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REQUIREMENTS, TECHNOLOGY AND CONFIGURATION EVALUATION FOR CRASH SURVIVABLE FLIGHT DATA RECORDING (CSFDR) SYSTEM

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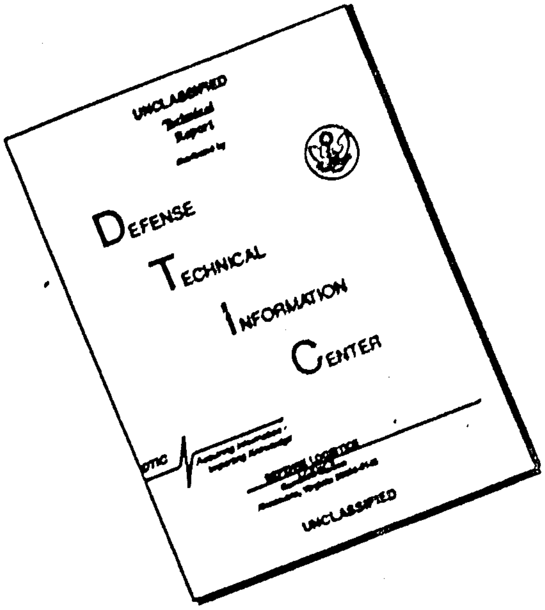

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This report addresses the tasks required to determine whether or not a Crash-Survivable Flight Data Recording (CSFDR) System which meets the critical performance requirements and cost constraints dictated by the attack/fighter/trainer (A/F/T) application, can be defined with current avionics technology for a volume production program. → (over)

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The first task addressed is that of determining the technical requirements. This task is subdivided into a flight parameter evaluation, an installations investigation, and a crash-survivability investigation. Following this, the tasks required to formulate the well-defined technical approach are addressed. These tasks include studies relative to standardization, expanded recording, data security, required readout equipment, and future aircraft applications.

Special emphasis is given to potential memory technologies, data processing/compression techniques, and required software/firmware for the CSFDR system.

Following these technical areas of study, the economic areas for life cycle costs (LCC) and cost/benefit are analyzed.

The recommendation is to continue work in the CSFDR area.

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Also, Mr. Leroy Burrows of the Army Aviation R and D Command supplied some very useful information relative to the Army AIRS program.

SUMMARY

This report addresses the tasks required to determine whether or not a Crash-Survivable Flight Data Recording (CSFDR) System which meets the critical performance requirements and cost constraints dictated by the attack/fighter/trainer (A/F/T) application, can be defined with current avionics technology for a volume production program.

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Special emphasis is given to potential memory technologies, data processing/compression techniques, and required software/firmware for the CSFDR system.

Following these technical areas of study, the economic areas for life cycle costs (LCC) and cost/benefit are analyzed.

The study shows that there are five primary driving functions which must be optimized in order to assure a CSFDR system capability for A/F/T aircraft. These are:

- Minimize the total volume (size) of the CSFDR system because space (real estate) is critical on A/F/T aircraft.
- Minimize the total weight (including all cables, brackets, and CSFDR components) impact to the aircraft because weight is also critical for A/F/T aircraft.
- Minimize the LCC of the CSFDR system.
- Crash protect and install the protected memory to survive A/F/T Class-A mishaps.
- Design the CSFDR system to operate throughout the high-g maneuvers which are typical of A/F/T profiles.

The study also concludes that these five primary driving functions are satisfied if the following technical approach is taken:

- Separate the survivable memory pack from the remainder of the CSFDR system electronics.
- Use a solid-state memory in conjunction with state-of-the art techniques for data conversion/data processing/data compression.

Three CSFDR system configurations are analyzed in this report:

Configuration I - records the maximum number of flight parameters for the longest practical time needed to determine the cause of an A/F/T accident/mishap.

Configuration II - records only the highest priority flight parameters for the minimum time needed to determine the cause of an A/F/T accident/mishap.

Configuration III - similar to Configuration I, but includes non-crash-survivable memories to achieve expanded recording functions for aircraft structural integrity, turbine engine data, and flight control monitoring.

Conclusions show that the current state-of-the art in electronic technology permits Configuration II, with a minimum level of input parameters (typically 35) and an average real-time storage of 19 minutes, to be designed and produced at a size and weight applicable to A/F/T aircraft. The size and weight are significantly less than contemporary electromechanical recorders.

Also, Configuration I, with a higher level of input parameters (typically 56) and an average real-time storage of 29 minutes, can be designed and produced at a size and weight applicable to A/F/T aircraft. The size and weight of this configuration are also significantly less than contemporary electromechanical recorders. Moreover, the addition of solid-state Mass Storage Units permits this configuration to be used for expanded airborne recording functions. The resulting recorder system, Configuration III, is a single standardized family of modules which can be used for any set of airborne recording functions.

The memory technologies most suitable for incorporation into the Crash-Survivable Memory Unit (CSMU) are the EE-PROM and MNOS types.

A data compression technique which uses floating apertures and a zero-order polynomial predictor, which is adaptive to flight conditions, can be used to reduce the crash-survivable memory required. This, in turn, reduces the overall cost of the CSFDR system.

The reprogrammability feature of the CSFDR system permits a common design to be used for various aircraft. The A-10, F-15, and F-16 were studied for specific applications. Enough commonality exists such that a single CSFDR system concept can be implemented for these aircraft. In addition, the standard CSFDR system can be reprogrammed for many other applications.

All configurations studied had very positive cost/benefit ratios for the three-aircraft program (A-10, F-15, and F-16). Characteristics of these configurations are shown in table 1.

Table 1. Characteristics of Configurations I, II, and III

Completely solid-state sytem	-	Data Processor Unit (DPU) and Crash-Survivable Memory Unit (CSMU)
Expanded recording functions	-	Via Mass Storage Units (MSU)
CSMU and MSU separable from DPU	-	Installed as single unit or in combinations of DPU plus remotely located memories
Low-Power Crash-Protected Memory (CPM)	-	Very low power, solid-state, non-volatile
Microprocessor controlled	-	Data conversion, processing, and compression, including BIT
CSMU survivability	-	Per recommended A/F/T crash-survivability specification

Characteristic		DPU	CSMU	MSU	TOTAL
Size:	I	212 in^3	42 in^3	-	254 in^3
	II	197 in^3	35 in^3	-	232 in^3
	III	212 in^3	42 in^3	108 in^3	362 in^3
Weight:	I	8.4 lbs	2.8 lbs	-	11.2 lbs
	II	7.6 lbs	2.4 lbs	-	10.0 lbs
	III	8.4 lbs	2.8 lbs	6.0 lbs	17.2 lbs

Table 1. Characteristics of Configurations I, II, and III (Continued)

Characteristic		DPU	CSMU	MSU	TOTAL
Power:	I	40 watts	1 watt	-	41 watts
	II	35 watts	1 watt	-	36 watts
	III	40 watts	1 watt	10 watts	51 watts
Average Flight Time Retained:	I	-	29 min	-	-
	II	-	19 min	-	-
	III	-	29 min	15 hrs	-
Memory Required:	I	-	131,072 bits	-	131,072 bits
	II	-	65,536 bits	-	65,536 bits
	III	-	131,072 bits	256Kx16 bits	264Kx16 bits
MTBF:	I	5,258 hrs	63,613 hrs	-	4,856 hrs
	II	5,580 hrs	89,047 hrs	-	5,251 hrs
	III	5,258 hrs	63,613 hrs	3,400 hrs	2,000 hrs
Maint. Mn/hrs per 1000 Operating Hours:	I	2.899 hrs	0.204 hrs	-	3.103 hrs
	II	2.733 hrs	0.146 hrs	-	2.879 hrs
	III	2.899 hrs	0.204 hrs	3.823 hrs	6.926 hrs
Program Memory:	I	3,140 wds	-	-	3,140 wds
	II	3,000 wds	-	-	3,000 wds
	III	3,400 wds	-	-	3,400 wds
Random Access Memory:	I	2,000 wds	-	-	2,000 wds
	II	2,000 wds	-	-	2,000 wds
	III	2,000 wds	-	-	2,000 wds

The expanded recording functions have only a minor effect on the conversion and processing functions of Configuration I. These expanded recording functions are easily achieved by adding Mass Storage Units to the basic system.

Encryption techniques which result in only one-half of a board of processor "real estate" can be used to provide all the security protection features required for operation at or near enemy territory.

A readout station having a four-level readout capability can easily be provided to Norton AFB for mishap investigations. This station would utilize a solid-state data processor retrieval unit made directly compatible with the existing Norton AFB EDP facility. Alternate readout facilities are also possible at minimum risk to the USAF.

A portable Data Retrieval Unit (DRU) can also be used to extract data from the CSFDR system. This unit utilizes Data Transfer Modules (DTMs) which are already in the USAF inventory. Each DTM consists of 8 K words x 16 bits of solid-state memory. These solid-state "cassettes" can then be sent to Norton AFB for timely use in the mishap investigation. Only one DRU is required at each base.

The overall CSFDR system concept is shown in figure 1.

The recommendation is to continue work in the CSFDR system area as soon as funding permits. Although all three configurations studied had positive cost/benefit ratios, Configurations II and III are the only configurations recommended for future development and production. If budget and time for development are not extremely critical, Configuration III is recommended. If either budget or time is felt to be critical by the affected USAF agencies, then Configuration II is recommended.

Also, Configuration II is recommended for retrofit applications where the aircraft structural integrity, turbine engine data, and flight control recorders have already been procured and installed. For new aircraft applications, Configuration III is the recommended recorder system, and additional recorders need not be procured for these aircraft.

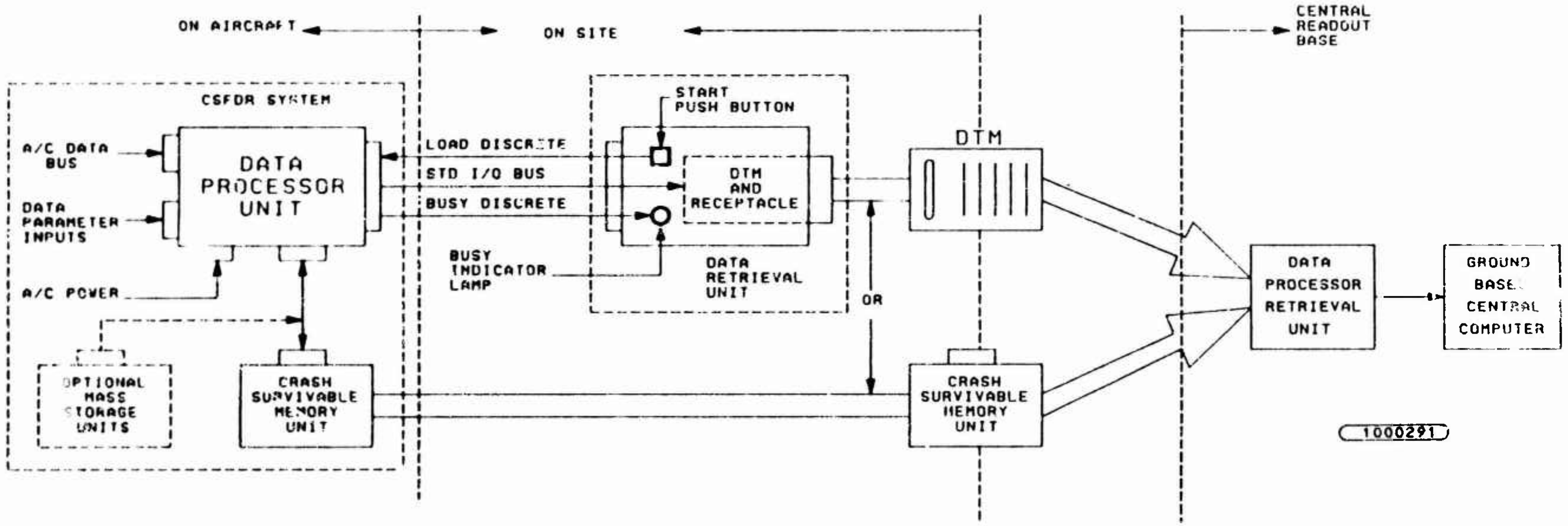

Figure 1. Crash-Survivable Flight Data Recording (CSFDR) System Concept

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1. INTRODUCTION

There are two broad objectives of the CSFDR system study as described herein:

a. Perform technical feasibility studies which relate specific equipment configurations and capabilities to various aircraft applications, and to evaluate alternative technical approaches for meeting the application goals.

b. Perform economic studies which compare life cycle costs (LCC) to potential benefits resulting from incorporating a standard CSFDR system into various aircraft programs.

The final output of the study allows factually backed decisions to be made to continue the program into the prototype and production stages.

The top priority of the study is to cover the requirements for attack/fighter/trainer (A/F/T) aircraft and the study is scaled accordingly. Portions of the study which are covered, but ranked lower in priority, are tri-service standardization, large-scale standardization, and expanded recording applications.

General and specific studies for the A/F/T class of aircraft are conducted. Specific aircraft include the A-10, F-15, and F-16. A general A/F/T type of aircraft is hypothesized and application of the CSFDR system to both existing and future aircraft is addressed. The state of the art of crash-survivable recording systems is reviewed in terms of memory technologies to determine the applicability of these systems to the A/F/T problem. More advanced memory systems using solid-state technology are analyzed in detail.

Specific technical tasks are:

- Flight parameter evaluation
- Aircraft installation investigation
- Crash-survivability investigation
- Tri-service standardization investigation
- Application to future A/F/T aircraft
- Large-scale standardization investigation
- Expanded recording applications
- Security of airborne recorded data
- Data readout facilities
- Determination of technical approach
- Reliability and maintainability analysis

Specific economic tasks are:

- LCC calculations for Configurations I, II, and III.
- Cost/benefit analysis for Configurations I, II, and III.

It is recognized from the onset that solving the problem of providing a CSFDR system capability for A/F/T aircraft is one of the more difficult problems facing the avionics industry. Therefore, a heirarchy of design requirements was formulated for the study and each specific area of the study was oriented to satisfying the top priority requirements. These top priority requirements are:

- Minimum size
- Minimum weight impact to aircraft
- Minimum LCC
- A high degree of survivability
- Continual uninterrupted recording through high-g maneuvers.

Although there are many additional requirements which the CSFDR system must meet, it is believed that optimization of the top priority requirements will provide the long sought after CSFDR system capability for A/F/T aircraft.

2. AIRCRAFT CRASH-SURVIVABLE FLIGHT DATA RECORDING SYSTEMS

2.1 Summary of the problem and its facets

Accident/mishap statistics for attack/fighter/trainer (A/F/T) aircraft show an alarming trend in terms of cost per incident. The percentage of incidents, in which the cause is unknown, remains unacceptably high. Moreover, peacetime operational incidents have contributed directly to the continuing problem of force shrinkage. In fact, during the past several years, one service has bought fewer A/F/T aircraft than are being lost in peacetime operational accidents. Current rates of inflation and limited combat resources of an irreplaceable nature strongly dictate that a CSFDR capability for A/F/T aircraft be developed as soon as technology permits.

When aircraft accidents occur, it is extremely important to determine the cause in order to reduce the probability of future accidents. Military and commercial aviation have definite procedures to cope with mishaps as they occur. AFM 127-1, entitled Aircraft Accident Prevention and Investigation, provides the framework for the USAF procedures.[1] Actual authority and establishment of requirements for investigating Air Force aircraft accidents and incidents is contained in AFR 127-4.[2]

The following words are taken directly from AFM 127-1, section 8-1, page 8-1:

> Aircraft accidents can be prevented when their causes are known. Causes can be determined only by investigation.... Investigation provides information and statistical data which serves as the basis for corrective action and for strengthening the accident prevention effort.

It is important to note the reference to statistical data and its importance as a basis for corrective action. A CSFDR system would greatly supplement the amount and accuracy of such statistical data.

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[1] USAF Manual, 127-1, "Aircraft Accident Prevention and Investigation". Effective date 14 July 1976.

[2] USAF Regulation, 127-4, "Investigating and Reporting U.S. Air Force Mishaps". Effective date 18 January 1980.

The following paragraph is also taken directly from AFM 127-1, section 8-2, page 8-1:

> The purpose of an aircraft accident investigation is to determine all factors, human and material, which directly or indirectly contributed to the accident. This information can be used by pilots, supervisors, commanders and staffs to eliminate the cause factors and thus prevent recurrence of similar accidents. Each accident investigation adds to the overall USAF accident experience, providing a basis for corrective action. The proper use of accident experience results in the elimination of accident potentials. Moreover, the requirements for additional training are disclosed, realistic maintenance requirements are determined, material is improved, future design criteria are established and many other long-range results are achieved through the use of accident history. The accuracy and thoroughness of investigation determines the adequacy of ultimate action to remove or eliminate factors that cause or contribute to accidents.

It is important to note the reference to accuracy and thoroughness of investigation, which, in turn, determines the adequacy of ultimate action. Again, the CSFDR system would be invaluable in this effort.

The need for recorded data is indicated from the two AFM 127-1 excerpts. However, this need is expressed more formally in the official Statement of Need (SON) for Flight Data Recorder (FDR) for Attack/Fighter/Trainer Aircraft.[3] Paragraph 3a of the SON states the operational deficiency as follows:

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[3] USAF "SON for FDR for Attack/Fighter/Trainer Aircraft", from AFISC dated 27 August 1979, signed by General Garry A. Willard, Jr.

> Mishap investigations are inherently tedious, time consuming, and costly. Many findings of mishap investigation boards are based on probable sequence of events due to lack of concrete evidence. Most of the time, physical evidence of systems operation or malfunction is destroyed in the mishap. The lack of an FDR to record and make available systems operation or malfunction information greatly hampers these investigations.

Thus, the need for recorded data is well established. Since existing A/F/T aircraft are not equipped with CSFDRs, current mishap information is often vague and qualitative in nature. This information now comes from reports from the other aircraft in the flight, eyewitness accounts, study of the wreckage, study of the accident site scars, and related data such as weather conditions, flight records, and maintenance records. Thus, in many cases, the probable cause remains undetermined, inaccurate, or too vague to satisfy the expressed need for corrective action. Additionally, some mishaps have been charged to "pilot error" in spite of the fact that certain types of pilot error are design-induced and the actual conditions which led to pilot error remain unknown.

It should also be noted that aircraft complexity and performance have made the accident investigation process more difficult. This is especially true for A/F/T aircraft. Moreover, the expense of A/F/T aircraft has made the consequences more severe. Thus, there has recently been an increased demand from accident investigators for accurate quantitative data.

Benefits to be derived from the CSFDR system are summarized as follows:

- Improved accident/mishap information data (which permits a more accurate conclusion and a reduced number of future accidents).
- Reduced aircraft and aircrew losses.
- Reduced accident/mishap investigaton costs.
- Reduced reaction time in identifying and correcting operational deficiencies.
- Reduced reaction time in identifying and correcting aircraft hardware deficiencies.

- Improved strike capability due to reduced fleet down times following an accident/mishap.
- Improved pilot morale by eliminating the possibility of a spate of accidents due to similar causes.
- Improved history of parameter limit exceedance for A/F/T.
- Improved pilot performance/training.
- Improved data concerning subsystem performance.
- Improved maintenance data.

2.2 Background

Current CSFDRs are designed for use in large transport-type aircraft and are electromechanical in nature. Two types are in use today: (1) oscillographic recorders which produce markings on a metal foil, and (2) magnetic tape recording systems which require a digital data acquisition unit and a separate crash-protected digital magnetic tape recorder. Both types are too large (usually over 700 cubic inches) and too heavy (usually over 20 pounds) for effective incorporation into A/F/T aircraft. Moreover, the technology associated with these electromechanical recorders is very mature and, therefore, it is very unlikely that significant weight/volume improvements will be achieved in the foreseeable future.

Nevertheless, the requirement exists for crash-survivable recording systems on military aircraft as evidenced by directives and advisories issued by the U.S. Air Force and Navy. Some systems have been installed on large Air Force aircraft such as the C-5A, C-141, and C-135 transports. A system has been specified and developed for the Air Force B-1 prototypes. Some of these systems increase the probability of data retrieval by ejecting a data pack from the aircraft when high acceleration or breakup is detected. A radio beacon is included to aid in locating the package. A policy statement exists within the Air Force which advises the use of crash recorders.[4] For large aircraft such as those mentioned above, the policy statement can be met with existing hardware.

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[4] U.S. Air Force, "Air Force Policy on Flight Data Recorders and Crash Position Indicators", Chief of Staff Policy Letter dated 16 June 1973, signed by General John D. Ryan.

However, the requirements of the policy statement cannot be fulfilled on high-performance aircraft, such as trainers and fighters, because of the high cost, size, and weight of available equipment. As a result, no high-performance aircraft, in inventory or coming on line, have such a system installed for routine military operations. This represents a paradox to many people because the accident rate of high performance aircraft is significantly higher than that of transport type aircraft.

Within the U.S. Navy, a directive is currently in force that requires an ejectable type of system on all new aircraft being delivered.[5]

The Navy system contains voice and data and includes a radio beacon located within the ejectable portion of the system. Large Navy aircraft currently being delivered have such systems. However, for A/F/T aircraft, such as the F-14 and F-18, the requirement has been waived because of the size, weight, and cost associated with present technology.

2.3 Solving the problem

Emerging solid-state electronics and insulation technologies now appear to offer an approach which is technically and economically feasible for the A/F/T problem. Solid-state memories such as MNOS and CMOS permit increased reliability, elimination of periodic maintenance, reduced size, and reduced weight. Microprocessors permit a more efficient recording process by analyzing the data and only recording the non-redundant portions, thereby minimizing the amount of crash-protected memory required. Microprocessors also permit easy growth to new, expanded recording functions because of their high speed and reprogrammability features. New insulation technologies, such as those currently being used in the NASA space program, appear to offer equivalent thermal capabilities at reduced weight and volumes.

Thus, the application of new CSFDR systems appears to be feasible for small, high performance aircraft in the current and planned USAF inventory.

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[5] U.S. Navy, "Crash Position Indicator/Flight Data Recorder Systems for Naval Aircraft". Chief of Naval Operations Message CNO 1416102, April 1972.

3. TASK/TECHNICAL REQUIREMENTS

3.1 Determination of requirements

3.1.1 Flight parameter evaluation

3.1.1.1 RFP requirements - As an introduction to the flight parameter evaluation section, a restatement of the RFP requirements is given. The evaluation should be done in terms of:

a. Parameter characteristics

- Dynamic range
- Data source
- Relationship to time history
- Interrelationship of parameters between subsystems

b. Parameter relative importance

- Benefit in accident/mishap analysis
- Difficulty or cost to acquire
- Difficulty or ease of data processing for recording and use
- Installation accessibility
- Volume and weight addition
- Reliability of data and effects on monitored systems
- Safety effects on monitored systems

c. A general prioritized parameter list with rationale and supporting data shall be compiled.

d. Specific parameter lists shall be compiled for typical example aircraft: A-10, F-15, and F-16. These lists shall meet the requirements of Configuration I (maximum number of parameters for the longest practical time for A/F/T aircraft), Configuration II (smallest number of parameters to provide adequate accident investigation in optimized size and cost) and Configuration III (Configuration I with added parameters necessary to round out the list for the structural integrity program, engine health and flight control monitoring).

e. These specific lists shall differ from the general list as necessary for the unique requirements of the three example aircraft. The priority sequence shall also be tailored to the unique requirements.

3.1.1.2 General discussion of parameter needs, uses, and types

a. Flight parameter types and groupings can be organized into the following generalized categories:

- Flight dynamics
- Flight control systems (including pilot input)
- Engine/power plant (including hydraulic)
- Avionics systems/reference systems
- Weapons/stores inventory and delivery systems
- Miscellaneous subsystems and devices (such as landing gear, antiskid, nosewheel steering, etc.)
- Environmental systems
- Electrical power systems

b. Types of contributions to mishaps and accidents. The parameters to be recorded are intended to provide sufficient information to deduce the cause of the accident/mishap which may be precipitated by individual or combinations of the following conditions or situations:

- Structural, equipment or component failure. If all accidents could be attributed to failures, then a comprehensive status and BIT monitoring system would provide all of the parameter data required. Dynamic data, flight control input and response data would be unnecessary. Such is not the case. Most accidents occur when the pilot or aircraft is at or near the limits of the respective performance capability.

- Operation outside of and departure from the safe flight envelope. With all systems working perfectly, the aircraft's capabilities or its subsystems' capabilities may be exceeded, resulting in stalls, spins, collisions, failure to pull up, induced structural failure, etc. This, in the broad sense, could be attributed to pilot error, but, for analysis purposes, it is necessary to record parameters defining the aircraft dynamic responses and flight path.

- Exceeding operational limits. Again, this can be called pilot error, but is separated out for the purpose of this study because it requires that certain distinct parameters be recorded. Consider the relatively simple case of deteriorating weather and diminishing fuel supply. Time, total fuel, power settings, and aircraft configurations, for example, are all important in deducing the cause of the crash if the pilot does not survive.

- Human error/physical impairment. Obviously, errors in instrument reading and pilot judgment cannot be recorded. The effects, to a great extent, can be recorded. If sufficient parameters are recorded to show the instrument and other inputs to the pilot, and points are monitored that record the pilots reaction, then the pilot's judgement and response can be deduced. These same parameters allow for a reasonable deduction of the possibility of physical impairment.

- Outside influences, catastrophic or deteriorating situations. These situations can be recognized by examples such as midair collision, terrain impact, and bad weather with icing or heavy turbulence. Some of these can be related to pilot and equipment limitations with final overwhelming by the outside influences. Recording of navigation parameters, secondary aircraft functions such as anti-ice status and g forces would be useful for the above examples.

