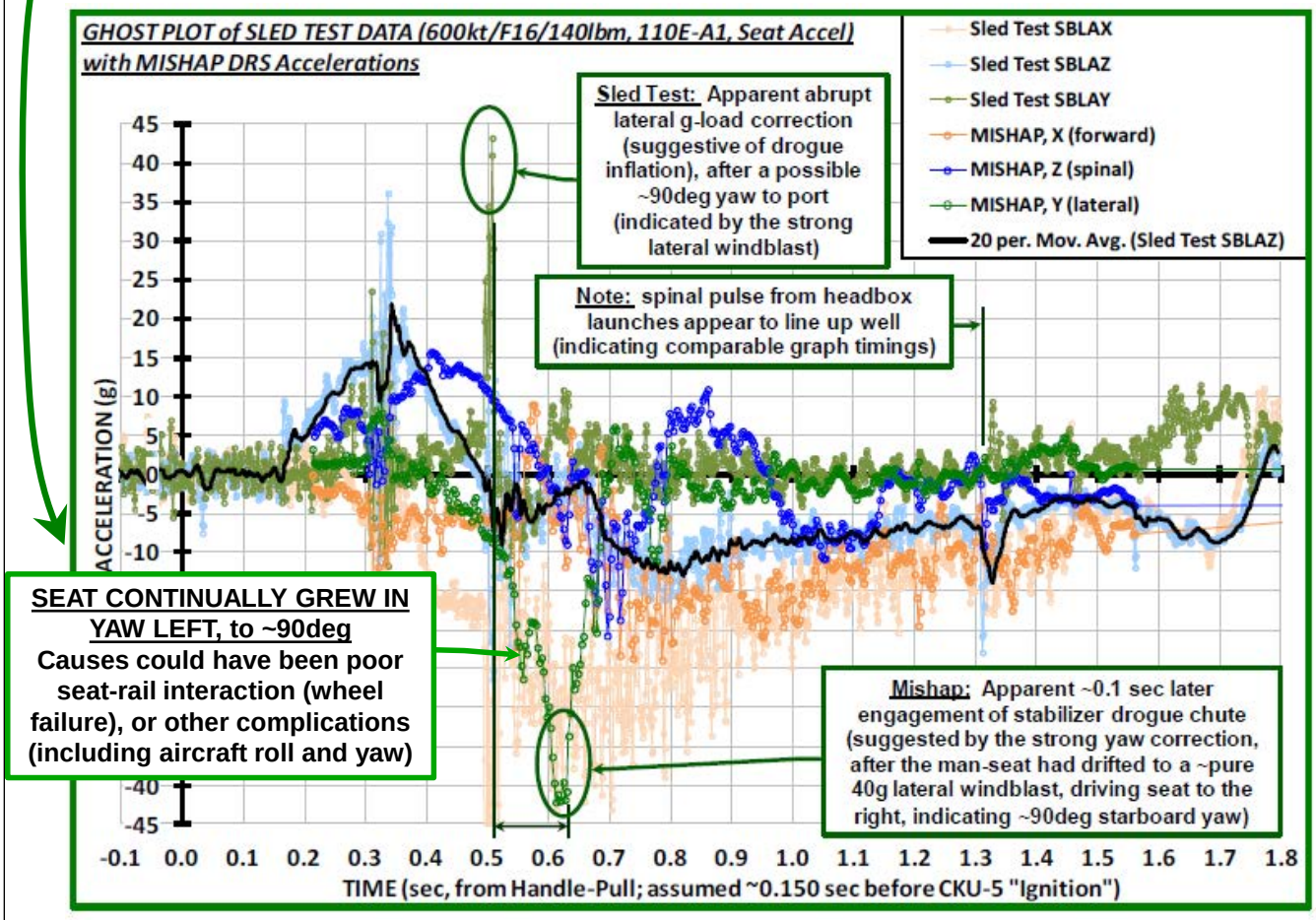


Figure 3 – Prior Graph from Reference-1: Mishap Artifact #1 (Apparent "Low-g" Region)

As for "Artifact #2" (the drogue inflation delay, aggravated by the seat having drifted to ~90-deg Yaw) – this seat rotation in yaw may have been caused by the perturbing ambient aircraft yaw and roll, or by a seat roller failure, or – potentially - a combination of both. As shown in Figure 4 (which includes an excerpt from Reference (1)) – the lateral seat acceleration of the Aviano mishap's man-seat (shown as the lowest green dots) grew steadily from the point of man-seat departure from the aircraft's seat rails, ultimately reaching (possibly clipping) at ~43g's – which indicates the man-seat yawed ~90deg against the windblast. The period of this yaw was during free-flight; between seat-rail departure (t=0.3 sec, on the graph) and drogue chute inflation (t=0.6 sec, which appears to be ~0.1 sec later than a comparable sled test). The rate of this yaw is uncertain, but *averages* a strong rate of 300 deg/sec = 90deg/(0.6s-0.3s). When the drogue chute inflated, the correction "snapped" the man-seat back to face-forward. While the cause of this progressive man-seat yaw is not known, motion difficulty on the rail (wheel friction and failure) is among the possible drivers (along with aircraft roll and yaw, intrinsic man-seat aero-instability, pilot shift and slump, asymmetric helmet movement, asymmetric limb flail, etc.).



At Yaw=90: F_drag = ½ rho A Cd V^2 = 0.5(0.0019)(4*2+2.5)(1.5)(1000fps)^2 = 15000 lbf,
Or: Accel-Y = F/m = 15000/350lbm = 43g, which matches mishap g-Y (although ~clipped)



(Previous Report: Figure 18 – Mishap Artifact #2: Apparent ~0.1 sec Delay in Drogue Chute Inflation)

Figure 4 – Recap of Artifact #2; Apparent Man-Seat Yaw of ~90deg plus Drogue Chute Delay

Estimating Windblast Emergence Thresholds from Sled Test 110E-A1 (600 KEAS, F-16 dual seat)

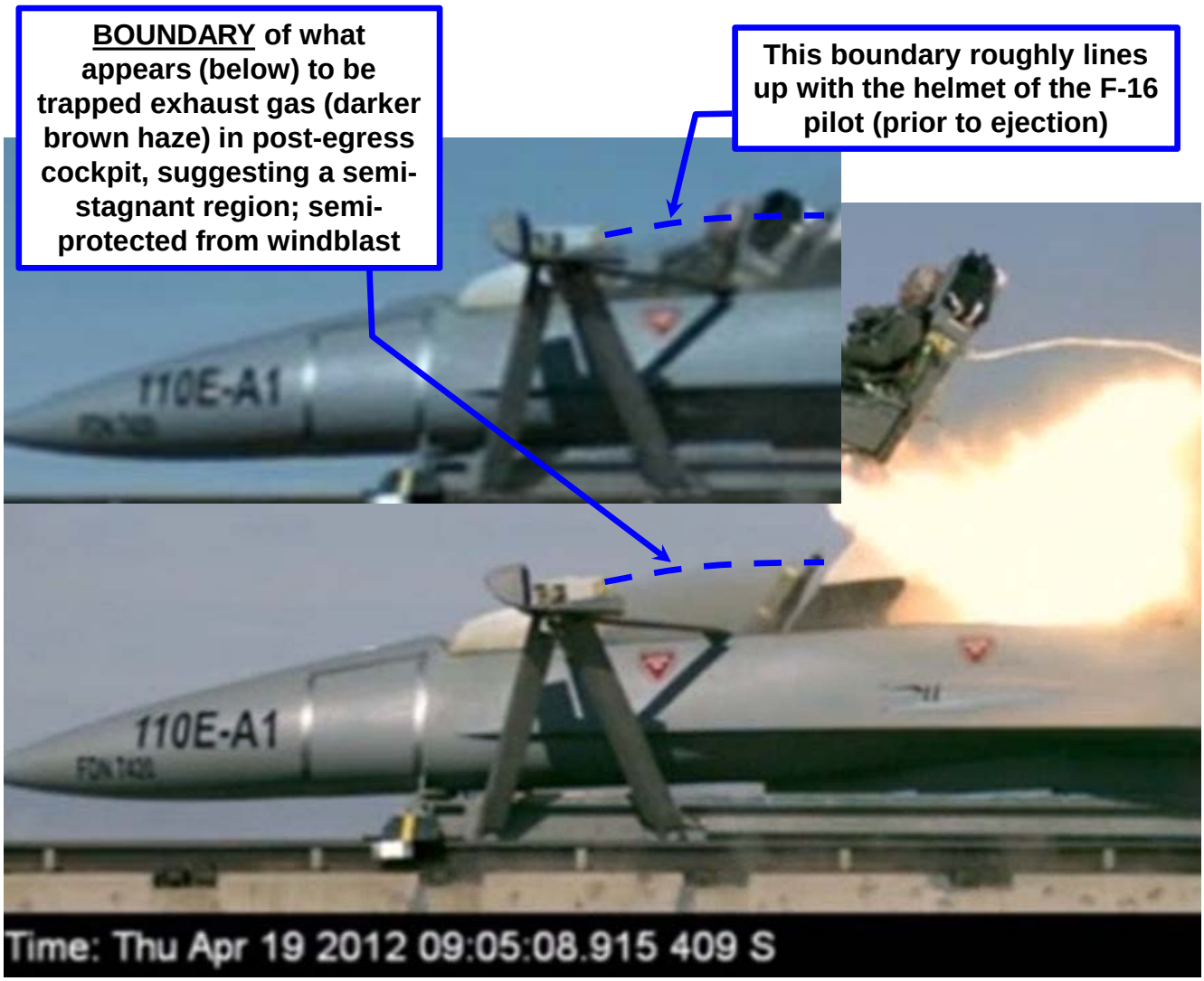


Figure 5 – Sled Test Example of Windblast Emergence (Between Elbow and Head Height)

However, at the time of Reference (1), no explanation was readily available for this "underperformance" of the ACES-II seat (~30-70% low acceleration), or the drivers of yaw. Numerous experimental calculations were performed during the initial study, in an attempt to explain these anomalies (see Appendix B) – such as "misplaced aerodynamic objects" (helmet snagged on seat pitot tube, foot or leg asymmetrically flailing, etc.), thrust anomalies, and extreme center-of-mass shifts. "Emergence" may occur earlier (lower) from behind the F-16's minimal dash, compared to other aircraft, so studies varied thresholds from the waist to as high as the helmet (as suggested in Figure 5). No mechanism was found which reproduced the anomalies of "low-g" – or the strong yaw - as the Aviano man-seat traveled.

Failing to identify the cause of Artifact #1 by the time of delivery for the Aviano SIB products (which was to support seat recovery from the Adriatic Sea), a preliminary fault-tree analysis was developed as Appendix A of Reference (1) - and recommendation was made for further study.

APPROACH

In the subsequent two years since the report of the Aviano study (Reference (1)), intermittent efforts were attempted to explain Artifact #1 (low-g period at the top of seat rails). Of the surviving branches of the fault tree (Appendix-A of Reference (1), also included in this report, for reference), a 6-DOF mechanical-dynamics-structural-trajectory analysis was performed in the ADAMS Ejection Trajectory Model, to address branch "3.1: Lost Energy; Seat Rail & Roller Mechanics". This branch captures anomalies from rail or seat or roller flexure, failure, binding, skidding, or other imperfect motion, as compared to unimpeded seat motion from "frictionless" wheels. A redundant set of aero- and mechanical-dynamic calculations were made via "hand calculations" (first order, classical principals), to verify the results of the 6-DOF Ejection Trajectory Model.

The current configuration of the ACES-II Seat Rollers is shown in Figure 6, from TO 13A5-68-2 (and is essentially the same seat roller design since conception in the late 1970's – and that roller design itself was inherited from the prior-generation, "ESCAPAC" seat). As indicated, the ACES-II Seat Rollers apparently are hand-assembled steel wheels on dry metal shafts, with only metal spacers for positioning.

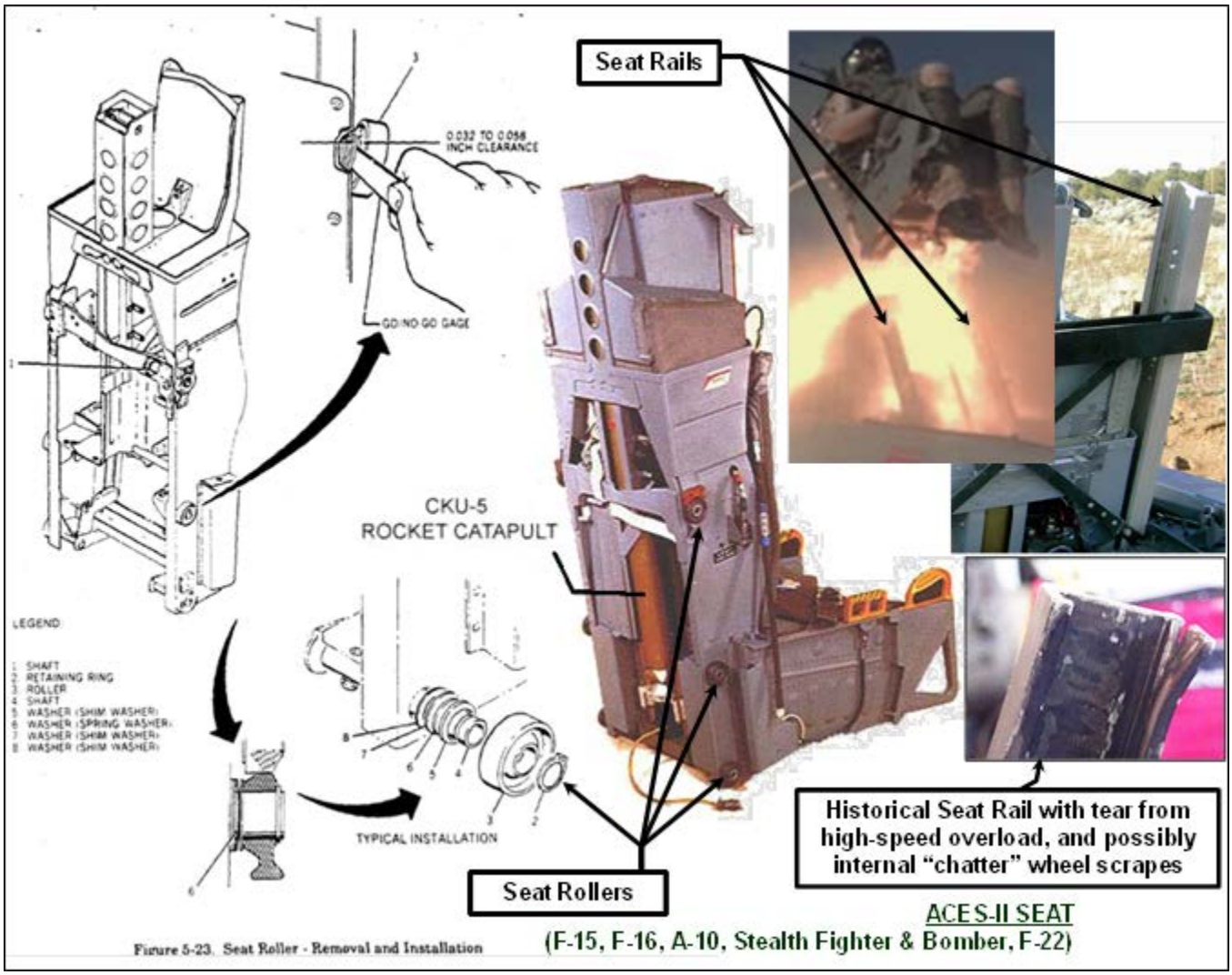


Figure 6 – Diagram of Current ACES-II Seat Roller Design, Installation, and Use

Figure 7 provides some images from the myriad of hundreds of COTS cam rollers which are currently available, and which would approximate the “zero friction” (u=0.0 to ~0.01) behavior analyzed as the first simulation in the ADAMS design study.

