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Development and demonstration of atmospheric electricity hazards protection ⁽⁺⁾

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Résumé. — Un programme de développement avancé pour développer et démontrer l'efficacité de méthodes de protection contre les dangers de l'électricité atmosphérique pour les catégories de véhicules aériens du type avion de combat, avion de transport/bombardier, hélicoptère et missile de croisière est entrepris sous contrat de l'Air Force Wright Aeronautical Laboratories (AFWAL) par la Boeing Military Airplane Company (BMAC) ; d'autres agences gouvernementales apportent aussi leur soutien à ce programme. Les paramètres caractérisant la menace due à la foudre ont été définis pour des foudroiements modérés et des foudroiements sévères, ces derniers étant caractérisés par une amplitude crête de 200 kA et par une vitesse de montée de 200 kA par microseconde. Dans le passé l'attachement de la foudre aux aéronefs a produit de nombreuses pertes. Ces pertes ont été causées à la fois par les dommages physiques produits sur la structure de l'avion et par des effets électriques sur les éléments et systèmes jouant un rôle critique pour le vol de l'avion. Les pertes associées avec le dérèglement et/ou le dommage ont tendance à s'accroître avec l'utilisation de circuits intégrés sensibles dans des applications critiques pour le vol, et avec l'utilisation de matériaux composites qui réduisent l'efficacité du blindage électromagnétique apporté par la structure. Pour éviter les dommages on peut utiliser différents concepts de protection : blindage des circuits et systèmes ; protection des sorties et des câbles ; planchers conducteurs. On présente ci-dessous une méthodologie au niveau de la conception qui tient compte des caractéristiques de la structure ainsi que des caractéristiques et du caractère critique des circuits et systèmes. Cette méthode doit conduire à l'identification de schémas de protection équilibrée.

On attend de la mise en œuvre de l'AEHP qu'elle améliore la souplesse opérationnelle des véhicules aériens par un taux de confiance accru dans leur sécurité de fonctionnement au cours d'opérations tout-temps. Nous décrivons ci-dessous la phase de démonstration d'efficacité de l'AEHP ADP sur une cellule modifiée de F14 avec des systèmes avancés d'avionique et d'alimentation électrique.

Un hélicoptère ACAP est aussi utilisé comme modèle d'essai. Le modèle d'essai sera soumis à des injections de courant sous forme d'une onde sinusoïdale à faible niveau, d'une impulsion à niveau modéré et d'une impulsion à fort niveau. Cette méthode permet d'évaluer le coefficient de sécurité des principes de protection retenus.

Abstract. — An Advanced Development Program (ADP) to develop and demonstrate effective Atmospheric Electricity Hazards Protection (AEHP) for the fighter, transport/bomber, helicopter and cruise missile classes of air vehicles is being conducted under an Air Force Wright Aeronautical Laboratories (AFWAL) contract with Boeing Military Airplane Company (BMAC). Other Government agencies are also supporting the ADP. The parameters characterizing the lightning threat have been defined for moderate and severe flashes ; e.g., 200 kA peak and 200 kA/microsecond rise rate for the severe threat lightning current. The attachment of lightning flashes to aircraft has resulted in many losses of aircraft in the past. The losses have been caused by both physical damage to the aircraft frame or structure, and electrical effects to aircraft flight critical elements and systems. The losses associated with upset and/or damage may increase with the advent of sensitive integrated circuitry being used in flight critical applications, and the use of composite material in these airframes and structures thereby reducing its electromagnetic shielding effectiveness. Protection concepts ; e.g., circuit and system shielding, terminal protection, conducting floors and cable protection ; may be used to prevent damage. A design methodology considering airframe characteristics, and circuit and system characteristics and criticality, which will lead to identification of balanced protection schemes is presented. Incorporation of AEHP is expected to enhance the operational flexibility of air vehicles through increased confidence of all-weather operational integrity. The effectiveness demonstration phase of the AEHP ADP using a modified F-14 airframe with advanced avionic and power systems is described. An ACAP helicopter is also to be used as a testbed. The testbeds will be subjected to low-level continuous wave (CW), moderate-level pulse, and severe-level pulse current injection. This method evaluates the safety margin of the generic protection design.