- Temporary induced failure. As an example, consider the events or conditions leading to a flameout. This type of situation may use the same parameters for analysis that are recorded for the analysis of engine failure. In addition, however, the pilot's actions and aircraft dynamic response just prior to flameout are needed to help determine the cause, not just the fact of the flameout. It is the cause of the anomaly that is sought, not the result of the anomaly.

3.1.1.3 Development of the flight parameter general list - The flight parameter general list is developed in the following manner. First a comprehensive list is generated for each of the categories listed in 3.1.1.2a. This list is intended to contain every obtainable parameter in each category that could be of conceivable use in accident/mishap investigation. Since the list is not specialized, many of the parameters will be general, but hopefully sufficient to prevent overlooking of similar specific parameters for the special lists presented later. The general list is followed by another list which has been put into a prioritized order based on past user lists and stated priorities. It is listed in the exact order derived. Additional details will appear in that section. Upon reviewing the first prioritized list, it becomes apparent that certain relationships and balances will require some reordering of the list. Next, specific lists are presented for the A-10, F-15, and F-16. The lists are comprehensive listings showing the Alternate Configuration I list of parameters. Reasons for specific selections are explained. The list is then edited down to Configuration II, the minimum number of parameters deemed necessary for accident/mishap analysis.

Section 3.2.4 will cover the additional parameters needed to replace the functions of the existing ASIPs recorders, the engine health recorders, and any remaining flight control parameters.

a. General parameters list (table 2). The general parameters list is categorized according to the parameter characteristics listed in 3.1.1.2a. It is intended to contain all parameters useful to accident investigation, structural integrity, engine health and flight control functions.

b. Interrelationship of parameters. The interrelationship of many parameters will often permit some to be omitted from direct recording and, instead, to be derived from the others. Reciprocal derivations do not always produce satisfactory data as will be indicated later. This paragraph will only touch the surface of the subject with some simple examples.

Inertial Measurement Units are being considered on most aircraft, and have certain outputs available on the multiplex bus that cover the full dynamic range of the aircraft. Unfortunately for accident/mishap analysis, the velocity and acceleration data is in the fixed-earth axis coordinate system (for navigation). The IMUs also output roll, pitch and heading data which supply the needed Euler angles for conversion to aircraft axis information which can be computed on the ground. Also derivable are angle-of-attack, sideslip and rotational rates. The derivable parameters are mathematically correct only in a no-wind condition since the inertial data represents motion in respect to (for purposes of this discussion) the earth which may include strong winds. The data needed for the accident/ mishap investigation is mostly aircraft motion in the airmass. Wind data, if known, could be used in the derivations, although it would not, however, be practical unless recorded with the other data. Such is possible, since the IMUs output true heading, aircraft heading and ground track in some form. TACAN inputs would be helpful. Generally, angle-of-attack and sideslip angles obtained by derivation contain large errors because of local disturbances, the extreme smoothing of the navigation data, and the complications of the derivations with dynamically changing attitudes and the number of variables in the computation. Where the difficulty or expense of adding primary aircraft axes motion sensors is prohibitive, data derived from existing IMU outputs would probably be adequate for most mishap analyses (although obviously dependent upon a functional IMU). LSI is presently using derived roll, pitch, and yaw rates for HUD inputs for air-to-air use in a foreign fighter aircraft update program.

Table 2. General Parameters List

1.A. Dynamics parameters

1.	Time	
2.	Cal airspeed	
3.	h (altitude)	
4.	Heading	
5.	V_x	Body axes velocities
6.	V_y	
7.	V_z	
8.	N_x	Body axes accelerations
9.	N_y	
10.	N_z	
11.	θ (pitch attitude)	Euler angles
12.	Φ (roll attitude)	
13.	ψ (yaw (Δ heading))	
14.	$\dot{\theta}$ (pitch rate)	
15.	$\dot{\Phi}$ (roll rate)	
16.	$\dot{\psi}$ (yaw rate)	
17.	$\ddot{\Phi}$ (roll acceleration)	
18.	β (sideslip)	
19.	α (angle of attack)	
20.	$\dot{h}$ (vertical velocity) (from ADC)	
21.	V_x'	Earth reference velocities
22.	V_y'	
23.	V_z'	
24.	O.A.T.	
25.	Weight and balance	
26.	Mach no.	
27.	Latitude and longitude	

Table 2. General Parameters List (Continued)

1.B. Flight control systems parameters

Primary

1. δ_R (rudder(s) position)
2. δ_{HT} (horizontal tail(s) position)
3. δ_A (aileron(s) position)
4. F_R (rudder pedal force (or position))
5. F_E (longitudinal stick force (or position))
6. F_A (lateral stick force (or position))
7. Trim X
8. Trim Y
9. Trim Z
10. Status discretes

Secondary

1. Flaps position
2. Slats (L.E.F.) position
3. Speed brake or spoiler position
4. Wing sweep angle
5. Flap handle position
6. Slat position command
7. Speed brake command
8. Sweep angle command

Table 2. General Parameters List (Continued)

CAS & SAS

1. Roll, pitch, yaw monitor and status
2. Paddle switch actuation
3. Autopilot status

1.C. Power plant (jet, turboprop) parameters

1. RPM (N_1, N_2, propeller)
2 EGT, FTIT, ITT
3. CDP, EPR
4. Vane position CIVV, RCVV
5. Nozzle position
6. Thrust reverser position
7. Throttle position
8. Afterburner status
9. Torque
10. Oil pressure
11. Oil quantity
12. Fuel flow
13. Fuel pressure
14. Oil temp
15. Fuel temp
16. Hydraulic pressure
17. Hydraulic oil level
18. Utility hydraulic pressure
19. Starters, JFS etc.
20. EPU fuel

Table 2. General Parameters List (Continued)

1.C. (Continued)

21. Chip detector
22. Gear box temp
23. Vibration sensors
24. Status warning discretes

1.D. Avionics systems parameters

Only some avionics systems are of interest, and of those, certain limited parameters including status, BIT data, and bus data are provided by the central computer.

<u>CADC</u>

1.	Validity status	
2.	h (altitude)	
3.	Airspeed	Listed in 1.A. also
4.	$\dot{h}$ (vertical velocity)	
5.	α	
6.	β	

<u>Radar</u>

1. Altitude
2. Terrain clearance pitch commands
3. Functional status

Table 2. General Parameters List (Continued)

1.D. (Continued)

IMU (INU, INS)

1. Validity status
2. Ground speed
3. Inertial true airspeed

AHARS

1. Validity status
2. Roll attitude
3. Pitch attitude
4. Yaw rate

(Items 2 and 3:) Listed in 1.A., could back up IMU-derived parameters

Fuel management system

1. Validity status
2. Fuel per tank (internal and external)
3. Balance warning signals
4. Bingo fuel
5. Purge system status
6. Pump functions
7. Engine feed tank levels
8. Some parameters listed with engine section

Table 2. General Parameters List (Continued)

Central or fire control computer

1. Validity status

Many of the derived parameters originating in IMU, AHARS, CADC, etc. are available as Computer MUX Bus outputs. The resultant desired parameters are in the dynamics list. The computer can usually select from between several sources and provide the best available data.

1.E. Weapons stores inventory and delivery system parameters

1. Pylon stores identification and inventory
2. Gun status
3. Rounds remaining
4. Delivery mode selection
5. Weapons release and intervals
6. Malfunctions

Table 2. General Parameters List (Continued)

1.F. Miscellaneous subsystems parameters

1. Landing gear position
2. Landing gear control position
3. Antiskid status (or wheel rpm)
4. Nose wheel steering
5. Drag chute status
6. Arresting hook status
7. Flares and chaff dispenser status and count
8. Comm. status
9. Transmit keying
10. Fire lights
11. Master caution light
12. Halon pressure
13. Squat switch
14. Caution panel warning lights
15. Marker beacon passage
16. Glide slope
17. Localizer
18. Tacan bearing
19. DME
20. Canopy lock
21. Internal stores doors and racks
22. Anti-ice
23. Accumulator pressures
24. Strain gages

Table 2. General Parameters List (Continued)

1.G. Environmental parameters

1. Cabin temperature
2. Cabin altitude
3. Oxygen pressure
4. Oxygen remaining
5. Oxygen flow
6. Equipment cooling
7. g levels (previously listed)

1.H. Electrical parameters

1. Gen voltage (AC)
2. Gen status (AC)
3. Bus status (may be 4-5 discretes)
4. 28 VDC gen or converter voltage and status
5. Emergency gen status
6. APU, EPU, JFS status and output
7. Inverter voltage
8. Battery voltage

Another form of interrelationship involves parameters of the same family. For example, if roll attitude, roll rate, and roll acceleration are all available, should all three be recorded? Presumably, if the roll attitude sensor has the response capability, and enough samples are recorded, then the other two are available as derivatives. The second (acceleration) derivative may be quite noisy. If the accelerometer output is used instead, and integrated twice, the error in attitude will grow rapidly with time unless the sensor and electronics approach the quality of the IMU or at least of a strapdown system. If all three (or even two) are available, they need occupy no more memory space in the recorder than would one parameter with optimized compression. Since they are related parameters, a small amount of preprocessing under software control requires only recording a starting or reference attitude, a time-related peak acceleration, the slope (or rate) when stabilized, and, again, the attitude at the inflection point (slope zero and maximum acceleration). This simple linear differential relationship permits accurate motion reconstruction with a minimum number of data points. The position, rate and acceleration can be derived from a single sensor through preprocessing and recorded in the same manner (with less final accuracy). A third example can be demonstrated by choosing one axis (such as lateral) of a relatively complex control system of a modern fighter aircraft. There is no direct feel of the pressure on an aileron reflected back to the stick. There exists a rather complex system of mechanical hydraulic and electrical control along with emergency backup, Q controlled gain changes, automatic trim changes, artifical feel, etc. The desire is to determine control stick inputs vs. aileron output. This could involve linear output transducers for each signal and up to 20 resolution steps for each parameter to be recorded. Also recorded would be CAS/SAS status, failure discretes, etc.

The known relationship, under all normal operating conditions, of the stick position and pressure vs. aileron position can be used to reduce the data samples to be recorded. The stick pressures can be sampled in twenty increments (plus and minus), while the aileron position can be inferred in normal operation. Further verification of aileron motion can be deduced by roll rates induced. There are, however, certain maneuvers or failure conditions where the inferred data may be wrong. To preclude this, the aileron position can be recorded in much lower resolution steps than the stick, and, in most cases, the intervening positions can then be interpolated adequately. A more sophisticated approach providing a further reduction in data recorded during normal operation is to model the expected aileron positioning in respect to inputs such as stick position and gain change and failure discretes, and to record aileron position only when it does not conform to the model. Once it is outside of the model envelope it's position would be incrementally recorded. Many dynamics, flight control and engine parameters are candidates for the modeling method.

3.1.1.4 Minimized general list - Table 3 is the general list from table 2 reduced to contain the minimum number of parameters assumed to be adequate for most accident/mishap investigations. It is organized in the same parameter type sequence as table 2.

Each category consists of three lists. The first list represents those parameters inputted to and monitored by the recorder subsystem some of which are recorded. The second list is of parameters which can be derived from the recorded ones during ground playback and post-processing. The third list consists of those minimum parameters deemed necessary for post-crash analysis. The lists are not prioritized at this point in the analysis.

3.1.1.5 Prioritization and selection methods - It is desirable to format parameter lists in descending order of importance. By placing the lowest priority parameters at the bottom of the list, they may be lopped off as necessary to reduce the list to manageable size. This approach is a good goal, but many parameters can be better prioritized in groups (e.g., the groupings used in earlier paragraphs such as: dynamics, engine, flight controls, etc.). A comprehensive list will contain many parameters of each group. Engine parameters, as a group, may be expanded or reduced as may the dynamics parameters. Listing by group makes it easier to tailor the lists to specific aircraft and application. In a final minimum list that may fit within a small size of recorder memory, a particular parameter may be very important, whereas, it may have been easily derivable from other parameters in the expanded list and, therefore, of low recording priority in the expanded list.

Table 4 is a work sheet used to derive a composite of previously prioritized lists such as the National Transportation Safety Board (typical for transport aircraft), the parameter preference lists[6] compiled by Norton AFB for the A-10, F-15, and F-16 accidents and a priority list made up from 221 Class-A accidents for A/F/T aircraft. The statement of need (SON) list ranking is compared with the composite list (last column of table 4, "Composite Priority List Work Sheets"). There is very little resemblance in the ranking of the two lists. The most asked for parameters appear to be completely random in respect to category or source of the parameter as might be expected. Most of the "source" lists follow a particular order, generally with dynamics parameters followed by flight control parameters and engine parameters, then others. Table 5 presents the composite priority list in ranking order for a comprehensive list, prepared to prevent omission or oversight

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[6] Letter from Philip J. Greeley, Col USAF, Dated 7 October 1980, to Lear Siegler, Inc.

Table 3. Minimized General Parameters List

2.A. Dynamics parameters

(1) Input to recorder preprocessor

1.	Time		
2.	V_x'	Fixed axis velocities	Reduced to the equivalent of 3 parameters for recording by preprocessing *
3.	V_y'		
4.	V_z'		
5.	N_x'	Fixed axis accelerations	
6.	N_y'		
7.	N_z'		
8.	θ	Euler angles	
9.	Φ		
10.	Heading (ψ)		
11.	Altitude		
12.	Ground track (or lat. and long.)		
13.	Cal airspeed		
14.	α (if available direct)	Not recorded if not available direct	
15.	β (if available direct)		
16.	Total fuel (affects performance envelope)		

* Alternatively, some body axes dynamic data can be obtained directly from Flight Control System sensors.

Table 3. Minimized General Parameters List (Continued)

(2) Ground station processor output

1.	V_x	Body axis translatory velocities (derived) (IMU)	
2.	V_y		
3.	V_z		
4.	N_x	Body axis translatory accelerations (derived) (IMU)	
5.	N_y		
6.	N_z		
7.	θ (pitch attitude)	Direct (IMU or AHARS)	
8.	Φ (roll attitude)		
9.	ψ (yaw (Δ heading))		
10.	$\dot{\theta}$ (pitch rate)	Derived (direct if available)	
11.	$\dot{\Phi}$ (roll rate)		
12.	$\dot{\psi}$ (yaw rate)		
13.	$\ddot{\Phi}$ (roll acceleration)	Derived (direct if available)	
14.	β	Direct	(or derived, possible high error)
15.	α	Direct	
16.	Heading	Direct	
17.	Ground track (or lat./long.)	Direct	
18.	Mach no.	Derived	
19.	Altitude	Direct	(IMU or CADC)
20.	Cal airspeed	Direct	(ADC)
21.	Vertical velocity	Direct	(V_z' or CADC)
22.	Time	Direct	
23.	Total fuel	Direct	

Table 3. Minimized General Parameters List (Continued)

This shows that 23 parameters can be obtained from the recording of 14 to 16 parameters. If the IMU is not present, then other direct sources of body axis attitudes, rates and accelerations are required.

The total recorded parameters will not increase since certain inertial data required in the transformations are not required with the direct body axis data.

(3) Most important dynamics parameters to be used for analysis.

1. Time
2. Cal airspeed
3. Altitude
4. Vertical velocity
5. Normal acceleration
6. Lateral acceleration
7. Pitch rate
8. Yaw rate
9. Pitch attitude
10. Roll attitude
11. Roll rate
12. Roll acceleration
13. Angle of attack (From ADC)
14. Sideslip angle (From ADC)
15. Heading (Inertial)

Several of the dynamic parameters can be eliminated for specific aircraft.

Table 3. Minimized General Parameters List (Continued)

2.B. Flight control systems parameters

(1) Input to recorder preprocessor

1. δ_R
2. δ_{HT}
3. δ_A
4. F_R
5. F_E
6. F_A
7. Pitch trim
8. Status discretes of CAS/SAS
9. Slats on LEF open/closed discrete
10. Flaps up/down discrete
11. Wing sweep when applicable (F-111)
12. Speed brake open/close discrete

Preprocessing philosophy suggests no need to record any of the above variables 1-6 unless the status discretes indicate failure modes, or if aircraft motion sensors indicate high acceleration or rates above predetermined thresholds.

Table 3. Minimized General Parameters List (Continued)

(2) Typical recorded flight control data available to ground processor

1.	Pitch trim position when changed	
2.	Wing sweep position (where applicable)	
3.	FCS CAS/SAS status discretes when changes occur	
4.	Slat position when changed	
5.	Flap position when changed	
6.	F_R	Only when pre-defined criteria are met
7.	F_A	
8.	F_E	
9.	δ_R	Only when exceed preprocessor model or tolerances
10.	δ_A	
11.	δ_{HT}	
12.	Speed brake when changed	

Very little flight control data will be recorded unless failures or turbulent flight occur.

(3) Most important flight control parameters

1. Pitch trim (some aircraft)
2. FCS status and failure discretes
3. Slat or flap position (specific aircraft)
4. F_A
5. F_R
6. F_E

Table 3. Minimized General Parameters List (Continued)

7.	δ_A	Can be reconstructed from input data and model used in preprocessor or recorded data when model exceeded
8.	δ_R	
9.	δ_E	

Where recording capacity is limited, control surface position may be deduced from control inputs and aircraft response in most cases.

2.C. Power plant parameters

(1) Input to recorder preprocessor

1.	RPM (N_1 or N_2)	(Record predetermined increments)
2.	EGT, FTIT or ITT	(Record predetermined increments)
3.	Throttle position	(Record predetermined increments)
4.	Nozzle position	Model in preprocessor and record only if outside model limits
5.	Fuel Flow	
6.	Vibration sensor	(Requires special conditioning)
7.	Fire light	(discrete)
8.	CDP or EPR	If available (Record increments)
9.	Oil pressure	Record increments
10.	Hydraulic pressure	Record increments
11.	Afterburner status	

(2) Typical recorded power plant data

1. RPM
2. FTIT
3. Throttle position
4. Nozzle position

Table 3. Minimized General Parameters List (Continued)

5.	Fuel Flow	
6.	Vibration sensor	(Only certain changes)
7.	Fire light	(Only in the event of Fire)
8.	CDP or EPR	(Only available on some aircraft)
9.	Oil pressure	(Record fail discrete)
10.	Hydraulic pressure	(If out of normal range)
11.	Afterburner status	

(3) Most important power plant data available for analysis

1.	RPM	(Actual)
2.	FTIT	(Actual)
3.	Throttle position	(Actual)
4.	Nozzle position	Available from model or actual if excessive deviation from model
5.	Fuel flow	
6.	Fire light	Discrete indications of problems
7.	Oil pressure	
8.	CDP or EPR	(Actual if available)
9.	Afterburner status	(Derived from other parameters)
10.	Hydraulic pressure	(If abnormal)

Typical flights would only record three or four power plant variables, and then only when certain deltas are exceeded.

Table 3. Minimized General Parameters List (Continued)

2.D. Avionics systems parameters

(1) Input to recorder preprocessor (parameters listed with other sources will not be relisted unless they provide backup or alternate sources)

1. CADC validity status or words
2. Vertical velocity (CADC alternate source)
3. α (alternate source)
4. β (alternate source)
5. IMU validity
6. AHARS validity
7. Roll attitude (AHARS backup)
8. Pitch attitude (AHARS backup)
9. Yaw rate (AHARS backup)
11. Roll rate (HUD source backup)
12. Yaw rate (HUD source backup)
13. Pitch rate (HUD source backup)
14. Central computer (FCC) status word

(2) Recorded avionics systems data

1. CADC status and validity (Only if abnormal)
2. AHARS status and validity (Only if abnormal)
3. FCC status and validity (Only if abnormal)
4. IMU status and validity (Only if abnormal)

Table 3. Minimized General Parameters List (Continued)

(3) Most important avionics parameters. The most important avionics parameters in the list of 2.D. are the validity indications for avionics subsystem parameters being recorded. These will amount to an average of four to five digital discretes for each subsystem contributing data (with about 15 total).

2.E. Weapon stores and inventory parameters (also external fuel tanks)

(1) Input to recorder preprocessor

1. Rounds remaining
2. Stores status for each pylon or station (type of weapon on stations can be logged when installed, eliminating the need to record.)

(2) Recorded stores data available to ground station

1. Data logged when weapons loaded
2. Stores dropped or fired per station (with time)

Table 3. Minimized General Parameters List (Continued)

(3) Minimum stores data recorded

1. Stores fired or dropped from one wing tip to fuselage centerline (acceptable where the number of recorded parameters are limited since stores are dropped or fired from alternate sides to maintain symmetry).

2. Hung stores status

2.F. Miscellaneous subsystems parameters

(1) Input to recorder preprocessor

1. Master caution
2. Transmitter keying
3. Canopy lock (cargo or hatch door)
4. Anti-ice status
5. Landing gear position
6. Weight on gear
7. Antiskid

(2) Typical recorded miscellaneous parameters available to ground processor (same as in 2.F.(1))

(3) Most important miscellaneous parameters

1. Master caution
2. Landing gear status
3. Weight on gear

Table 3. Minimized General Parameters List (Continued)

2.G. Environmental parameters

(1) Input to recorder preprocessor

1. Cabin temperature (to be recorded only if out of normal range)

2. Cabin altitude (model against outside altitude and record only if out of model limits) (only if transducer available)

3. Oxygen remaining

(2) Typical recorded data available to ground station

1. Cabin temperature
2. Cabin altitude (derived from model or actual if out of tolerance)
3. Oxygen remaining (actual)

(3) Most important environmental parameters

1. Oxygen remaining

Table 3. Minimized General Parameters List (Continued)

2.H. Electrical parameters

(1) Input to recorder preprocessor

1. AC main bus voltage
2. Main alternator status
3. Backup alternator status
4. Emergency power unit status
5. DC bus voltage
6. Battery voltage or status
7. Various buses' status
8. 26 VAC instrument bus voltage

(2) Typical recorded data to ground station

1. AC voltage (if out of normal limits)
2. Power source (main generator, emergency generator, etc.)
3. DC voltage (if out of normal limits)
4. Battery voltage (if all other DC power down)

(3) Most important electrical parameters

1. AC power available and within limits
2. DC power available and within limits

Table 4. Composite Priority List Work Sheets

1.0	Miscellaneous	F-16 (A)	$\frac{1}{A} \times 10$	F-15 (B)	$\frac{1}{B} \times 10$	A-10 (C)	$\frac{1}{C} \times 10$	A/F/T (D)	$\frac{1}{D} \times 10$	NTSB (E)	$\frac{1}{E} \times 5$	$\Sigma(A \rightarrow E)$	Comp. Rank	SON Rank
1.1	Transmitter keyed time	-		-		10	1.0	-		6	.833	1.833	45	
1.2	Elapsed time (relative)	-		-		9	1.11	1	10.0	1	5	16.11	2	
1.3	Anti-skid ON/OFF/FAIL	-		-		-		-		-				
1.4	Radar altitude	4	2.5	11	.91	9	1.11	-		24	.208	4.728	31	
1.5	Halon pressure	-		-		-		-		-				

(A) = Priority ranking number from F-16 Investigators' list (Table 12)
(B) = Priority ranking number from F-15 Investigators' list (Table 9)
(C) = Priority ranking number from A-10 Investigators' list (Table 6)
(D) = Priority ranking number from A/F/T composite list based upon 221 Class-A accidents
(E) = Priority ranking number from NTSB parameters list
$\Sigma(A \cdot E)$ = sum of ranking reciprocals times weighting factors
Comp. Rank = Composite Rank
SON Rank = Statement-of-Need Rank

Table 4. Composite Priority List Work Sheets (Continued)

2.0	CADC Functions	F-16 (A)	$\frac{1}{A} \times 10$	F-15 (B)	$\frac{1}{B} \times 10$	A-10 (C)	$\frac{1}{C} \times 10$	A/F/T (D)	$\frac{1}{D} \times 10$	NTSB (E)	$\frac{1}{E} \times 5$	Σ(A-E)	Comp. Rank	SON Rank
2.1	A.O.A	-		9	1.11	3	3.33	19	.53	17	.294	5.26	24	1
2.2	Cal. airspeed	3	3.33	2	5.0	5	2.0	3	3.33	2	2.5	16.16	1	5
2.3	Sideslip	4	2.5	-		-		34	.294	-		2.794	38	24
2.4	Baro alt.	4	2.5	3	3.33	4	2.5	2	5.0	3	1.67	15.00	4	2
2.5	Mach	4	2.5	11	.91	9	1.11	46	.217	-		4.737	30	29
2.6	CADC status (see discretes)*	-		10	1.0	-		35	.286	-		1.286	46	34
2.7	OAT/IAT	-		10	1.0	-		-		25	.200	1.200	49	
2.8	Vertical vel (Baro) (see 3.12)	-		-		-		8	1.25	-		1.25	47	13

* Same as 8.9

Table 4. Composite Priority List Work Sheets (Continued)

3.0	Orientation Parameters	F-16 (A)	$\frac{1}{A} \times 10$	F-15 (B)	$\frac{1}{B} \times 10$	A-10 (C)	$\frac{1}{C} \times 10$	A/F/T (D)	$\frac{1}{D} \times 10$	NTSB (E)	$\frac{1}{E} \times 5$	$\Sigma(A \to E)$	Comp. Rank	SON Rank
3.1	Pitch attitude	3	3.33	7	1.43	2	5.0	7	1.43	10	.500	11.69	8	12
3.2	Roll attitude (Bank angle)	4	2.5	8	1.25	2	5.0	12	.83	11	.455	10.035	10	11
3.3	Heading	4	2.5	-		9	1.11	23	.435	4	1.25	5.295	25	14
3.4	Yaw angle	-		-		-		21	.48	-		0.48	54	
3.5	Norm load (vert. accel.)	3	3.33	7	1.43	5	2.0	25	.40	5	1.0	8.16	13	3
3.6	Lateral accel.	-		-		-		37	.270	19	.263	.533	53	
3.7	Long accel.	-		-		-		36	.278	7	.714	.992	51	
3.8	Yaw rate	3	3.33	-		1	10.0	20	.50	-		13.83	6	6
3.9	Pitch rate	4	2.5	-		-		9	1.11	-		3.61	33	7
3.10	Roll rate	4	2.5	-		-		17	.59	-		3.09	36	4
3.11	Inertial altitude	-		-		-		-		-				
3.12	Vertical vel. (see 2.8) (inert. ref.)	-		-		-		8	1.25	-		1.25	47	13

Table 4. Composite Priority List Work Sheets (Continued)

4.0	Control and Surface Positions	F-16 (A)	$\frac{1}{A} \times 10$	F-15 (B)	$\frac{1}{B} \times 10$	A-10 (C)	$\frac{1}{C} \times 10$	A/F/T (D)	$\frac{1}{D} \times 10$	NTSB (E)	$\frac{1}{E} \times 5$	$\Sigma(A\text{-}E)$	Comp. Rank	SON Rank
4.1	Rudder position	-		8	1.25	2	5.0	11	.91	9	.556	7.716	14	10
4.2	Elevator, elevon or stabilator position	-		5	2.0	5	2.0	14	.71	9	.556	5.266	23	8
4.3	Stabilizer* position	-		-		-		-		-				
4.4	Aileron (Flaperon) position	-		7	1.43	3	3.33	10	1.0	9	.556	6.316	18	9
4.5	Roll trim position	-		10	1.0	5	2.0	-		-		3.0	37	
4.6	Pitch trim position	-		10	1.0	5	2.0	-		12	.417	3.417	34	
4.7	Yaw trim position	-		10	1.0	5	2.0	-		-		3.0	37	
4.8	Stick long. position or force	-		6	1.67	4	2.5	4	2.5	-		6.67	17	28
4.9	Stick lat. position or force	-		6	1.67	4	2.5	4	2.5	-		6.67	17	28
4.10	Rudder ped. position or force	-		8	1.25	6	1.67	5	2.0	-		4.92	29	27

* Same at pitch trim 4.6.