Figure 7 – Images of some Typical Cam Rollers and Bearings

The 6-DOF ADAMS Ejection Trajectory Model (Figure 8) includes all six (6) rollers of the ACES-II seat, with interaction (stiffness, damping, and friction) against the aircraft rail, and incorporates most major aircraft and ejection dynamics, mechanics, and aerodynamics (dozens of objects with dozens of parametric variables; multiple seat thrusts, emergence into windblast, aircraft roll/yaw/altitude/etc, parachute inflation rates, headbox deployment, etc. – with optional internal propellant ballistics and aircraft features; landing gear, arresting hooks, lift and drag forces, center of gravity, etc.).

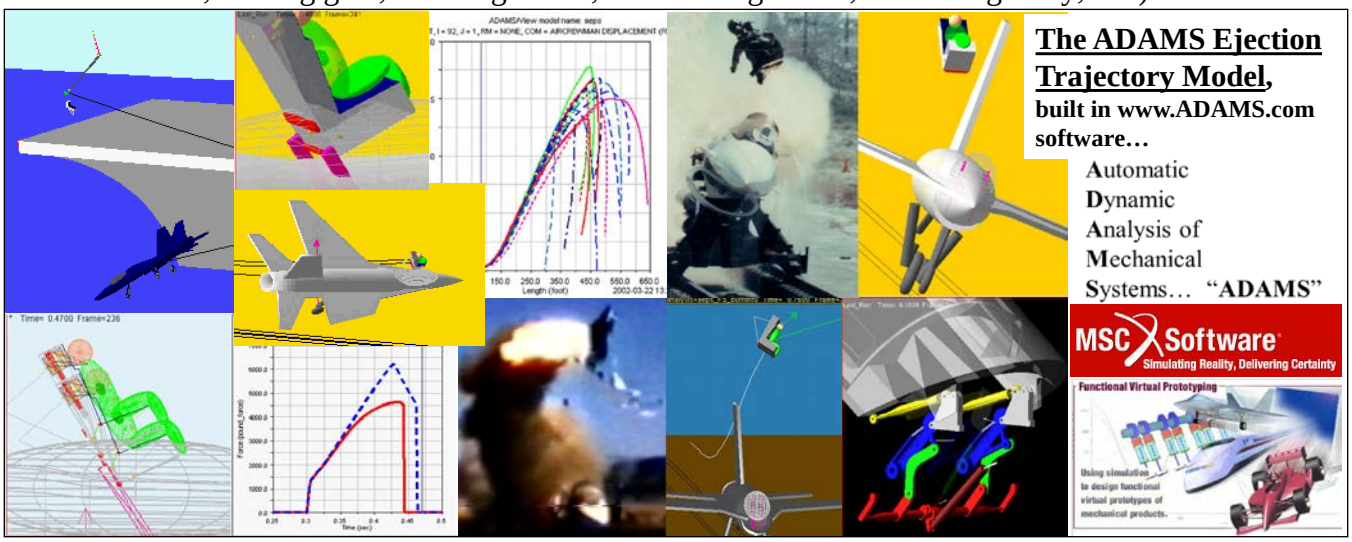


Figure 8 – Joint AF/Navy ADAMS Ejection Trajectory Model (Developed/Maintained since 1995)

For the ADAMS model analysis, a design study was performed for the ACES-II seat roller "friction coefficient" (u; an approximation of the mixed "least-resistance" path of ACES-II seat roller; sometimes locking up and "scraping", sometimes rolling, etc.), using the Aviano Mishap flight regime (pitch=~18deg dive, through 7100ft-msl altitude, at ~600kt airspeed) as the study conditions. The performed design study varied the ACES-II seat roller-to-rail friction coefficient (u) from 0.0 to 0.8. For comparison:

u=0.0 is "frictionless" (near to a functional bearing; ball, needle, or cone-bearing cam follower)

u=0.2 is close to a "greased steel-to-steel" interface

u=0.3 is close to a dry steel-on-steel "wagon wheel friction" (where a larger outer diameter leverages against the friction from a smaller diameter hub; approximately 2-to-1 in the case of a successfully-rolling ACES-II seat wheel).

u=0.6 is close to a "dry steel-to-aluminum" interface (such as when the ACES-II seat wheels lock on their axle and scrape their way up the rail, grinding flats on themselves, as seen on some high-speed ejections).

u=0.8 may represent additional resistance from wheels also being side-loaded (lateral Y-axis; from aircraft yaw, aircraft rollrate, etc), or suffering mechanical deformation (galling), binding, and/or eventual structural failure (as seen on several ACES-II seats, following high-speed ejections; missing wheels).

u=1.0 is the theoretical limit (without severe mechanical deformation) where a seat roller would restrain the man-seat with as much force as is applied "normally" against the rail (such as loads from windblast – which is expected approach a magnitude of ~10,000 lbf - and from thrust-Cg imbalances, which generally peak at ~1,500 lbf per wheel).

As a verifying study, classical hand-calculations were also performed, to assure the same relations occurred (among parameters of windblast, friction, catapult thrust, net acceleration, etc.).

RESULTS

As summarized in Figures 9 and 10, all four sets of results indicate the current seat roller friction coefficients are sufficient to detrimentally slow the man-seat and nominally quadruple the roller loads (by increasing the dwell time in the windblast), eliminating the majority of tail clearance margin, and observably reducing apogee.

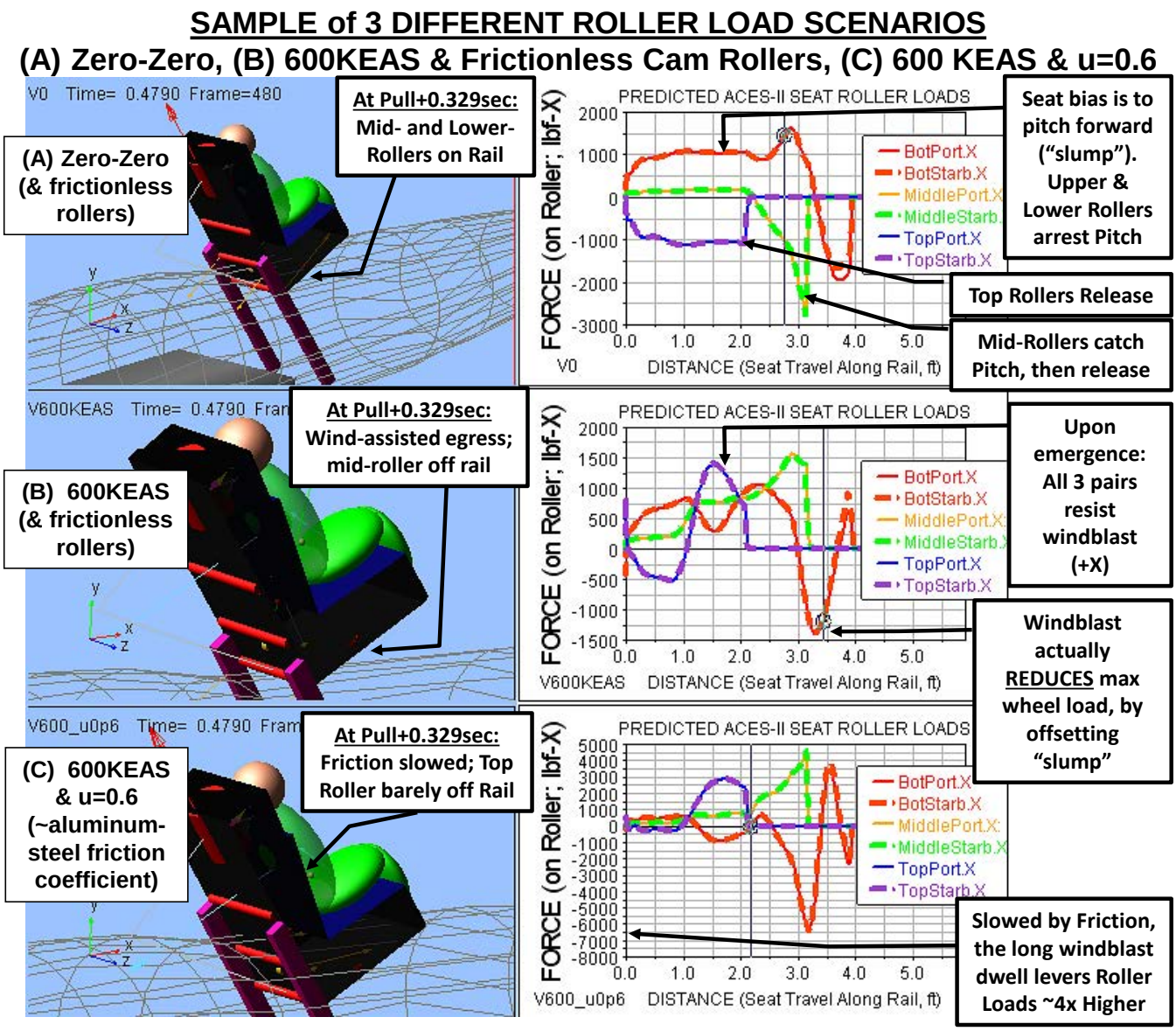


Figure 9 – ADAMS-Predicted ACES-II Seat Roller Loads (Fx) at Two Friction Coefficients

Figure 10 shows the continued flyout of Scenarios B and C (the two 600KEAS friction variants, from Figure 9), illustrating the reduced tail clearance (reduced from yards to feet), lower apogee (reduced from ~110ft to ~80ft), and reduced time of flight (~1.5 seconds less to complete the parachute stabilization, deceleration, and pendulum swing).

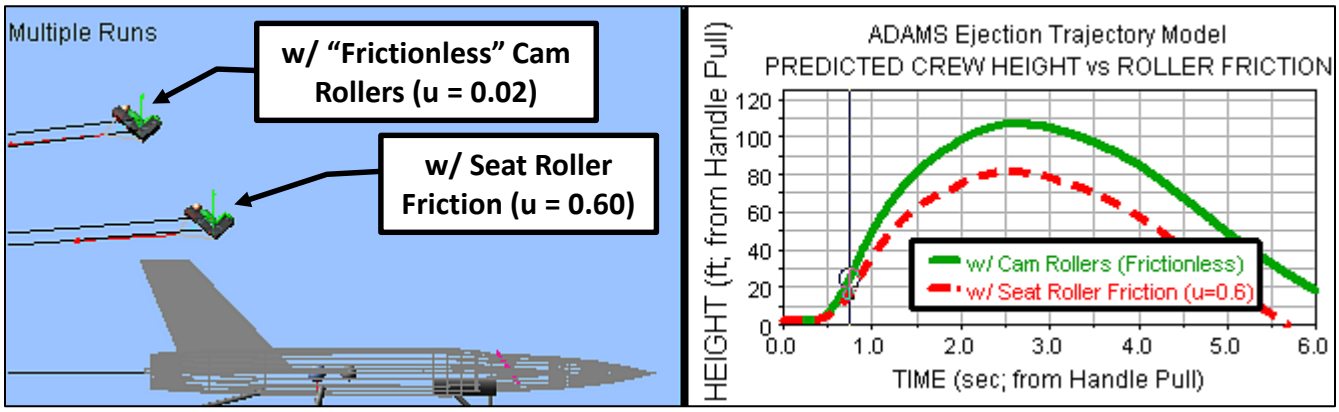


Figure 10 – ADAMS-Predicted ACES-II Tail Clearance and Apogee at Two Friction Coefficients

Four (4) versions of these results are provided (all in agreement); ADAMS 6-DOF results, Sled Test data, hand calculations, and a "logic exercise". These results indicate that expectations are realistic for friction of the ACES-II seat rollers (u = ~0.3 to 0.6) to cause severe (~20-50%) reductions in the CKU-5 ROCAT's ability to accelerate the man-seat from the aircraft, and intermittent "bad day excursions" (u=0.8, such as locked-up/skidding wheels, side-loads from adverse aircraft angles, etc.) produce the nearly-complete losses in catapult performance (~70 to 100%), as seen on the Aviano Mishap.

RESULT SET #1 (ADAMS 6-DOF Design Study):

Figure 11 shows ADAMS-predicted man-seat spinal accelerations for the studied range of ACES-II Seat Roller friction (u=0 to 0.8), plotted against time (upper right quadrant) and seat motion (lower right quadrant), for flight conditions comparable to the Aviano mishap (~18 deg dive through ~7100 ft-msl at ~599KEAS). Results confirm majority losses are possible (ultimately up to "near zero" acceleration).

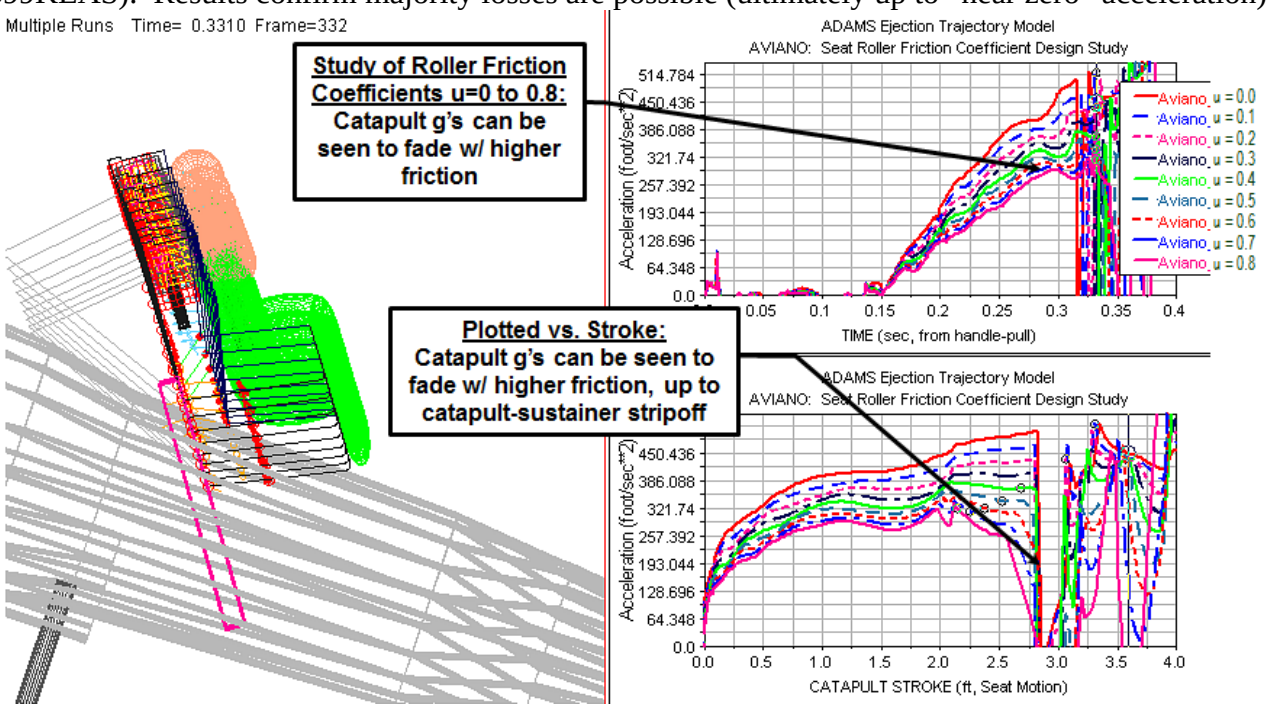


Figure 11 – Results from ADAMS Design Study of Seat Roller/Rail Friction Coefficients

These same results (cropped to only show the CKU-5's catapult phase; excluding the sustainer onset, for clarity), are shown in Figure 12, with the Aviano Mishap seat accelerations overlaid. This overlay reminds that – in the mishap – additional lateral accelerations were simultaneously occurring, so the additional loss in spinal acceleration may be explained by the additional friction from these lateral loads, and further "intermittent drops" in spinal performance (such as at t = 0.300 sec) may have been caused by (X-axis) oscillation; the dynamic rocking of the seat forward and aft; "banging" rollers up the rails.