(+) Cet article a fait l'objet d'une communication à la Conférence Internationale sur la Foudre et l'Electricité Statique (Paris, 10-15 juin 1985).

1. Introduction.

Atmospheric Electricity interactions with advanced aircraft pose a potentially significant hazard. In the last fifteen years, seven metal aircraft employing conventional avionic packages have been lost to lightning and precipitation-static (P-static) associated upset or damage in the United States. This, despite the acknowledged protection afforded by metal airframes and skins and the insensitivity to noise associated logic error or burnout afforded by vacuum-tube or discrete semiconductor electrical/electronic systems. With the advent of lower conductivity airframes and skins and advanced electrical/electronic systems the loss/damage/error record is likely to suffer adversely unless explicit actions are taken to counter the threats posed by atmospheric electricity interactions with advanced aircraft. To provide demonstrated technology on a timely basis, the AEHP program is being conducted by the Air Force Wright Aeronautical Laboratories (AFWAL). Program resources have been provided by several United States Government agencies, in addition to the Air Force.

2. AEHP program overview.

The principal part of the AEHP ADP is being conducted through an AFWAL contract with the Boeing Military Airplane Company (BMAC). The driver behind the AEHP ADP is the concurrent introduction of advanced materials ; e.g., Graphite Epoxy (GR/EP) ; for aircraft structure and Very Large-Scale Integration (VLSI) and Very High Speed Integrated Circuits (VHSIC) for avionics ; which demands that a total systems view, such as can be provided by a major airframe company, is afforded the definition and development of AEHP schemes. The contracted program for the ADP is being pursued in two phases. In phase I, the AEH related threat levels were explored and balanced protection schemes for aircraft wiring and avionic equipment were defined. Finally, interim design guidelines for protection of avionic equipment were defined and the work required for demonstration of AEHP effectiveness during phase II redefined.

The AEHP ADP has now entered phase II. Testbeds for demonstration of protection effective-

ness will be prepared from a variable geometry wing aircraft and a rotary wing aircraft (helicopter). These testbeds are being prepared to provide airframe and skin structures and avionic systems which are representative of those anticipated to be available in the period following 1990. Following validation of the effectiveness of the AEHP provided for these vehicles through application of programs developed for such definition, design guides will be finalized to assist with preparation of appropriate AEHP as a function of anticipated scenarios. In addition, procedures for qualifying the effectiveness of various AEHP schemes, as well as for assessing the continuing effectiveness of such protection, will be defined. Special attention is being afforded the compatibility/synergism between protection against electrical/electronic system upset and damage by AEH associated electro-magnetic environments and protection against structural damage or fuel system ignition through direct effects of the AEH environments on advanced airframes.

Implementation of appropriate AEHP schemes defined under the AEHP ADP will enable the successful completion of critical missions and safe, economical operations in the face of adverse atmospheric electricity threats. The products from the AEHP ADP will benefit both military and commercial operations as we move toward the more sophisticated operations made possible by the advances in aircraft materials and avionics.

3. Lightning threat definition.

The atmospheric electricity lightning threat parameters used in the AEHP ADP are shown in table I.

A double exponential representation of a single stroke of the severe and moderate cloud-to-ground lightning discharge are shown in figure 1.

The lightning current flow through and the electro-magnetic fields established near electrical/electronic equipment on board an aircraft interacting with the lightning environments discussed above will depend largely on the aircraft structure, as well as specific parameters associated with any particular lightning flash. For instance, impedance considerations suggest that high levels of lightning discharge may flow across conductive (metallic) surfaces while only low

Table I.