Table 4. Composite Priority List Work Sheets (Continued)

4.0	Control and Surface Positions (Cont.)	F-16 (A)	$\frac{1}{A} \times 10$	F-15 (B)	$\frac{1}{B} \times 10$	A-10 (C)	$\frac{1}{C} \times 10$	A/F/T (D)	$\frac{1}{D} \times 10$	NTSB (E)	$\frac{1}{E} \times 5$	$\Sigma(A \rightarrow E)$	Comp. Rank	SON Rank
4.11	Flap or flaperon position	-		-		9	1.11	26	.385	13	.385	1.880	44	30
4.12	Flap handle position	-		-		-		-		-				
4.13	Slat or leading edge flap position	-		-		2	5.0	42	.238	14	.357	5.595	20	
4.14	Slat or LEF control position	-		-		-		-		-				
4.15	Speed brake position (or spoiler)	-		-		5	2.0	29	.345	15	.333	2.678	40	32
4.16	Gear position (3)	-		-		-		28	.357	-		.357	57	31
4.17	Gear handle position	-		-		-		-		-				
4.18	Wing sweep angle	-		-		-		31	.323	-		.323	58	

Table 4. Composite Priority List Work Sheets (Continued)

5.0	Engine and Fuel Parameters	F-16 (A)	$\frac{1}{A} \times 10$	F-15 (B)	$\frac{1}{B} \times 10$	A-10 (C)	$\frac{1}{C} \times 10$	A/F/T (D)	$\frac{1}{D} \times 10$	NTSB (E)	$\frac{1}{E} \times 5$	Σ(A-E)	Comp. Rank	SON Rank
5.1	Throttle position	2	5.0	8	1.25	7	1.43	6	1.67	-		9.35	11	25
5.2	N_1	2	5.0	4	2.5	4	2.5	13	.77	-		10.77	9	
5.3	N_2	1	10.0	7	1.43	5	2.0	13	.77	8	.625	14.825	5	15
5.4	EGT	2	5.0	8	1.25	5	2.0	16	.63	-		8.88	12	16
5.5	EPR	-	-	-	-	-		-		-				
5.6	CDP	4	2.5	6	1.67	11	.91	-		8	.625	5.705	19	
5.7	A/B position/ nozzle	4	2.5	9	1.11	-		27	.370	-		3.98	32	26
5.8	Oil pressure	4	2.5	11	.91	8	1.25	24	.417	-		5.077	28	22
5.9	Oil quant.	-		-		-		33	.303	-		.303	59	33
5.10	Fuel flow	1	10.0	3	3.33	8	1.25	15	.67	-		15.25	3	17
5.11	Fuel quant. (total)	2	5.0	9	1.11	10	1.0	18	.56	-		7.67	15	23
5.12	Tank or Balance	3	3.33	9	1.11	11	.91	-		-		5.35	22	
5.13	Main Hyd. Pressure A & B	-		5	2.0	4	2.5	22	.455	27	.185	5.140	27	18
5.14	Util. hyd. pressure	-		10	1.0	7	1.43	30	.333	-		2.763	39	19
5.15	FTIT	-		6	1.67	-		-		8	.625	2.295	42	
5.16	Alt./Inv./ Gen. Output	-		11	.91	8	1.25	35 38	.286 .263	29	.172	2.602	41	20 21
5.17	APU/EPU/EEC/ JFS status	-		11	.91	10	1.0	-		-		1.91	43	
5.18	EPU fuel remaining	-		-		-		-		-				
5.19	CIVV position	-		-		-		-		-				
5.20	Thrust reverser	-		-		-		-		20				
5.21	Fuel pressure	-		-		-		-		-				
5.22	Fuel temp.	-		-		-		-		-				

Table 4. Composite Priority List Work Sheets (Continued)

6.0	FCS and SAS*	F-16 (A)	$\frac{1}{A} \times 10$	F-15 (B)	$\frac{1}{B} \times 10$	A-10 (C)	$\frac{1}{C} \times 10$	A/F/T (D)	$\frac{1}{D} \times 10$	NTSB (E)	$\frac{1}{E} \times 5$	Σ(A+E)	Comp. Rank	SON Rank
6.1	Yaw aug. status	4	2.5	10	1.0	6	1.67	32	.313	-		5.483	21	
6.2	Pitch aug. status	-		7	1.43	6	1.67	32	.313	-		3.413	3	
6.3	Roll aug. status	3	3.33	9	1.11	5	2.0	32	.313	-		6.753	16	
6.4	Autopilot ON/OFF	-		-		-		39	.256	16	.313	.569	52	
6.5	Alt. or Att. hold	-		-		-		-		16	.313	.313	56	
6.6	Turn rate or heading	-		-		-		-		16	.313	.313	56	
6.7	Paddle switch action	-		-		9	1.11	-		-		1.11	50	

*SAS or CAS

Table 4. Composite Priority List Work Sheets (Continued)

		F-16 (A)	$\frac{1}{A} \times 10$	F-15 (B)	$\frac{1}{B} \times 10$	A-10 (C)	$\frac{1}{C} \times 10$	A/F/T (D)	$\frac{1}{D} \times 10$	NTSB (E)	$\frac{1}{E} \times 5$	Σ(A-E)	Comp. Rank	SON Rank
7.0	Life Support													
7.1	Oxygen Flow	-		-		-		-		-				
7.2	Oxygen Pressure	-		-		-		-		-				
7.3	Oxygen Quant.	-		-		-		-		-				
7.4	Cockpit altitude	-		-		-		40	.250	28	.179	.429	55	
7.5	Cockpit Temp.	-		-		-		41	.244	-		.244	61	

Table 4. Composite Priority List Work Sheets (Continued)

8.0	Annuc./Warnings/ Status (Discretes)	F-16 (A)	$\frac{1}{A} \times 10$	F-15 (B)	$\frac{1}{B} \times 10$	A-10 (C)	$\frac{1}{C} \times 10$	A/F/T (D)	$\frac{1}{D} \times 10$	NTSB (E)	$\frac{1}{E} \times 5$	Σ(A→E)	Comp. Rank	SON Rank
8.1	Master caution light	-		1	1.0	4	2.5	43	.233	-		12.733	7	
8.2	Overheat light	-		-		-		-		-				
8.3	Fire warning light	4	2.5	8	1.25	10	1.0	44	.227	26	.192	5.169	26	
8.4	Bingo fuel	-		-		-		-		-				
8.5	Eng. inlet anti-ice switch position	-		-		-		-		-				
8.6	Nav. status	-		-		-		-		-				
8.7	IMU/INU status	-		-		-		-		-				
8.8	FCC status	-		-		-		45	.222	-		.222	64	35
8.9	CADC status*	-		10	1.0	-		35	.286	-		1.286	46	34
.10	AHARS status	-		-		-		-		-				
8.11	HUD status	-		-		-		-		-				
8.12	Radar status	-		-		-		-		-				
8.13	EEC caution status	-		-		-		-		-				
8.14	SAS/CAS status	-		-		11	.91	32	.313	-		1.223	48	
8.15	Squat switch	-		-		-		-		18	.278	.278	60	
8.16	Marker of beacon passage	-		-		-		-		21	.238	.238	62	
8.17	Localizer	-		-		-		-		22	.227	.227	63	
8.18	Glide slope	-		-		-		-		23	.217	.217	65	

*same as 2.6

Table 5. Composite General Parameters Priority List

RANK	ID NO. TABLE 4	NAME
1	2.2	Calibrated airspeed
2	1.2	Relative or elapsed time
3	5.10	Fuel flow
4	2.4	Baro altitude
5	5.3	N_2
6	3.8	Yaw rate
7	8.1	Master caution light
8	3.1	Pitch attitude
9	5.2	N_1
10	3.2	Bank (roll) attitude
11	5.1	Throttle position
12	5.4	E.G.T.
13	3.5	Normal load (vert. accel.)
14	4.1	Rudder position
15	5.11	Total fuel quantity
16	6.3	Roll SAS status
17 (2)	4.8, 4.9	Stick long. or lat. position or force
18 (see 44)	4.4	Aileron or flaperon position
19	5.6	Compressor discharge pressure (CDP)
20	4.13	Slat or leading edge flap position
21	6.1	Yaw SAS status
22	5.12	Tank quantity or balance
23	4.2	Elevator, elevon or stabilator pos.
24	2.1	Angle of attack
25	3.3	Heading
26	8.3	Fire warning light
27	5.13	Main hydraulic pressure
28	5.8	Oil pressure

Table 5. Composite General Parameters Priority List (Continued)

RANK	ID NO. TABLE 4	NAME
29	4.10	Rudder ped. position or force
30	2.5	Mach no.
31	1.4	Radar altitude
32	5.7	Afterburner position
33	3.9	Pitch rate
34	4.6	Pitch trim position
35	6.2	Pitch SAS status
36	3.10	Roll rate
37 (2)	4.5, 4.7	Roll and yaw trim position
38	2.3	Sideslip angle
39	5.14	Utility hydraulic pressure
40	4.15	Speed brake or spoiler position
41	5.16	Alt./Inv./Gen. output
42	5.15	FTIT
43	5.17	APU/EPU/JFS status
44 (see 18)	4.11	Flap or Flaperon position
45	1.1	Transmitter keyed
46	2.6 (8.9)	CADC status
47	2.8 (3.12)	Vert. velocity
48	8.14	SAS/CAS status light
49	2.7	O.A.T./I.A.T.
50	6.7	Paddle switch
51	3.7	Longitudinal accel.
52	6.4	Autopilot ON/OFF
53	3.6	Lateral accel.
54	3.4	Yaw angle
55	7.4	Cabin pressure
56 (2)	6.5, 6.6	Alt. or Att. hold, turn rate or heading

Table 5. Composite General Parameters Priority List (Continued)

RANK	ID NO. TABLE 4	NAME
57	4.16	Gear position
58	4.18	Wing sweep angle
59	5.9	Oil quantity
60	8.15	Squat switch
61	7.5	Cabin temperature
62	8.16	Marker beacon passage
63	8.17	Localizer
64	8.8	FCC status
65	8.18	Glide slope
66	5.21	Fuel pressure
67	-	Oil chip detector
68	1.3	Anti-skid
69	1.5	Halon pressure
70	3.11	Inertial altitude
71	4.17	Gear handle position
72	4.14	Slat command position
73	4.12	Flap handle position
74	7.1	Oxygen flow
75	7.2	Oxygen pressure
76	7.3	Oxygen quantity
77	5.22	Fuel temp.
78	5.20	Thrust reverser

of parameters. The lists, by category, are the best starting point. The comprehensive ranked parameter list is useful for empirically realized relative worth of the various parameters. However, it does not directly follow that a minimum list can be prepared by lopping off the bottom of the comprehensive list. No minimum list is meaningful unless prepared for a specific aircraft. The parameter selection may then be biased in the direction that existing accident investigations dictate. Caution here is also advised since, as causes are corrected, accidents will tend to shift toward a random cause, and the parameters monitored should be general enough to shed light on a variety of causes.

3.1.1.6 Parameter types - Parameters can be source related. In this study, the sources or names of sources may vary slightly with aircraft type but are essentially as listed:

- Engine
- CADC
- FCS (CAS, SAS)
- AHARS
- INS (IMU)
- Master bus controller
- Fire Control (or Central) Computer
- HUD
- SAS
- Aircraft miscellaneous
- SMS (Stores Management System)

The parameter data may be supplied from the following signal types:

- 1553 Data bus (or equivalent)
    - Digital data
    - Digital discretes
- Synchro
- Other AC analog
- DC analog
- +28 VDC discretes
- Low level complementary discrete
- Variable frequency
- AC discretes

Tables are provided for the A-10, F-15, and F-16 parameters and include source, description, and parameter data specifications. These tables are included in 3.1.1.8.

3.1.1.7 Existing sensors and data sources vs. added sensors and signal sources - For the most economical recorder installation and implementation, it is desirable to obtain the parameter data from existing in-place sources when possible. The most economical source is the MUX bus. If the existing signal is inadequate for accident/mishap analysis purposes, first alternative parameters must be investigated as possible sources of derivable data, or new sensors must be added for direct data acquisition. Addition of new sensors also means addition of new mounting and wiring kits along with the extra installation time. When existing sources are marginal, a trade-off must be made as to whether to accept limited data or to add the new sensor at additional cost. The lists provided for the A-10, F-15, and F-16 assume use of existing signals where possible. Sensors are added only as a last resort. The previously given comprehensive list (table 5) was prioritized strictly on the basis of usefulness, need, or request. Other items that can or should affect ranking of parameters are the items that dictate cost effectiveness of each parameter; that is, the need must be weighed against the cost of acquisition. Some basic parameters must, of course, be recorded anyway.

The following characteristics should be known for each parameter and/or source to assist in determining the most effective selection.

- Relative need (priority from general list)
- Relative cost of acquisition (size, weight, price, installation)
- Complexity (signal processing complexity, etc.)
- Safety (impact on existing systems)
- Reliability of source (leading to or during mishap)
- Maintainability (added maintenance cost vs. none added if existing sources used)

The policy followed in formulating the A-10, F-15, and F-16 lists is not to re-rank parameters as these last considerations are evaluated, but rather to provide each parameter with a figure of merit of from 1 to 5 for each characteristic. A rating of 1 being least desirable and a 5 being most desirable.

3.1.1.8 Lists for specific aircraft - Representative lists have been prepared for the A-10, F-15, and F-16. The lists are intended to be accurate enough to provide data requirement recommendations and inputs to other sections of the study for installation planning and cost trade-offs. Multiple sources of some parameters exist and the one chosen for the list might not be the one used in an actual design effort. Availability points in the aircraft are given to identify the source, but are not necessarily given to physically show where connections would be made.

a. A-10. Table 6, the A-10 priority list in accordance with parameters requested by accident investigators (reference 6), is included to show the relative importance of various parameters for A-10 accident investigations as indicated by the investigators themselves (questionnaire tabulation). The list shows 49 parameters divided into 12 groupings of descending priority. Time, though of low priority on their list was placed at the top. The percentage of time that a parameter was requested is shown in the fourth column.

The ranking as shown in the general priority list (table 5) is entered in column 5 for relative comparison.

Table 7 is the final recommended arrangement of parameters and is presented as the Configuration I list for the A-10. It is expanded to list parameters for each engine and control surface, and is rearranged to move some high priority parameters from the general list to higher spots relative to the A-10 investigators' list. The Configuration I list must be comprehensive and general enough to permit analysis of accidents from almost any cause. Minimum lists, by necessity, often tend to be biased toward parameters useful in analyzing the most recent and most common accidents for that aircraft to date. This trend should be guarded against in a long-term crash recorder program. Where desired data is available from a MUX bus, reprogramming of the recorder provides flexibility for priority shifting. Where sensors must be added for concentrated special area monitoring, changes are costly. Forty-four "continuous" signals and 61 discrete signals are listed. They are prioritized separately because their processing and memory requirements are drastically different. Many discretes can be recorded for the "price" of one continuous signal. Table 8 is the recommended minimum parameter list for the A-10. An attempt has been made to balance parameter needs for long-term general accident analysis with those determined by the "to-date" needs. Explanations of special problems of some parameters follow each table as necessary.

Table 6. A-10 Investigators' List

No.	Parameter	Ranking Group	Request %	General List Ranking
1	Time	9	18	2
2	Yaw rate	1	71	6
3	Bank attitude	2	65	10
4	Pitch attitude	2	65	8
5	Slat position	2	65	20
6	Rudder position	2	65	14
7	AOA	3	59	24
8	Aileron position (2)	3	59	18
9	N_1 (2)	4	53	9
10	Baro. alt.	4	53	4
11	Stick position (2)	4	53	17
12	Hyd. pres. (2)	4	53	27
13	Master caution	4	53	7
14	Cal. airspeed	5	47	1
15	Norm. load	5	47	13
16	Speedbrake position	5	47	40
17	Elev. position (2)	5	47	23

Table 6. A-10 Investigators' List (Continued)

No.	Parameter	Ranking Group	Request %	General List Ranking
18	N_2 (2)	5	47	5
19	EGT (2)	5	47	12
20	CAS roll	5	47	16
21	Trim (3)	5	47	34, 37
22	Rudder ped. position	6	35	29
23	CAS pitch	6	35	35
24	CAS yaw	6	35	21
25	Throttle position (2)	7	29	11
26	Util. hyd. pressure	7	29	39
27	Fuel flow (2)	8	24	3
28	Oil pressure (2)	8	24	28
29	Gen. (2)	8	24	41
30	Mach no.	9	18	30
31	Heading	9	18	25
32	Flap position	9	18	44

Table 6. A-10 Investigators' List (Continued)

No.	Parameter	Ranking Group	Request %	General List Ranking
33	Paddle switch	9	18	50
34	Altitude (radar)	9	18	31
35	Inverter	9	18	41
36	Fuel total	10	12	15
37	Comm. transmit	10	12	45
38	Fire light (3)	10	12	26
39	EPU (APU)	10	12	43
40	Fuel/tank	11	6	22
41	CDP (2)	11	6	19
42	Starter	11	6	43
43	SAS status	11	6	48
44	Gear position	12	0	57
45	CADC status	12	0	46
46	Anti-skid	12	0	68
47	Nav. status	12	0	-
48	A/B position	12	0	32
49	OAT	12	0	49

Table 7. A-10 Configuration I Parameter List

NO	CONTINUOUS	SOURCE CODE	TYPE CODE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIGITAL WORD ID	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT		ASIP LIST	A-10 ACC. LIST PRIORITY	SOURCE OF DATA OR COMMENTS
										PARAM. WORTH	PARAM. COST			
1	Time	1-5	5	0-4 sec	LSB = 64 μsec	.01%	108-02	50/sec	16 bits	5	5	√	9	A-10 ICD page A-85
2	Cal airspeed	1-2	5	50-600 kn	LSB = .0625 kn MSB = 512 kn	±1.5 kn	C01-06	25/sec	14 bits + sign	5	5	√	5	ICD page A-10
3	Normal load	8	3	-3g +10g		0.1 g	Available at ABK-17 counterset 1J1 pins 30 & 31			4	4	√	5	Use counter accelerometer
4	Press altitude	1-2	5	-1000 ft to +45,000 ft	LSB = 2.5 ft MSB = 40,960	±100 ft at 45K	C01-02	25/sec	15 bits + sign	5	5	√	4	Baro is available on C02-03 page A-6
5	Bank angle	1-5	5	$-\pi$ to $+\pi$ radians	LSB = $\frac{\pi}{32,768}$ MSB = $\pi/2$	.00175 radians rms	108-10	50/sec	15 bits + sign	5	5		2	Page A-93 A-10 ICD
6	Pitch attitude	1-5	1-5	$-\pi$ to $+\pi$ radians	LSB = $\frac{\pi}{32,768}$ MSB = $\pi/2$	.00175 radians rms	108-11	50/sec	15 bits + sign	5	5		2	(Also available from HARS synchro p.A-94) A-10 ICD p.A-94
7	Yaw rate	3	3					45 mv/deg	Millivolt level	4	3	√	1	Use SAS "Vyro"
8	AOA	2	1	±30°		±.25°			Assume 0-11.8 VAC 400 Hz	3	3		3	Spare digital slot as word No. C01-07 could be added
9	Rudder pos. rt.	10	3 or 7	±25°	0.2 VDC per deg	1%		assume 0-10 VDC	Rotary pot added	3	2		2	Synchro preferred as alternate
10	Rudder pos. lt.	10	3 or 7	±25°	0.2 VDC per deg	1%		assume 0-10 VDC	Rotary pot added	3	2		2	Synchro preferred as as alternate
11	Aileron pos. rt.	10	3 or 7	28° up 10° down	.263 v/deg	1%		Assumed 0-10 VDC	Add linear pot	3	2		3	Pot mounted to actuator shaft. LVDT preferred alternate

Source Code:
1. 1553 data bus
2. CADC
3. F.C.S. (CAS,SAS)
4. AHARS
5. INS
6. Master bus controller
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors

Type Code:
1. Synchro
2. +28V discrete
3. D.C. analog
4. Digital discrete
5. Digital data
6. Low level comp. discrete
7. AC analog

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 7. A-10 Configuration I Parameter List (Continued)

NO.	CONTINUOUS	SOURCE CODE	TYPE CODE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIGITAL WORD ID	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT PARAM. WORTH	FIGURES OF MERIT PARAM. COST	ASIP LIST	A-10 ACC. LIST PRIORITY	SOURCE OF DATA OR COMMENTS
12	Aileron pos. lt.	10	3 or 7	28° up 10° down	.263 v/deg	1%		Assumed 0-10 VDC	Add linear pot	3	2		[illegible]	Pot mounted to actuator shaft. LVDT preferred alternate.
13	Elevator pos rt.	10	3 or 7	35° up 10° down	.222 v/deg	1%		Assumed 0-10 VDC	Add rotary pot	3	2		5	Synchro preferred alternate
14	Elevator Pos lt.	10	3 or 7	35° up 10° down	.222 v/deg	1%		Assumed 0-10 VDC	Add rotary pot	3	2		5	Synchro preferred alternate
15	Stick pos. (roll)	10	3 or 7	±3.25°	1.6 v/°	1%		Assumed 0-10 VDC	Add rotary pot	3	2		4	Added pots are in accordance with Fairchild Flight Test installations. Synchro preferred.
16	Stick pos. (pitch)	10	3 or 7	9°24' fwd. 10°54" aft.	1.6 v/°	1% 1%		Assumed 0-10 VDC	Add rotary pot	3	2		4	Added pots are in accordance with Fairchild Flight Test installations. Synchro preferred.
17	N_1 rt. (fan)	9	7	0-100% 0-5 VAC	100% = 7,850 rpm	2%				5	4		4	
18	N_1 lt. (fan)	9	7	0-100% 0-5 VAC		2%				5	4		4	
19	N_2 rt. (high pressure)	9	7	0-100% 0-5 VAC	100% = 17,800 rpm	2%				4	4		5	
20	N_2 lt. (high pressure)	9	7	0-100% 0-5 VAC		2%				4	4		5	
21	ITT rt.	9	7	0-1200°C 0-5 VAC		5%				5	4		5	No EGT
22	ITT lt.	9	7	0-1200°C 0-5 VAC		5%				5	4		5	No EGT
23	Hyd. pres. rt.	9	3	0-4500 psi 0-5 VDC	1.111 mv/psi	2%			XDUCER	4	4		4	Can also use 400 Hz cockpit instrument line. Voltage not known.

