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A Suitable Platform for Storm Penetration, Risk Analysis for the SPA-10 Aircraft Modification

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Abstract

The SPA-10 project, sponsored by U.S. National Science Foundation, is to acquire and qualify a replacement for the retired T-28 "storm penetration" aircraft previously used to acquire meteorological data to enable understanding and modelling of mid-continent thunderstorms. The National Science Foundation selected the Fairchild A-10 (bailed from the U.S. Air Force) as the platform to be adapted to perform the storm penetration mission to altitudes of eleven kilometers, and funded Naval Postgraduate School's Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) as prime contractor. An expert panel conducted a review of the SPA-10 project in 2014 and recommended a risk analysis addressing hazards to the aircraft and pilots, such as icing, hail, turbulence and lightning. This paper presents the results of the risk analysis performed in response to this need, including recommended mitigations.

In general the A-10 aircraft systems and structure were shown to be robust and suitable, reinforced by an operational plan for incremental exposure to the full force of the storm. A key challenge was obtaining the necessary information to resolve the expert panel's concerns for a military aircraft designed in the 1970's, with significant upgrades since, for a radically different mission. The support and assistance of the USAF and the engine manufacturer, General Electric was critical to this endeavor. The participation of the operator of the previous storm penetration T-28 aircraft, the South Dakota School of Mines and Technology, was a crucial source for understanding the mission and operational environment.

Introduction

T-28 Aircraft: Storm Penetration Pioneer

The original "storm penetration" research platform was a modification of a T-28 Trojan, an aircraft designed and developed at North American Aviation in 1949 and produced through 1957 as an advanced trainer for the U.S. Air Force, Navy and Marine Corps. [1] A surplus T-28 was acquired by the South Dakota School of Mines and Technology (SDSM&T) in the early 1970's and modified to accommodate instrumentation to measure meteorological conditions in "deep convective clouds" including the violent and destructive mid-continental thunderstorms occurring in the North American Midwest.

As described by Honomichl, Detwiler & Smith [2] (the source of the information in this section), "These modifications allowed the T-28 storm-penetrating aircraft to fly through, and obtain microphysical observations within deep convective clouds, including severe thunderstorms that produced heavy hail, severe turbulence, extreme icing conditions, and lightning." The primary T-28 modification was armoring vulnerable areas with heat treated aluminum reinforcements tested to withstand 7.62 cm hailstones, adding 700 pounds to the aircraft (about 10% of the original empty weight). Further mitigations for the hazards of storm penetration flights include:

- Conductive canopy reinforcement
- Lightning rods and static dischargers
- Deicing the propeller & carburetor

Avoiding regions of high radar reflectance associated with hail diameter > 2.5 cm helped to preserve exposed instrumentation by reducing the probability of an encounter to 0.2%. Heavy hail is less common at higher altitudes above the 0° isotherm. [2]

Moderate to severe icing conditions were to be expected at all storm penetrations, corresponding to 2.5 cm ice accumulation during a passage through an updraft, usually either rime or mixed ice. (SDSM&T noted that the usual procedure to shed the ice buildup was to exit the storm and descend to warmer altitude.)

At the altitudes typical of T-28 storm penetrations (4 to 7 km) heavy and severe turbulence could be expected during 2% and 0.1% of the time in the cloud, respectively, and more so in the 4.7 to 5.7 km altitude range. This was apparently tolerable for the pilots.

Lightning was not a serious threat, any strikes were conducted through the conductive aluminum structure, leaving small pits at the exit point. The mechanical aircraft controls were unaffected.

With these precautions, plus rigorous inspection and corrective maintenance of any indications of distress, SDSM&T performed 300 storm penetrating flights over 32 years, accumulating 1700 deep convective cloud penetrations estimated to total over 1000 hours of exposure, all with the same airframe and no notable harm to the crew members.

In 2004 the SDSM&T T-28 was retired with the termination of National Science Foundation (NSF) funding, primarily due to limited altitude capability (7 km) and endurance [3], which constrained the scope of data collection.

The A-10 Storm Penetrating Aircraft Program

Figure 1. Fairchild A-10 Thunderbolt, a.k.a "Warthog" Note the positioning of the engine inlets relative to the inner wing section. https://img.planespotters.net/photo/302000/original/80-0194-usaf-united-states-air-force-fairchild-a-10c-thunderbolt-ii_PlanespottersNet_302341.jpg.