A. Cloud-to-Ground

Single stroke threat	Peak current	Maximum rate of rise	Time to half amplitude	Action integral
Moderate (expected)	20 kA	50 kA/μs	50 μs	$1.5 \times 10^4 \text{ A}^2\text{-s}$
Severe	200 kA	200 kA/μs	50 μs	$1.5 \times 10^6 \text{ A}^2\text{-s}$

B. Cloud-to-Cloud

Moderate (expected)	5 kA	50 kA/μs	50 μs	$9 \times 10^2 \text{ A}^2\text{-s}$
Severe	20 kA	200 kA/μs	50 μs	$1.4 \times 10^4 \text{ A}^2\text{-s}$

Fig. 1.

amounts of lightning flash currents are expected to flow across low-conductivity dielectric and composite material surfaces. Balancing this relationship, however, is the ease of penetration of electromagnetic fields through low-conductivity materials and the excellent shielding afforded against such fields by high-conductivity materials.

4. AEHP concepts.

Testing performed with ALCM and YG-16 aircraft mock-up testbeds during phase I of the AEHP ADP have confirmed the threat relations discussed above and permitted empirical establishment of hazard characteristics for equipment locations in advanced aircraft. Appropriate AEHP schemes have been derived from synergistic application of AEHP concepts and their effectiveness evaluated using these testbeds. Several AEHP concepts are applicable to use in all airframes and require only careful attention to application detail in order to be effective when specifics of scenarios of interest will permit the use of such general concepts. Among these general AEHP concepts are cable routing, fiber optics application, bonding and grounding, and system redundancy.

For advanced airframes, e.g. GR/EP, one may wish to increase the amount of structural shielding which is contributing to balanced protection. This can be realized by use of metal foils or mesh screens over general areas of the aircraft or only in selected areas. To complement this approach, it may also be necessary to employ extensive shielding for many signal wires, including selected shielding of power cables in some instances. As an alternative, it may be possible to utilize localized conductive floor elements to off-load signal wires and power cables

from undesirable coupling with atmospheric electricity associated voltages, currents and electromagnetic fields. In addition to these approaches, AEHP can be assisted by applying protection at the Line Replaceable Unit (LRU), or box level. Here again, shielding can be of significant value. However, weight may become a limiting factor for use of this technique, as may maintenance of shielding integrity over a system's life. Another AEHP concept which may be applied here is filtering and transient clipping in order to achieve « box-level » hardening. Zener diodes, varistors and surge suppressors may be of value. Many applications of these concepts have been effective, but care must be exercised to assure noninterference with signal and electrical power transmission within bands of interest. All of these concepts have attractive features, as well as certain limitations. A mixture of these AEHP concepts may therefore be necessary to achieve the best possible balanced protection for applications of interest. Included in the mix no doubt will be structural, as well as electrical/electronic specific protection elements.

5. Phase II plans and activities.

An F-14A aircraft has been modified to provide a testbed representative of « 90's aircraft technology » in order to demonstrate the effectiveness of AEHP schemes for fighter scenarios. In addition, a helicopter testbed will be prepared to demonstrate the effectiveness of applying AEHP schemes for scenarios related to this class of vehicles. In order to perform the AEHP demonstrations planned for the ADP both continuous wave and pulsed lightning simulators are employed with these testbeds.

This portion of the AEHP ADP is being conducted to demonstrate and evaluate the effectiveness of AEHP achieved for various classes of vehicles. The work required is shown in figure 2. Full-scale simulated lightning is being utilized. To establish a high degree of credibility for the AEHP methodology developed. The full-scale lightning simulation capability is provided through a pulse generator built for BMAC by Maxwell Laboratories, Inc. The simulator is capable of delivering pulses with 680 kJ energy content with up to 200 kA peak amplitudes and a peak current rate of rise of 2×10^{11} A/s with fall to half-value of greater than 50 microseconds. In order to realize this capability, it has been necessary to achieve precision generator triggering with subnanosecond jitter and a precisely reproducible crowbar switch, as well as tight control over generator and load impedance balances. The waveform for the lightning simulator which can be delivered into a 100 milliohm, 8 microHenry load is shown in figure 3. It can be seen that the rise-time from 0.1 to 0.9 of the 200 kA peak magnitude is on the order of 1 microsecond with the sine-wave leading edge resulting from operation of the 3.9 megavolt Marx generator included in the pulser array. The Marx generator output is crowbarred to ground near the first current peak

Fig. 2.