Source Code:
1. 1553 data bus
2. CADC
3. F.C.S. (CAS,SAS)
4. AHARS
5. INS
6. Master bus controller
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors

Type Code:
1. Synchro
2. +28V discrete
3. D.C. analog
4. Digital discrete
5. Digital data
6. Low level comp. discrete
7. AC analog

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 7. A-10 Configuration I Parameter List (Continued)

NO.	CONTINUOUS	SOURCE CODE	TYPE CODE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIGITAL WORD ID	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT		ASIP LIST	A-10 ACC. LIST PRIORITY	SOURCE OF DATA OR COMMENTS
										PARAM. WORTH	PARAM. COST			
24	Hyd. pres. lf.	9	3	0-4500 psi	1.111 mv/psi	2%			XDUCER	4	4		4	Can also use 400 Hz cockpit instrument line. Voltage not known.
25	Rudder pedal position	8	3	6 inch travel		1%		Assume 0-10 VDC	Add rotary pot	3	2		6	Added Pots in accordance with Fairchild Flight Test Installation. Synchro preferred.
26	Throttle position rt.	10	3	50° 0-100%	0.2v/deg	1%		Assume 0-10 VDC	Add rotary pot	4	2		7	Added Pots in accordance with Fairchild Flight Test Installation
27	Throttle position lf.	10	3	50° 0-100%	0.2v/deg	1%		Assume 0-10 VDC	Add rotary pot	4	2		7	Added Pots in accordance with Fairchild Flight Test Installation
28	Fuel flow rt.	8	7	0-5000 #/hour		2%		0-5 VAC		4	4		8	
29	Fuel flow lt.	8	7	0-5000 #/hour		2%		0-5 VAC		4	4		8	
30	True heading	1-5	5	$-\pi$ to $+\pi$ rad.	LSB $\frac{\pi}{32,76B}$ MSB $\frac{\pi}{2}$	.000175 rad.	108-17	50/sec		3	5		9	A-10 ICD Page A-95
31	Roll rate	3	3	200°/sec				45mV/deg		5	4	√		Use F.C.S. "Vyro"
32	Pitch rate	3	7	45°/sec				100mV/deg		5	4	√		Use F.C.S. rate gyro
33	Lateral accel.	10	3							5	0	√		Use ASIP type accelerometer
34	Fuel total	8	3	0-25,000#		Variable with quantity		Assume 0-5V	Pot. source	4	4	√	10	Would be from fuel indicator totalizer aux. output

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5. INS
6. Master bus controller
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors

Type Code:
1. Synchro
2. +28V discrete
3. D.C. analog
4. Digital discrete
5. Digital data
6. Low level comp. discrete
7. AC analog

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 7. A-10 Configuration I Parameter List (Continued)

NO.	CONTINUOUS	SOURCE CODE	TYPE CODE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIGITAL WORD ID	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT PARAM. WORTH	FIGURES OF MERIT PARAM. COST	ASIP LIST	A-10 ACC. LIST PRIORITY	SOURCE OF DATA OR COMMENTS
35	Vertical vel. (Vz)	1-5	5	-2500 +2500 f.p.s.	LSB $\frac{1}{262,144}$ MSB 4096		108-07, 08	50/sec	31 bits + sign	5	5	√		A-10 ICD page A-90
36	Flap position	3	3	0° 7° 20°				DC, probably limited to 5V or 10V active range		1	4	√	9	1 sensor for 4 flaps. T.O. 1A-10A-2-27 TS-1 Page (2-3)
37	Mach No.	1-2	5	.10- 80M	LSB=$\frac{1}{16,384}$ MSB 2.0		C01-05	25/sec + sign	14 bits	3	5		9	A-10 ICD Page A-9
38	Present true ground track	1-5	5	$-\pi$ to $+\pi$rad	LSB $\frac{1}{32,768}$ MSB $\frac{\pi}{2}$		107-23	6.25/sec	15 bits + sign	3	5			A-10 ICD page A-145
39	26 VAC Inst. voltage	8	7	15-30 VAC	0.1 volt	0.1 volt				2	4			
40	Pitch trim	10	3						add pots	3	0		5	Synchros or LVDTS preferred alternate
41	Roll trim	10	3						add pots	3	0		5	Synchros or LVDTS preferred alternate
42	Yaw trim	10	3						add pots	3	0		5	Synchros or LVDTS preferred alternate
43	Oil pressure rt.	9	7					26 VAC excit.		2	2			
44	Oil pressure lt.	9	7					26 VAC excit.		2	2			

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Table 7. A-10 Configuration I Parameter List (Continued)

NO.	DISCRETES	SOURCE CODE	TYPE	TRUE, FAIL	FALSE, OK	DEVICE (SOURCE)	AVAILABLE AT	FIGURES OF MERIT		ASIP LIST	A-10 ACC. LIST PRIORITY	DATA SOURCE COMMENTS
								PARAM. WORTH	PARAM. COST			
1	Slat pos. rt.	8	2	Ext. Ret.	0v = extend	28v = retract	2762P10 Pin A	5	5		2	Pick up control valve voltage Retract only if rt. hand hyd. pressure present. See TO 1A-10A-2-27TS-1 page 2-5.
2	Slat pos. lt.	8	2	Ext. Ret.	0v = extend	28v = retract	2761P10 Pin A	5	4		2	Pick up control valve voltage. Retract only if rt. hand Hyd. pressure present. See TO 1A-10A-2-27TS-1 page 2-5
3	Master caution light	8	2	+28 VDC	0	relay contact	Cockpit wiring	5	4		4	
4	Speed brake 7-10% switch	8	2	+28 VDC	0	contact	2762P12 Pins D, E, C	4	4	√	5	TO 1A-10A-2-27TS-1 page 2-7
5	Speed brake 80% switch	3	2	+28 VDC	0	contact	2762P12 Pins A, H, 8	4	4	√	5	TO 1A-10A-2-27TS-1 page 2-7
6	Emergency retract (S.B.)	8	2	+28 VDC	0	switch	2762P8 Pin A	4	4	√	5	TO 1A-10A-2-27TS-1 page 2-7
7	Lt. ail. jam light	3	2	+28 VDC	0	switch	2712J5 Pin F	4	4		5	Switch in disconnector TO 1A-10A-2-27 TS-1 page 2-11
8	Lt. ail. disengage switch	3	2	+28 VDC	0	switch	2712J5 Pin C	4	4		5	Emergency control panel
9	Rt ail. jam light	3	2	+28 VDC	0	switch	2712J4 Pin F	4	4		5	Same as 7
10	Rt. ail. disengage switch	3	2	+28 VDC	0	switch	2712J4 Pin C	4	4		5	Same as 8
11	Ail. disengage caution light	3	2	+28 VDC	0	switch	4612P1 Pin MM	4	4		5	Disengage switch from l. and r. aileron disconnector TO page 2-11

All discretes "easily" accessible from aircraft wiring (i.e., no new "box" outputs needed)
Numbers 7 through 13 are Roll CAS/SAS parameters.

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10. Added sensors

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5. Digital data
6. Low level comp. discrete
7. AC analog

Relative Figures of Merit: 0 - Lowest Merit; 5 = Highest Merit

Table 7. A-10 Configuration I Parameter List (Continued)

NO	DISCRETES	SOURCE CODE	TYPE	TRUE, FAIL	FALSE, OK	DEVICE (SOURCE)	AVAILABLE AT	FIGURES OF MERIT PARAM. WORTH	FIGURES OF MERIT PARAM. COST	ASIP LIST	A-10 ACC. LIST PRIORITY	DATA SOURCE COMMENTS
12	Lf. aileron tab caut. light	3	2	+28 VDC	0	switch	2761P1 Pin D	4	4		5	Indicate control shifted to tabs. Switch in shifter.
13	Rt. aileron tab caut. light	3	2	+28 VDC	0	switch	2762P1 Pin D	4	4		5	Indicate control shifted to tabs. Switch in shifter. TO 1A-10A-2-27TS-1 page 2-10.
14	Lf. elev. jam light	3	2	+28 VDC	0	switch	2712J3 Pin F	3	4		6	same as 7
15	Lf. elev. disengage switch	3	2	+28 VDC	0	switch	2712J3 Pin C	3	4		6	same as 8
16	Rt. elev. jam light	3	2	+28 VDC	0	switch	2712J6 Pin F	3	4		6	Same as 7
17	Rt elev. disengage switch	3	2	+28 VDC	0	switch	2712J6 Pin C	3	4		6	Same as 8
18	Elev. disengage caution light	3	2	+28 VDC	0	switch	4612P1 Pin NN	3	4		6	Same as 11
19	Left hyd. pres. switch CAVT light	8	2	+28 VDC	0	Press switch		3	4		6	Hyd. pres. fail discrete
20	Rt. hyd. pres. switch CAVT light	8	2	+28 VDC	0	Press switch		3	4		6	Hyd. pres. fail discrete
21	Yaw CAS status	8	2	+28 VDC	0	Press switch		4	5		6	Assume manual reversion if 19 and 20 light (below 400 psi)
22	Rt. yaw SAS engage	3	2	+28 VDC operate	Not engage 0 VDC	Switch SAS CONT. PAN.	2J1-23	3	4		11	For items 18-23, see T.O. 1A-10A-2-27 TS-1 page 2-8A
23	Lf. yaw SAS engage	3	2	+28 VDC operate	Not engage 0 VDC	Switch SAS CONT. PAN.	2J1-35	3	4		11	For items 18-23, see T.O. 1A-10A-2-27 TS-1 page 2-8A

All discretes "easily" accessible from aircraft wiring (i.e., no new "box" outputs needed)

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Table 7. A-10 Configuration I Parameter List (Continued)

NO.	DISCRETES	SOURCE CODE	TYPE	TRUE, FAIL	FALSE, OK	DEVICE (SOURCE)	AVAILABLE AT	FIGURES OF MERIT		ASIP LIST	A-10 ACC. LIST PRIORITY	DATA SOURCE COMMENTS
								PARAM. WORTH	PARAM. COST			
24	Rt. pitch SAS engage	3	2	+28 VDC operate	Not engage 0 VDC	Switch SAS CONT. PAN.	2J1-25	3	4		11	For items 18-23, see T.O. 1A-10A-2-27 TS-1 page 2-8A
25	Lf. pitch SAS engage	3	2	+28 VDC operate	Not engage 0 VDC	Switch SAS CONT. PAN.	2J1-37	3	4		11	For items 18-23, see T.O. 1A-10A-2-27 TS-1 page 2-8A
26	Yaw SAS caution light	3	2	+28 VDC	0	SAS comp. relay	1J1-34	3	4		11	Light can also be picked up at caution panel
27	Pitch. SAS Caution Light	3	2	+28 VDC	0	SAS comp. relay	1J2-34	3	4		11	Light can also be picked up at caution panel
28	Lf. eng. fire light	9	2	+28 VDC	0	Relay		3	4		10	Light in extinguisher handle
29	Rt. eng. fire light	9	2	+28 VDC	0	Relay		3	4		10	Light in extinguisher handle
30	APU fire light	8	2	+28 VDC	0	Relay		3	4		10	Light in extinguisher handle
31	Paddle switch	8	2	0 VDC disconnect	+28 VDC operate	Switch	Cockpit wiring	4	4		9	Emergency disconnect lever
32	CADC mode word	1-2	4	0 fail	1 valid	C01-01 (word)	Rate 50/sec	5	5			8 validity bits. See A-10 ICD page A-5
33	INS mode word	1-5	4	1	0	108-01	Rate 50/sec	5	5			Page A-84 A-10 ICD
34	MBC status	6	6	B-HI C-LO	B-LO C-HI	MD-01	J4-B,C	5	5			True - bus controller False - under INS control ICD page A-297
35	GAU-8 trigger signal	8	2	28 VDC	0	Switch on stick	FCR8 J2-8	5	4	√		Flight control relay box T.O. 1A-10A-2-27 TS-1 page 2-8A
36	GAU-8 ready light	8	2	28 VDC	0	Contact	Inst. panel light	3	4			Flight control relay box T.O. 1A-10A-2-27 TS-1 page 2-8A
37	GAU-8 unsafe light	8	2	28 VDC	0	Contact	Caution light panel	3	4			Flight control relay box T.O. 1A-10A-2-27 TS-1 page 2-8A

All discretes "easily" accessible from aircraft (i.e., no new "box" outputs needed)

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2. CADC
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5. INS
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7. HUD
8. Acft. misc.
9. Engine
10. Added sensors

Type Code:
1. Synchro
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5. Digital data
6. Low level comp. discrete
7. AC analog

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 7. A-10 Configuration I Parameter List (Continued)

NO.	DISCRETES	SOURCE CODE	TYPE	TRUE, FAIL	FALSE, OK	DEVICE (SOURCE)	AVAILABLE AT	FIGURES OF MERIT PARAM. WORTH	FIGURES OF MERIT PARAM. COST	ASIP LIST	A-10 ACC. LIST PRIORITY	DATA SOURCE COMMENTS
38	Weight on wheels	8	2	0 VDC	28 VDC	switch	3213A K01K10 relay	5	4	√		T.O. 1A-10A-2-27 TS-1 page 2-7
39	Pylon station #1 store drop	8	2					3	4	√		T.O. 1A-10A-34-1-1 Monitor left stores, assume right stores the same.
40	Pylon station #2 store drop	8	2					3	4	√		T.O. 1A-10A-34-1-1 Monitor left stores, assume right stores the same.
41	Pylon station #3 store drop	8	2					3	4	√		T.O. 1A-10A-34-1-1 Monitor left stores, assume right stores the same.
42	Pylon station #4 store drop	8	2					3	4	√		T.O. 1A-10A-34-1-1 Monitor left stores, assume right stores the same.
43	Pylon station #5 store drop	8	2					3	4	√		T.O. 1A-10A-34-1-1 Monitor left stores, assume right stores the same.
44	Pylon station #6 store drop	8	2					3	4	√		T.O. 1A-10A-34-1-1 Monitor left stores, assume right stores the same.
45	Ext. stores jettison #1	8	2					3	4			T.O. 1A-10A-34-1-1 Monitor left stores, assume right stores the same.
46	Ext. stores jettison #2	8	2					3	4			T.O. 1A-10A-34-1-1 Monitor left stores, assume right stores the same.
47	DC essential bus status	8	2	outside limits	within +22 to 30V			3	3		8	
48	Aux DC essential bus status	8	2	outside limits	within +22 to 30V			3	3		8	
49	Left DC bus status	8	2	outside limits	within +22 to 30V			3	3		8	
50	Right DC bus status	8	2	outside limits	within +22 to 30V			3	3		8	

Source Code:
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2. +28V discrete
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Table 7. A-10 Configuration I Parameter List (Continued)

NO	DISCRETES	SOURCE CODE	TYPE	TRUE, FAIL	FALSE, OK	DEVICE (SOURCE)	AVAILABLE AT	FIGURES OF MERIT PARAM. WORTH	PARAM. COST	ASIP LIST	A-10 ACC. LIST PRIORITY	DATA SOURCE COMMENTS
51	Landing gear down	8	2					3	4			
52	AC essential bus status	8	8	outside limits	within 102 to 124 VAC			3	3			
53	AC aux ess. bus status	8	8	outside limits	within 102 to 124 VAC			3	3			
54	Left AC bus status	8	8	outside limits	within 102 to 124 VAC			3	3			
55	Right AC bus status	8	8	outside limits	within 102 to 124 VAC			3	3			
56	Comm. transmit	8	2	28 VDC	0V	MLC key		4	4			
57	APU switch	8	2	28V on	0V off			3	4		10	
58	APU gen caution light	8	2	28V on	0V off			3	4		10	
59	Engine start cycle light							4	4			
60	Engine fuel flow override (R)	8	8	115 VAC override	0V normal	switch		3	4			
61	Engine fuel flow override (L)	8	8	115 VAC override	0V normal	switch		3	4			

All discretes "easily" accessible from aircraft wiring (i.e., no new "box" outputs needed)

Source Code:
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5. INS
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9. Engine
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Type Code:
1. Synchro
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5. Digital data
6. Low level comp. discrete
7. AC analog

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 8. A-10 Configuration II Parameter List

NO.	PARAMETER (CONTINUOUS)	NO. ON CONFIG. I LIST	A-10 ACC. LIST PRIORITY
1	Time	1	9
2	Cal airspeed	2	5
3	Normal load	3	5
4	Press altitude	4	4
5	Bank angle	5	2
6	Pitch attitude	6	2
7	Yaw rate	7	1
8	AOA	8	3
9	Rudder position (rt)	9	2
10	Rudder position (lt)	10	2
11	Aileron position (rt)	11	3
12	Aileron position (lt)	12	3
13	Elevator position (rt)	13	5
14	Elevator position (lt)	14	5
15	Stick position (roll)	15	4
16	Stick position (pitch)	16	4
17	N_1 (rt)	17	4
18	N_1 (lt)	18	4
19	ITT (rt)	21	5
20	ITT (lt)	22	5
21	Rudder ped position	25	6

Table 8. A-10 Configuration II Parameter List (Continued)

NO.	PARAMETER (CONTINUOUS)	NO. ON CONFIG.I LIST	A-10 ACC. LIST PRIORITY
22	Throttle position (rt)	26	7
23	Throttle position (lt)	27	7
24	Fuel flow (rt)	28	8
25	Fuel flow (lt)	29	8
26	Flap position	36	9
27	True heading	30	9
28	Roll rate	31	-
29	Pitch rate	32	-

NO.	PARAMETER (DISCRETES)	NO, ON CONFIG.I LIST	A-10 ACC. LIST PRIORITY
1	Slat position (rt)	1	2
2	Slat position (lt)	2	2
3	Master caution light	3	4
4	7-10 percent speed brake	4	5
5	80 percent speed brake	5	5
6	Lt ail. jam light	7	5
7	Lt. ail. disengage	8	5
8	Rt. ail. jam light	9	5
9	Rt. ail. disengage	10	5
10	Lt. elev jam light	14	6

Table 8. A-10 Configuration II Parameter List (Continued)

NO.	PARAMETER (DISCRETES)	NO. ON CONFIG.I LIST	A-10 ACC. LIST PRIORITY
11	Lt elev disengage	15	6
12	Rt elev jam light	16	6
13	Rt elev disengage	17	6
14	Ail disengage caution light	11	5
15	Elev disengage caution light	18	6
16	Left hyd pres switch CAVT light	19	6
17	Right hyd pres switch CAVT light	20	6
18	Pitch SAS caution light	27	11
19	Yaw SAS caution light	26	11
20	Left fire light	28	10
21	Right fire light	29	10
22	APU fire light	30	10
23	Paddle switch	31	9
24	GAU-8 trigger signal	35	-
25	GAU-8 unsafe light	37	-
26	Weight on wheels	38	-
27	Left DC bus status	49	8
28	Right DC bus status	50	8

The following is an explanation of certain parameters in table 7.

No. 3. Normal load (aircraft z axis acceleration). This parameter can be obtained from the INS word I01 (not used in the A-10 but on the MUX bus in the normal mode). To obtain it, all three inertial axes accelerations and the Euler angles must be either recorded for later conversion, or the conversion must be done in the crash recorder preprocessor before recording. The latter saves memory but requires greater processing capability (preferred). It is unavailable if the INS has failed.

An alternate source is the linear accelerometer which supplies the basic input to the accelerometer counter set which is on all airplanes. It is understood that the A-10 ASIP recorder does not use this signal as does the F-15 but has its own accelerometer. If used, it would be available on only approximately 20 percent of the fleet and would need to be added to others. At this time, the best trade-off for normal acceleration parameters source appears to be the counter accelerometer.

No. 7. Yaw rate. Yaw rate is desired because there is no direct source of sideslip angle (β computed from inertial signals is not considered satisfactory). Using INS data V_x', V_y', V_z', heading, Euler angles and ground track, the rates of all three body axes can be computed but would be unavailable with IMU failure.

Additional installation of the ASIP-type rate gyros (SBU-3A) could be added to non-ASIP aircraft. Yaw rate signals could be obtained for most blocks of A-10s from the SAS computer test connector. Recent aircraft use a "vyro"* in the SAS yaw system and the output is adequate. For this study this latter source is considered for use. Loss of SAS, of course, causes a loss of rate data.

No. 31. Roll rate. Roll rate can be derived from roll attitude from the INS with probably satisfactory results but does require the preprocessing of the signal, or the recording at much higher rates resulting in some loss of data compression. The ASIP type roll rate gyro presently used in 20 percent of the aircraft could also be added for use in the remaining 80 percent at somewhat added cost. Roll rate can also be picked off of a test connector on the SAS computer. Recent aircraft use a "vyro" for this signal which has adequate rate output and high reliability.

* "Vyro" is a term applied to a vibrating device (similar to a tuning fork) which provides a highly reliable substitute for a rate gyro.

If the "vyro" or SAS computer failed, roll rate data might be lost. However, the monitoring of SAS status discretes and loss of the system may provide the desired data anyway. The trade-off involves higher initial and life cycle cost of added transducers (with improved and lower cost of processing and recording of data) versus the savings of no added transducer (but higher recorder/processor costs, possibly poorer data, and non-standardization). The difference in these methods will disappear in the total life cycle costs and cost benefit ratios, so the choice is based on other than economic reasons.

For the A-10 installation, the SAS "vyro" is initially recommended as the most economical source.

No. 32. Pitch rate. The same comments apply as for roll rate except a SAS gyro is used in the pitch axis.

No. 33. Lateral acceleration. Comments for No. 3 apply except no accelerometer counter exists, so the added ASIP type accelerometer is recommended.

Nos. 9, 10, 11, 12, 13, and 14. It is assumed pots will be added for these parameters. LVDTs exist in portions of the SAS system but provide only SAS/manual differential outputs. LVDTs usually supply a more reliable signal than pots but compared to pots probably would add to the cost and installation effort. For purposes of the study, the lower cost pot installation is assumed.

Discrete Nos. 4, 5, and 6. Speed brake position is determined from a position transducer in early blocks, but later aircraft and modifications provide only limit switch signals. To determine speed brake at specific positions, the voltage (+28V VDC discrete) at SB position switch number 1 and number 2 N.O. and N.C. contacts will be monitored (available from cable connector 2762P12).

b. F-15. Table 9, F-15 Investigators' List (reference 6), is included to show the relative importance of various accident investigations as indicated by the investigators themselves (questionnaire tabulation). The list shows 50 parameters of which only 36 were requested by the investigators. They are listed in 12 groupings of descending priority. As in the A-10 list, the time parameter was moved to the head of the list because all other parameters will be time related in the proposed recording method. The percentage that a parameter was requested is shown in column 4 and the ranking in the general list is shown in column 5.

Table 10, is the final recommended arrangement of parameters to be used as the Configuration I representative list for the F-15. The general comments in the prior A-10 section concerning table 7 also apply to table 10. The F-15 presents some special problems of its own (as does the A-10) in respect to control surface position transducers. The list is planned on the assumption that the Flight Control System can be used as a source of roll, pitch and yaw rate. It is also assumed that lateral acceleration and normal acceleration are obtained from the FCS. An alternate source for the normal acceleration is from the ABK-17 acceleration counterset on all aircraft. There is no direct source of longitudinal acceleration. This parameter can generally be deduced from airspeed, attitude, vertical velocity, etc. Another alternate source of aircraft axis linear velocities and accelerations is from the Inertial system outputs. Roll rate, pitch rate and yaw rate can be derived from the IMU parameters 5, 7, 10, 14, 49, and 50 shown in table 10. Parameters 5, 7, 51, 52, and 53 can be used to derive aircraft axes linear accelerations.

Parameters 47 through 54 (except 48) can be easily eliminated if previously listed parameters are recorded.

Weapon status is obtained from Digital Words NC1 394 through 403 with the individual bits designated CC175 through CC199. This discrete data coming from the Bus requires no extra wiring, as do, for example, 28 VDC discretes, and hence is a very "cost effective" data source. To save memory, the armament data could be recorded once at gear-up in a fixed location in memory and then the status of each bit changed as an event occurs.

Table 11 is a minimum list derived from table 10 for the Configuration II list.