Starting in 2005, the scientific community considered options and launched studies for a plan to acquire and modify a more capable platform to build on the T-28 heritage, one with an 11 km ceiling, greater endurance, and more space and power for instruments and data collection. As early as 2008 the USAF A-10 was identified as a preferred platform and questions arose of its suitability for operation in the storm penetration environment with the hazards of hail, icing, turbulence and lightning.

In 2010 the National Science Foundation provided funding to the Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS) to acquire a Fairchild A-10 aircraft by inter-service transfer within the Department of Defense, and modify it for airborne atmospheric research missions in collaboration with the Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology. In 2013 the USAF delivered an A-10 to CIRPAS's designated modification center, Zivko Aeronautics Inc., located in Guthrie Oklahoma. (This aircraft was immediately demilitarized by removing sensitive components, including all armament.)

An expert review panel was convened by NSF in 2013 & 2014, and reported dissatisfaction with the identification and mitigation of a number of issues, many safety related: airworthiness approval, adding engine inlet anti-ice, reviews & assessment of suitability considering turbulence, icing, hail, lightning (including fuel tank explosion), pilot physiology, and science operations, closer coordination with the USAF SPO and review prior relevant test reports and operational assessments. This included a call for analysis of risks to the aircraft, operations, science return and costs.

This paper reports the initial risk analysis performed during 2014 in response to this need, based on study of Honomichl, Detwiler & Smith [2] and discussions with the authors to understand the thunderstorm environment, T-28 operations and procedures, the Zivko team detailing the proposed A-10 modifications, analysis of A-10 mishap reports referencing to lightning, icing, and hail, and qualification test reports for the GE TF-34 turbofan engine.

Initial A-10 Storm Penetration Risk Analysis

Significant USAF Mishap Reports: 1994-2014

USAF A-10 Pilot Operational Procedures [3] states: *7.6.1. Do not attempt flight through severe weather; however, if unavoidable, prior to severe weather penetration, obtain separate clearances. If not feasible, flights may assume an in-trail formation with a minimum of 1 NM separation between aircraft/elements. Obtain ATC clearance for a non-standard formation.*

This order may have limited A-10 exposure to severe weather, but a significant sample of mishap records was obtained from the Air Force Safety Automated System (AFSAS) to glean information on the relevant hazards and consequences. The request was limited to hazards particularly relevant to storm penetration missions; icing conditions and ice ingestion, hail and lightning.

There were eighteen (18) AFSAS mishap reports of damage due to engine ice ingestion in the period 1994-2014, seven of which noted damage to both engines, and one also noting "low power". These occurred in various locations in the United States, and in Germany, Afghanistan and Korea, and in all cases the A-10 was able to return to base with both engines operating. The damaged fan blades are replaceable in the field at acceptable cost, and these mishaps were rated as Class C or D. (For comparison, an engine ingestion of a turkey vulture in South Carolina in 2003 resulted in an uncontained fan blade failure and return to base on one engine, which was rated Class B.)

There were also six AFSAS mishap reports of hail damage, all reporting minor damage to slats or lights including one mishap report of a wing of six (6) aircraft all incurring similar hail & lightning damage, and one mishap report of a windscreen cracked by hail.

TF34-GE-100 Engine Qualification

General Electric provided the qualification reports for the A-10's GE TF34-GE-100 turbofan engines, including the Official TF34 Qualification Test Report [5]. The test results pertinent to the risks to the A-10 storm penetration mission are discussed below.

Ice Ingestion Test

Mauch [7] details the Bird and Ice Ingestion Test, which includes the following ice ingestion test results:

1. With fan rpm @ 6800 - 7000, sequentially introduce seven ¼ inch sheets of ice: three @ 6”×4”, two at 9”×4” and two at 18”×4”. Result: a total of eight curled blade tips with less than 1% thrust loss.
2. With fan rpm @ 1700 - 1900, fire three 1-inch hailstones sequentially @ 200 to 250 feet/sec. at blade pitch, tip and root, then @ 6800-7000 rpm fire another three 1-inch hailstones @ 365-405 feet/sec. at spinner, blade tip and blade root. Result, no foreign object damage
3. With fan rpm @ 1700 - 1900, fire three 2-inch hailstones sequentially @ 200 to 250 feet/sec. at blade pitch, tip and root, then at 6800-7000 rpm fire another three 2-inch hailstones @ 365-405 feet/sec. at spinner, blade tip and blade root.