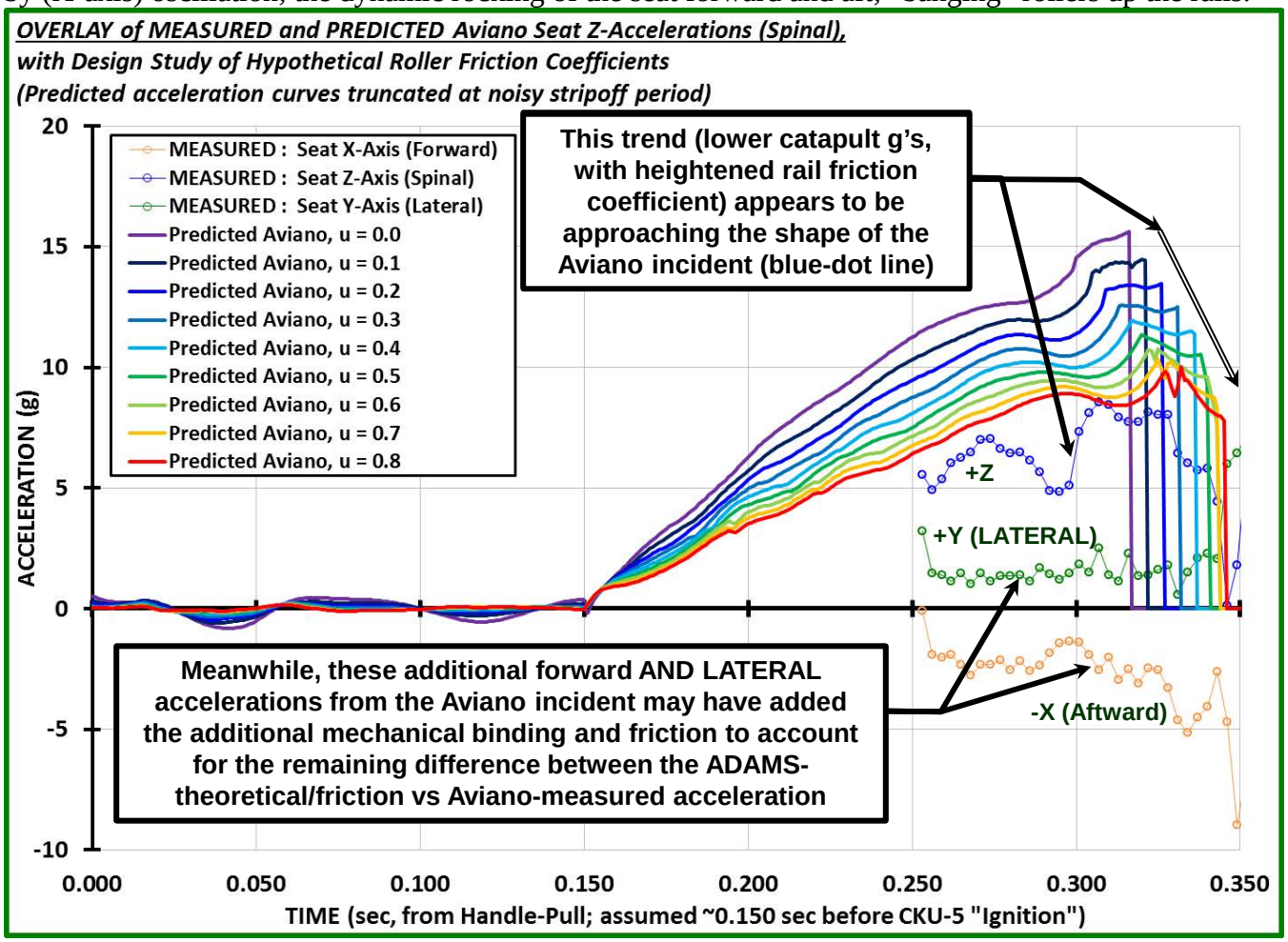


Figure 12 – Superposition of ADAMS Design Study with Aviano Seat Accelerations

RESULT SET #2 (Sled Test Data; Apparent ~2-9g Loss Due to Friction):

To investigate the "best case" (lowest friction) high speed ejection – a "straight and level" sled test was reviewed. These straight-and-level sled tests have no lateral (yaw or roll-rate) flight loads burdening the man-seat. This pristine flight condition allows the seat rollers their best chance at motion without the wheels also being pressed left or right (i.e. rubbing against their spacers and the rail web). Subtraction of the onboard CKU-5 catapult pressure reading from the onboard accelerometer reading can then suggest a "back-calculated" measurement of restraint on the man-seat.

Figure 13 shows results from this frictional back-calculation, performed on a comparable sled test (110E-A1-Aft; 95th percentile pilot with a man-seat mass of ~390lbm, ejection from an F-16 mockup at 600KEAS, straight-and-level). In this test (the sled test example overlaid in Figure 1 – orange curve - showing a ~30% performance loss) – there is an additional T-splitter added at the CKU-5 ROCAT's

head-end "metering tube", into which a pressure transducer is installed (ideally grease-filled, to protect from thermal drift when the membrane is heated by the flow of combustion gases). This pressure report allows some indication of the internal catapult chamber pressure (with some encroachment from other loads; thermal, pressure, electronic, and other errors are seen in this measurement, but nevertheless some tracking of the chamber pressure is provided).

Multiplying this internal chamber pressure by the CKU-5's telescoping catapult tube's "piston area" (0.785 sq.in.) suggests the thrust (F=PA, and resulting acceleration) which "should" have been observed on the man-seat. Subtracting that "pressure-implied thrust" from the "acceleration-implied thrust" (the motion actually observed by the onboard accelerometer; F=ma) suggests the interfering "friction" force which appeared to be restraining the man-seat during its attempt to ascend the rails.

Note that this simplified relation (F_friction = ma – PA) excludes what may have been an additional "wind assist" ascending the rails. As shown in Figure 2, a frictionless seat roller should allow additional man-seat acceleration due only to vectored wind forces "getting under the man-seat" on a 34-deg reclined F-16 aircraft rail.

As shown in Figure 13, the simplified measurement appears to report ~500-1000 lbf of frictional restraint on the man-seat, and occurs over most of the catapult phase, when the catapult thrust would have ranged ~1000-4500 lbf.

However, as noted: This measured friction was simultaneously overcoming what is presumably up to ~6.7g (see Figure 2) in additional wind-assist; acceleration which should have been measured as a "negative friction" (acceleration exceeding the F=PA value), had roller friction been zero. Therefore, the actual seat roller friction may have been thousands of pounds higher than this F=ma-PA measurement, in order to have finally been measured as a "restraint" on the man-seat (or on the CKU-5 ROCAT).

Regardless (i.e. even if neglecting the expected "wind assist"), the seat roller friction is observed to have been at least ~500-1000 lbf. This magnitude of restraint is ~1.5 to 3g of egress loss (a=F/m, with a ~350lbm man-seat); up to ~30% of the CKU-5's ~1000-4500 lbf catapult performance. So, even this "small" amount of friction (~500-1,000 lbf) is a significant portion taken from a ~3500 lbf ROCAT, and appears to be of a comparable magnitude to the loss described in Figure 1 (~30%).

Also - from the viewpoint of an internal propellant ballistician/designer: This condition (500-1000 lbf of frictional restraint) is far from the design envelope of the CKU-5 ROCAT. Over decades of refinement, the catapult has undergone multiple tunings of propellant formulations, mixing processes, and cast/bored/trimmed grain dimensions, in order to adjust catapult thrust profiles to particular balances of biomechanical injury criteria (DRI/MDRC), apogee and event-time heights and airspeeds, and aircraft tail clearance – across ranges of pilot masses (continually expanding) and operating temperatures (-65F to +165F). All of these design decisions were based on a "frictionless" man-seat. Unilaterally adding 1000's of pounds of drag to this device, during high-speed ejections (due to seat rail friction, and/or adverse aircraft conditions), is departing from the envelope for which the CKU-5 ROCAT was designed.

In the more likely case that even more friction (1000's of pounds) was occurring, this range of load on the ACES-II seat rollers also becomes a threat to structural integrity.

In either case; indications are that seat roller friction is causing real-life losses in egress performance.

EXAMPLE of SEAT-RAIL FRICTION OCCURING ON A "SLED TEST" ("Straight and Level" aircraft conditions; no adverse Yaw Windblast or Roll to aggravate rail friction)

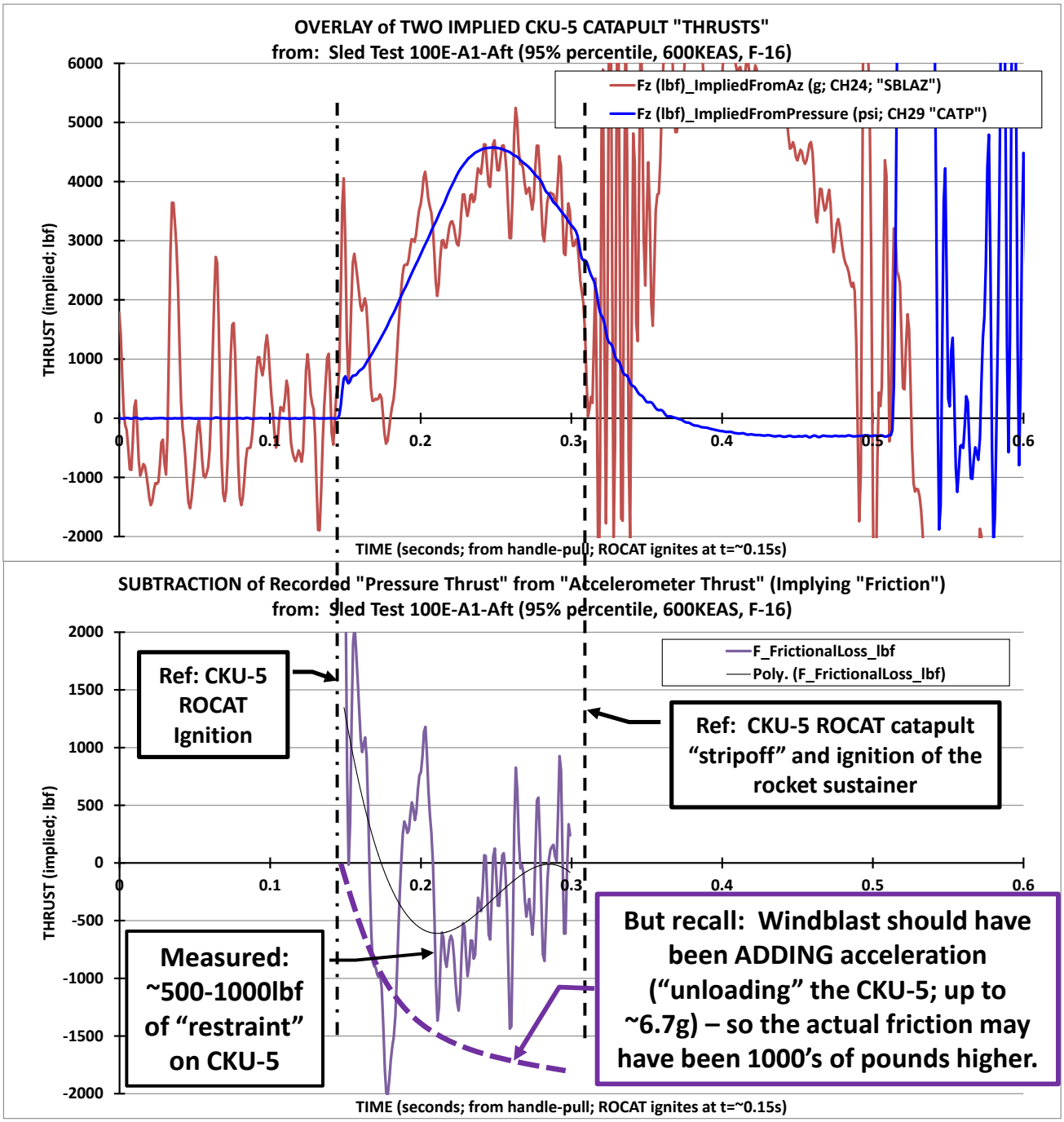
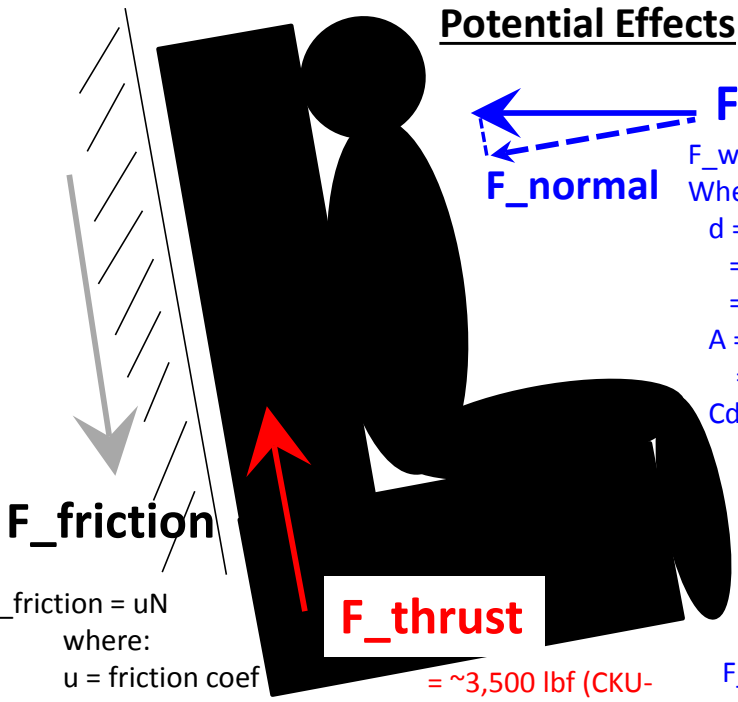


Figure 13 – Sled Test Indication of Seat-Rail Friction (at "Straight and Level" Conditions)

RESULT SET #3 (Hand-Calculation Example & Verification):

As shown in Figure 14, hand-calculations indicate a similar magnitude of response (that seat roller friction can match – or overcome – the nominal thrust of a CKU-5 ROCAT).

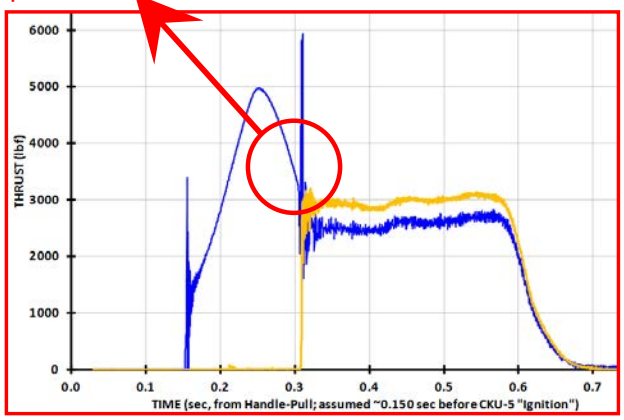
Hand-Calculation Review of ACES-II Seat Rail Friction Potential Effects



F_wind blast = 1/2dACdV^2
Where:
d = density of air (slug/ft^3)
= 0.002377 @ Sea Level,
= 0.0019 @ ~7100ft msl
A = presented area of man-seat
= ~4ft x 1.5ft wide
Cd = drag coefficient
= ~0.5-1.5 (for a mixture of blunt, rounded and flat contours)
V = airspeed (fps)
= 600kt/0.592377 = ~1000fps
F_windblast
= 0.5(.002377)(4x1.5)(1)1000^2
= 7,100 lbf
F_normal = 7100lbf COS(34)=5886

F_friction = uN
where:
u = friction coef
= (~0 to 0.8)
= 0.6 (dry steel-to-alum)
N = Normal force
= can be due to windblast, Cg imbalance (as a function of CKU-5 catapult vs time), etc
=u(F_normal)
=0.6(5,886lbf)
= 3500 lbf

= ~3,500 lbf (CKU-5C catapult ranges ~3000-5000lbf, low near top of seat rails)



F_net = F_thrust – F_friction
= 3500 - 3500 = 0 lbf = 0g
(Rail friction can neutralize thrust)

NOTES: Some aircraft may allow windblast earlier (F-16), vs providing a "shadow" (F-15 retains a windscreen), so presented area may vary w/ aircraft and emergence. Some "ballistic feedback" may also occur (higher burnrate and pressures, with catapult restriction), resulting in higher thrust. Otherwise…
CONCLUSION: Hand calculations (0g) match the observed Aviano low-g extremes (datapoints at 0, -1.2, and -0.9g; see Figure 3 of this report, at t = 0.30 through 0.33 sec).