Table 9. F-15 Investigators' List

NO.	PARAMETER	RANKING GROUP	REQUEST %	GENERAL LIST RANKING
1	Time	12	0	2
2	Master caution	1	92	7
3	Cal airspeed	2	77	1
4	Fuel flow	3	69	3
5	Baro. alt.	3	69	4
6	N_1	4	62	9
7	Hyd. pres.	5	54	27
8	Elev. position	5	54	23
9	Stick position	6	46	17
10	CDP	6	46	19
11	FTIT	6	46	42
12	Pitch attitude	7	38	8
13	Norm. load	7	38	13
14	Aileron position	7	38	18
15	CAS/SAS pitch	7	38	35
16	N_2	7	38	5
17	Bank attitude	8	31	10
18	Rudder position	8	31	14
19	Throttle position	8	31	11
20	Rudder ped. position	8	31	29
21	EGT	8	31	12

Table 9. F-15 Investigators' List (Continued)

NO.	PARAMETER	RANKING GROUP	REQUEST %	GENERAL LIST RANKING
22	Firelight	8	31	26
23	AOA	9	23	24
24	Fuel total	9	23	15
25	Fuel/tank	9	23	22
26	CAS/SAS roll	9	23	16
27	A/B pos.	9	23	32
28	CADC	10	15	46
29	CAS/SAS Yaw	10	15	21
30	OAT	10	15	49
31	Util. hyd. pres.	10	15	39
32	Trim	10	15	34,37
33	Mach no.	11	8	30
34	Oil pres.	11	8	28
35	Rdr. alt.	11	8	31
36	Gen	11	8	41
37	EPU/APU	11	8	43
38	Heading	12	0	25
39	Yaw rate	12	0	6
40	Gear pos.	12	0	57
41	Flap pos.	12	0	44

Table 9. F-15 Investigators' List (Continued)

NO.	PARAMETER	RANKING GROUP	REQUEST %	GENERAL LIST RANKING
42	SB pos.	12	0	40
43	Slat pos.	12	0	20
44	Comm. transmit	12	0	45
45	Paddle switch	12	0	50
46	Anti-skid fail	12	0	68
47	NAV status	12	0	-
48	Inverter	12	0	41
49	Starter	12	0	43
50	Sideslip	12	0	38

Table 10. F-15 Configuration I Parameter List

PARAM. NO.	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT		ASIP LIST	F-15 ACC. LIST PRIORITY	SOURCE AND COMMENTS
										PARAM. WORTH	PARAM. COST			
1	Time	1-6	5							5	5	✓	12	Use data bus clock and count in recorder
2	Calibrated airspeed	1-6	5	0-1600 knots	Bit 1 = 512 Kn Bit 11 = .5		CC-134 NC1-278		12 bits Bit 0 = -1024	5	5	✓	2	TO 1F-15A-2-16-2 page 1-30 G
3	Baro altitude	1-6	5	-1560 to 80,336 ft	Bit 1 = 65,536 ft Bit 15 = 4		CC-276 NC1-362		16 bits Bit 0 = -131,072	5	5	✓	3	TO 1F-15A-2-16-2 page 1-34
4	Normal acceleration	3	3				Available at 93A-B006 1J3-14		Buffer demodu-	5	5		7	TO 1F-15A-2-20 page 4-246
5	Pitch attitude	1-6	5	-90° to +90°	Bit 1 = 90° Bit 17 = .0014°		CC-273 NC1-359		17 bits Bit 0 = -180°	5	5		7	TO 1F-15A-2-16-2 page 1-41
6	Pitch rate	3	7				Available at 52P-N004 pins 19,20		26 VAC excit	5	4	✓		TO 1F-15A-2-20 page 4-246, needs demodulator
7	Bank angle	1-6	5	-180° to +180°	Bit = 90° Bit 17 = .0014°		CC-274 NC1-360		17 bits Bit 0 = -180°	5	5		8	Same as 5
8	Roll rate	3	3				Available at 93A-B008 2J3-46		Buffer demodulator	5	4	✓		TO 1F-15A-2-20 page 4-277 or add rate gyro
9	Roll acceleration	11	3							3	1	✓		Added roll accelerometer
10	True heading	1-6	5	-180° to +180°	Bit 1 = 90° Bit 17 = .0014°		CC-275 NC1-361		17 bits Bit 0 = -180°	3	5		12	TO 1F-15A-2-16-2 page 1-34
11	Yaw rate	3	3				Available at 93A-B008 2J3-55 or 99		Buffer demodulator	5	4	✓	12	TO 1F-15A-2-20 page 4-277 or add rate gyro
12	AOA (α)	1-6	5	-45° to +45°	Bit 1 = 22.5° Bit [illegible] = .16°		CC-171 NC1-386		8 bits Bit 0 = -45°	5	5	✓	9	TO 1F-15A-2-16-2 page 1-30 K

Source Code:
1. MUX BUS
2. ADC/CADC
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. FDA

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 10. F-15 Configuration I Parameter List (Continued)

PARAM NO.	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT		ASIP LIST	F-15 ACC. LIST PRIORITY	SOURCE AND COMMENTS
										PARAM. WORTH	PARAM. COST			
13	Lateral acceleration	1	3				Available at 93A-B008 2J3-27		Buffer demodulator	4	4	√		TO 1F-15A-2-20 page 4-277 or add accelerometer
14	Vertical velocity	1-5	5	-1500 to +1500 FPS	Bit 1 = 1024 FPS Bit 14 = 0.125		IMU-11 NC1-145 -2048		15 bits Bit 0 = -2048	5	5			TO 1F-15A-2-16-2 page 1-27
15	Total fuel	8	3	0 - ∓ 25,000#			Available at 52J-J120 pins 70, 71, 69, 72			4	4	√	9	From pot provided for signal data recorder TO 1F-15A-2-12 page 8-50
16	Fuel flow (L)	8	1	0 - 100,000 lbs/hr	500 lbs. per hr.	∓ ±250 pph	Available at pins 28, 29, .		56	4	4		3	TO 1F-15A-2-12 page 2-70 ØB excite
17	Fuel flow (R)	8	1	0 - 100,000 lbs/hr	500 lbs. per hr.	∓ ±250 pph	Available at 52P-D120 pins 18, 19, 20			4	4		3	TO 1F-15A-2-12 page 2-70 ØB excite
18	Throttle position (L)	10	7						LVDT 26 VAC excit.	4	1		8	Added transducer
19	Throttle position (R)	10	7						LVDT 26 VAC excit.	4	1		8	Added transducer
20	N_2 (L)	9	7	0-110%	1%			rpm proportional to frequency of engine-mounted PM. alternator. Intermediate voltage level		5	3		7	TO 1F-15A-2-9-1 page 3-27
21	N_2 (R)	9	7	0-110%	1%					5	3		7	TO 1F-15A-2-9-1 page 3-27
22	FTIT (L)	9	3	200° to 1400°C	10°			Millivolt level	Chromel alumel thermocouple	5	3		6	TO 1F-15A-2-9-1 page 3-29
23	FTIT (R)	9	3	200° to 1400°C	10°			Millivolt level	Chromel alumel thermocouple	5	3		6	TO 1F-15A-2-9-1 page 3-29

Source Code:
1. MUX BUS
2. ADC/CADC
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. FDA

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 10. F-15 Configuration I Parameter List (Continued)

PARAM NO.	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT		ASIP LIST	F-15 ACC. LIST PRIORITY	SOURCE AND COMMENTS
										PARAM. WORTH	PARAM. COST			
24	Nozzle (L)	9	1	0-100% open				11.8 VAC 400 Hz	3-wire synchro	4	3			TO 1F-15A-2-9-1 page 3-31
25	Nozzle (R)	9	1	0-100% open				11.8 VAC 400 Hz	3-wire synchro	4	3			TO 1F-15A-2-9-1 page 3-31
26	Stabilator position (L)	3	3	24-28" up 14-16" down			Available at 93P-B006F pin 9			3	4	√	5	TO 1F-15A-2-20 page 4-253
27	Stabilator position (R)	3	3	24-28" up 14-16" down			Available at 93P-8006F pin 7			3	4	√	5	TO 1F-15A-2-20 page 4-252
28	Aileron position (L)	10	7	±12.4 in ±0.9 in					LVDT 26 VAC excit	3	1	√	7	Add LVDT IAW ASIP
29	Aileron position (R)	10	7	±12.4 in ±0.9 in					LVDT 26 VAC excit	3	1	√	7	Add LVDT IAW ASIP
30	Rudder position (L)	10	7	±15.2 to 18.2 in.					LVDT 26 VAC excit	3	1	√	8	Add LVDT IAW ASIP
31	Rudder position (R)	10	7	±15.2 to 18.2 in.					LVDT 26 VAC excit	3	1	√	8	Add LVDT IAW ASIP
32	Pitch stick force	3	3	23.2-28# forward 34.9-42.3# aft			Available at 93A-B006 1J3-25		Buffer demodulator	4	4		6	TO 1F-15A-2-20 page 4-246
33	Roll stick force	3	3	20-39.6# right and left			Available at 93A-B008 2J3-51		Buffer demodulator	4	4		6	TO 1F-15A-2-20 page 4-268
34	Rudder pedal travel	3	7	165# right and left			Available at 52J-J087 pins 81, 82		LVDT 26 VAC excit	4	3		8	TO 1F-15A-2-20 page 4-277

Source Code: 1. MUX BUS 2. ADC/CADC 3. FCS 4. HARS 5. INS/IMU 6. CC 7. HUD 8. Acft. misc. 9. Engine 10. Added sensors 11. FDA

Type Code: 1. Synchro 2. +28 VDC discrete 3. DC analog 4. Digital discrete 5. Digital data 6. Low level complementary discrete 7. AC analog 8. AC discrete 9. Frequency

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 10. F-15 Configuration I Parameter List (Continued)

PARAM NO.	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT PARAM. WORTH	FIGURES OF MERIT PARAM. COST	ASIP LIST	F-15 ACC. LIST PRIORITY	SOURCE AND COMMENTS
35	N_1 (L)	9	9	0-110%				Low level AC freq proportional to N_1 rpm		3	3		4	TO 1F-15A-2-9-1 page 3-35
36	N_1 (R)	9	9	0-110%				Low level AC freq proportional to N_1 rpm		3	3		4	TO 1F-15A-2-9-1 page 3-3 5
37	Hyd. pressure (R)	8	1	0 - 4500 psi			52J-L022 pins 11, 12, 13		3-wire synchro	4	3		5	TO 1F-15A-2-7 page 1-80
38	Hyd. pressure (L)	8	1	0 - 4500 psi			52J-L022 pins 73, 74, 93		3-wire synchro	4	3		5	TO 1F-15A-2-7 page 1-77
39	Utility (L) hyd. pressure	8	1	0 - 4500 psi			52P-N022 pins 19, 20, 21		3-wire synchro	2	3		10	TO 1F-15A-2-7 page 2-43
40	26 VAC Inst. voltage level	8	7	15-30 VAC	0.1 volt	0.1 volt				2	4			TO 1F-15A-2-27
41	Trim, yaw	3	7				Available at 52J-J087 pin 48, 68		LVDT 26 VAC excit	2	3		10	TO 1F-15A-2-20 page 4-273
42	Trim, roll	3	3				Available at 93P-B008D or F pin 18		Buffer demodulator	2	4		10	TO 1IF-15A-2-20 page 4-263
43	Trim, pitch	3	3				Available at 93P-B006E pin 58 or 38		Buffer demodulator	2	4		10	TO 1F-15A-2-20 page 4-240
44	Oil pressure (L)	9	1	0-110 psi	2.5 psi	Available at 52J-J120 pins 62, 87, 88		11.8 VAC 400 Hz	3-wire synchro	3	3		11	TO 1F-15A-2-9-1 page 3-32
45	Oil pressure (R)	9	1	0-110 psi	2.5 psi	Available at 52J-H056 pins 67, 87, 88		11.8 VAC 400 Hz	3-wire synchro	3	3		11	TO 1F-15A-2-9-1 page 3-32
46	Pitch ratio	3	7	0-1			Available at 52P-E161A pins 17, 18		LVDT 26 VAC excit	2	3			TO 1F-15A-2-5 page 2-56
47	Mach	1-2	5	.0985 to 3.0195M	Bit 1 = 2 Bit 14 = .0002		ADC-10 NC1-123		15 bits Bit 0 = 4	2	5		11	TO 1F-15A-2-16-2 page 1-18

Source Code:
1. MUX BUS
2. ADC/CADC
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. FDA

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Relative figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 10. F-15 Configuration I Parameter List (Continued)

PARAM NO.	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT		ASIP LIST	F-15 ACC. LIST PRIORITY	SOURCE AND COMMENTS
										PARAM. WORTH	PARAM. COST			
48	CAS servo position	3	3				Available at 93P-B006D pin 59		Buffer demodulator	2	4			TO 1F-15A-2-20 page 4-248
49	East-west velocity	1-5	5	-3000 to +3000 FPS	Bit 1 = 2048 FPS Bit 14 = 0.25		IMU-10 NC1-144		15 bits Bit 0 = -4096	2	5			TO 1F-15A-2-16-2 page 1-27
50	North-south velocity	1-5	5	-3000 to +3000 FPS	Bit 1 = 2048 FPS Bit 14 = 0.25		IMU-9 NC1-143		15 bits Bit 0 = -4096	2	5			TO 1F-15A-2-16-2 page 1-27
51	Vertical acceleration	1-5	5	-4G to +10G	Bit 1 = 256 Bit 11 = 0.25		IMU-14 NC1-132		12 bits Bit 0 = 512	2	5		7	TO 1F-15A-[illegible]-2 page 1-27
52	North-south acceleration	1-5	5	-7G to +7G	Bit 1 = 128 Bit 10 = 0.25		IMU-12 NC1-130		11 bits Bit 0 = -256	1	5			TO 1F-15A-2-16-2 page 1-27
53	East-west acceleration	1-5	5	-7G to +7G	Bit 1 = 128 Bit 10 = 0.25		IMU-13 NC1-131		11 bits Bit 0 = -256	1	5			TO 1F-15A-2-16-2 page 1-27
54	OAT	8	3				B9P-N001 pins C, D, E		Probe element	3	2		10	TO 1F-15A-2-17 (unused sensor) page 1-133

Source Code: 1. MUX BUS 2. ADC/CADC 3. FCS 4. HARS 5. INS/IMU 6. CC 7. HUD 8. Acft. misc. 9. Engine 10. Added sensors 11. FDA

Type Code: 1. Synchro 2. +28 VDC discrete 3. DC analog 4. Digital discrete 5. Digital data 6. Low level complementary discrete 7. AC analog 8. AC discrete 9. Frequency

Relative figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 10. F-15 Configuration I Parameter List (Continued)

PARAM. NO.	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT PARAM. WORTH	FIGURES OF MERIT PARAM. COST	ASIP LIST	F-15 ACC. LIST PRIORITY	SOURCE AND COMMENTS
55	Rounds remaining	1-6	5	0-990	count to 99		CC175 NC1-394		8 bits (0-7)	3	5	√		TO 1F-15A-2-16-2 page 1-30
56	Station 2 A/G weapon count	1-6	5	0-6	1		CC184 NC1-396		3 bits (0-2)	2	5	√		TO 1F-15A-2-16-2 page 1-30
57	Station 5 A/G weapon count	1-6	5	0-6	1		CC-185 NC1-396		3 bits (3-5)	2	5	√		TO 1F-15A-2-16-2 page 1-30
58	Station 8 A/G weapon count	1-6	5	0-6	1		CC-186 NC1-397		3 bits (0-2)	2	5	√		TO 1F-15A-2-16-2 page 1-30
59	Station 2,5,8 CRU status	1-6	5	1 present	0, not present		CC-187 NC1-397		3 bits (3-5)	3	5	√		TO 1F-15A-2-16-2 page 1-30
60	Station 2 A/A identification	1-6	5	000 = none or AIM-9J 0001 = AIM9L others = spares			CC-189 NC1-398		3 bits (1-3)	1	5	√		TO 1F-15A-2-16-2 page 1-30
61	Station 8 A/A identification	1-6	5	000 = none or AIM-9J 001 = AIM9L others = spares			CC-190 NC1-398		3 bits (4-6)	1	5	√		TO 1F-15A-2-16-2 page 1-30
62	Fuel pallets aboard	1-6	5	1 = on board	0 = none		CC-190A NC1-398		1 bit (7)	3	5	√		TO 1F-15A-2-16-2 page 1-30
63	Station 2 A/G identification	1-6	5	For identification see TO 1F-15A-2-16-2 page 1-30			CC-191 NC1-399		5 (0-4)	1	5	√		TO 1F-15A-2-16-2 page 1-30
64	Station 3 identification	1-6	5	00 = none, 01 = spare, 10 = AIM-7F, 11 = spare			CC-193 NC1-400		2 (1,2)	1	5	√		TO 1F-15A-2-16-2 page 1-30
65	Station 7 identification	1-6	5	00 = none, 01 = spare, 10 = AIM-7F, 11 = spare			CC-194 NC1-400		2 (3,4)	1	5	√		TO 1F-15A-2-16-2 page 1-30
66	Station 5 A/G identification	1-6	5	Same as station 2 A/G			CC-195 NC1-401		5 (0-4)	1	5	√		TO 1F-15A-2-16-2 page 1-30

Source Code:
1. MUX BUS
2. ADC/CADC
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. FDA

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Relative figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 10. F-15 Configuration I Parameter List (Continued)

PARAM. NO.	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT		ASIP LIST	F-15 ACC. LIST PRIORITY	SOURCE AND COMMENTS
										PARAM. WORTH	PARAM. COST			
67	Station 4 identification	1-6	5	Same as station 3			CC-197 NC1-402		2 (1,2)	1	5	✓		TO 1F-15A-2-16-2 page 1-30
68	Station 6 identification	1-6	5	Same as station 3			CC-198 NC1-402		2 (3,4)	1	5	✓		TO 1F-15A-2-16-2 page 1-30
69	Station 8 A/G identification	1-6	5	Same as station 2 A/G			CC-199 NC1-403		5 (0-4)	1	5	✓		TO 1F-15A-2-16-2 page 1-30
70	Month	1-6	5	1-12	Bits 0-3 = tens Bits 4-7 = ones		CC-200 NC1-408		8 (0-7)	4	5	✓		TO 1F-15A-2-16-2 page 1-30
71	Day	1-6	5	1-31	Bits 0-3 = tens Bits 4-7 = ones		CC-201 NC1-409		8 (0-7)	4	5	✓		TO 1F-15A-2-16-2 page 1-31
72	Year	1-6	5	0-99	Bits 0-3 = tens Bits 4-7 = ones		CC-202 NC1-410		8 (0-7)	4	5	✓		TO 1F-15A-2-16-2 page 1-31
73	Mission type	1-6	5	0-99	Bits 0-3 = tens Bits 4-7 = ones		CC-203 NC1-411		8 (0-7)	3	5	✓		TO 1F-15A-2-16-2 page 1-31
74	Aircraft no. digits 3 and 4	1-6	5	0-99	Bits 0-3 = tens Bits 4-7 = ones		CC-204 NC1-412		8 (0-7)	1	5	✓		TO 1F-15A-2-16-2 page 1-31
75	Aircraft no. digits 1 and 2	1-6	5	0-99	Bits 0-3 = tens Bits 4-7 = ones		CC-205 NC1-413		8 (0-7)	1	5	✓		TO 1F-15A-2-16-2 page 1-31
76	Squadron no. digits 3 and 4	1-6	5	0-99	Bits 0-3 = tens Bits 4-7 = ones		CC-206 NC1-414		8 (0-7)	1	5	✓		TO 1F-15A-2-16-2 page 1-31
77	Squadron no. digits 1 and 2	1-6	5	0-99	Bits 0-3 = tens Bits 4-7 = ones		CC-207 NC1-415		8 (0-7)	1	5	✓		TO 1F-15A-2-16-2 page 1-31

Source Code:
1. MUX BUS
2. ADC/CADC
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. FDA

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Relative figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Parameter Nos. 55 through 77 add 17 digital words to be recorded at start of flight and as status changes (these are also ASIP functions).

Table 10. F-15 Configuration I Parameter List (Continued)

PARAM. NO.	DISCRETES	SOURCE CODE	TYPE	FALSE STATE	TRUE STATE	DEVICE, SOURCE	AVAILABLE AT	BIT NO.	FIGURES OF MERIT		ASIP LIST	F-15 ACC. LIST PRIORITY	SOURCE OF DATA AND COMMENTS
									PARAM. WORTH	PARAM. COST			
1	Firelight 3 lights	9	2	open	+28 VDC	Relay contacts	52I-C028 JFS/AMAD, pin 24 Rt. eng., pin 39 Lt. eng., pin 50		5	4		8	TO 1F-15A-2-9-1 page 4-10
2	Master caution ON	8	2/8	AC or DC volts up to 28	Gnd (on)	Tran-sistor driver	35P-J001A pin 20		5	4		1	TO 1F-15A-2-17 page 1-134
3	Landing gear UP	8	Contact closed	Contact open	Relay contacts	52P-L029 pins 59,60	52P-L029 pins 59, 60		4	4	✓	12	TO 1F-15A-2-17 page 5-27
4	L. EEC warning light	9		Gnd	+28 VDC warn	Pull-P resistor	52P-J011A pin 1		4	4			
5	R. EEC warning light	9		Gnd	+28 VDC warn	Pull-P resistor	52P-J011B pin 19		4	4			
6	Weight OFF wheels	1-11	4	1, on wheels	0, off wheels	HSIS-16 NC1-480		0	4	5			TO 1F-15A-2-16-2 Digital word discretes page 1-26
7	ADC status	1-11	4	0 Fail	1	HSIS-17 NC1-480		1	4	5		10	TO 1F-15A-2-16-2 Digital word discretes page 1-26
8	AHRS status	1-11	4	0 Fail	1	HSIS-18 NC1-480		2	4	5			TO 1F-15A-2-16-2 Digital word discretes page 1-26
9	HUD status	1-11	4	0 Fail	1	HSIS-19 NC1-480		3	2	5			TO 1F-15A-2-16-2 Digital word discretes page 1-26
10	HSI status	1-11	4	0 Fail	1	HSIS-20 NC1-480		4	3	5			TO 1F-15A-2-16-2 Digital word discretes page 1-26

Source Code:
1. MUX BUS
2. ADC/CADC
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. FDA

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Table 10. F-15 Configuration I Parameter List (Continued)

PARAM. NO.	DISCRETES	SOURCE CODE	TYPE	FALSE STATE	TRUE STATE	DEVICE, SOURCE	AVAILABLE AT	BIT NO.	FIGURES OF MERIT PARAM. WORTH	PARAM. COST	ASIP LIST	F-15 ACC. LIST PRIORITY	SOURCE OF DATA AND COMMENTS
11	IMU status	1-11	4	0 Fail	1	HSIS-21 NC1-480		5	5	5		12	TO 1F-15A-2-16-2 Digital word discretes page 1-26
12	ACS status	1-11	4	0 Fail	1	HSIS-22 NC1-480		6	3	5			TO 1F-15A-2-16-2 Digital word discretes page 1-26
13	LCG status	1-11	4	0 Fail	1	HSIS-23 NC1-480		7	2	5			TO 1F-15A-2-16-2 Digital word discretes page 1-26
14	CC go	1-11	4	16 zeros Fail	1 followed by 15 zeros	CC-61 NC1-482		8	2	5			TO 1F-15A-2-16-2 Digital word discretes page 1-300
15	NC1 status	1-11	4	0 Fail	1	HSIS-25 NC1-480		9	4	5			TO 1F-15A-2-16-2 Digital word discretes page 1-26
16	Radar status	1-11	4	0 Fail	1	HSIS-26 NC1-480		10	2	5			TO 1F-15A-2-16-2 Digital word discretes page 1-26
17	RWR status	1-11	4	0 Fail	1	HSIS-27 NC1-480		11	2	5			TO 1F-15A-2-16-2 Digital word discretes page 1-26
18	IG status	1-11	4	0 Fail	1	HSIS-28 NC1-480		12	4	5			TO 1F-15A-2-16-2 Digital word discretes page 1-26
19	Fuel level low warn light	8	2	Gnd fuel hi	+20 VDC fuel low	Pull-up resistor	52P-L008 pin 62		4	4			TO 1F-15A-2-12 page 8-54

Source Code:
1. MUX BUS
2. ADC/CADC
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. FDA

Type Code:
1. Synchro
2. +28 VDC discrete
3. OC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Table 10. F-15 Configuration I Parameter List (Continued)

PARAM. NO.	DISCRETES	SOURCE CODE	TYPE	FALSE STATE	TRUE STATE	DEVICE, SOURCE	AVAILABLE AT	BIT NO.	FIGURES OF MERIT		ASIP LIST	F-15 ACC. LIST PRIORITY	SOURCE OF DATA AND COMMENTS
									FARAM. WORTH	PARAM. COST			
20	Bingo fuel light	8	2	Gnd fuel hi	+20 VDC bingo	Pull-up resistor	52P-J067 pin 28		4	4			TO 1F-15A-2-12 page 8-54
21	Pitch ratio switch	3	2	≅ 200 Ω auto	+20 VDC EMERG	Solenoid coil	520-H061 pin 116		3	4		7	TO 1F-15A-2-20 page 4-242
22	Pitch ratio light	3	2	Gnd (lite off)	+20 VDC warn	Pull-up resistor	35P-J001A pin 27		3	4		7	TO 1F-15A-2-5 page 2-56
23	Roll ratio switch	3	2	≅ 200 Ω auto	+28 VDC EMERG	Solenoid coil	52P-H080 pin 16		3	4		8	TO 1F-15A-2-5 page 1-75
24	Roll ratio light	3	2	Gnd (lite off)	+20 VDC caution	Pull-up resistor	52P-L086A pin 19		3	4		8	TO 1F-15A-2-20 page 4-270
25	Rudder limiter light	3	2	Gnd (lite off)	+20 VDC caution	Pull-up resistor	52P-L258A pin 68		3	4			TO 1F-15A-2-5 page 3-53
26	CAS yaw caution light	3	2	Gnd	+20 VDC	Pull-up resistor	35P-J001 pin 49		3	4		10	TO 1F-15A-2-20 page 4-284
27	CAS roll caution light	3	2	Gnd	+20 VDC	Pull-up resistor	35P-J001 pin 11		3	4		9	TO 1F-15A-2-20 page 4-284
28	CAS pitch caution light	3	2	Gnd	+20 VDC	Pull-up resistor	35P-J001 pin 42		3	4		7	TO 1F-15A-2-20 page 4-284
29	Pitch/roll attitude hold	3	2	≅ 200 Ω	+28 VDC	Solenoid coil	93P-H004 pin 27		3	4		7/8	TO 1F-15A-2-20 page 4-260
30	Altitude hold	3	2	≅ 200 Ω	+28 VDC	Solenoid coil	93P-H004 pin 29		3	4		3	TO 1F-15A-2-20
31	CAS yaw switch ON	3	2	>2K	+28 VDC ON	Switch	52P-B087 pin 32		3	4		10	TO 1F-15A-2-20 page 4-275
32	CAS roll switch ON	3	2	>2K	+28 VDC ON	Switch	52P-8087 pin 31		3	4		8	TO 1F-15A-2-20 page 266
33	CAS pitch switch ON	3	2	>2KΩ	+28 VDC ON	Switch	52P-B087 pin 30		3	4		7	TO 1F-15A-2-20 page 4-243
34	Canopy unlock warn light	8	8	≅ 200 Ω	6-28 VAC	Switch	52P-J060 pin 74		3	4			TO 1F-15A-2-11 page 3-65

Source Code:
1. MUX BUS
2. ADC/CADC
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. FDA

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Table 10. F-15 Configuration I Parameter List (Continued)