Note: 1” = 2.54 centimeters, ¼” = 0.62 centimeters

The foreign object damage (FOD) in these tests was limited to local deformation of fan blades and a dent in the spinner, with a loss of thrust less than 1%.

The A-10 has no wing or nacelle anti-ice or deicing provisions, unlike most similar commercial aircraft and the Navy S-3 aircraft, which also uses the GE T-34 turbofan. The sheet ice ingestion tests appear to be representative of the ingestion of ice expected to be released from the A-10’s wing after flight through icing conditions. The ¼” thick ice sheets tested appear light relative to the 2.5 cm (1”) icing thickness cited in Honomichl et al [2]. This needs to be watched in initial storm penetrations in light of the AFSAF mishap reports involving flight into icing.

The 5.08 cm (2”) diameter hailstone tests indicate a margin of safety relative to the 2.5 cm experience in Honomichl et al [2].

Environmental Icing Tests

The purpose of these tests was to qualify the TF34-GE-100 engine for flight in icing conditions. The General Electric Environmental Icing Test Report [6] details the setup, procedures and results of this test. The test setup did not include the aircraft nacelle, the icing conditions were created in an 8 foot diameter inlet plenum feeding directly to the engine inlet. Ice buildup in engine inlet was photographed during the runs, and in situ after shutdown.

Six test run conditions gave the following results:

1. Idle at 5000’ altitude & 23^0 F, with a liquid water content of 2 gm/cubic inch. 5 minutes of running gave a light to moderate clear ice buildup on the engine inlet. No issues.
2. Operation at 25%, 43% & 51% maximum continuous power at 5000’ altitude & 23^0 F, with a liquid water content of 2 gm/cubic inch. No ice buildup observed.
3. Operation at idle & 25% maximum continuous power at 5000’ altitude & -4^0 F, with a liquid water content of 1 gm/cubic inch. Moderate milky ice buildup observed, no effect on engine running.
4. Operation at 34% maximum continuous power at 5,000’ altitude & -4^0 F, with a liquid water content of 0.5 gm/cubic inch. Light to moderate milky ice buildup observed.
5. Operation at 51% and maximum continuous power at 5,000’ altitude & -4^0 F, with a liquid water content of 0.5 gm/cubic inch. Light to moderate milky ice buildup observed. (Throttle chops & bursts reduce vibration.)
6. Operation at maximum continuous power, 51% and idle at 20,000’ altitude & -4^0 F, with a liquid water content of 0.5 gm/cubic inch. Light ice buildup. There was one bent fan blade after the maximum continuous power run.

Turbulence and Lightning Considerations

Honomichl et al [2] provides a thorough treatment of turbulence, due to the strong updrafts and downdrafts in the heart of the storm. Since probing this regime is fundamental to storm penetration, this risk is hard to mitigate. However, as the A-10 wing loading is almost twice that of the T-28, the “g” forces on the pilot should be less. However, study of the turbulence effect on wing loading and structural life seems advisable considering the radical modification of the gun bay, and with respect to the cost of wing replacement due to cyclic loading.

Lightning was initially a contentious issue, but appears to be primarily managed by maintaining electrical bonding between all exterior panels to assure the integrity of the Faraday cage preventing electrical discharges within the fuselage. Early concerns on the possibility of lightning igniting the vapor in fuel tank ullage were captured in the assessment of this risk, pending confirmation of information that the wing fuel tanks have bladders and the fuselage fuel tanks are protected with reticulated plastic foam and self-sealing membranes, a common measure on military aircraft at risk of cannon fire.

Aircraft Icing and Hail Damage

The baseline conversion plan proposes to add de-icing to the inner wing leading edges to protect the engine fan blades from ice shed from the inner wing sections. This relates to a proposal to adopt a drooped leading edge on the inner wing sections, in development to allow removal of the existing inner wing leading edge slats. The baseline conversion program includes armoring wing and empennage leading edges. It may be effective to defer these measures until the basic conversion is cleared and initial storm penetration runs can assess the need.

The single AFSAS mishap report of hail cracking a pilot canopy suggests “armoring” similar to the SDSM&T T-28 canopy modifications.