Figure 14 – Hand Calculation Supporting Conclusion of Causal ACES-II Seat Roller Friction

RESULT SET #4 (Logic Discussion & Verification):

The "Logic-Based" Results are shown below, including justifications for the seat rollers' design being considered an emergent and urgent subject, exponential in its effects, complex in its coupled relations, and possibly causal to the Aviano Mishap anomalies. Figure 15 is provided as an illustration (quantitative; ADAMS 6-DOF results) to show these coupled relationships of friction, velocity, and increased rail loads.

1) AERODYNAMIC LOADS ARE LARGE. The windblast force on the man-seat – as depicted in Figures 2 and 14 – can ultimately reach over 7,000 lbf at high speeds and low altitudes (for comparison: Predicted for Aviano Mishap; ~6,000 lbf). For the bulk of this discussion, we will assume this near-maximum value of a "7,000 lbf windblast".
2) MAGNIFICATION: This aerodynamic load is then mechanically magnified (leveraged, as the seat nears the top of the rails) by applying most of the windblast on the top/torso and man-seat's upper regions, while only the two lower sets of rollers (the "middle" and "lower" pairs) remain engaged in the seat rail – a couple of feet below the center of aerodynamic windblast. As the middle and lower roller pairs attempt to resist this aerodynamic "bending moment" – in addition to resisting the translational (aftward) aerodynamic load - the mechanical leverage can then double the windblast load on the middle rollers (depending on seat position, aerodynamics, dwell time, etc.).
3) SLOWER MOTION CAUSES HIGHER FORCES. If the dwell time of the man-seat at the top of the rails is brief (i.e. a lightweight pilot "shooting up the rails" at the highest speeds), then there may be insufficient time for the windblast to fully "rock back" the seat to cause back-loading of the seat rail and rollers. Conversely, if the dwell time of the seat at the top of the rails is large - sufficient to fully "rock back" the seat against the rails (enough to cause full deflection; i.e. semi-static reaction loads), then the windblast is able to fully transfer mechanically into the seat rails and rollers. In this case, due to the leverage advantage of having only two pairs of rollers engaged while the man-seat emerges, the middle rollers could arguably approach a sharing of ~14,000 lbf between the two wheels (~7,000 lbf per wheel), due to resisting both the windblast (translational) and the leveraged reaction (bending moment) with the bottom rollers. Meanwhile, the lower rollers are rocked FORWARD, and share ~7,000 lbf (~3,500 lbf per wheel), from this same bending moment. Prior to this (i.e. before onset of windblast, or without wind loads; a "zero-zero" ejection), the bias of a man-seat during catapult is to "rock forward" (rather than aerodynamically "rock backward"), as virtually all of the man-seat mass is in front of the ROCAT's catapult line-of-thrust, rails, and rollers. Therefore, the "dwell time" in windblast at the top of the rails is primary to the seat roller loads, as a short dwell time will not allow aerodynamic loads to be transferred to the seat rollers (zero-wind max wheel load: ~1500 lbf per wheel), while a long dwell time will allow the full aerodynamic and leveraged forces to apply on the rollers (i.e. max load, with thrust and dynamic collisions, could be on the order of ~10,000 lbf per wheel).

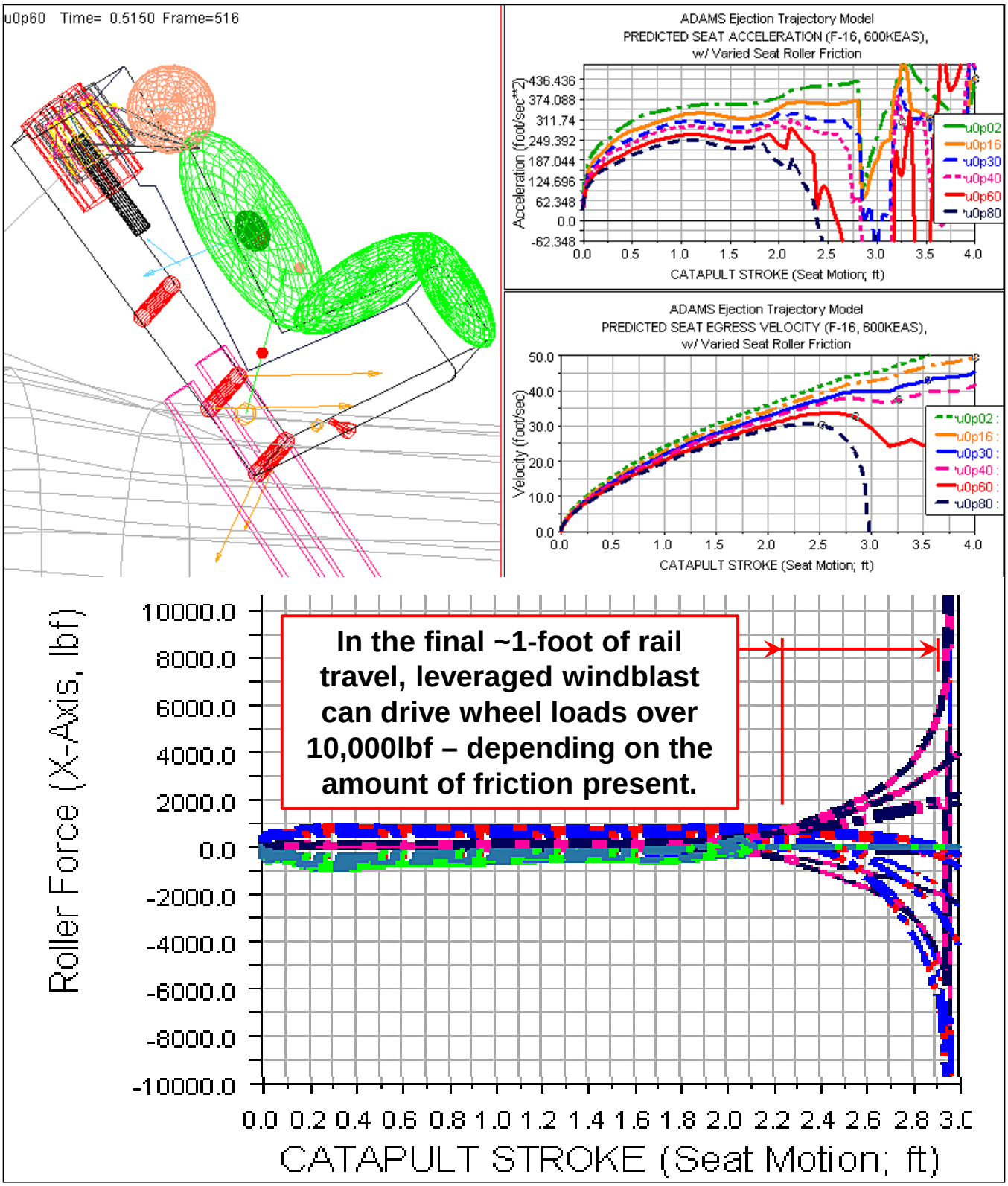


Figure 15 – Results from ADAMS Design Study: Friction Can Drive Roller Loads Above 10,000bf

4) FRICTION PROBLEMS ARE EXPONENTIAL. Because of this relation of "dwell time" at the top of the rails (i.e. the need of the seat to fully "rock back" to apply this full aerodynamic and leveraged load to the seat rollers) – the friction of the seat rollers becomes an exponential relation to the final roller loads (i.e. friction causes friction). As a roller's loaded friction coefficient increases, not only does the tangential (frictional) force increase, but the man-seat also slows down. This slower travel up the seat rail increases the dwell time of the man-seat at the top of the rails – allowing the aerodynamics more time to rock the seat backward and apply more loads to the seat rollers (in the extreme case: bringing the seat to a full stop, at a friction coefficient of ~0.8, neglecting the exponential solid propellant burnrate response – and potential explosion – from the man-seat being restrained). Further, as these loads on the seat rollers increase – their mechanical ability to survive and function will decrease (unlike when the wheel "free spins" during installation or removal of the seat, the deformation, galling, and structural failure of a roller under load may increase friction). For this reason, the friction coefficient of a seat roller is a "triple penalty"; burdening the roller by its own frictional load, then suffering mechanical deformation and frictional increases, then allowing the seat to "rock back" from the aerodynamic windblast and burden the roller further from thousands of pounds of leveraged aerodynamics – all of which may combine to catastrophically overload the roller (structurally fail the wheel, potentially causing malfunctions in seat deployment), and/or decelerate the seat (reducing ejection apogee and overpressurizing the CKU-5 catapult tubes).

5) MODERN PROBLEMS. Because of this exponential feedback relation (resistive loads exponentially increasing with slower seat motion) – there may also exist the eventual likelihood of a "perfect storm", where modern changes "couple" with roller malfunction to produce even worse low-g anomalies. For example: If one or more of these seat wheels produces a high amount of friction (slows the seat, due to a high-speed windblast or otherwise), that ejection may also be occurring on an aircraft with modern "limb restraints" (which apply an additional burden – i.e. reduced acceleration - to the catapult and man-seat). Then, this combination may occur with a pilot whose weight has been waived to the modern limits (i.e. originally limited to 211 lbm pilots for seat qualification, now waived up to 245 lbm nude) – further slowing the seat and extending wheel load exposure time. These new conditions combine with the modern evolution of the CKU-5C ROCAT to have a somewhat more "rolled off" (regressive; 5,000 lbf max down to 3500 lbf) catapult thrust near sustainer ignition (the seat position where it is high on the rails and exposed to the maximum windblast) - thus causing an even slower acceleration. So, while the ACES-II Seat Rollers may have "been around for 40 years" – this modern combination has not; the potential for a "perfect storm" of seat deceleration conditions has never previously been possible (limb restraints, pilot weight overages, and the CKU-5C catapult thrust profile – combining with the ACES-II seat's high-friction roller design).

6) WIND FORCE MAGNITUDES. For perspective, it is worth noting that these magnitudes of aerodynamic forces (~5,000-7,000+ lbf, depending on altitude, temperature, cockpit, etc) are generally greater than the onboard thrust capabilities of the seat (primarily from CKU-5 ROCAT; ~3,000-5,000 lbf). Realization of this windblast strength is significant for two reasons. In the best case (i.e. if the seat rollers work "perfectly"; no friction) – then the windblast beneath the seat (as it nears the top of the rails) can assist egress and virtually double the Z-axis (spinal) catapult acceleration, adding egress height and assisting clearance above the F-16 tail, while remaining below biomechanical injury thresholds (DRI_Z = 18, Z_Accel = 25g, MDRC=1, etc.). However, if the roller friction is significant (u=0.2 to 0.6 or more, like dry steel on steel or aluminum), then the windblast creates a RESISTIVE force to the ejection which can overpower the CKU-5's thrust – bringing the ejection acceleration to near zero (as

seen on the Aviano ejection) – or worse. As shown in Reference (1), and re-included in this report as Figure 13, a typical CKU-5 thrust ranges from ~3,000 to ~5,000 lbf (classically closer to ~3,000 lbf near the top of the seat rail, where windblast has reached its maximum). In addition to this windblast being the "dominant force" in the ejection environment, any friction coefficient from the seat rollers will then be *opposing* the action of the CKU-5 ROCAT, and with magnitudes of seat roller loads sometimes ~14,000 lbf on the middle pair and ~7,000 lbf on the lower pair – a friction coefficient of merely u=0.1 (fairly greased and sliding) can respond with thousands of pounds resistive frictional force on the man-seat… essentially negating the CKU-5 thrust (i.e. zero egress acceleration). More likely friction coefficients during an overload (~0.6; dry steel on aluminum or steel) can then even cause a NEGATIVE seat acceleration (a DE-celeration), as some data points indicate in the Aviano Mishap.

7) INTERMITTENT and MULTI-WHEEL FAILURES. The "low-g" readings on the Aviano Mishap may indicate intermittent "scraping", rolling, and galling… and/or periods of travel where one or more of these wheels is intermittently bouncing, skidding, and rolling – for a fairly complex possibility with six wheels, once wheels begin to malfunction. For this reason, this ADAMS design study was not intended to match each "dip and spike" in the measured Aviano seat acceleration, but merely to calculate that this phenomena of a seat roller's friction is capable of producing the resistive forces necessary to explain the observed sled test and Aviano "low-g" anomaly.

8) SIDE LOADS. While the potential is shown for these wheel malfunctions to cause intermittent and complex deceleration patterns on the seat due to "X-axis" (forward; normal) loads on the seat (such as from windblast and catapult moment) – additional friction may also be contributed if the aircraft induces "lateral" (Y-axis) loads on the seat rollers – as shown on Figure 12 from the onboard seat accelerometer measurements of the Aviano mishap, showing ~1-2g lateral loads during ejection). Adding these lateral forces on a wheel not designed to remain frictionless under this "thrust" (axial) load, may make the friction response even more exponential.

9) MAN-SEAT YAW & ROLL DRIVER. This varied level of wheel failure (i.e. some wheels dragging, some rolling, some tearing away in a catastrophic loss, such as the Aviano Mishap's seat being found with a missing wheel) may also be a contributor to the severe (~90-deg) seat yaw – as observed in the Aviano Mishap ("Artifact #2"), as well as to man-seat roll – as seen on other high-speed tests and incidents. As the seat ascends the rail, the catastrophic loss of a wheel may create an asymmetric reaction on the seat against windblast, initiating a yaw that continues (or even accelerates, due to aerodynamic instability) - until ultimately arrested by inflation of the drogue chute. This yaw perturbation then is a precursor to the drogue becoming violent and injurious, as the man-seat is "snapped back" to a forward position. In addition to the possible yaw perturbation caused by a wheel failure releasing one side of the seat from X-axis reaction (thus pirouetting the seat around the Z-axis), this rail asymmetry (some wheels dragging, some wheels lost, etc) may additionally cause a "roll" perturbation to the man-seat. If one rail (port or starboard) remains engaged and frictional on the seat – pulling downward against the CKU-5 propulsion – while the other side partially releases the seat (due to the wheel failure; eliminating friction), a roll-torque on the man-seat may be produced that is several thousand foot-pounds around the X-axis. Either mal-turn (yaw or roll) presumably erodes the margins of apogee and divergence.