PARAM. NO	DISCRETES	SOURCE CODE	TYPE	FALSE STATE	TRUE STATE	DEVICE, SOURCE	AVAILABLE AT	BIT NO.	FIGURES OF MERIT PARAM. WORTH	PARAM. COST	ASIP LIST	F-15 ACC. LIST PRIORITY	SOURCE OF DATA AND COMMENTS
35	Autopilot caution light	3	2	Gnd off	+20 VDC caution	Pull-up resistor	35P-J001 pin 50		3	4			TO-1F-15A-2-20 page 4-260
36	Oxygen low	8	2	Gnd	+20 VDC warn	Pull-up resistor	52P-L008 pin 24		3	4			TO-1F-15A-2-8 page 1-47 turns on at 2 liters
37	Comm. transmit	8	2	32 VDC	Gnd	Switch	76P-B001B pin P		2	4		12	TO 1F-15A-2-21-1 page 1-57
38	Speed brake OUT	8	2	Contact open	Contact closed	Relay contacts	52P-L062 pins 11, 64		4	4	√	12	TO 1F-15A-2-5 page 4-33
39	Flaps down	8	2	≈ 200 Ω	28/6-14 VAC		52J-J067 pin 18		4	4		12	TO 1F-15-A-2-5 page 6-31
40	Flaps moving	8	2	≈ 200 Ω	28/6-14 VAC		52J-J067 pin 51		4	4		12	TO 1F-15-A-2-5 page 6-31
41	Anti-skid	8	2						3	4			TO 1F-15A-2-6
42	Left generator	8	7	Gnd	+20 VDC	Pull-up resistor	35P-J001A pin 60		[illegible]	3		11	TO 1F-15A-2-27 page 1-85
43	Right generator	8	7	Gnd	+20 VDC	Pull-up resistor	55P-J001A pin 62		3	3		11	TO 1F-15A-2-27 page 1-85
44	Left DC bus	8	3	out-limit	in-limit				3	4			TO 1F-15A-2-27 page 1-85
45	Right DC bus	8	3	out-limit	in-limit				3	4			TO 1F-15A-2-27 page 1-85
46	Essential +28 VDC bus	8	3	out-limit	in-limit				3	4			TO 1F-15A-2-27 page 1-85
47	Emergency generator on	8	8	0 volts	28V AC or DC		35Z-J001 P2 pins 44,45		3	4			TO 1F-15A-2-27 page 2-51
48	Refuel ready light												TO 1F-15A-2-12
49	Station 2B missile present	1-6	4	0	1	CC-176 NC1-395		0	3	5	√		TO 1F-15A-2-16-2 page 1-30

Source Code:
1. MUX BUS
2. ADC/CADC
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. FDA

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Table 10. F-15 Configuration I Parameter List (Continued)

PARAM. NO.	DISCRETES	SOURCE CODE	TYPE	FALSE STATE	TRUE STATE	DEVICE, SOURCE	AVAILABLE AT	BIT NO.	FIGURES OF MERIT		ASIP LIST	F-15 ACC. LIST PRIORITY	SOURCE OF DATA AND COMMENTS
									PARAM. WORTH	PARAM. COST			
50	Station 2A missile present	1-6	4	0	1	CC-177 NC1-395		1	3	5	√		TO 1F-15A-2-16-2 page 1-30
51	Station 8A missile present	1-6	4	0	1	CC-178 NC1-395		2	3	5	√		TO 1F-15A-2-16-2 page 1-30
52	Station 8B missile present	1-6	4	0	1	CC-179 NC1-395		3	3	5	√		TO 1F-15A-2-16-2 page 1-30
53	Station 3 missile present	1-6	4	0	1	CC-180 NC1-395		4	3	5	√		TO 1F-15A-2-16-2 page 1-30
54	Station 4 missile present	1-6	4	0	1	CC-181 NC1-395		5	3	5	√		TO 1F-15A-2-16-2 page 1-30
55	Station 6 missile present	1-6	4	0	1	CC-182 NC1-395		6	3	5	√		TO 1F-15A-2-16-2 page 1-30
56	Station 7 missile present	1-6	4	0	1	CC-183 NC1-395		7	3	5	√		TO 1F-15A-2-16-2 page 1-30
57	Station 2 A/G MER status	1-6	4	0	1 (present)	CC-188 NC1-398		0	3	5	√		TO 1F-15A-2-16-2 page 1-30
58	Station 5 A/G MER status	1-6	4	0	1 (present)	CC-192 NC1-400		0	3	5	√		TO 1F-15A-2-16-2 page 1-30
59	Station 8 A/G MER status	1-6	4	0	1 (present)	CC-196 NC1-402		0	3	5	√		TO 1F-15A-2-16-2 page 1-30

Source Code:
1. MUX BUS
2. ADC/CADC
3. FCS
4. NARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. FDA

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Numbers 49 through 59 add 11 digital discretes using 1 additional digital word for numbers 49 through 56. The other discretes are in words previously listed in the "continuous" section of table 10. The discretes would be recorded once at start-of-flight and as status changes (these are also ASIP type functions).

Table 11. F-15 Configuration II Parameter List

NO.	PARAMETER (CONTINUOUS)	NO. ON CONFIG. I LIST	F-15 ACC.LIST PRIORITY
1	Time	1	12
2	Cal airspeed	2	2
3	Baro alt	3	3
4	Norm accel	4	7
5	Pitch attitude	5	7
6	Bank angle	7	8
7	Yaw rate	11	12
8	AOA	12	9
9	True heading	10	12
10	Vertical vel	14	-
11	Fuel flow (L)	16	3
12	Fuel flow (R)	17	3
13	N_2 (L)	20	7
14	N_2 (R)	21	7
15	FTIT (L)	22	6
16	FTIT (R)	23	6
17	Hydraulic pressure (L)	37	5
18	Hydraulic pressure (R)	38	5

Table 11. F-15 Configuration II Parameter List (Continued)

NO.	PARAMETER (CONTINUOUS)	NO. ON CONFIG. I LIST	F-15 ACC.LIST PRIORITY
19	Roll stick force	33	6
20	Pitch stick force	32	6
21	Stabilator position (L)	26	5
22	Stabilator position (R)	27	5
23	Aileron position (L)	28	7
24	Aileron position (R)	29	7
25	Rudder position (L)	30	8
26	Rudder position (R)	31	8
27	Rudder pedal position	34	8
28	Roll rate	8	-
29	Pitch rate	6	-
30	Total fuel level	15	9
31	Nozzle (L)	24	-
32	Nozzle (R)	25	-

Table 11. F-15 Configuration II Parameter List (Continued)

NO.	PARAMETER (DISCRETES)	NO. ON CONFIG. I LIST	F-15 ACC.LIST PRIORITY
1	Master caution	2	1
2	Fire warn lights	1	8
3	ADC status	7	10
4	IMU status	11	12
5	CC status	14	-
6	CAS yaw caution light	26	10
7	CAS pitch caution light	28	7
8	CAS roll caution light	27	9
9	Autopilot caution light	35	-
10	Oxygen low light	36	-
11	Speed brake out/in	38	12
12	Flaps down	39	12
13	Fuel low warning light	19	-
14	Rt gen out	43	11
15	Lt gen out	42	11

c. F-16. Table 12, F-16 Investigators' List of desired parameters requested by accident investigators (reference 6), is included to show the relative importance of various accident investigations as indicated by the investigators themselves (questionnaire tabulation). The list shows 51 parameters of which only 25 were rated by the investigators. They are listed in six groups of descending priority. The "Time" parameter was again moved to the head of the list since all other parameter data will be time related. Note that in itself, time of events does not appear to be important to the investigators. Engine data appears to dominate the concern of the investigators in F-16 mishaps. This is probably because of the early engine-related problems and its being single-engined. Also, the flight control data has been available on the ejection seat recorder. The most requested parameters do not individually correlate well with the composite general list sequence, but the lower priorities on the two lists do, on the average, compare. Flight control data is in the lower ranked group.

Table 13 is the final recommended arrangement of parameters for the F-16 Configuration I representative list. The general comments of the A-10 section apply to table 13 also. Of special interest, the F-16 appears to have the most useful parameters for accident investigation available on the MUX bus. This makes for relative low cost and simplified data acquisition. The F-16 list is presented with the aircraft dynamic data shown taken from the FCS or the MUX bus with most MUX data from the IMU or FCC. As presently on the list, the pitch, roll, and yaw rates are obtained from the FCS. Alternatively, they can be computed from the IMU data using alternate parameter numbers 36 through 41 (as discussed in earlier paragraphs). Lowest cost for recorder installation would require some IMU or FCC software changes to provide the body axes dynamics data directly onto the bus, or alternatively, the data could be computed in the recorder preprocessor, or at post-playback on the ground. The most straightforward way is to use the FCS sensors where possible. Total systems cost will not vary greatly, and either method has its merits.

Of special interest is the parameter No. 30, which provides fault and status readouts of most systems on the aircraft (except the FCS and engine). The data appears on the bus only after a fault is enunciated, and the pilot acknowledges. The words would only be recorded as faults occur and the pilot acknowledges. This is an economical source of much status and fault data (reprogramming to place the data on the bus, addressed to the recorder, would remove the pilot from the loop).

Table 14 lists the minimum parameters for the F-16 Configuration II recorder. Twenty-eight continuous type parameters are listed. Eighteen discretes are listed. More discretes can be easily added in respect to signal processing and memory capacity. Discretes do, however, rapidly add up additional wire runs unless obtained in digital form from the MUX bus or from the ejection seat Manchester buses.

Table 12. F-16 Investigators' List

NO.	PARAMETER	RANKING GROUP	REQUEST %	GENERAL LIST RANKING
1	Time	5	0	2
2	N_2	1	80	5
3	Fuel flow	1	80	3
4	Throttle position	2	60	11
5	N_1	2	60	9
6	EGT	2	60	12
7	Total fuel	2	60	15
8	Cal. airspeed	3	40	1
9	Pitch attitude	3	40	8
10	Yaw rate	3	40	6
11	Norm acceleration	3	40	13
12	Fuel per tank	3	40	22
13	Roll CAS/SAS	3	40	16
14	Baro altitude	4	20	4
15	Mach no.	4	20	30
16	Bank attitude	4	20	10
17	Heading	4	20	25
18	CDP	4	20	19
19	Yaw CAS/SAS	4	20	21
20	Roll rate	4	20	36
21	Pitch rate	4	20	33

Table 12. F-16 Investigators' List (Continued)

NO.	PARAMETER	RANKING GROUP	REQUEST %	GENERAL LIST RANKING
22	Oil pressure	4	20	28
23	A/B position	4	20	32
24	Radar altitude	4	20	31
25	Fire light	4	20	26
26	Sideslip (β)	4	20	38
27	AOA (α)	5	0	24
28	Stick position	5	0	17
29	Rudder ped. position	5	0	29
30	Elev. position	5	0	23
31	Aileron position	5	0	18
32	Rudder position	5	0	14
33	CADC	5	0	46
34	CAS/SAS pitch	5	0	35
35	CAS/SAS roll	5	0	16
36	CAS/SAS yaw	5	0	21
37	Gear position	5	0	57
38	Flap position	5	0	44
39	S/B position	5	0	40
40	Slat position	5	0	20
41	Comm. transmit	5	0	45

Table 12. F-16 Investigators' List (Continued)

NO.	PARAMETER	RANKING GROUP	REQUEST %	GENERAL LIST RANKING
42	OAT	5	0	49
43	Anti-skid fail	5	0	68
44	Nav. status	5	0	-
45	Hyd. pres.	5	0	27
46	Util. hyd. pres.	5	0	39
47	Gen.	5	0	41
48	Inverter	5	0	41
49	Master cont.	5	0	7
50	EPU	5	0	43
51	Starter	5	0	43

Table 13. F-16 Configuration I Parameter List

PARAM NO.	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT		ASIF LIST	F-16 ACC. LIST PRIORITY	SOURCE OF DATA AND COMMENTS
										PARAM. WORTH	PARAM. COST			
1	Time	1-5	5	0 to 4.19424 sec.	LSB = 64 μsec		101-02	50/sec	16 bits	5	5	√	5	F-16 ICD page 99
2	Calibrated airspeed	1-2	5	50 to 1000 kn	LSB .0625 MSB 512 kn		C01-06	25/sec	14 bits + sign	5	5	√	3	F-16 ICD page 63
*3	Normal load Az'	1-7	5	-10G to +10G	LSB $\frac{1}{128}$ G MSB 8G		H01-36	50/sec	11 bits + sign	5	5	√	3	
*3A	Normal load	3	3		0.417 VDC/deg		2714P111 pins 6,37			5	3	√	3	TO 1F-15A-2-00SD-00-1 page 417
4	True heading	1-5	5	-1 to +1 semi-circles	LSB $\frac{1}{8192}$ MSB ½	00175 rad	101-12	50/sec	13 bits + sign	3	5		4	F-16 ICD page 108
5	Baro reference altitude	1-2	5	-1500 to 80,000 ft MSL	LSB 2.5 MSB 40,960 ft		C01-02	25/sec	15 bits + sign	5	5	√	4	May want pressure altitude instead (word C01-03). page 60
6	Vertical velocity (V_z,)	1-5	5	-2500 to +2500 FPS	LSB $\frac{1}{64}$ MSB 4096 FPS		101-07, 08	50/sec	19 bits + sign	5	5			F-16 ICD page 104
7	Pitch attitude	1-5	5	-1 to +1 semi-circles	LSB $\frac{1}{8192}$ MSB ½	.00175 rad	101-11	50/sec	13 bits + sign	5	5		3	F-16 ICD page 107
8	Pitch rate	3	3		20mV/deg/sec		2714P111 pin 36, 9		OP. amp. output	3	3	√	4	TO 1F-16A-2-00SD-00-1 page 417
9	Yaw rate	3	3		20mV/deg/sec		2714P111 pin 36, J11		Op. amp. output	4	3	√	3	TO 1F-16A-2-00SD-00-1 page 417

* alternate choices

Source Code:
1. MUX BUS
2. ADC/ECA
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. SMS

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 13. F-16 Configuration I Parameter List (Continued)

PARAM. NO.	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT		ASIP LIST	F-16 ACC. LIST PRIORITY	SOURCE OF DATA AND COMMENTS
										PARAM. WORTH	PARAM. COST			
10	Bank angle (roll)	1-5	5	-1 to +1 semi-circles	LSB $\frac{1}{8192}$ MSB ½	.00175 rad	101-10	50/sec	13 bits + sign	5	5		4	F-16 ICD page 196
11	Roll rate	3	3	308°/sec			2714 P111 pin 10, 24			3	3	√	4	TO 1F-16A-2-00SD-00-1 page 417
12	Side slip (β)	1-6	5	-20° to +20° semi-circles	LSB $\frac{1}{32,768}$ MSB ½ semi-circles		F10-17	50/sec	15 bits + sign	5	5		4	F-16 ICD page 323
13	AOA (true) (α)	1-2	5	-5° to +40°	LSB = $\frac{45°}{4096}$ MSB 90°		C01-07	25/sec	14 bits + sign	5	5		5	F-16 ICD page 64
14	Fuel flow	(Fuel trans-mitter) 8	1	0 to 80,000# per hr.	2° = 1000#/hr.		7A-01		0°=40k# per hr. 80°=80k 280°= 0k	5	4		1	10 kΩ min. Rcvr. load phase "A" ref. 0 - 11.8 VAC 400 Hz page 202 of ICD
15	Fuel quantities and reference volts	(Fuel mgt. con-trol) 8	3	0+5VDC	5V=20k#		UA-01	Ref. on UR.02, +6 volts	Available on P424 pins 11, 12, 15	5	4	√	2	Rcvr. load .5 μamp max. 600 Ω output Z (741 op amp) page 201, 217 of ICD
16	N_2	9	1	0-110%	1%		N_2 indicator P1, pins 2, 3			5	3	√	1	TO 1F 16A-00SD-00-1 page 420
17	FTIT	9		200°C 1200°C	10°C			Milli-volt level	CR/AL thermo-couple	5	3		2	TO 1F-15A-00SD--00-1 page 420
18	Throttle position	8	3				J262 pins 8, 20, 2		-15 VAC excita-tion	5	4		2	Position Pot on all later blocks (added for ASIP) TO 1F-16A-2-00SD-00-1 page 425

Source Code:
1. MUX BUS
2. ADC/ECA
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. SMS

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 13. F-16 Configuration I Parameter List (Continued)

PARAM. NO.	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT		ASIP LIST	F-16 ACC. LIST PRIORITY	SOURCE OF DATA AND COMMENTS
										PARAM. WORTH	PARAM. COST			
19	Leading edge flap position	2	3	-2° +250°	12.89V per rad			±12°/sec nominal	DC pot	2	4		5	
20	Nozzle position	9	3	0-100%						4	3		4	Shows command, not actual position
21	Oil pressure	9	1	0-100 psi			synchro			3	3		4	TO 1F-16A-2-00SD-00-2 section 12-77-00-01
22	Hyd. pressure "A"	9	1	0-4500 psi			synchro			4	3		5	
23	Hyd. pressure "B"	9	1	0-4500 psi			synchro			4	3		5	
24	Rudder position	10	7	±30° (120°/sec)	Connections shown in TO 1F-16A-2-005D-00-1 page 419 ASIP installation		J3 pins 1, 2, 3, 4		19 VAC ref. LVDT	4	1	✓	5	TO 1F-16A-4-31 Page 1-13 LVDT type 16VF011-20
25	Flaperon position (R)			±20° -23° (80°/sec)	Connections shown in TO 1F-16A-2-005D-00-1 page 419 ASIP installation		J1 pins 1, 2, 3, 4		19 VAC ref. LVDT	4	1	✓	5	TO 1F-16A-4-31 Page 1-13 LVDT type 16VF011-20
26	Flaperon position (L)			+20° -23°	Connections shown in TO 1F-16A-2-005D-00-1 page 419 ASIP installation		J5 pins 1, 2, 3, 4		19 VAC ref. LVDT	4	1	✓	5	TO 1F-16A-4-31 Page 1-13 LVDT type 16VF011-20
27	Stabilator (R)			±25° (60°/sec)	Connections shown in TO 1F-16A-2-005D-00-1 page 19 ASIP installation		J4 pins 1, 2, 3, 4		19 VAC ref. LVDT	4	1	✓		TO 1F-16A-4-31 Page 1-13 LVDT type 16VF011-20
28	Stabilator (L)			±25° (60°/sec)	Connections shown in TO 1F-16A-2-005D-00-1 page 419 ASIP installation				19 VAC ref. LVDT	4	1	✓		TO 1F-16A-4-31 Page 1-13 LVDT type 16VF011-20
29	Lateral acceleration	3	3		0.417 VDC/deg.		2714P111 pin 2, 37			3	3	✓		TO 1F-16A-2-00SD-00-1 page 417

Source Code: 1. MUX BUS 2. ADC/ECA 3. FCS 4. HARS 5. INS/IMU 6. CC 7. HUD 8. Acft. misc. 9. Engine 10. Added sensors 11. CMS

Type Code: 1. Synchro 2. +28 VDC discrete 3. DC analog 4. Digital discrete 5. Digital data 6. Low level complementary discrete 7. AC analog 8. AC discrete 9. Frequency

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 13. F-16 Configuration I Parameter List (Continued)

PARAM. NO.	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT		ASIP LIST	F-16 ACC. LIST PRIORITY	SOURCE OF DATA AND COMMENTS
										PARAM. WORTH	PARAM. COST			
30	Avionics status	1-5	4	Fault warn light			F04-03A	12.5/ sec	Bit 14 set to "1" indicates fault	4	5			Monitor bit 14 for a "1". Indicates fault data available page 968 of ICD
30	Fault acknowledge	1-11	4	Fault acknowledge			P01-03A	12.5/ sec	Bit 11 set to "1"	4	5			Pilot acknowledges fault indicated on FCNP and presses button
30	Alpha display left character	1-6	5	First 6 bits A-Z			F04-02A	12.5/ sec	6 bits	4	5			F-16 ICD page 967
30	Alpha display middle character	1-6	5	First 6 bits A-Z			F04-03A	12.5/ sec	6 bits	4	5			F-16 ICD page 968
30	Alpha display right character	1-6	5	First 6 bits A-Z			F04-04A	12.5/ sec	6 bits	4	5			F-16 ICD page 969
30	Left misc. display	1-6	5	Six 4-bit groups			F04-05A, 06A	12.5/ sec	24 bits	4	5			F-16 ICD page 970
30	Right misc. display	1-6	5	Six 4-bit groups			F04-07A, 08A	12.5/ sec	24 bits	4	5			F-16 ICD page 971
31	Longitudinal stick force	3	7	+10.86 G's = 40# -4 G's = -17.65#			2712P108 pins 9, 10	19mV RMS/#	800 Hz 26 VAC LVDT	4	4		5	TO 1F-16A-2-00SD-00-1 page 313
32	Lateral stick force	3	7	308°/sec = 17# TO & land 167°/sec = 17#			2714P110 pins 11, 12	38mV RMS/#	800 Hz 26 VAC LVDT	4	4		5	TO 1F-16A-2-00SD-00-1 page 268
33	Rudder pedal force	3	7	30° = 110#			2714P110 pins 13, 14	62mV RMS/#	800 Hz 26 VAC LVDT	4	4		5	TO 1F-16A-2-00SD-00-1 page 294
34	26 VAC Instrument bus	8	7	18-35 VAC						3	3			

* The 7 digital words comprising parameter number 30 provide status and failure data on most avionics systems except the FCS and engine.

Source Code:				
1. MUX BUS	4. HARS	7. HUD	10. Added sensors
2. ADC/ECA	5. INS/IMU	8. Acft. misc.	11. SMS
3. FCS	6. CC	9. Engine	

Type Code:		
1. Synchro	4. Digital discrete	7. AC analog
2. +28 VDC discrete	5. Digital data	8. AC discrete
3. DC analog	6. Low level complementary discrete	9. Frequency

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 13. F-16 Configuration I Parameter List (Continued)

PARAM. NO.	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT PARAM. WORTH	FIGURES OF MERIT PARAM. COST	ASIP LIST	F-16 ACC. LIST PRIORITY	SOURCE OF DATA AND COMMENTS
35	Inertial altitude	1-5	5	-1060 to +80,000 ft	LSB 4 ft MSB 65536 ft		101-25	50/sec	15 bits + sign	2	5			May be used instead of param no. 5. Page 117 of ICD.
36	Vertical acceleration	1-5	5	-512 to +512 ft/sec^2	LSB = 1 MSB = 512	.064 ft per sec^2 rms	101-16	50/sec	10 bits + sign	1	5		3	May be used instead of param no. 3. page 112 of ICD
37	Platform Velocity (V_z')	1-5	5	-2500 to +2500 FPS	LSB $\frac{1}{64}$ MSB = 4096 FPS		10 1-03, 04	50/sec	19 bits + sign	1	5			F-16 ICD page 101
38	Platform velocity (V_y')	1-5	5	-2500 to +2500 FPS	LSB $\frac{1}{64}$ MSB = 4096 FPS		10 1-05, 05, 06	50/sec	19 bits + sign	1	5			F-16 ICD page 103
39	Acceleration (A_x')	1-5	5	-512 to +512 FPS	LSB = 1 MSB = 512 FPS		101-14	50/sec	10 bits + sign	1	5			F-16 ICD page 110
40	Acceleration (A_y')	1-5	5	-512 to +512 FPS			101-15	50/sec	10 bits + sign	1	5			F-16 ICD page 111
41	True airspeed	1-5	5	70 to 1700 kn	LSB=0.125 MSB=1024 kn		C01-04	50/sec	14 bits + sign	1	5			F-16 ICD page 61
42	Rounds remaining	1-11	5	0-510 rounds	LSB = 1 MSB = 256		S01-04	6.25/sec	10 bits sign = 0	2	5	√		F-16 ICD page 695
43	Station 1 weapon inventory	1-11	5	Ident. & quant.	Octal 000 no weapon		S01-11	6.25/sec	12 bits	2	5	√		F-16 page 702
44	Station 2 weapon inventory	1-11	5	Ident. & quant.	Octal 000 no weapon		S01-12	6.25/sec	12 bits	2	5	√		F-16 ICD page 703
45	Station 3 weapon inventory	1-11	5	Ident. & quant.	Octal 000 no weapon		S01-13	6.25/sec	12 bits	2	5	√		F-16 ICD page 704
46	Station 4 weapon inventory	1-11	5	Ident. & quant.	Octal 000 no weapon		S01-14	6.25/sec	12 bits	2	5	√		F-16 ICD page 705

Numbers 36-41 are IMU parameters that with 7 and 10 can be used to compute body axes velocities and accelerations. These are alternate parameters.