Fig. 3.

at $t = t_3$, which results in the long exponential decay desired. The pulser has been designed to provide highly reproducible waveforms representative of lightning attachment to full-size fighter and helicopter aircraft.

In addition to the full-scale lightning simulation pulse generator discussed above, a 20 kA pulse generator is also available for AEHP demonstration/evaluation. This simulator was prepared by Boeing to provide simulation of the « moderate level » lightning threat with a maximum rate of rise of 5×10^{10} A/s. This lower amplitude lightning simulator, together with variable frequency continuous wave equipment has allowed much data collection and pulse response prediction and analysis work to be performed in a short period of time. The latter tests have proved to be especially important to characterize and quantify the transfer functions

defining coupling between airplane and electrical/electronic circuit responses to atmospheric electricity stimulation. Comparison of the empirically defined transfer functions with analytical predictions establish confidence in our understanding of the electromagnetic coupling which occurs. Finally, the measured responses to simulated lightning pulses have been compared with the response predicted by application of the transfer functions derived during the program through analytical and variable frequency investigations. A representative comparison is shown in figure 4 for a structural return on the all-composite forward fuselage of the YG-16 testbed.

Fig. 4.

6. F-14 testbed preparation.

The F-14A aircraft has been used as the starting point for preparation of a testbed for demonstration of AEHP effectiveness during phase II of the program. Appropriate equipment and instrumentation installations and vehicle modifications have been made to evaluate the impacts of advanced fabrication methods and appropriate AEHP concepts.

In order to demonstrate the effectiveness of the AEHP provided by the concepts employed, the operational avionics suite on the F-14A has been disabled or removed and Special Test Equipment (STE) installed. Care has been taken to involve a significant portion of the testbed with the STE layup, as shown in figure 5. The STE used in the F-14A tests will also be employed for testing in a helicopter testbed later in phase II. This will provide a basis for comparison of AEH threats by vehicle type, as well as a common operational system which to gauge AEHP effectiveness. The STE used has principally been drawn from the Air Launched Cruise Missile (ALCM) avionics suite with augmentation by advanced digital electronics interfacing with a databus. In addition, appropriate power units incorporating AEHP are provided on the testbeds. The electrical/electronic elements of primary interest are listed in table II.

Current and voltage measurements have been made at several test points for these systems. In addition, several elements have also been functionally monitored to assess their response to the simulated lightning applied.

ITEM NO	ACCESS PANEL NO	COMPONENTS
1	1122-4	UMBILICAL ENCLOSURE ☐ AIR DATA COMP ☐
2	1222-2	INERTIAL NAVIGATION ELEMENT ☐ MONITOR NODE ☐ INSTRUMENTATION BOX ☐
3	1222-3	FLIGHT CONTROL SYS. ELEMENT ☐ RATE/ACCELERATION SENSOR ☐ MISSILE RADAR ALTIMETER ☐ TEMPERATURE PROBE ☐
4	2122-4	POWER J-BOX ☐ FUEL PUMP INVERTER ☐ SEPERATION SWITCH ☐ ARM/DISARM DEVICE ☐ AIRBORNE COMP. ☐
5	2222-1	BUS INTERFACE UNIT ☐ CONTROL DISTRIBUTION BOX ☐
6	2221-3	ECM C & D PANEL ☐
7	1132-3	ECM C & D POWER SUPPLY GENERATOR/HYDRAULIC MOTOR ☐
8	30121-2	ELEVON ACTUATOR CONTROLLER ☐
9	30121-2	RH ACTUATOR ☐ LH ACTUATOR ☐

Legend

- ▲ Data bus terminator
- ☐ Equipment with no data bus interface (Part I TE)
- Equipment/data bus interface (Part II TE)
- ▨ GR/EP paneled areas

Fig. 5.