Initial A-10 Program Risk Analysis

As requested by the A-10 Storm Penetrating Aircraft Review Panel Report [3], risk analysis was initiated following the Naval Syscom Risk Management Policy prescribed by NAVAIRINST 5000.21. [10] (The current NAVAIRINST 5000 issue was 21B, and draft of issue 21C dated 10 December 19, 2014 was consulted and adopted.) The scope of the instruction covers risk identification, degraded technical performance, schedule and cost.

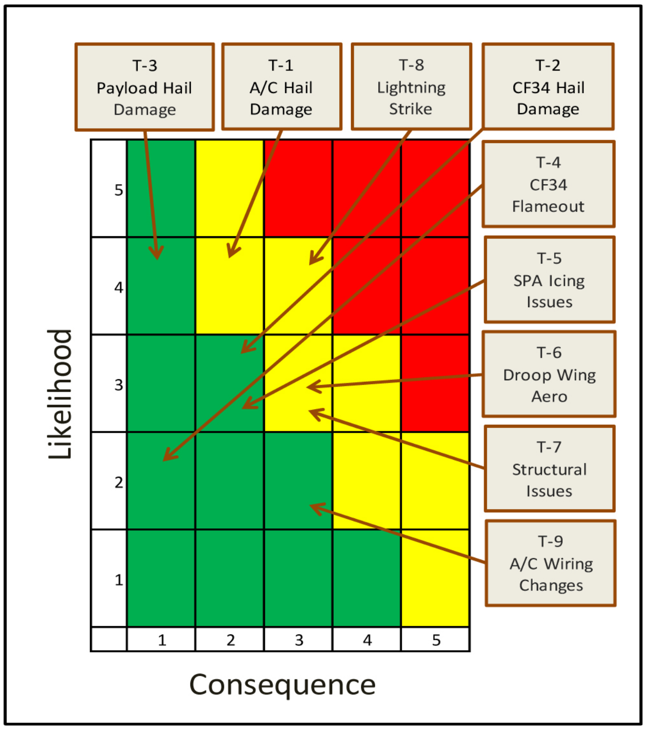

Figure 2. SPA-10 Risk Analysis Matrix adapted from the Naval program risk reporting template in NAVAIRINST 5000.21B [10] for reporting "risk management status in terms of likelihood and consequence".

Table 1. SPA-10 Likelihood Key for reporting risk management status in terms of likelihood used in the modified A-10 evaluations reported here. The likelihood level probabilities of occurrence seem appropriate for the risk incurred over one season of storm penetration missions.

Likelihood

Level	Likelihood	Probability of Occurrence
1	Not Likely	~10%
2	Low Likelihood	~30%
3	Likely	~50%
4	Highly Likely	~70%
5	Near Certainty	~90%

At the time of the work reported here, late 2014 through Q1, 2015, comprehensive mission capabilities & technical requirements and a detailed modification schedule and cost had not been established. The focus was on system safety related technical performance risk identification and mitigation planning to guide the A-10 modification program definition through qualification of the demilitarized and modified A-10 configuration, including consideration of hazards to the planned instrumented mid-continent storm penetration proving trials, but not to the instrumentation payload.

Table A.1, Technical Performance Risk Assessments, in the appendix to this paper, details the information and considerations from which the consequence levels were defined. Since the emphasis was on system safety, the technical risks considered are system safety driven, and program schedule and cost were not considered.

Table2. NAVAIRINST 5000.21B [10] Consequences Key, utilized in reporting risk management status for technical performance in terms of consequence used in the modified A-10 evaluations reported here.

Consequence

Level	Technical Performance
1	Minimal or no consequence to technical performance
2	Minor reduction in technical performance or supportability, can be tolerated with little or no impact on program; same approach retained
3	Moderate reduction in technical performance or supportability with limited impact on program objectives; workarounds available
4	Significant degradation in technical performance or major shortfall in supportability; may jeopardize program success; workarounds may not be available or may have negative consequences
5	Severe degradation in technical performance; cannot meet KPP or Key technical/supportability threshold; will jeopardize program success; no workarounds available

Conclusions & Recommendations

The reporting format was endorsed by the CIRPAS A-10 team as an effective tool to report the technical performance risk status.