Source Code:
1. MUX BUS
2. ADC/ECA
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. SMS

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discrete
9. Frequency

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 13. F-16 Configuration I Parameter List (Continued)

PARAM NO	CONTINUOUS	SOURCE CODE	TYPE	RANGE	SIG. RES.	ACCUR.	SIG. OR DIG. WORD IDENT.	DATA RATE AVAIL.	NO. BITS ETC.	FIGURES OF MERIT PARAM. WORTH	FIGURES OF MERIT PARAM. COST	ASIP LIST	F-16 ACC. LIST PRIORITY	SOURCE OF DATA AND COMMENTS
47	Station 5 weapon inventory	1-11	5	Ident. & quant.	Octal 000 no weapon		S01-15	6.25/sec	12 bits	2	5	√		F-16 ICD page 706
48	Station 6 weapon inventory	1-11	5	Ident. & quant.	Octal 000 no weapon		S01-16	6.25/sec	12 bits	2	5	√		F-16 ICD page 707
49	Station 7 weapon inventory	1-11	5	Ident. & quant.	Octal 000 no weapon		S01-17	6.25/sec	12 bits	2	5	√		F-16 ICD page 708
50	Station 8 weapon inventory	1-11	5	Ident. & quant.	Octal 000 no weapon		S01-18	6.25/sec	12 bits	2	5	√		F-16 ICD page 709
51	Station 9 weapon inventory	1-11	5	Ident. & quant.	Octal 000 no weapon		S01-19	6.25/sec	12 bits	2	5	√		F-16 ICD page 710
52	Station 1 rack inventory	1-11	5	Rack ident.	Octal 000 No rack		S01-20	6.25/sec	8 bits	2	5	√		F-16 ICD page 711
53	Station 2 rack inventory	1-11	5	Rack ident.	Octal 000 No rack		S01-21	6.25/sec	8 bits	2	5	√		F-16 ICD page 712
54	Station 3 rack inventory	1-11	5	Rack ident.	Octal 000 No rack		S01-22	6.25/sec	8 bits	2	5	√		F-16 ICD page 713
55	Station 4 rack inventory	1-11	5	Rack ident.	Octal 000 No rack		S01-23	6.25/sec	8 bits	2	5	√		F-16 ICD page 714
56	Station 5 rack inventory	1-11	5	Rack ident.	Octal 000 No rack		S01-24	6.25/sec	8 bits	2	5	√		F-16 ICD page 715
57	Station 6 rack inventory	1-11	5	Rack ident.	Octal 000 No rack		S01-25	6.25/sec	8 bits	2	5	√		F-16 ICD page 716
58	Station 7 rack inventory	1-11	5	Rack ident.	Octal 000 No rack		S01-26	6.25/sec	8 bits	2	5	√		F-16 ICD page 717
59	Station 8 rack inventory	1-11	5	Rack ident.	Octal 000 No rack		S01-27	6.25/sec	8 bits	2	5	√		F-16 ICD page 718
60	Station 9 rack inventory	1-11	5	Rack ident.	Octal 000 No rack		S01-28	6.25/sec	8 bits	2	5	√		F-16 ICD page 719

Source Code:
1. MUX BUS
2. ADC/ECA
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. SMS

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discre
9. Frequenc

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 13. F-16 Configuration I Parameter List (Continued)

PARAM NO.	DISCRETES	SOURCE CODE	TYPE	TRUE (FAIL)	FALSE (OK)	DEVICE, SOURCE	FIGURES OF MERIT		ASIP LIST	MAX DISCRETES PER PARAM.	F-16 ACC. LIST PRIORITY	COMMENTS
							PARAM. WORTH	PARAM. COST				
1	Firelight	10	2	+28 VDC	0	Relay contact. Warn light P2-A.	4	4		1	4	
2	Master caution	8	2				4	4		1	5	Lights for each caution event on panel, if reset
3	FCS caution light	3	2	Gnd (fail)	28 VDC (thru bulb)	Pressure switch	3	4		5	5	5 discretes for 5 surfaces if obtained from FCS panel.
4	FCS DUAL fail warning light	3	2	> +20 VDC (fail)	0 volts	S.S. driver	3	4		5	5	Single discretes if from caution panel or warn light. TO 1F-16A-2-00SD-00-1 page 238
5	Horiz. tail servo arm R or L	3	2	+28 VDC (arm)	0 volts	Switch	3	4		2	5	TO 1F-16A-2 00SD-00-1
6	Flaperon servo arm R or L	3	2	+23 VDC (arm)	0 volts	Switch	3	4		2	5	
7	Rudder servo arm R or L	3	2	+28 VDC (arm)	0 volts	Switch	3	4		1	5	
8	Elect system caution light	3	2	+28 VDC	0 volts	Caution panel P260-14	3	4		1	5	TO 1F-16A-2-00SD-00-1 page 350
9	After burner ON	8	2	28 VDC above A/B	0 VDC below A/B	Switch	3	4		1	2	Use A/B On/off switch point
10	L.E.F. caution light	2	2	28 VDC	0 VDC	Relay contacts	3	4		1	5	TO 1F-16A-2-00SD-00-1 page 236 Caution panel P260-5
11	Forward fuel low light	8	2	28 VDC	0	Relay contact Caution panel P260-18	4	4		1	5	TO 1F-16A-2-00SD-00-1 page 387
12	Aft fuel low light	8	2	28 VDC	0	Relay contact Caution panel P260-11	4	4		1	5	TO 1F-16A-2-00SD-00-1 page 387
13	Manual pitch ovr'd switch	3	2			Switch	3	4		1	5	

Source Code: 1. MUX BUS 2. ADC/ECA 3. FCS 4. HARS 5. INS/IMU 6. CC 7. HUD 8. Acft. misc. 9. Engine 10. Added sensors 11. SHS

Type Code: 1. Synchro 2. +28 VDC discrete 3. DC analog 4. Digital discrete 5. Digital data 6. Low level complementary discrete 7. AC analog 8. AC discrete 9. Frequency

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 13. F-16 Configuration I Parameter List (Continued)

PARAM. NO.	DISCRETES	SOURCE CODE	TYPE	TRUE (FAIL)	FALSE (OK)	DEVICE, SOURCE	FIGURES OF MERIT PARAM. WORTH	 PARAM. COST	ASIP LIST	MAX DISCRETES PER PARAM.	F-16 ACC. LIST PRIORITY	COMMENTS
14	Transmit switch	8	2	Gnd	+28 VDC	Switch on Throttle grip J261 VHF-20, VHF-30	3	4		1	5	TO 1F-16A-2-00SD 00-1 page 135
15	Oxygen low	8	2				3	4		1	5	Pressure below 42 psi or quantity below 0.5 liter
16	BUC light	10	2				5	4		1	5	Engine operating on back-up controls
17	Speed brake	3	3	Open	Close	Switch	3	4		1	5	
18	Main generator	8	2	28 VDC	0	Elect. Control Panel P257-4	3	4			5	TO 1F-16A-2-00SD-00-1 page 151
19	Cabin pressure warn	8	2	28 VDC	0	caution D260/1 panel pin 13	2	4			5	TO 1F-16A-2-00SD-00-1 page 125
20	Canopy lock	8	2				2	4			5	
21	28 VDC #1 essential bus	8	2	out-limits	in-limits		3	4			5	
22	28 VDC #2 essential bus	8	2	out-limits	in-limits		3	4			5	
23	Battery bus	8	2	out-limits	in-limits		3	4			5	
24	Emergency generator	8	2	28 VDC	0	P257-3	3	4			5	TO 1F-16A-2-00SD-00-1 page 150
25	Landing gear	8	2				3	4			5	
26	Weight off wheels	8	2				3	4			5	

Source Code:
1. MUX BUS
2. APC/ECA
3. FCS
4. HARS
5. INS/IMU
6. CC
7. HUD
8. Acft. misc.
9. Engine
10. Added sensors
11. SMS

Type Code:
1. Synchro
2. +28 VDC discrete
3. DC analog
4. Digital discrete
5. Digital data
6. Low level complementary discrete
7. AC analog
8. AC discret
9. Frequency

Relative Figures of Merit: 0 = Lowest Merit; 5 = Highest Merit

Table 14. F-16 Configuration II Parameter List

NO.	PARAMETER (CONTINUOUS)	NO.ON CONFIG.I LIST	F-16 ACC.LIST PRIORITY
1	Time	1	5
2	Cal airspeed	2	3
3	Normal load	3	3
4	Baro altitude	5	4
5	Vert. velocity	6	-
6	Pitch attitude	7	3
7	Pitch rate	8	4
8	Bank angle	10	4
9	Roll rate	11	4
10	Heading	4	4
11	β (sideslip)	12	4
12	α (AOA)	13	5
13	Fuel flow	14	1
14	Fuel quant.	15	2
15	N_2	16	1
16	FTIT	17	2
17	Hyd. pres. A	22	5
18	Hyd. pres. B	23	5
19	Rudder position	24	5
20	Flaperon position R	25	5

Table 14. F-16 Configuration II Parameter List (Continued)

NO.	PARAMETER (CONTINUOUS)	NO.ON CONFIG.I LIST	F-16 ACC.LIST PRIORITY
21	Flaperon position L	26	5
22	Stabilator R	27	5
23	Stabilator L	28	5
24	Longitudinal stick force	31	5
25	Lateral stick force	32	5
26	Rudder ped. force	33	5
27	Oil pressure	21	4
28	Yaw rate	9	3

Table 14. F-16 Configuration II Parameter List (Continued)

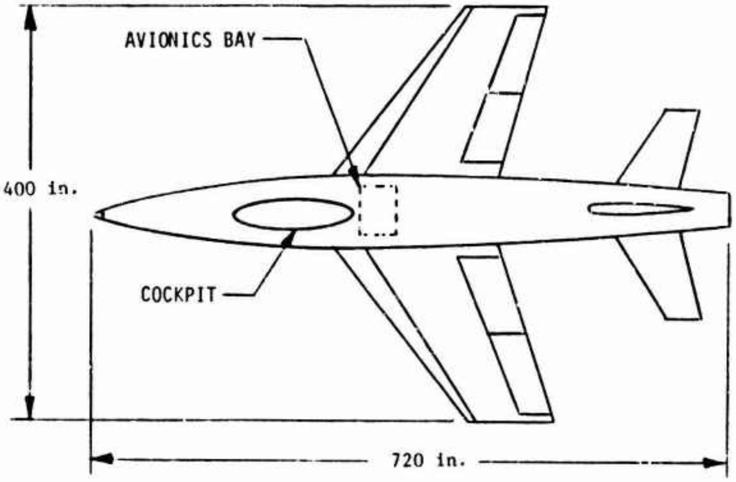
NO.	PARAMETER (DISCRETES)	NO. ON CONFIG. I LIST	F-16 ACC. LIST PRIORITY
1	Master caution	2	5
2	Fire light	1	4
3	FCS caution	3	5
4	FCS dual fail	4	5
5	Horizontal tail servo arm R or L	5	5
6	Flaperon servo arm R or L	6	5
7	Rudder servo arm	7	5
8	Elec. system warn light	8	5
9	Throttle position (above/below A/B)	9	2
10	L.E.F. caution lite	10	5
11	Fwd. fuel low	11	5
12	Aft. fuel low	12	5
13	BUC lite	16	5
14	Oxy. low	15	5
15	Speed brake open/close	17	5
16	Canopy lock	20	5
17	Gear up	25	5
18	Weight on wheels	26	5

3.1.2 Aircraft installation investigation

3.1.2.1 Objective - LSI's overall objective for the installation phase of the CSFDR study was to provide a generalized CSFDR system installation concept which can be applied to the A-10, F-15, and F-16 aircraft and to other attack, fighter, or trainer (A/F/T) aircraft. The primary CSFDR system configuration recommended by LSI consists of two units. One unit, the Data Processing Unit (DPU), which does not possess crash-survivable properties, provides the data conversion, data processing and data compression functions. The DPU interfaces with existing aircraft systems and flight controls to obtain required data. The second unit is a Crash-Survivable Memory Unit (CSMU), possessing crash-survivable properties located in a remote area of the aircraft and connected to the DPU by means of an electrical cable. In determining the location of the DPU and the CSMU, the following goals and requirements were considered:

- Adequate space for the unit, the mounting bracketry, and attaching electrical cables.
- Survivability for the Crash-Survivable Memory Unit.
- Proximity of all units of the CSFDR system
- Proximity of the CSFDR system to the data sources.
- Accessibility of the individual units for ease of maintenance and data extraction.
- Adequate strength of the surrounding aircraft structure to support and hold the added units with respect to the individual aircraft's mission environment.
- Minimization of the CSFDR system impact on the aircraft's weight and balance properties.

3.1.2.2 Installation trade-off study - The initial step in determining a generalized CSFDR system installation concept was to perform an installation trade-off study comparing various installation concepts. A generalized representative aircraft was assumed for the purpose of this study in lieu of a specific aircraft in the Air Force inventory. The aircraft size and configuration was based on the existing inventory of USAF aircraft in the attack, fighter, and trainer categories (A-10, F-4, F-5, F-15, F-16, F-111, and T-38). Of these aircraft, the average size appeared to be that of the F-4 or slightly smaller. Consequently, the hypothetical aircraft used in this study was assumed to have the dimensions and configurations illustrated in figure 2.



ASSUMPTIONS

1. Aircraft configured as above
2. CSFDR Production Run of 500 Systems
3. Flight Control Position Sensors:

LOCATION	QUANTITY
Leading Edge Flaps	2
Trailing Edge Flaps	2
Ailerons	2
Stabilator	1
Rudder	1
Speed Brakes	2

4. MIL-C-38999 Electrical Connectors
5. MIL-W-22759 Electrical Wire
6. All CSFDR units are hardmounted
7. Combination of MIL-STD-1553 Data Bus and Analog Data Signals
8. Aircraft to DPU Interface cable consists of 60 wires.
9. DPU to CSMU cable consists of 14 wires.

2000546

Figure 2. Installation Trade-off Study Hypothetical Aircraft

A further assumption was made that flight control position sensors would be required as a part of the CSFDR system installation. This involves mounting the sensors at the flight control locations and routing signal cables from the sensors to the CSFDR system.

The purpose of the study was to obtain representative costs for the Group-A Kit and representative installation times in man-hours of direct labor to install the Group-A Kit. Included in the estimated A-kit cost were the bracketry to mount the flight control position sensors, the bracketry to mount the recording system, the interconnecting electrical cables, and all associated hardware. The cost of the CSFDR Group-B components were not included. The A-kit costs reflected recurring costs only. Developmental costs were not included. The A-kit costs were estimated based on a large continuous production run (200 units minimum), thereby minimizing manufacturing set-up charges. The estimated man-hours for each of the installations were for installing and checking the entire CSFDR system, data processor, memory, and flight control position sensors.

Four basic installations were considered during this study. Each installation was estimated assuming that some of the required data was available from a MIL-STD-1553-type data bus and some data had to be obtained directly from the data source.

- Installation I: DPU and CSMU combined as a single unit and located in the aircraft avionics bay.
- Installation II: DPU and CSMU combined as a single unit and located in the aircraft tail section.
- Installation III: DPU located in the aircraft avionics bay with multiple semi-hardened memories located in the tail, wing tips, and canopy.
- Installation IV: DPU located in the aircraft avionics bay and the CSMU located in the tail.

The costs of each of the above four installations were estimated, compared to a base installation (Installation I), and subjectively analized with respect to the above stated goals (see table 15).

a. Installation I. DPU and CSMU combined as a single unit and located in the aircraft avionics bay.

Group-A Kit cost = 1.0 (normalized to 1.0)

Installation time = 1.0 (normalized to 1.0)

Table 15. Comparison of Four Installations

INSTALLATION	GROUP-A KIT COST	INSTALLATION TIME
I	1.00	1.00
II	1.14	1.26
III	2.73	3.28
IV	1.43	1.58

The kit cost and installation time for this installation were the lowest of the four considered. These values were used as a base for the comparison of the remaining three installations. Thus, the kit cost and installation time for Installation I are normalized to one. The relatively low cost of the A-kit and minimal kit installation time are attributable to the proximity of the CSFDR system to the various data sources, thereby minimizing the length of the interface cable between the aircraft and the DPU. Also, the single unit location in the avionics bay contributes to the ease of installation and the accessibility of the units for maintenance and data extraction. Locating the entire system in the aircraft avionics bay minimizes the adverse impact on the aircraft's weight and balance properties by placing the CSFDR units close to the aircraft center of gravity. However, a review of Air Force Class-A mishap data (reference 6) shows that the avionics bay in a typical Class-A mishap does not exhibit a high degree of survivability. The mishap data shows that the avionics bay experiences the most severe environment when considering both structural break-up and heat damage. Therefore, the memory module would be exposed to an extremely hostile environment when compared to other aircraft locations.

b. Installation II. DPU and CSMU combined as a single unit and located in the aircraft tail section.

Group-A Kit cost = 1.14

Installation time = 1.26

The kit cost for this installation as for Installation I is relatively low. By locating the CSFDR system in the tail, the survivability of the memory unit is enhanced, since the Air Force Class-A mishap data (reference 6) shows that the aircraft extremities (wing tips and tail) experience the maximum survivability rate. However, with a CSFDR system installed in the aircraft tail section, all of the signals must be transmitted from the data source to the tail. Assuming a typical mix of data bus and source data wires, an aircraft to CSFDR system interface cable would consist of more than 60 wires. Since most of the data sources are located in the cockpit area of the aircraft the relatively large interface cable must be routed from the cockpit through the fuselage to the CSFDR system in the tail.

In today's modern A/F/T aircraft available space is often at a premium, and in aircraft extremities such as the wing tips and tail section even available space puts severe constraints on the permissible form factor of units so located. Thus, even a relatively low volume (200 cubic inches) CSFDR system would necessitate special packaging to conform to available space in the tail. Such special packaging would increase the cost of the CSFDR system and would decrease the commonality of CSFDR systems between models of aircraft (i.e., F-16 versus F-15). The tail area of an A/F/T type aircraft generally is not very accessable and has limited mounting areas for electrical equipment, thereby increasing the difficulty of installation. Also, the decreased accessibility limits the maintainability of the system and increases the difficulty of data extraction from the system.

Of all the installations considered, this installation would have the maximum adverse impact on the aircraft weight and balance since the entire CSFDR system would be located far from the aircraft's center of gravity and would require a large cable to be routed from the cockpit area to the tail. However, even at the maximum, the adverse impact is minimal since the weight of the CSFDR system is approximately twelve pounds (not including Group-A Kit). With the Group-A Kit the system weighs approximately 25 pounds for this installation.

c. Installation III. DPU located in the aircraft avionics bay with multiple semi-hardened memories located in the tail, wing tips, and canopy.

Group-A Kit cost = 2.73

Installation time = 3.28

This installation is the most expensive and time consuming installation of the four considered. The large increase in kit cost and installation time results from installing four separate memories in different extremities of the aircraft and installing the electrical cabling from the DPU to the separate memories. However, this installation does incorporate the two positive characteristics of the previous installations of locating the memory in a survivable area of the aircraft and of locating the DPU in an accessible area of the aircraft close to the data sources.

Although this installation provides for two primary system attributes, survivability and accessibility, it does so at great expense. The increased cost of the system deployment (kits and installation) would make the CSFDP system non-cost-effective for retrofit applications.

d. Installation IV. DPU located in the aircraft avionics bay and the CSMU located in the tail.

Group-A Kit cost = 1.43

Installation time = 1.58

Although this installation costs more in dollars and man-hours than I or II, it incorporates the positive features of all three previous installations. The memory is located in a survivable area of the aircraft. Since the memory is smaller than the single unit CSFDR, it can be located in more remote areas of the aircraft than the single unit, thereby increasing its survivability. The DPU is located in the avionics bay close to the data signal sources. Being located in the avionics bay, the DPU is accessible and thus easily maintained.

The increase in the Group-A Kit cost is attributable to the extra installation bracketry and time for the CSMU since it is separate from the DPU. However, the increase in cost and installation time is offset by the attributes of this installation. As stated above, the CSMU is located in a remote area of the aircraft (tail) and thus will exhibit a higher rate of survivability as evidenced from the Air Force mishap data (reference 6). Since the CSMU is of relatively small size (42 cubic inches), the typically limited available space in the aircraft extremities is no longer a problem as in Installation II where the entire CSFDR system was located in the tail.

By locating the DPU in the avionics bay, a number of benefits are realized. Since the avionics bay is proximate to a majority of the data sources, the aircraft-to-CSFDR interface cable (60 wires) is held to a minimum length. Although separating the CSMU and the DPU requires an extra interface cable over the single unit configurations, this cable only consists of 14 wires, which is only 25 percent of the weight and volume required by the cable for Installation II. This small cable is thus easier to route and integrate into the typically small A/F/T airframe. The DPU in the avionics bay also enhances the accessibility of the system for maintenance and for data extraction, as the very nature of the equipment in the avionics bay requires ease of access.

Typically, an aircraft airframe is not designed to accept the installation of larger electronic units in its extremities (tail and wing tips). However, there is no great design obstacle to install a unit such as the CSMU, which has a relatively light weight and low volume, in the tail and wing tip areas. An aircraft avionics bay is designed to accept the type and size unit as displayed by the DPU. This installation takes the requirements and characteristics of the CSFDR system into account and directly applies them to the A/F/T aircraft under consideration in this study.

e. Conclusions from general study. The discussion and cost evaluation of the four installations considered above show that although Installations I and II are the least costly in terms of dollars and manhours, they have disadvantages in the areas of maintainability, survivability, and accessibility. Installation III, while overcoming the disadvantages of Installations I and II, becomes costly in the areas of kit cost and installation time. Installation IV overcomes both the shortfalls of Installations I and II and the costliness of Installation III.

Installations I, III, and IV also contain added benefits. The location of the DPU in the avionics bay provides for ease of addition of optional memory devices for the recording of Aircraft Structural Integrity Program (ASIP) data, turbine engine health data, flight control monitoring data, or aircraft incident data. None of these functions requires crash-survivable hardware, therefore, the memory devices can be located close to the DPU in an accessible area for ease of data extraction. Separating the DPU and the CSMU provides for maximum adapatibility to the various Air Force airframes and minimum impact to the basic CSFDR system design, thereby resulting in a CSFDR system that is standardized to the maximum extent possible. The separate units of the CSFDR system are also adaptable to airframes used within the other services of the DOD as well, thus contributing to interservice standardization in addition to intraservice standardization. Adopting a design whereby the CSMU is located in a survivable extremity of the aircraft and the DPU is located close to the data sources will provide a CSFDR system that is survivable, maintainable, flexible, and standardized for various models of aircraft.

3.1.2.3 General installation concept

a. Crash-Survivable Memory Unit (CSMU). The CSMU is located in either the tail section or a wing tip of the aircraft. Air Force Class-A mishap data, and other data from the NTSB and Navy, indicate that these are the two areas of the aircraft that enjoy the highest degree of survivability in a destructive mishap. The ejection seat and canopy also enjoy a high degree of survivability. However, these two locations were discarded because their survivability is directly related to the ejection rate. The ejection rate for the three subject aircraft is 41.1 to 80 percent and the survivability goal of the CSMU is 90 to 100 percent. If ejection is not accomplished, the CSMU would remain in the cockpit which does not enjoy a high degree of survivability in a destructive mishap. Attaching the CSMU to the canopy or ejection seat would probably require the recertification of both mechanisms for each model of aircraft. Such a process would unnecessarily increase the developmental cost and schedule of the CSFDR system and present a very complex design and test program, which may turn out unfavorably. Also, 3.4.1 of the RFP required the CSMU to be retained in the aircraft until post-crash recovery which would not be possible if attached to the canopy or ejection seat.

The CSMU is designed to be attached to the aircraft structure with standard threaded fasteners. Depending upon the application aircraft, the CSMU may be mounted directly to existing aircraft structure or may be mounted to bracketry designed specifically for the installation of the CSMU. Materials used in manufacturing will be approved materials listed in MIL-HDBK-5C and mounting hardware will be selected from MS, NAS, and AN specifications.

b. Data Processing Unit (DPU). The DPU is located close to the cockpit, as the cockpit area is the major source of the data signals required for the CSFDR system. For ease of maintenance and data extraction, a typical installation for the DPU implies a location in an existing avionics bay. The access panel to the bay employs quick-release latches or easily removable fasteners for minimal access time. Within the bay the DPU is located so as to require minimal or no equipment removal to facilitate DPU removal or data extraction from the CSFDR system.

The DPU is retained in the avionics bay attached to the aircraft structure by means of two MS14108 self-locking electronic equipment fasteners or the equivalent. These fasteners are attached directly to the existing equipment racks in the bay or to bracketry added to facilitate the installation of the DPU. The MS14108 fasteners apply a downward and rearward force to the DPU, holding the front of the unit in place and forcing the rear portion of the DPU into a retaining device.

The installation of the DPU is such that vibration isolators may be added if the operating environment in the avionics bay is sufficiently severe to warrant the isolators. However, the DPU is designed to be hardmounted to the aircraft airframe, and the necessity of added vibration isolation is highly unlikely. The installation of the DPU in the avionics bay is of sufficient strength to comply with the flight load criteria for the various models of aircraft. Special crash protection above the normal design goal of standards MIL-A-008860A (USAF) and MIL-A-008865A (USAF) is not warranted since the function of the DPU is completed upon catastrophic impact with the ground.

c. Electrical interface. The DPU and the CSMU are interconnected by means of an electrical cable. This cable consists of six twisted pairs of conductors for data transmission and one shielded twisted pair used to supply power to the CSMU for a total of fourteen conductors. The grounded shield around the power conductors provides EMI protection between the power line and data transmission lines. The shield also protects the data conductors from being shorted to the power conductors in the event of aircraft structure penetrating the cable or in the event an aircraft fire begins to melt the cable. Fire and heat protection is also accomplished through the use of MIL-W-25038 or equivalent high-temperature and fire-resistant aircraft electrical wire. Further fire and heat protection, as well as cable penetration protection, is furnished as a side benefit by the application of dual layers of EMI shielding around the exterior of the cable. Connectors used on this cable are of an approved military series.

The second electrical cable used in the CSFDR system is the aircraft-to-DPU interface cable. This cable is larger than the previous cable since it must tie in to all of the CSFDR data sources. Depending on the CSFDR configuration (I, II, or III) and the aircraft model, the aircraft-to-DPU interface cable consists of 45 to 95 wires. The cable has braided sleeving for compactness and is multi-branched to reach all of the various data sources. The wire and connectors in this cable comply with approved military specifications for use in aircraft. This cable has not been given the fire and heat protection of the previous cable since it is not located near potential high-heat areas, such as engines and fuel cells. The cable complies with the environmental specifications of the area in which it is located.

The aircraft-to-DPU interface cable obtains a variety of signals from a number of data sources. The cable wires interface with the signals by splicing into existing aircraft wires or by picking up unused pins in existing electrical connectors. Assurance will be made during such interconnections that compatible interfaces exist for a properly integrated system and that disturbed systems are not adversely affected. These connections are terminated using military-approved methods and MS, NAS, AN or mil-spec hardware. Some of the subject aircraft are equipped with data bus communicators. The aircraft-to-DPU interface cable contains conductors that will be coupled to the data bus lines to extract data desired for storage in the CSMU.

Cables used to interconnect the DPU with optional memory devices are of construction similar to the DPU-to-CSMU cable. Wire and connectors comply with approved military series specifications. The cable is shielded and enclosed in braided sleeving.