10) BALLISTIC FEEDBACK. In reality (and optionally in the ejection models) – and in contrast with quick "F=ma" hand-calculations for seat acceleration approximations: The CKU-5

catapult responds to restraint (pilot mass, limb restraints, wheel friction, g-load, etc) by somewhat increasing its thrust (due to the ballistic feedback of gas generation rates in the telescoping tube volume, which drives the combustion pressure, which drives the propellant burn rate). This ballistic feedback may be one of the reasons we have not seen more catastrophic deceleration (seat stops) on the rails, and may account for the seat accelerometers recording "fits and starts" (wheel snags, then ballistic rebound, then wheel snags, etc). However, this type of "sputtering" up the rails is not the design intent of the egress, nor are the resulting pressure excursions within the CKU-5 catapult combustion chamber (increased due to restricted motion) going to be the designed pressure profile. Further, spinal injury to pilots can be magnified by "fits and starts" of acceleration; worse than a "constant 10g" (which compresses the vertebra, once) is the repeated unloading and reloading to 10g (which can cause an inertial "running start" and re-collision of the vertebra – like train cars re-engaging - now multiple times during an ejection).

11) SEVERITY of CURRENT FRICTION-BASED ROLLER. A wheel will generally rotate due to its axle being the "path of least resistance" (friction on the wheel at its axle is generally much less than friction at the wheel's contact surface – if for no other reason; due to the leverage afforded by the outer wheel's radius around the axle's radius). In the case of an "icy road", a tire can slide instead of roll, but even then: it's generally the brakes or transmission that is causing the tire to skid – not friction from the wheel's internal bearing. In the case of this ACES-II seat roller design (hand-assembled dry metal wheels on a metal shaft) – multiple wheels have been found with "flats" ground on their contact surface – indicating these wheels have "preferred" to lock and scrape their way up the rail during ejection, rather than roll around their axles. These grindings on the wheels communicate how badly the ACES-II roller assembly is currently functioning: During high-speed ejections, it's easier (less friction) to lock up the wheel and grind flats on steel wheels (in only 3 feet of travel), rather than to rotate the wheel on its shaft.

12) HIDDEN FAILURES with MODERN DISCOVERY. Even if seat roller friction was causing intermittent ejection malfunctions since the 1970s, identification of a design deficiency would have been difficult – as these wheels operate properly during routine hand-checks (seat installation and removal, "hand-spinning", with small ~20 lbf "handling" loads on the rollers), and at low airspeeds. Thereafter – when wheels have been discovered "torn off" - there is uncertainty as to whether ground- or water-impact during real-world ejections, or even the free-flight windblast, has caused this wheel loss. Additionally, the aircraft (with its seat rail evidence and half of the catapult hardware) is typically destroyed or lost in the ocean after an ejection. So, when the ACES-II seat wheels structurally fail or functionally "lock up" at high airspeeds, there is arguably "nobody around to confirm it" (except for investigators who are able to report "flats" have been ground on some recovered wheels). Only with the advent of modern electronics added to the ACES-II seats (three-axis accelerometers and digital recorders mounted onboard the seats during the last 6-10 years) have investigators had the opportunity to see this spinal acceleration dropout (which then drew attention to potential friction and roller design as being the cause).

13) CONCLUSION: The ACES-II seat (and virtually any other seat; the Mk16, future ACES-5, or otherwise) would benefit from an improved seat roller. Ejections would more closely achieve their design intent – as well as be more reliable, and more ballistically-repeatable – if seats use a more modern, durable, and semi-frictionless roller bearing design (a "cam follower"), rather than the current "friction-based" (sliding or bushing) rail guidance.

14) OPTIONS for ADVANCEMENT: Numerous "mid-range" improvements are conceivable; merely more-routine lubrication of the wheel and shaft, insertion of oil-impregnated brass bushings, etc. However, these mid-range improvements still retain a nominally-high friction coefficient (~0.05 to 0.15, compared to a roller bearing of ~0.001 to 0.005) so that when burdened with a ~10,000 lbf leveraged windblast they would still produce a sizeable friction resistance (hundreds or thousands of pounds). Additionally, these mid-range solutions may intrinsically vary more with dirt, salt, vibration, temperature, wear, and maintenance cycles – bringing the net ACES-II seat catapult performance back to an unpredictable state in high-speed ejections. The finely-tuned and sensitive response of a closed-volume propellant burn (an ejection catapult) would remain unpredictable if these friction responses are varying; occasionally high (thousands of pounds), and occasionally low (as the seat rollers vibrate and "bounce" off the rails – causing friction to intermittently disengage and reengage). In other words: A catapult can theoretically be designed for a zero-friction system, to safely eject a pilot (by achieving ~10-15g), or redesigned for high power to achieve that same 10-15g with a high-friction system (if the friction were reliable; consistently large) – but then that higher-powered system would overpower and injure the pilot if the friction intermittently disengages (by F=ma; a drop in friction over-accelerates the pilot, producing a high DRI & MDRC). The key is for the seat roller to respond consistently (either high or low friction – but not intermittently). Since the creation of the ACES-II seat (~40 years ago), hundreds of interchangeable "cam followers" have been developed that are finely computer-machined, off-the-shelf, industry-proven, of reasonable size for the ACES-II seat and rails, and appear of higher reliability than our current seat rollers. These modern rollers now include options for bearings that are high-strength (captured needles), thrust tolerant (tapered needles; cones), self-lubricating and sealed for thousands of zero-maintenance cycles across a wide range of temperature, dust, salt, and vibration environments. A brief market study could identify COTS parts that are readily replaceable in the existing mounting bores of the current seat rollers (or possibly with some additional fittings or minor brackets) – installed efficiently and with a low capital cost, requiring virtually no future maintenance, and providing a higher reliability in the same "form, fit, and function" as the current seat rollers. Restoring the ejection velocity (speed up the rails) to its design-intent (high speed and low friction, such as at low airspeeds) may also improve the survival of the seat rail and other seat/aircraft hardware, as the engagement dwell is reduced.

CONCLUSIONS

Having run simulations of the theorized causal capability of ACES-II Seat Roller friction to produce detrimental ejection anomalies, verified these results by hand-calculations, correlated these results with observed (incident and sled-test) findings, and reiterated them with logic of the dynamic mechanics, the following conclusions are made:

1) The legacy design of the ACES-II seat roller assembly (a dry metal wheel on a metal shaft; lacking load-rated roll bearings) appears to explain the Aviano (and several other) ejection anomalies (low-g, and possibly man-seat yaw), along with numerous under-performances during sled tests – all of which appear to erode the safety margin of high-speed ejections.

2) The CKU-5 ROCAT is designed for (and lot-acceptance-tested against; on a greased/Teflon slug-track) a "frictionless" egress of a man-seat up the seat rails, and as such: The CKU-5 ROCAT is currently being installed and used in a load environment for which it was neither designed nor lot-accepted (particularly: the high-friction ACES-II seat roller response; "locking up" and grinding up the rails, particularly during high-speed or adverse-angle ejections).

3) Improvement of the ACES-II seat roller design (to replace with "cam follower"-type, low-friction, load-rated bearings, or similar) will exponentially relieve the loads on the system (as the improved brevity of rail dwell will lessen the exposure from windblast loading the rollers) – and will presumably improve the ACES-II seat's safety by improving margin in escape apogee, tail clearance, seat divergence, injury criteria (DRI, MDRC, etc.), performance repeatability, propellant ballistics operation, and structural reliability.

RECOMMENDATIONS

1) As shown in Figure 16; develop a retrofit subassembly to replace the existing ACES-II seat's "bushing-style" wheel with a modern "bearing-style" roller, which…
    a. Can respond to the expected bearing loads (X-axis; ~2,000 lbf nominal per wheel, up to 10,000 lbf, depending on potential other conditions and failures to be discussed) with no structural failure, and a friction coefficient of 0.01 or less – when tested over a minimum period of 0.3 seconds and at roll speeds up to 50 fps, across the full qualification temperature range (-65F to 165F).
    b. Continues to operate (i.e. no structural failure, and friction coefficient remaining 0.01 or lower) while resisting 1,500 lbf per wheel of "thrust loads" (Y-axis loads; approximately 3g on a 350lbm man-seat, or 9g over all 3 wheels on a side, from the lateral acceleration of an aircraft's yaw and/or roll-rate).
    c. Fits readily into the ACES-II seat's current wheel mounting hardware or holes, to allow a minor (less than 15 minutes per wheel) change-out from the legacy wheel to the replacement assembly, during routine seat maintenance.
    d. Has an already-documented pedigree of reliability at 99.9% and 95% confidence for 10,000+ hours under comparable loads (thus alleviating major re-qualification programs; only static/hydraulic load-testing of the replacement assembly on several seats, then certainty of improved reliability is achieved by insertion of this roller as replacement of the current roller).

e. Leverages the modern advancements of off-the-shelf cam roller designs (interchangeable and selectable sizes for easy fit and compatibility, sealed ball/needle/frustum bearings for zero-maintenance, low-friction, heavy-duty designs, high-cycle-proven, salt/chemical-tested, vibration-tested, temperature-tested, etc).

2) Insure that no future system with a limited-energy catapult (such as a propellant charge; Mk16, ACES-5, or similar) is fielded to the fleet without a modern "roll bearing" release design (or at least a seat-to-aircraft friction coefficient which remains below 0.01 under normal (X-axis) loads of 10,000 lbf and lateral (Y-axis) loads of 1,500 lbf).

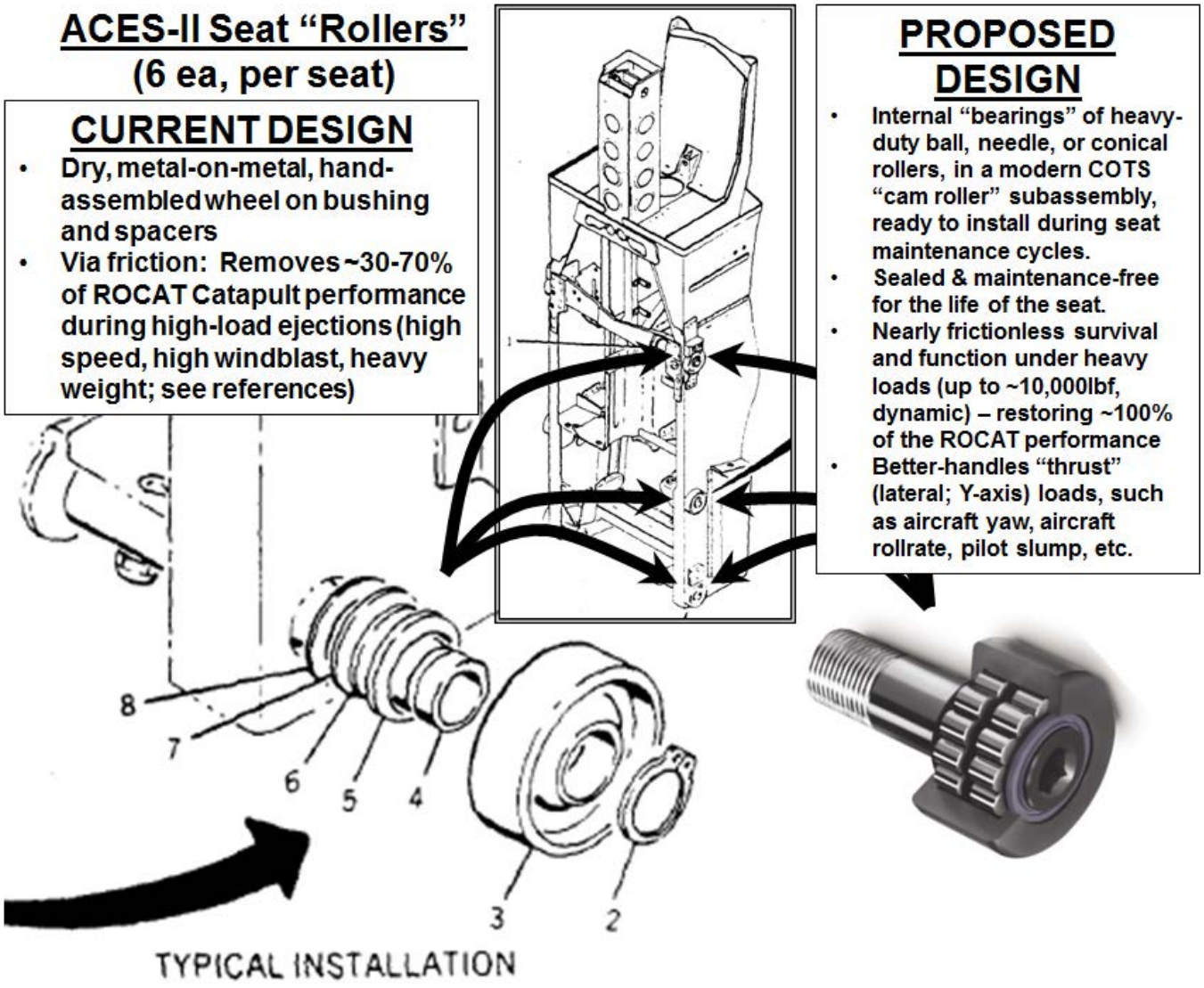


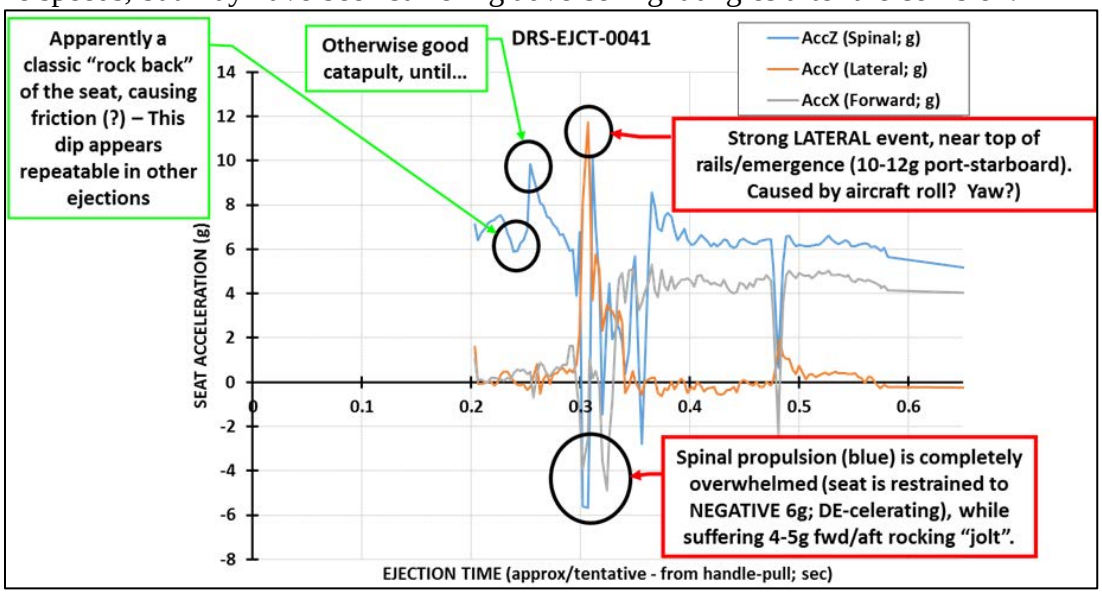
Figure 16 – Illustration of Recommended "Cam Roller" to Replace Current ACES-II Seat Rollers

AFTERWORD

During the signature process of this report, a cursory retrospective and another preliminary investigation of a recent ejection incident echoed the urgency to remedy this roller design.

1) B-1 Ejection, Montana, 19 August 2013: The second seat (of four) to eject from this aircraft – which was in an uncontrolled roll, and 400 knots – was observed via DRS to have suffered a negative-g acceleration (complete loss of catapult acceleration) during ascent up the rails… and lost all 4 of the lower wheels.

2) F-16 Mid-Air Collision near Charleston, SC, 7 July 2015: DRS of this successful ejection showed even more severe losses in man-seat acceleration, suggesting rail friction was grinding the seat into a complete reversal of egress acceleration (designed: +8g, actual: -6g). This aircraft was not at extreme speeds, but may have been suffering adverse flight angles after the collision.