Table II. — Avionic test systems.

Equipment	System
Flight Control System Equipment	ALCM
Inertial Navigation Equipment	ALCM
Missile Radar Altimeter	ALCM
1750 Data Processor	Data Bus
B-1B Electronic Countermeasures	Data Bus
Paladin Interface	Data Bus
Generator Control	Data Bus

The F-14A testbed has been further modified to make it more representative of aircraft of the 90's. To realize this goal, several skin panels have been removed and/or replaced with GR/EP panels during application of simulated lightning. In this way, it has been possible to assess the impact of nonconducting, as well as poorly conductive materials on AEHP for aircraft of the future. The results of the tests with the F-14A testbed will be directly applicable to transition vehicles which will employ high fractions of both metallic and non-metallic skin and structure. It is anticipated that the findings will also be applicable to « fully » composite vehicles of the future. GR/EP panels identified including the Turtle Deck and Overwing Fairings, as well as a forward fuselage Avionic Bay cover have been provided for this testbed. Other Avionic Bays were covered by aluminum aircraft skin or left open, as demanded by the Test Matrix specification for each test.

7. F-14A test matrix.

Lightning simulation tests for the F-14A testbed are planned for several STE and various aircraft skin panel configurations for each of two major test configurations, nose-to-tail and nose-to-wing. As can be seen in figure 6, several configurations of vehicles skins are involved, as well as three levels of testing using a combination of three separate simulation techniques. Level 1 testing is conducted using an internal sensor system to measure the impact of each vehicle configuration on the resultant electromagnetic field for several selected positions interior to the vehicle. These evaluations are conducted with both the moderate and severe pulse simulators, as well as a variable frequency signal generator. The avionic systems are utilized to assess coupling of the AEH threat with signal/power cables during Level 2 test, and finally the impact of the AEHP environments on operation of avionic system is experimentally assessed during Level 3 testing. Testing conducted in accordance with the Test Matrix is used to assess the impact of increasing uses of composite materials for aircraft structure. This careful process will provide a clean procedure for extending the findings to cover the case of a largely or fully composite aircraft.

The two basic attachment modes, nose-to-tail and nose-to-wing, allow the effect of aircraft current flow

<div>Configuration</div> <div>Test points</div>	Nose-to-tail					Nose to wing
	Configuration 1	Configuration 2	Configuration 3	Configuration 4	Configuration 4	Configuration 4
	All Metal Panels Installed	Gr/Ep Turtle Deck Panels Installed	Turtle Deck Panels Removed	Gr/Ep Turtle Deck Panels Installed and Forward Panels Removed	Gr/Ep Turtle Deck Panels Installed and Forward Panels Removed	Gr/Ep Turtle Deck Panels Installed and Forward Panels Removed
	CW 20kA	CW 20kA 200kA	CW 20kA	CW 20kA 200kA	CW 20kA 200kA	CW 20kA 200kA
LEVEL 1 : Vehicle Characterization						
— DC Resistance	×					
— Input Impedance	×					
— Structural Voltage	×	×	×	×	×	×
— Surface Current	×	×	×	×	×	×
LEVEL 2 : Avionics Transient Response						
— Open Circuit Voltage	×	×	×	×	×	×
— Cable Bundle Current	×	×	×	×	×	×
LEVEL 3 : Avionic Functional Response						
— Data Bus Equipment Response		×	×		×	×
— ALCM Equipment Response		×	×		×	×

Fig. 6. — F-14A Test Matrix.

paths to be assessed and a full capability established for defining the AEH threat for various aircraft stations. The phase II demonstration program is initiated at a low magnitude for each simulator and the intensity increased in a programmed fashion, as advised by test results during the test period. The limited testing in the nose-to-wing attachment mode is designed to confirm our understanding of the effect of attachment geometry on coupling of lightning current associated pulse environments with internal electrical/electronic circuits.