Launching program risk analysis, assessment and reporting early in the program demonstrated its effectiveness in driving data collection and analysis that informs program planning and priorities, effectively driving out speculation with factual information.

Continued updating and extension of the risk management policy to assess all modifications and the full configuration of the proposed the storm penetration A-10 variant is recommended, including baseline cost and schedule impacts.

Given the favorable outcome of the technical performance risk assessment of the modified A-10, which is also pertinent to the baseline A-10, it is appropriate to consider and evaluate the option of graduated mid-continent storm penetration trials with an unmodified A-10, to explore the baseline capabilities and vulnerabilities to lightning, turbulence, icing, hail and other unknowns (e.g., unexpected flight crew hazards and performance limitations).

Identifying and assessing limitations and capabilities of the unmodified A-10 in the storm environment will eliminate unknowns, potentially exposing risks, and opportunities, overlooked to date, enabling mitigation of both recognized and unanticipated hazards, cost and program delays. These trials would also inherently address the effectiveness and suitability operational procedures, a class of risk highlighted by the NSF expert panel.

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APPENDIX

Purpose

The Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS), a research center at the Naval Postgraduate School in Monterey, CA (in collaboration with the Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology) has been selected and directed by the National Science Foundation (NSF) to acquire an Fairchild A-10 aircraft by inter-service transfer within the Department of Defense, and modify it for airborne atmospheric research missions, replacing the capabilities of a modified T-28 aircraft retired a decade ago.

CIRPAS has taken possession of a serviceable A-10 provided by the USAF to be modified for service in mid-continent storm penetration missions. This aircraft has been selected to support a significant mission expansion to a maximum altitude of 11 kilometers from the T-28's 7 km limit. Zivko Aeronautics has been contracted to design and implement the significant modifications required to de-militarize and convert the acquired A-10 to this mission. The USAF System Program Office (SPO) responsible for the A-10 has a considerable role in reviewing and approving the initial demilitarized A-10 configuration, including flight test and SPO airworthiness clearance.

This purpose of these tables was to initiate the implementation of a risk management process for the SPA-10 program, following the risk management policy prescribed by NAVAIRINST 5000.21. (The current NAVAIRINST 5000 issue is 21B, but a draft of issue 21C dated 10 December 19, 2014 was also consulted.) The scope of this document covers technical risk identification, risk analysis & assessment and some elements of risk mitigation planning and implementation.

At the time of their preparation, early in 2015, comprehensive mission capabilities, complete technical requirements and a detailed modification program have not been defined. The focus was on system safety related program technical risk identification and mitigation planning to guide the A-10 modification program definition through qualification of the demilitarized A-10 configuration, including consideration of hazards to planned instrumented mid-continent storm penetration proving trials, but not to the instrumentation per se.

Figure 2 in the is the Program Risk Reporting Matrix prescribed by NAVAIRINST 5000.21 for reporting program risk management status in terms of likelihood and consequences for technical performance and program cost and schedule risk assessments. This format is used in this document as the designated tool to summarize the estimated technical risk status reported in the Table a.1 appended to this report. Since the emphasis is on system safety at this stage, the technical risks considered are system safety driven, and program schedule and cost are not addressed.

The SPA-10 Risk Reporting Matrix appears in Figure 2, and Table A.1 provides the technical risk analysis table used in preparing it.