As long as these artifacts (structurally removed wheels, and spinal accelerations deviating more than ~20% off of designed thrust values) are considered "anomalies", rather than "failures" – then resolution of these clear and hazardous deficiencies may remain inadequate.

APPENDICES

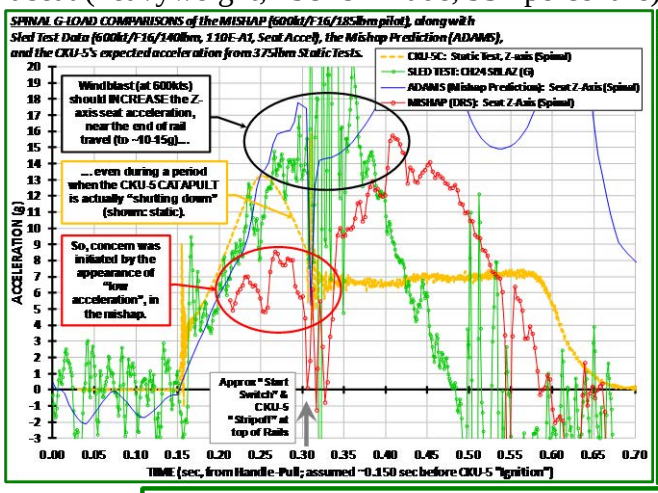
REF-1, APPENDIX A: PRELIMINARY "FAULT TREE" FOR "ARTIFACT #1"

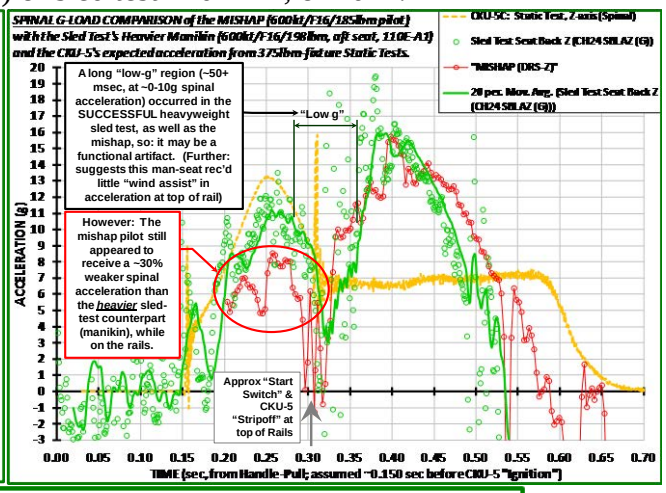
While no "failure" has been confirmed, and a ready explanation may become evident from other more expert members of the team, we will define here a "failure", only for purposes of mapping a fault tree to organize possible explanations.

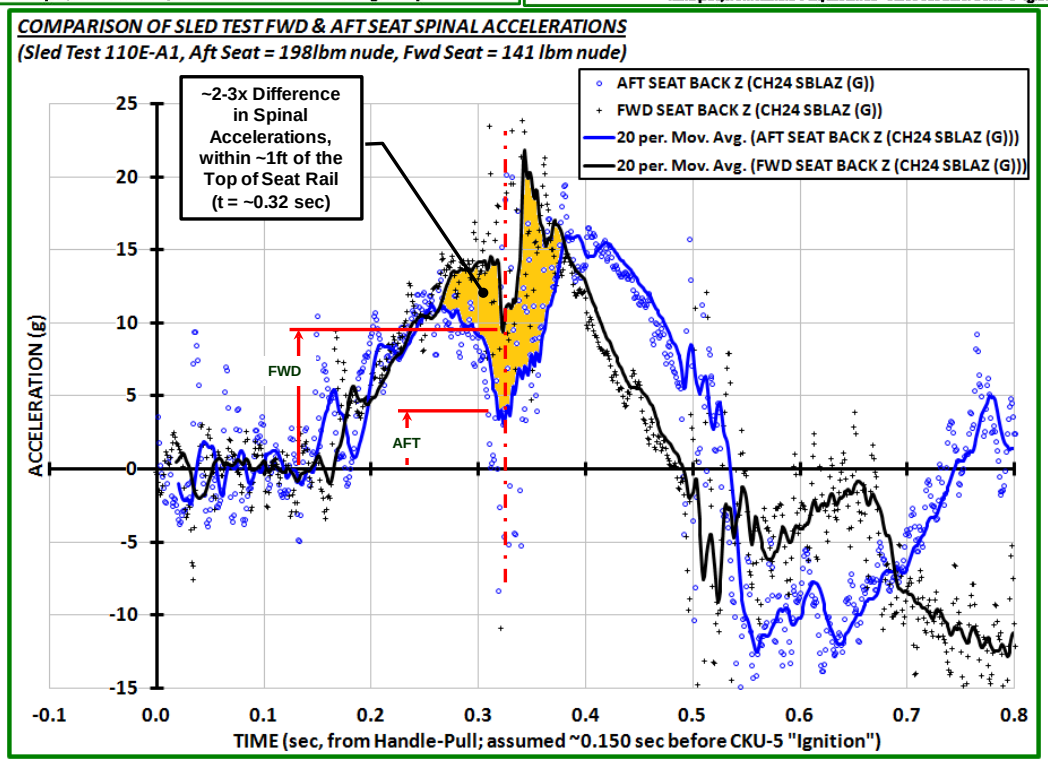
To that, the "failure" (Artifact #1) will be defined as:

"A low-g (~0-10g) spinal (Z) reading on the DRS of an ejecting ACES-II seat, any time during the CKU-5 catapult/rail travel, and within ~1-2 feet from departure of the top of rail, at F-16 airspeeds approaching 600 keas."

This behavior is indicated below [repeating Ref-1 figures], by the DRS of the subject mishap, and by the aft seat (heavyweight; 198 lbm nude, 95th percentile) of sled test 110E-A1, of 2012.







FAULT TREE

… for the "failure" defined as: "A low-g (~0-10g) spinal (Z) reading on the DRS of an ejecting ACES-II seat, any time during the CKU-5 catapult/rail travel, and within ~1-2 feet from departure of the top of rail, at F-16 airspeeds approaching 600 keas."

Legend:

GREEN =	Disproven; evidence indicates this parameter is not the cause of the failure
YELLOW =	Investigation remaining
RED =	Proven; evidence indicates this parameter is causal to the failure

1.0 DRS ERROR		**PRELIMINARY DISPOSITION**
1.1	DRS out of calibration, mis-designed, non-responsive, or otherwise inaccurate.	Not causal; DRS tracks sled test seat-back acceleration, manikin chest, and post-sustainer g's appear reasonable. (See Fig. 21)
1.2	DRS mis-reads a local seat "flexure mode", vice actual man-seat bulk translation	Not causal; DRS tracks sled test seat-back acceleration, manikin chest, and post-sustainer g's appear reasonable. (See Fig. 24)
1.3	"Slump" compression/extension of pilot/manikin causes mis-match of seat acceleration from pilot torso acceleration	Not causal; DRS tracks sled test seat-back acceleration, manikin chest, and post-sustainer g's appear reasonable. (See Fig. 24)
1.4	"Geometry Rotation Error"; the DRS's mounting (aft & starboard on seat) allows rotation of the seat (such as: around the seat Cg; an aft pitch or starboard roll) to drive the measurement of the DRS's Z-acceleration downward	Not causal; DRS tracks sled test seat-back acceleration, manikin chest, post-sustainer g's appear reasonable, and primary period of concern is orientation-restrained on the rails during the catapult phase. (See App. B)
1.5	"Time Shift" error of DRS data: Misalignment of (properly-performing) high and low acceleration regions creates the FALSE appearance of low g's during the catapult phase (when the early data should actually be deleted)	Reportedly not the case. Teledyne assures that proper time-alignment is: ~0.060sec after CKU-5 signal, the DRS's 0.090sec "Power On Phase" data begins (confirming: that aligns CKU-5 stripoff and headbox time indicators, and matches sled test successes). Conversely: DELETING the "Power ON Phase" and starting the "Ejection Phase" DRS data at the same 0.060sec after CKU-5 signal causes the catapult & sustainer performance to appear normal. (Apparently a cosmetic coincidence. See Fig. 23)

2.0 CKU-5; LOW ENERGY (CKU-5 propulsion; booster grain and sustainer grain burned at lower-than-expected performance)

2.1	Temperature lower than nominal (cold Winter night on tarmac, little heat soak from heated cockpit during mission)	Not suspected. Winter temperature in Aviano ranges ~30-50F, and this night's temperature remained above 28F; not the "arctic" sub-zero temperatures at which signature performance drops occur.

2.2	Intrinsic to this particular CKU-5 unit (other failure; propellant formulation, ignitability, etc)	Not likely. Unit is from a successful LAT lot, and showed no signs of unusual burn in the recovered motor section. (However, the catapult components remain with the aircraft at the bottom of the Adriatic, so no verification of catapult performance has been made).

3.0 LOST ENERGY

2015 Note: Branch color updated to "Red", for this report

3.1	SEAT RAIL & ROLLER MECHANICS (Flexure, failure, binding, skidding, or other imperfection vice "rolling", impedes seat travel)	TBD. While some roller wheels were found nominal, others were missing, and the rails remain with the aircraft at the bottom of the Adriatic, so no verification of rail condition has been made. Rail flexure above & below the upper support points is notable.
3.2	FLOOR (Aircraft floor - or connective hardware - flexes downward, particularly under heavyweight catapult & maneuver, reducing catapult compression)	TBD. Anecdotal sled test observations from the last ~2 years have noted, "Sled tests (with aircraft floors) seem to underperform static tests (in catapult thrust, sep velocity, and man-seat height), particularly at high speeds". This mishap aircraft was under an additional ~2 g's during catapult firing, high windblast, and heavy pilot. Current aircraft floor is with the aircraft at the bottom of the Adriatic, so no verification of floor condition has been made.
3.3	RESTRAINTS (F-22; arm/leg restraint mechanism taps energy off of the seat motion during catapult phase)	Not causal. (No arm/leg restraints were on this F-16 aircraft)
3.4	LEAKS - EXTERNAL (peripheral attachments to CKU-5; hoses, DRS hardline, splitters, etc)	Not causal. CKU-5 metering tube, and CCU-22 firing pins, restrict massive gas loss from the CKU-5 catapult phase, even if external peripherals are lost. Seat was recovered, and no anomalous breaches were noted.
3.5	LEAKS - INTERNAL (CKU-5 catapult o-rings, orifices, seals, gaskets, etc - intrinsically, or from misalignment of booster & launcher tubes due to seat/rail flexure or failure)	Not likely. The interior of the recovered tube was observed for anomalous erosion, scuffs, or other indication of blowby or misalignment damage, with none noted. However, the bulk of the catapult hardware remains with the aircraft at the bottom of the Adriatic, so no verification of catapult function has been made.

4.0 NORMAL ARTIFACT of NORMAL FUNCTION (although possibly/previously unknown)

4.1	"Drafting" eddy of windblast counter-intuitively arcs air "downward" on man-seat's attempt to climb the rails.	TBD. High-speed sled video (110E-A1, 600kt, fwd 5% & aft 95% pilots) generally shows the expected, strong aftward windblast, but anecdotal notes of counter-intuitive eddies have been made, and sustainer "plume flashes" into the cockpit are seen on the aft pilot. Transonic flow behavior can be chaotic.

4.2	SEAT PITCH ("Headwind", if man-seat pitches ~60-deg forward, causes CKU-5 sustainer to "fight" the oncoming windblast)	Not causal. While this phenomena is possible during the sustainer phase, that would not explain a "low g" during the catapult phase, when seat pitch is controlled. (Further, forward pitch is unlikely, even with imbalances such as boot windblast, when a 600kt windblast on the torso is tipping the man-seat backwards over the top of the rails).
4.3	AIRCRAFT G-LOAD (ongoing maneuver of aircraft; approx +2g spinal, could have "reduced" the catapult's acceleration performance measurement)	Not causal. Logical proofs: First, "subtraction" of a ~2g aircraft environment would not add up to the apparent ~5-10g deficiency. Second, a contained solid propellant (catapult) somewhat "self compensates" to restraint by increasing burn rate, so a superimposed "2g" would have a "less than 2g" effect. Third, since the DRS measures acceleration of the seat, aircraft acceleration would be INCLUDED ("added"), so if the DRS measures "+5g" during a time when the aircraft is "pulling +2g", then the actual egress performance was even LOWER (+3g).

REF-1, APPENDIX B: PRE-RESOLUTION OF SOME FAULT-TREE ITEMS FOR ARTIFACT #1

Over the various weeks of the SIB, particularly following the recovery of the DRS, numerous studies were conducted, profiling data from across the fields (graphical studies, test data, theoretical modeling, expert discussion, etc), in an attempt to explain "Artifact #1" (low spinal g-loads during catapult and rail departure). While no explanation was found (and no formal fault-tree was accomplished during that time), the following narrates some results of these studies.

Approximately two-dozen ADAMS model studies (experimental scenarios) were exercised, to explore the sensitivity of the DRS's recorded accelerations to various anomalies, such as pilot Cg shifts ("up and back" from Air Force defaults, for tall/thin body shapes), boot flail aerodynamics, arm flail mass and aerodynamic effects, drogue chute inflation delays, CKU-5 ROCAT performance variations, aircraft pitch and roll (and rate) effects, atmosphere effects (wind, density altitude based on colder weather), seat rail structural failure and early release at top of rails (including asymmetry), etc. No conclusive match was found, to explain "artifact #1". As an example of these analyses: Figure 17 shows the flyout predicted for this incident, if the aerodynamics are altered by the snagging of a helmet on the port pitot tube of an ACES-II seat).

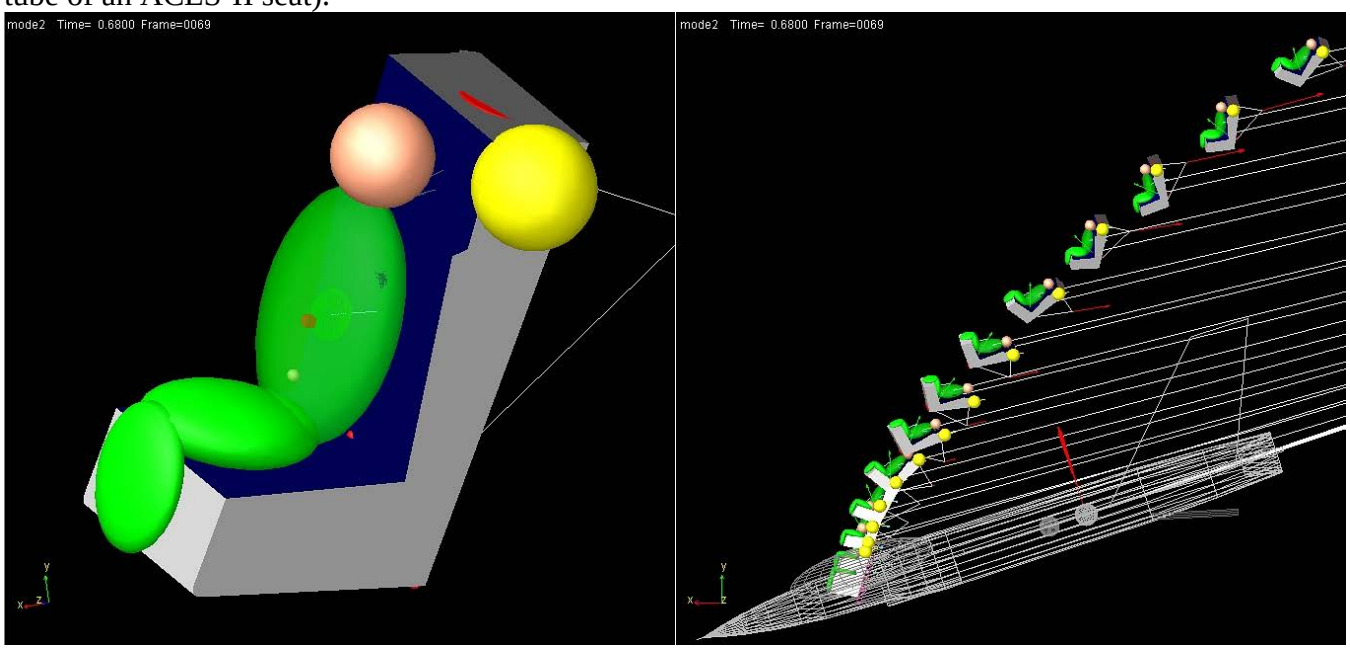


Figure 17 – Example of a Deviation Analysis; Aerodynamic Helmet on Pitot Tube (from ADAMS)

During this period, several conclusions were made which may eliminate several "branches" of a prospective "fault tree" to explain the cause of Artifact #1.