8. Helicopter testbed.

During 1986, a helicopter testbed will be prepared to demonstrate the applicability of AEHP concepts for that class of vehicles. It is anticipated that the testbed used will be derived from the helicopter developed by Bell Aerosystems under the US Army All Composite Airframe Program (ACAP). The Bell ACAP uses no metal for structure except for the engine mount.

The conventional metal helicopter also presents a significant challenge for AEHP in view of the need to preserve its light structure and also accommodate its many windows and associated open structure. For

the AEHP ADP testbed, the problem has been compounded by the extensive use of GR/EP composite material instead of a metal substructure. This has driven the AEHP design toward the application of efficient selective shielding in conjunction with the judicious application of terminal protection devices. For this application, the STE investigated throughout the ADP will again be employed. However, the AEHP concepts previously applied will be adjusted to explicitly address the demands associated with the helicopter class of vehicles. Such deliberate exercises of the AEHP concepts will establish an understanding for their applicability to all classes of air vehicles.

For the helicopter, special attention must be afforded the flow of lightning current into the vehicle following lightning attachment with the rotor blades/hub. In many cases, engine controls and vehicle electrical power elements may require careful attention in order to function satisfactorily in the high levels of AE electro-magnetic threat environments near the rotor shaft current path. This event may also subject bearings and other drive-train elements to pitting/burning damage as the result of direct interaction with the lightning current. The AEHP demonstration planned for the helicopter under the ADP will address these problems.

9. Design methodology.

The details of the optimum AEHP scheme required for each vehicle type and application scenario will vary depending on the unique features of each scenario. With some compromise, however, we may assure ourselves that the anticipated atmospheric electricity threats for various vehicle types can be accommodated by the AEHP schemes applied to aircraft and related systems. To define the preferred configuration for AEHP, several aspects of the aircraft and scenarios of interest must be considered.

First, it is necessary to define the Lightning Strike Zones for the aircraft. These depend principally on vehicle geometry, but are also strongly affected by flight envelope and airspeed, among other factors. The zones are divided into surfaces with a high probability of initial attachment, surfaces over which the lightning flash may be swept by airflow, and other aircraft surfaces. Even the latter aircraft surfaces may carry large amounts of lightning current as the attached flash current distributes from initial attachment to departure from the aircraft. Next the external and internal environments resulting from either lightning or P-static events must be determined. Parameters of these environments will include currents, voltages and resultant electromagnetic fields. Elements contributing to the resultant environments will include IR drop, gap voltage, aperture coupling, magnetic flux diffusion and direct coupling with unprotected conductors. Following the environment definition, we identify components, subsystems and systems which may be vulnerable to hazardous

effects from such environments. This allows us to establish the amount of AEHP required for full protection. At this point, trade-offs may be performed to balance mission assuredness for various threat levels with the costs associated with such protection. One may then proceed to design the protection selected to counter the mix/level of threats considered within the limit of available resources. Finally, the adequacy of the AEHP designed may be verified by analysis and/or qualifying test and the continuing effectiveness of the AEHP provided may be assessed to provide confidence in the level and integrity of AEHP accomplished.

10. Conclusion.

An overview of the Atmospheric Electricity Hazards Protection Advanced Development Program has been presented. We are now engaged in the demonstration/evaluation portion of the ADP to establish the effectiveness of the AEHP schemes for a wide mix of air vehicles and operational scenarios. Under the ADP, procedures to define the atmospheric electricity threat to be countered have been established and AEHP concepts for this purpose developed. The program to demonstrate the effectiveness of AEHP schemes based on these concepts for application to various classes of air vehicles has also been discussed. Finally, an outline of the procedure necessary to achieve the level of AEHP desired has been presented.