Table A.1. Technical Performance Risk Assessments

Risk Category	Risk #	Status	Title	Technical Risk Cause, Description & Consequences	Analysis / Mitigation	Likelihood	Technical Conseqence Code
Technical Risks	T-1	Open	Hail Damage to SPA-10 airframe & canopy	Large hailstone impacts may damage the canopy and degrade wing and empennage leading edge aerodynamics and structural integrity.	1. SPA-10 canopy is projectile resistant. 2. T-28 experience & trials indicate that the leading edge armoring (increased thickness) of the wing and empennage leading edges is effective in retaining structural integrity and can be replaced to restore the aerodynamic profile. Note: The de-ice modules (T5) are not in contact with the wing leading edges.	4	2
	T-2	Open	Hail Damage to SPA-10 Turbofans (2 x TF34-GE-100A & nacelle)	Large hailstones impacting fan and inlet may significantly degrade propulsion system performance and structural integrity resulting in mission abort and possible safety hazard.	Armoring the nacelle leading edge is expected to be effective, if needed. The CF-34 engine is certified to tolerate the worst expected hail size (2"). Fan blade refurbishment and replacement may be needed but can be accomplished in the field. The program has acquired spare engines & fan blades.	3	2
	T-3	Open	Hail damage to SPA-10 Payloads	Large hailstones impacting exposed mission instrumentation may degrade performance and reliability, with loss of mission critical data.	Appropriate design can mitigate loss of data, with periodic refurbishment as needed. Many instruments are duplicated/redundant.	4	1
	T-4	Open	Engine flameout due to water ingestion	Excessive water ingestion may result in engine flameout and mission abort. Concurrent flameout of both engines is a safety hazard.	CF-34 civil experience indicates flameout occurs rarely, and only at low power, e.g. descent. TF-34 is considered less susceptible.	2	1
	T-5	Open	SPA-10 icing degrades flying qualities	A-10 is cleared for 3/4" icing, with no anti-ice provisions fitted. Excessive buildup may degrade lift and increase gross weight, a potential flight hazard. A drooped leading edge has been designed the inner wing section. The effect of icing of this redesign is unknown.	Exiting the storm and descent to shed ice buildup is a proven T-28 mitigation, a potential loss of mission critical data & productivity. Shed ice may damage engine fan blades with no impact on flightworthiness, but requires replacement of damaged blades. A modification to deice the wing section in front of the engines is planned. This mitigation is incompatible with the existing slats in this wing section.	3	2

Risk Category	Risk #	Status	Title	Technical Risk Cause, Description & Consequences	Analysis / Mitigation	Likelihood	Technical Conseqence Code
Technical Risks	T-6	Open	Drooped wing leading edge aerodynamics	USAF have developed a drooped leading edge for the inner wing section to eliminate the present slats. This is planned for SPA-10 incorporation and will be qualified during SPA-10 flight test.	The SPO proposes flight testing with rakes to assess engine inlet airflow distortion. Note: It is not evident that this modification is required for the SPA-10 mission.	3	3
	T-7	Open	Airframe structural load changes due to modifications	Replacement of the cannon in the weapons bay with ballast, instrumentation and data handling may significantly affect load paths, structural integrity and life.	Zivco & USAF SPO analysis of weapons bay modifications is complex and difficult due to the mix of older and current analysis techniques. This may require instrumented flight test and possibly require SPA-10 airframe inspection & repairs in service.	3	3
	T-8	Open	Lightning strike	Lightning strike was common during T-28 storm penetration mission and the SPA-10 is expected to be exposed to the same risk. This is potentially a hazard to the SPA-10 pilot, airframe and flight critical systems' integrity, and may result in loss of the aircraft due to ignition of an explosive fuel vapor/air mixture in fuel tank ullage space.	The A-10 in service with the USAF has no record of serious safety hazards due to lightning strike, only limited damage to aircraft skin and external items. The T-28 had similar experience.. The A-10 has employs explosion suppressant reticulated foam mitigating fuel vapor explosion hazards. The tanks are also fitted with linings intended to prevent leakage from the tanks when penetrated by a projectile, which may add an insulating layer further mitigating this hazard.	4	3
	T-9	Open	Demilitarized wire harness definition & configuration control.	Definition and implementation of residual flight critical wiring harness may be difficult, error prone and hard to test & qualify.	Qualification and flight safety may be compromised.	2	3
Notes	1. SPA-10 functionality and airworthiness with the planned modifications to A-10 airframe and aircraft systems configuration will be established by design, analysis, inspection and test under the supervision and review of the responsible USAF SPO, including SPO defined and executed flight test. This intermediate flight test configuration will include structural provisions designed to accommodate the removal of the A-10 cannon, the installation of the SPA-10 gun replacement probe and the auxiliary instrumentation power system driven by the existing hydraulic supply to the cannon, plus the ballast necessary to restore nominal aircraft balance.						
	2. The SPA-10 configuration with the defined instrumentation power system, power and instrumentation wiring, data acquisition and management system, and a baseline storm penetration instrumentation suite will be established and tested to demonstrate airworthiness to the responsible authorities.						
	3. The above instrumented SPA-10 configuration, with any subsequently approved modifications, will be flown in typical mid-continent thunderstorms to establish and demonstrate safe and effective storm penetration flight procedures and limitations.						

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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