Confirmation was achieved (via review of sled test data, containing both "high-fidelity" accelerometers and onboard DRS) that the DRS appears to be capable of accurate readings; tracking well in both time & magnitude with the "high fidelity" accelerometers onboard the sled test seats. Figures 18 and 19 show this good match, between onboard DRS readings (on back starboard of seat) and their comparable sled test instrumentation measurements from additional high fidelity accelerometers (mounted on the back port of the same seat), for the same ejection event. This finding provides good confidence in the DRS design and concept (and suggests DRS errors were NOT the cause of Artifact #1).

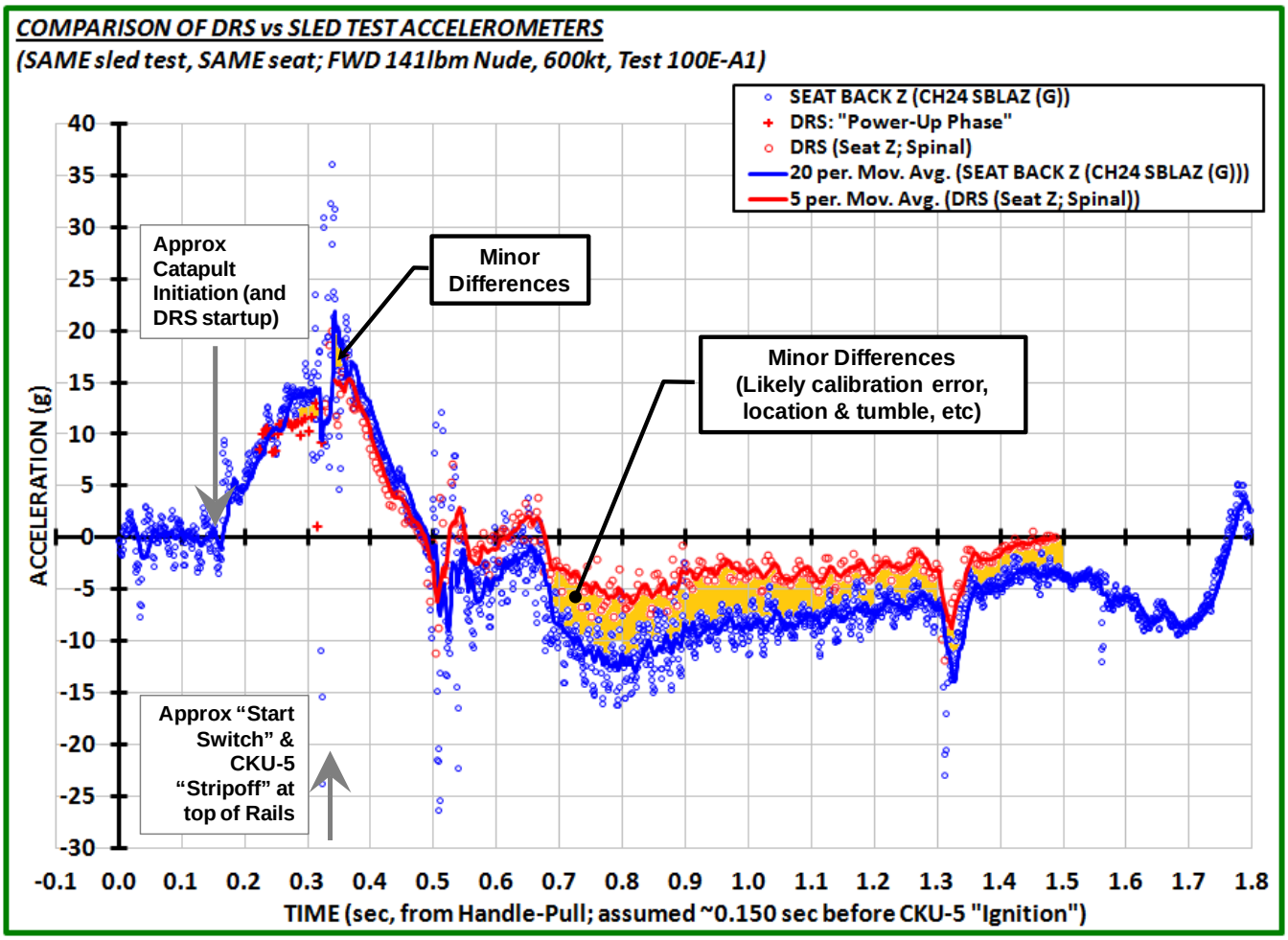


Figure 18 – Proof of DRS Accuracy; Mostly Complies w/ Lightweight Sled Test Instrumentation

It should be noted that the DRS intrinsically has a ~7.5 deg mounting alignment difference, off the Z-axis of the seat, so there will always be some (small) numerical, trigonometric deviation from "pure" Z-axis readings, prior to the DRS data being converted from this misalignment.

Figure 18 also captures the "good" (expected) performance of the catapult and 600kt-emerged sustainer phases; exhibiting 10+g spinal accelerations, throughout the regime of being "at the top of rail, +/- 1ft". Figure 18 also confirms the good timing-alignment achieved (aligning spinal acceleration timing marks from the headbox initiation at t = 1.3 sec, and earlier at top-of-rail "stripoff"). This finding confirms two things; the need to use a ~0.060sec delay (battery warm-up period) to start considering as the DRS's time of "first data", and that this "first data" is the initial "Power-On Phase" data (not the subsequent "Ejection Phase" data, which begins at the "Start Switch"; near the top of the rails). Further, this finding shows two more things; that the DRS's "Power On Phase" data (marked as red "+" signs, vice the "Ejection Phase" DRS data, marked as red circles) is largely capturing the majority of the CKU-5 catapult phase, and that the Power On Phase is measuring this catapult performance fairly accurately.

Figure 19 captures this same successful instrumentation as Figure 18, but also appears to have captured an "artifact #1" event of the spinal g-load dropping out to near-zero values within a foot or two of the top of rails (near the end of the catapult, and the beginning of sustainer phases of the CKU-5).

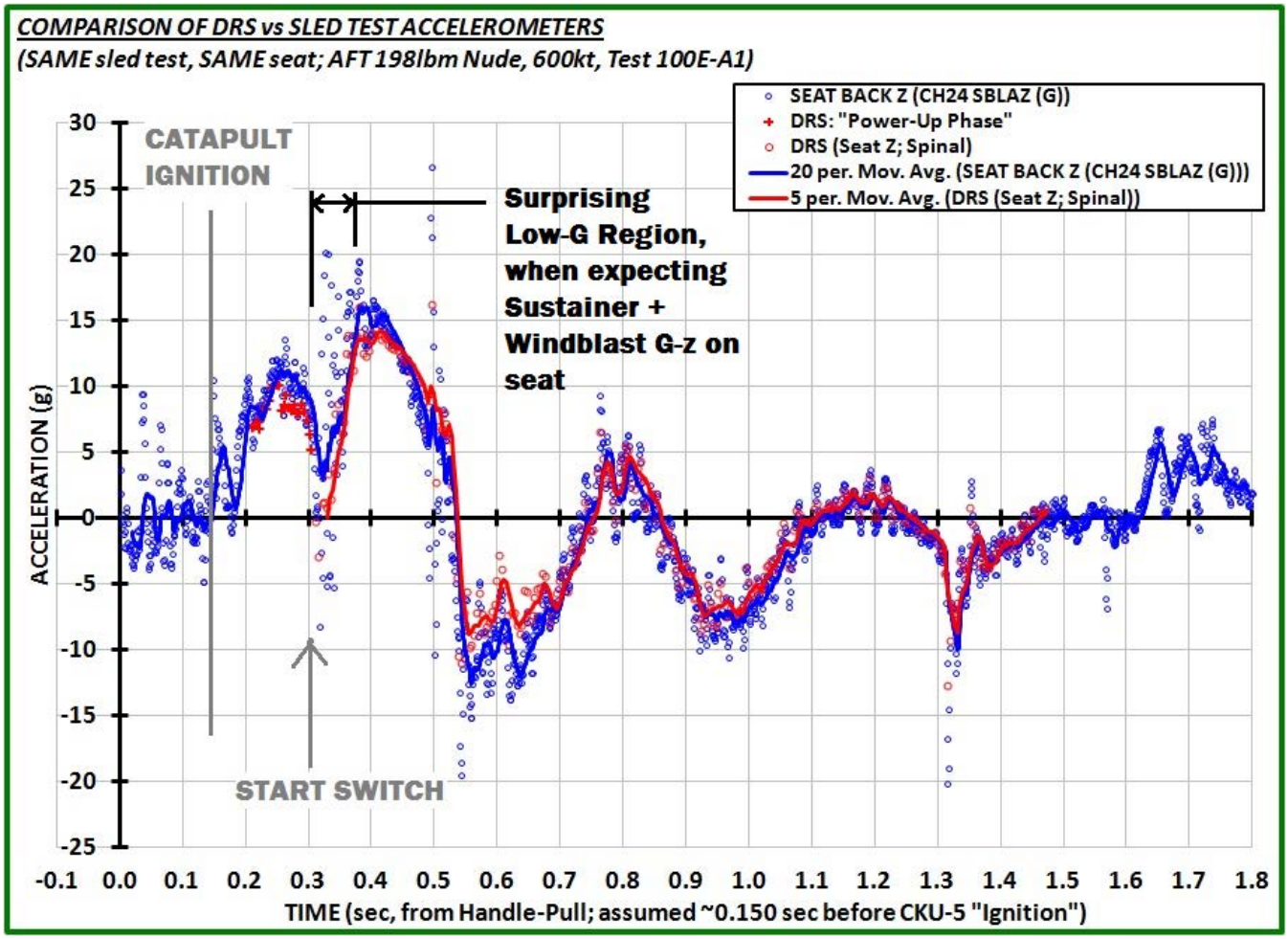


Figure 19 – Proof of DRS Accuracy; Mostly Complies w/ Heavyweight Sled Test Instrumentation

Therefore, it was confirmed that the DRS readings require ~40-60 milliseconds (nominal "best fit": ~60msec) to begin recording the first data point, from the time the CKU-5 ROCAT is first delivered its initiation pressure, until the time the DRS records its first acceleration measurement (in "Power On Phase"). This ~60 msec includes both the ~40msec nominal "battery start-up" time of the DRS, and the CKU-5's prior "catapult ignition" time to communicate the initiator gas into catapult chamber combustion and up the metering tube of the CKU-5, and down the hard pipe to the DRS. Confirmation was achieved that – contrary to the precedent of some Teledyne studies – the initial data of the "Power On Phase" from the DRS (prior to the "Ejection Phase", at the start-switch) – IS data of good fidelity (tracks numerically right with fully operating, high-fidelity "sled test" accelerometers). Further confirmation was achieved that the first data point of the "Power On Phase" – NOT the first data point of the "Ejection Phase" – is the data point intended when Teledyne teams report this "40 msec startup delay" of the DRS.

Previously, as shown in Figure 20: Multiple discussions had occurred, ranging from +0.100 sec delays (spec max), to -0.050 sec delays (if sneak paths or data recordings or phases were misunderstood), and – the latter (shifting time ~150msec earlier than the "max spec") did make the period of the CKU-5's operation appear "nominal", rather than "anomalous". However, these further studies of the sled test accelerometers and DRS data – complete with time-datums of CKU-5 stripoff, and later headbox launch

- confirmed that the nominal delay of ~0.060 sec (from CKU-5 initiation) is the proper alignment. The appearance of "nominal CKU-5 function", when shifting the DRS data to begin ~0.050 seconds BEFORE the CKU-5 (reportedly impossible), or deleting the ~0.090 second "Power Up Phase" data, appears to be only a cosmetic coincidence.

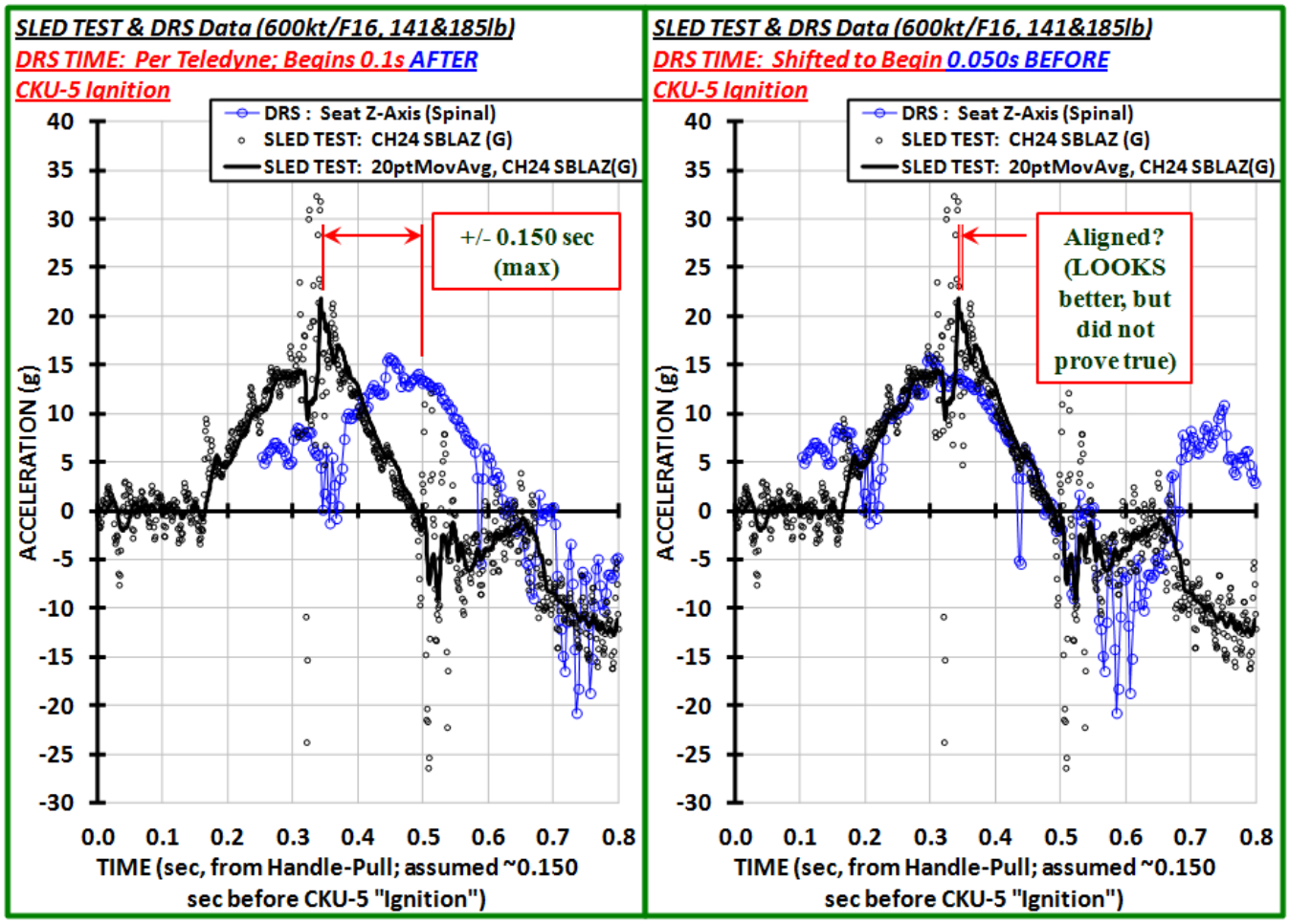


Figure 20 – Illustration of the Discussed "Time Shift", Cosmetically Fixes Artifact #1 & #2

As shown in Figure 21, confirmation was achieved that the "torso" of the pilot accelerates reasonably well with the seat-back (suggesting Artifact #1 was not caused by modal frequencies of flexure in the ACES-II seat's structure). The sled test's aft seat-back accelerometer (Channel 24, SBLAZ) , manikin torso (Channel 3, CLAZ), and DRS-Z all three agree, showing that the cause of the "low-g dropout" is NOT merely an instrumentation accident, or a localized "slump" or structural flexure artifact in the manikin or seat, but rather (apparently) a true, macro, seat-motion artifact. Additionally, the mishap's DRS-Z exhibited this same artifact; spinal acceleration largely "zeroed" for ~0.030 to 0.050 seconds, near the top of the rail.

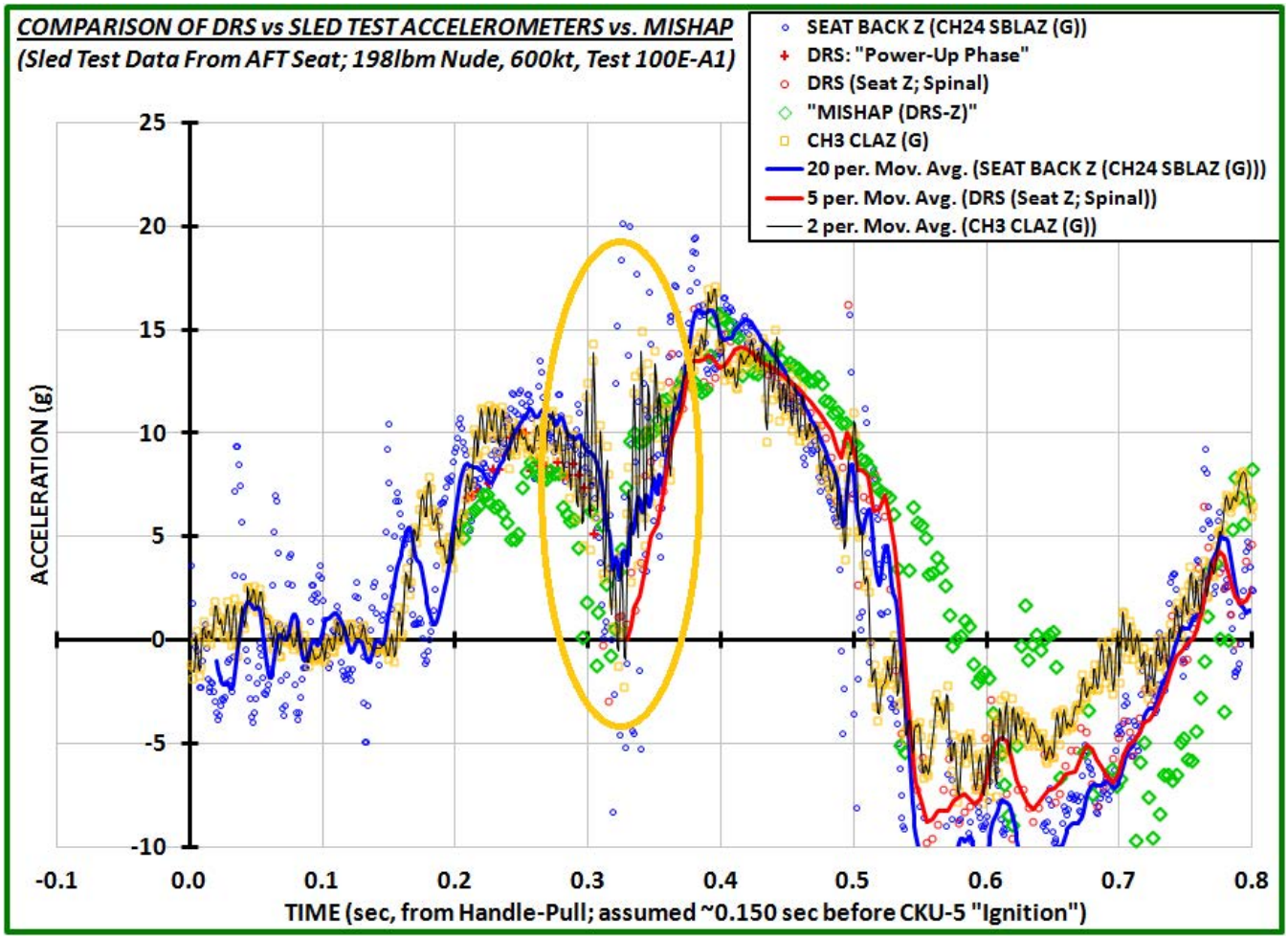


Figure 21 – Proof that Seat Flexure Didn't Cause Artifact #1 (Manikin Chest Accel Agrees w/ DRS)

Consideration was given that the ongoing "ambient" aircraft acceleration (about 2 g's) at the time of catapult firing could have "decreased" the CKU-5's catapult performance. The acceleration profile for the 90 seconds prior to the assumed ejection is shown in Figure 22, along with approximate Mach number. However, logical examination disproves this aircraft g-load from explaining artifact #1 ("low-g", including during catapult phase). First, while the aircraft was "bellying out" (positive AoA) as a high-g (~8-9g) "nose pull-up" maneuver, and retained approximately ~2-2.5g of this positive AoA at the time of ejection, "subtraction" of this ~2g from catapult performance would not explain the regions of catapult-phase acceleration which appear ~5-10g below the expected 10-15g performance, particularly during the "mid-catapult" g-load dropout of several g's, as shown in Figure 21, at approximately 0.25 seconds. Second, a contained solid propellant ("catapult") performance generally "self-compensates" against restraint, by increasing burn rate at higher pressures, so a superimposed "2g" aircraft environment would generally be expected to have a "less than 2g" reduction on the catapult's thrusted acceleration. Third, since the seat's DRS is mounted to measure inertial acceleration of the seat (not acceleration *from* the aircraft, or "infer" seat acceleration from thrust measurement), the aircraft's acceleration would be INCLUDED (i.e. somewhat "added") to the measurement of the CKU-5 driving performance on the seat. So, if the DRS measures "+5g" of spinal acceleration during the catapult phase, during a time when the aircraft is itself "pulling +2g" of spinal acceleration, then that

measurement indicates a net acceleration of the seat (departing the aircraft; catapult-driven) of only +3g (i.e. LESS than the DRS measurement of +5g).

Therefore, it would not be a reasonable attempt to explain a "low 5g catapult-phase acceleration" by suggesting the "aircraft g's inhibited this measurement", or that the ambient 2g aircraft acceleration should be "added" to this DRS reading, to report that the "actual ejection g-load was 7g". Conversely, the superposition of accelerations works the opposite; a 2g aircraft acceleration superimposed would suggest the CKU-5 catapult only added ~3g additional, to be measured as +5g by the DRS.

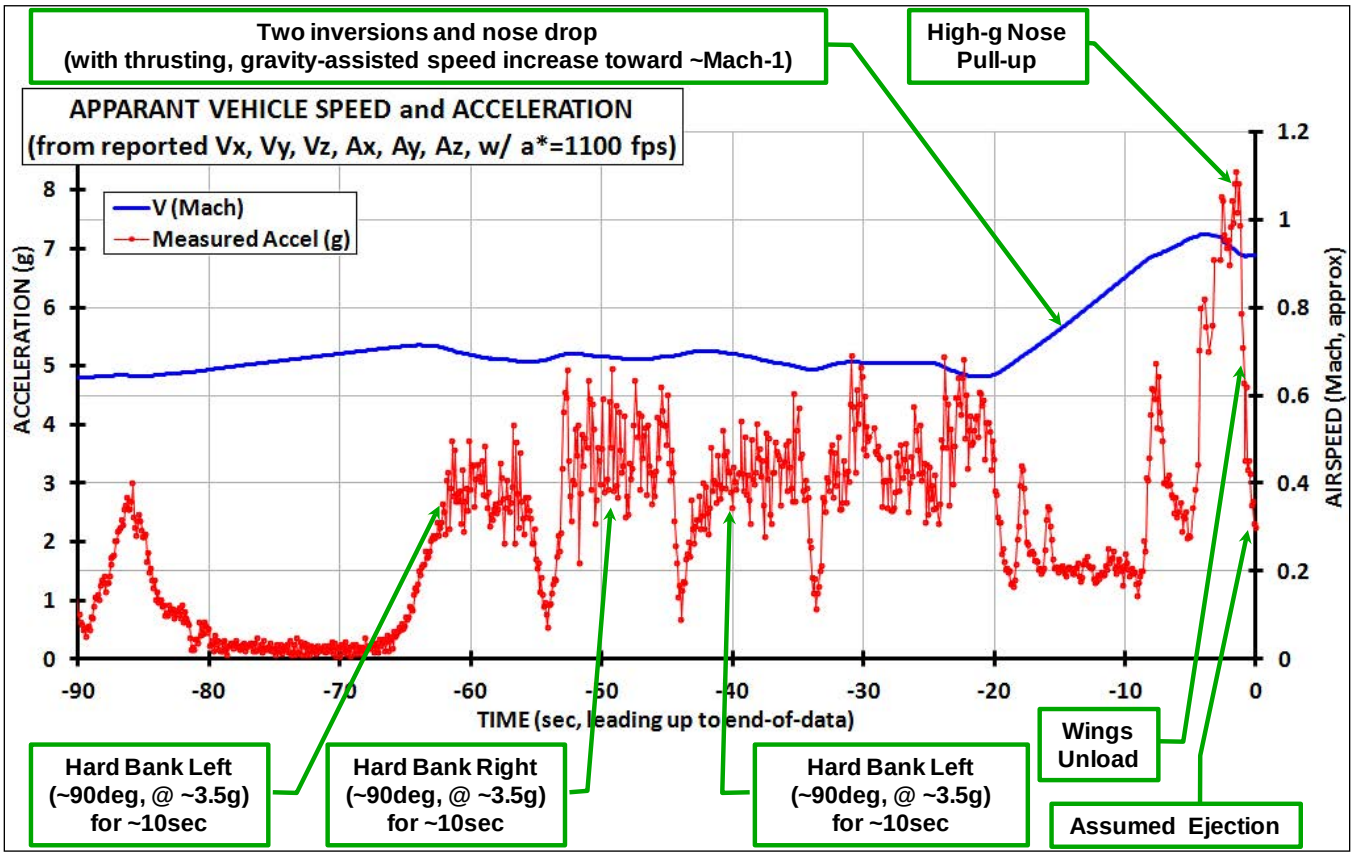


Figure 22 – Acceleration Report of Aircraft for 90sec Prior To Ejection (at ~2.3g)

(Note: the discussed aircraft "+2g nose pullup" example – while similar to the +2.2 to +2.4g observation of the mishap - is only approximated, and considered as being along the "spinal" axis for simplicity. The actual F-16's seat rail recline is 34 deg, so the actual spinal vector component is smaller than the "nose up" g's, and the seat rail friction/roller loads is higher).

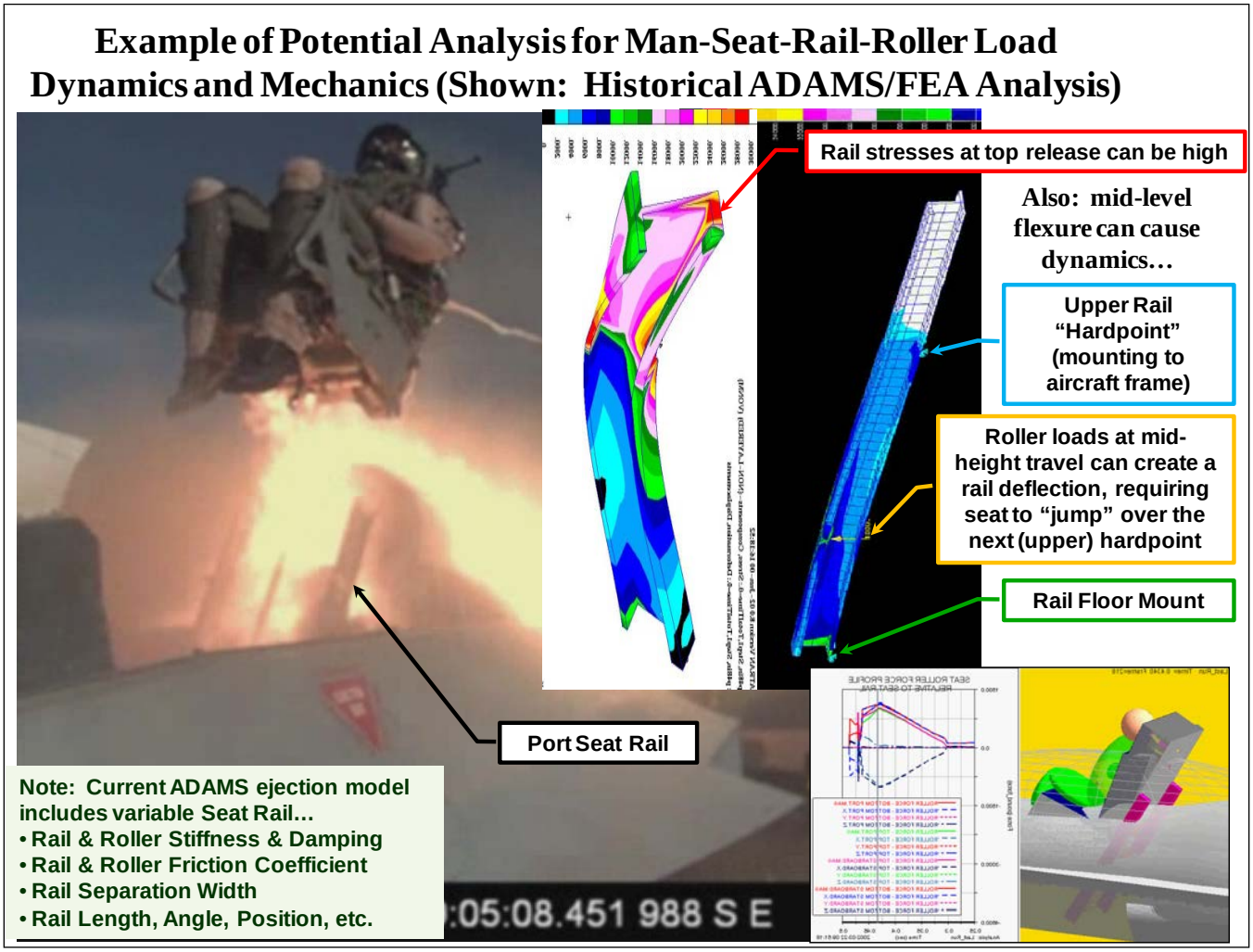


Figure 23 – Example of Potential Seat/Rail Mechanical Dynamics Analysis

While no analysis has been repeated for this particular scenario (high speeds, F-16 recline, heavyweight pilot, CKU-5C booster profile), Figure 23 shows an example of historical – and potential future - analysis of the man-seat-rail-roller interactions which could be re-analyzed, to check for motion restrictions caused by flexure or dynamics.