Electrical cable construction, termination, and routing comply with MIL-W-5088 "Aerospace Vehicle Wiring", technical order 1-1A-14 and applicable aircraft specifications. Where possible, electrical cable routing is accomplished along existing electrical cable runs. Long cables are designed with midpoint disconnects when required by aircraft construction, such as going through pressure bulkheads or through a structure that divides from the aircraft. Appendix C is a list of federal specifications, military standards and technical orders utilized by LSI in the design, fabrication, and installation of electrical Group-A Kit hardware on military aircraft.

d. Position sensors. Included in the desired data parameters to be recorded by the CSFDR system are the positions of various movable elements of the aircraft such as flight controls, throttles, and control sticks. The F-16 has a majority of these sensors installed prior to CSFDR while the F-15 has a limited number of existing sensors and the A-10 has very few.

Sensing the position of a movable element of the aircraft can be accomplished by mounting a precision potentiometer proximate to the flight control surface, throttle, or control stick, and mechanically linking the movable element of the potentiometer to the aircraft's movable element. As the control surface, throttle, or control stick is moved, the potentiometer varies the voltage of the electrical signal transmitted to the DPU. The various voltage levels are then stored in memory and can be translated to position data upon extraction from the CSFDR memory.

The wiring interconnecting the potentiometers and the DPU is designed, fabricated, and installed in accordance with the specifications used for the CSFDR system cables, as described in previous paragraphs. Mechanical mounting hardware, brackets, and connecting linkages are designed, fabricated and installed in accordance with applicable military specifications and military-approved hardware.

The precision potentiometers used in the sensor installation are relatively low in cost and meet the requirements of MIL-R-39023 and MIL-E-5272. The potentiometers are constructed of an aluminum case with stainless steel ball bearings and shaft. The resistive element is conductive plastic on a ceramic chip and the wiper is a precious-metal alloy. Typical characteristics are as follows:

Resistance value - 10K ohms
Linearity - .25%
Rotational angle - 350 degrees
Temperature range - -65°C to + 125°C
Vibration - 15 g
Shock - 50 g
Rotational load life - 25,000,000 revolutions

3.1.2.4 <u>A-10 installation</u> - The proposed CSFDR system installations for the A-10 aircraft make optimum use of available space and existing electrical cable routes in the aircraft. CSFDR unit locations are essentially identical for Configurations I, II, and III and have been coordinated with the airframe manufacturer. The general CSFDR installation is shown in figure 3.

The DPU is located in door F-10 on the right-hand side of the aircraft below the cockpit. For Configurations I and II, the DPU occupies the upper forward position in the bay (see figure 4).

The Configuration III CSFDR system replaced the existing Signal Data Multiplexer Converter and the Signal Data Recorder on ASIP designated aircraft with the CSFDR DPU and the optional memory units for aircraft structural integrity program, turbine engine health, and flight control monitoring. The Configuration III DPU and memory units are installed in the locations vacated by the existing multiplexer and recorder (see figure 5). The DPU location in door F10 is close to the major data sources insuring that the aircraft-to-DPU interface cable is maintained at minimum length and, therefore, has minimum impact on the aircraft weight and balance. This cable is connected to the DPU in door F10 and branches out to interface with all of the required data sources for the CSFDR system. The cable branches are routed along existing cables to minimize the impact on the aircraft configuration.

The interconnecting cable between the DPU and the CSMU is routed along existing electrical cable runs in the right-hand side of the aircraft fuselage to fuselage station 536. A cable disconnect is provided at this point to correspond to the existing aircraft configuration. The cable continues from fuselage station 536 through the aft fuselage and terminates at the CSMU. The CSMU is located in the upper tail cone area of the aircraft immediately forward of the forward horizontal stabilizer support bulkhead (door F57) at fuselage station 680 (see figure 6). This location was chosen to provide the CSMU with a maximum survivable environment based on the Air Force Class-A mishap data and on the airframe manufacturer's evaluation of A-10 mishaps.

CSFDR Configurations I, II, and III require the measurement of the position of various movable aircraft components. The components requiring such measurements are left and right rudder, left and right elevator, left and right aileron, throttles, rudder pedals, and pilot's control stick. This requirement necessitates the addition of eleven potentiometers to provide the measurements. The potentiometers are mounted as described in the preceding paragraphs. Wiring for the potentiometers is routed along existing electrical cable runs and is integrated with added CSFDR cables wherever possible.

3.1.2.5. F-15 installation - The CSFDR installations for the F-15 aircraft utilize existing available space and equipment to provide an optimum CSFDR system installation. The CSFDR unit locations for Configurations I and II are identical. The locations of the DPU and additional memory units change for Configuration III. The CSFDR unit locations for all configurations were coordinated with the airframe manufacturer. The

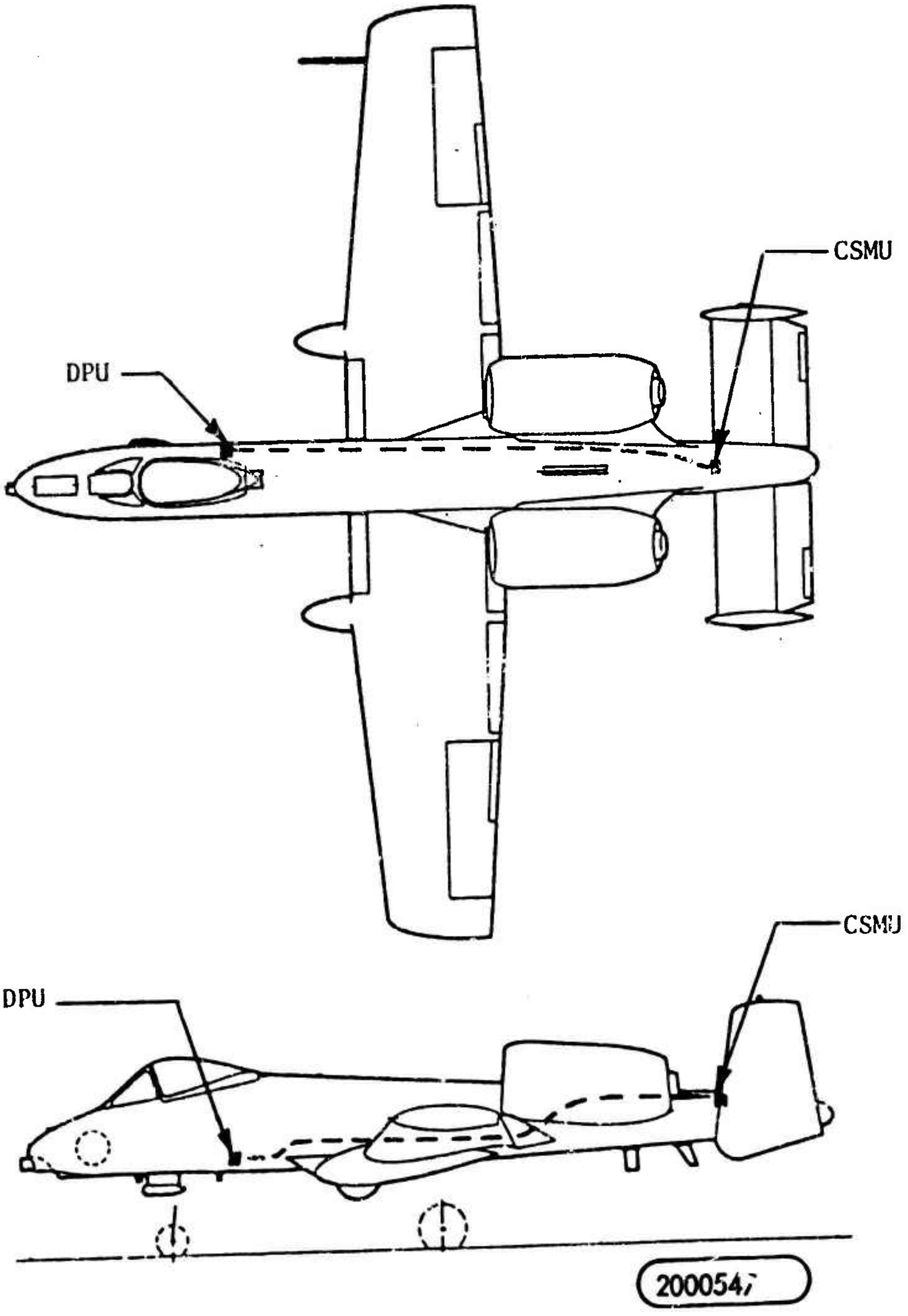


Figure 3. A-10 General CSFDR System Installation

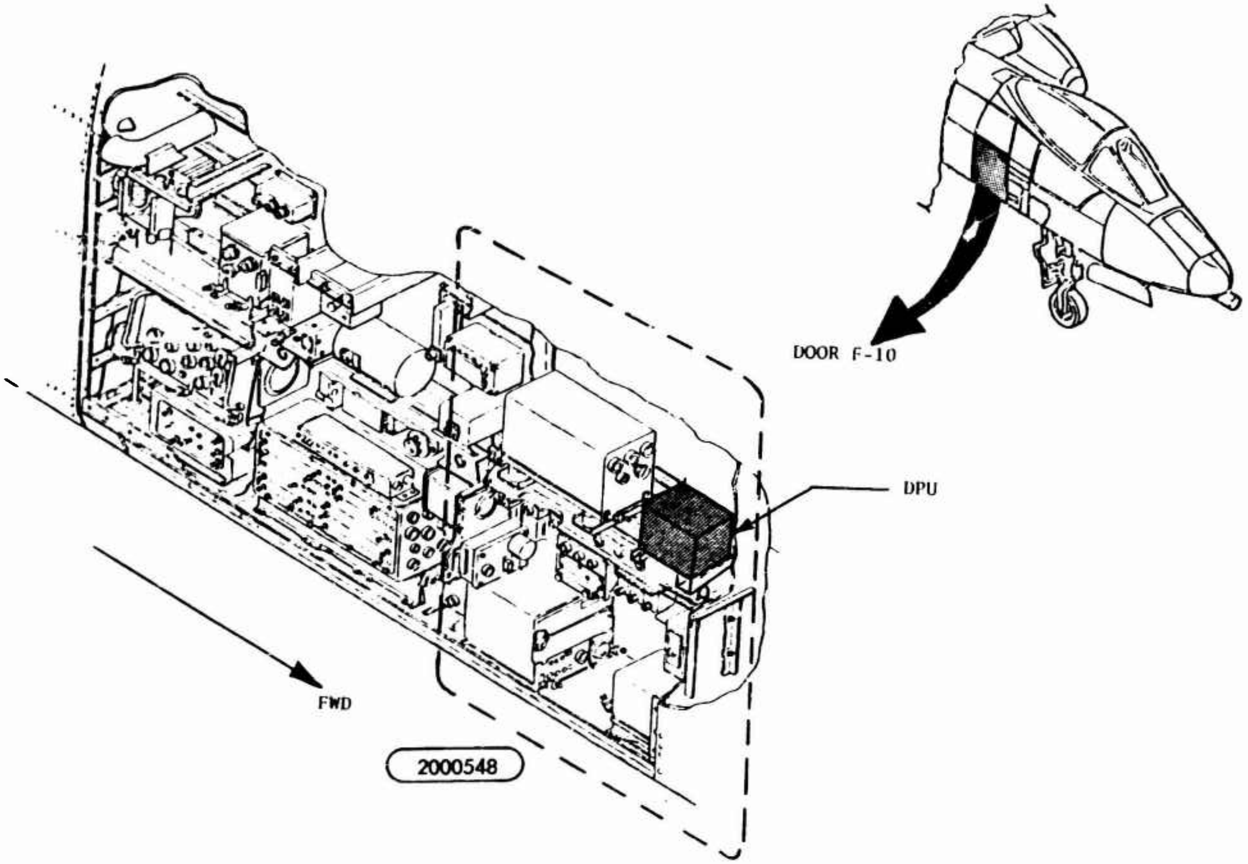


Figure 4. A-10 Configurations I and II DPU Location

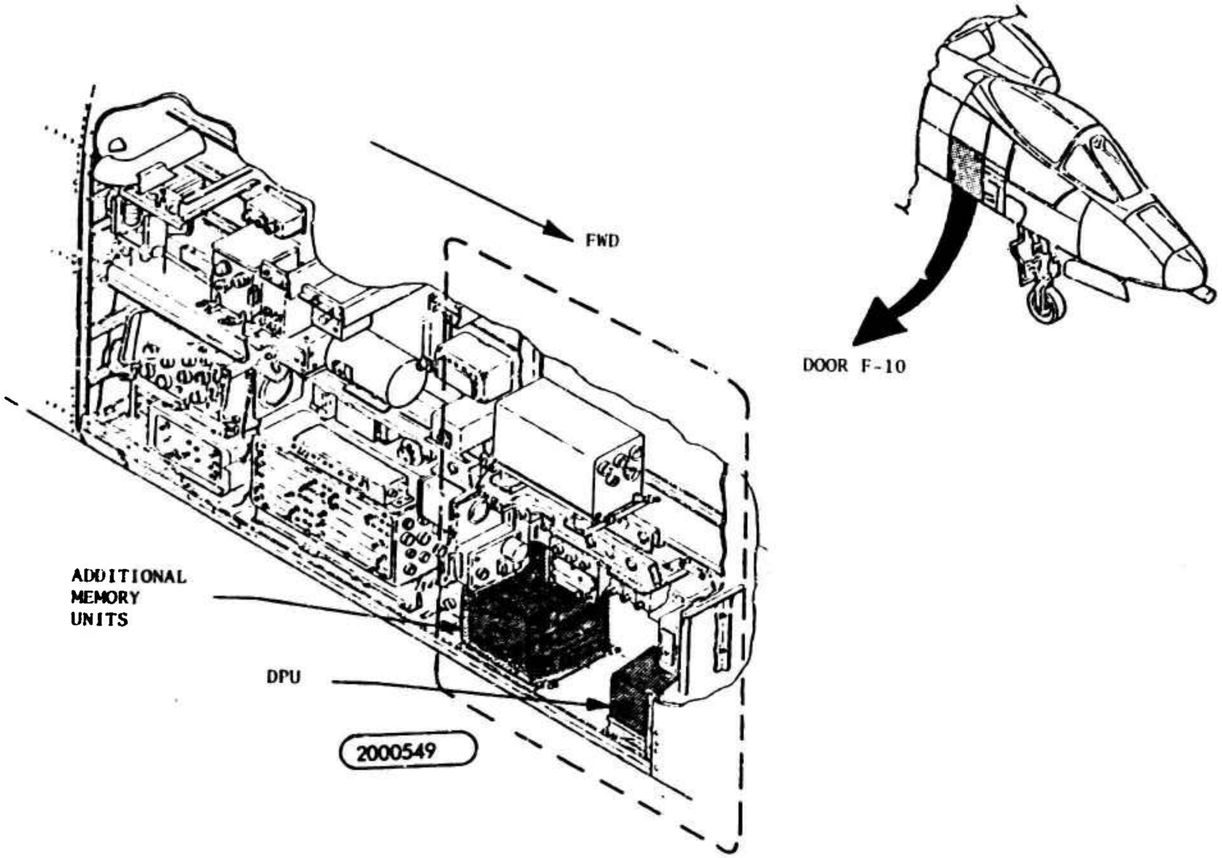


Figure 5. A-10 Configuration III DPU Location

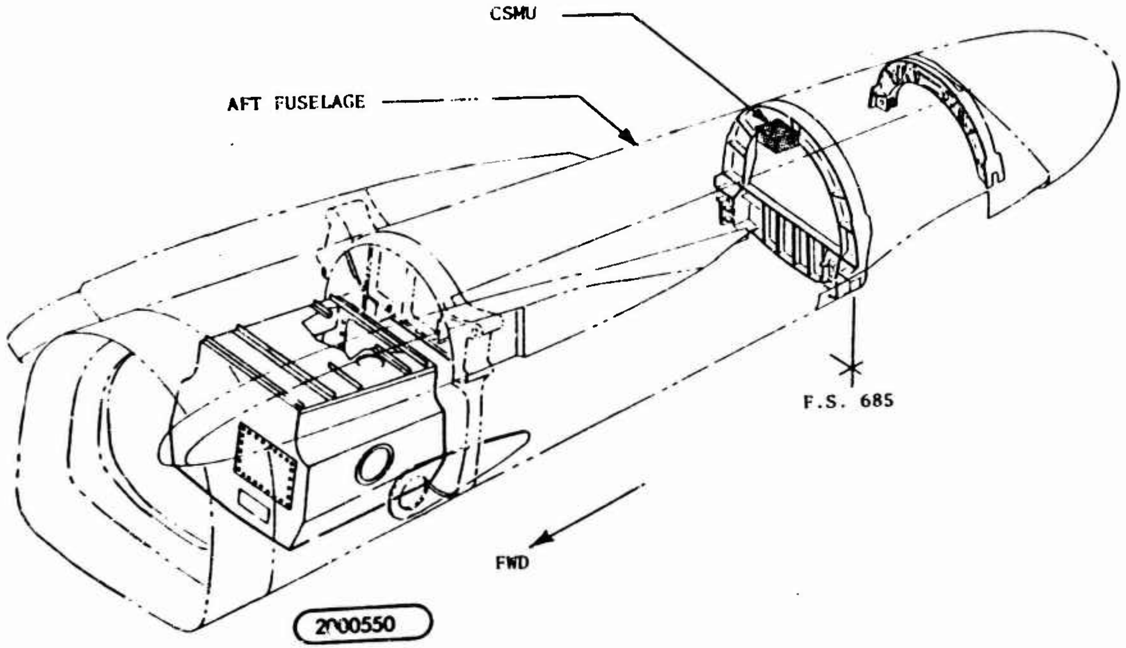


Figure 6. A-10 CSMU Location

general CSFDR installation for Configurations I and II is shown in figure 7 and for Configuration III is shown in figure 8.

For Configurations I and II, the DPU is located in the left-hand side of the environmental control systems' bay in door 15 (see figure 9). Discussions with the airframe manufacturer revealed that impending ECPs for the F-15 have depleted all available space in the forward equipment bays. Mounting of the DPU is accomplished by added structural brackets as described in preceding paragraphs. The DPU is located in a desirable position to interface with the required CSFDR data sources. The aircraft-to-DPU interface cable is connected to the DPU in the ECS bay and branches to both the left and right sides of the forward fuselage along existing electrical cables and interfaces with the various data sources.

For Configuration III, the DPU and the additional memory units for aircraft structural integrity, turbine engine health, and flight control monitoring are located in door 155L (see figure 10). These units replace the existing Signal Data Recorder. The DPU and memory units are mounted on added structural brackets. The aircraft-to-DPU cable interfaces with the data sources as in Configurations I and II. Door 15 is fastened with quad-lead type fasteners for quick access.

The interconnecting cable between the DPU and the CSMU is routed along existing cable runs in the aircraft. For Configuration III, the aircraft to DPU cable runs forward to the ECS bay. For all three configurations the cable is then routed above the left-hand engine intake aft to the trailing edge area of the left wing. At this point the cable runs outboard into the drv area of the left wing to door 143L. The CSMU is located in door 143L inboard of the aileron actuator (see figure 11). Air Force Class-A mishap data showed the F-15 wing tip areas to exhibit the maximum survivability along with the vertical stabilizer. The wing location was chosen over the vertical stabilizer for reasons of accessibility, maintainability, and ease of installation. The CSMU position in the wing and the DPU-to-CSMU interconnecting cable routing are located in areas readily accessible by removing existing panels. A tail location for the CSMU would have necessitated the addition of an access door for the CSMU, thus increasing CSMU installation costs.

Configurations I, II, and III require the measurement of left and right stabilator, left and right aileron, left and right rudder, throttle, rudder pedal, and pilot's control stick positions during flight. The aircraft has existing mechanisms installed to measure this data on the left and right aileron and the left rudder. These signals are interfaced with the CSFDR system. The remaining measurements can be accomplished by installing eight potentiometers at the various aircraft component locations and interfacing the outputs with the CSFDR system. The potentiometer installations are achieved as described in the preceding paragraphs. Wiring for the potentiometers is routed along existing

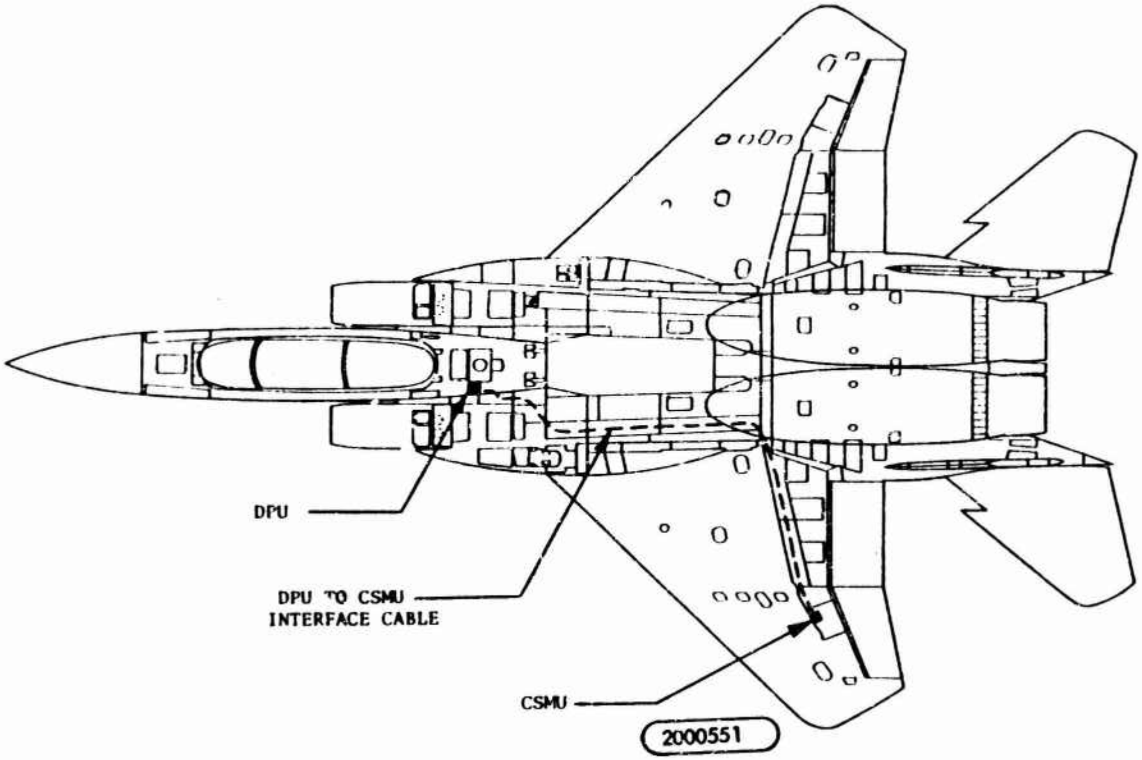


Figure 7. F-15 CSFDR System Configurations I and II

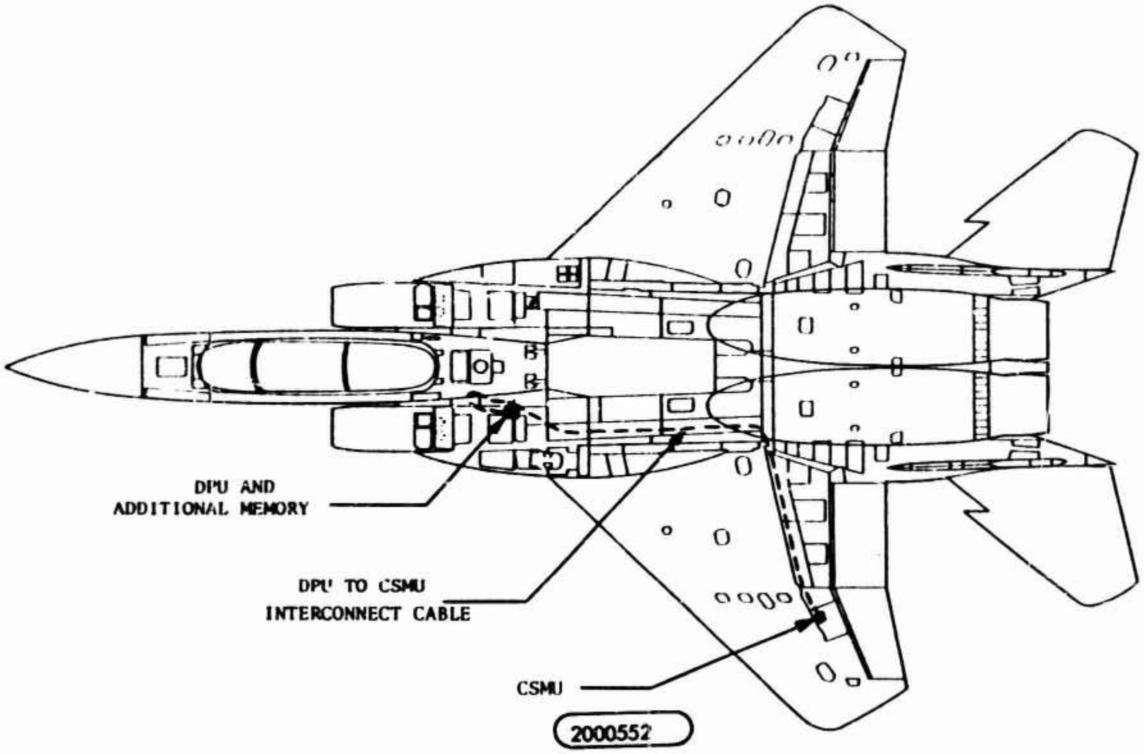


Figure 8. F-15 CSFDR System Configuration III

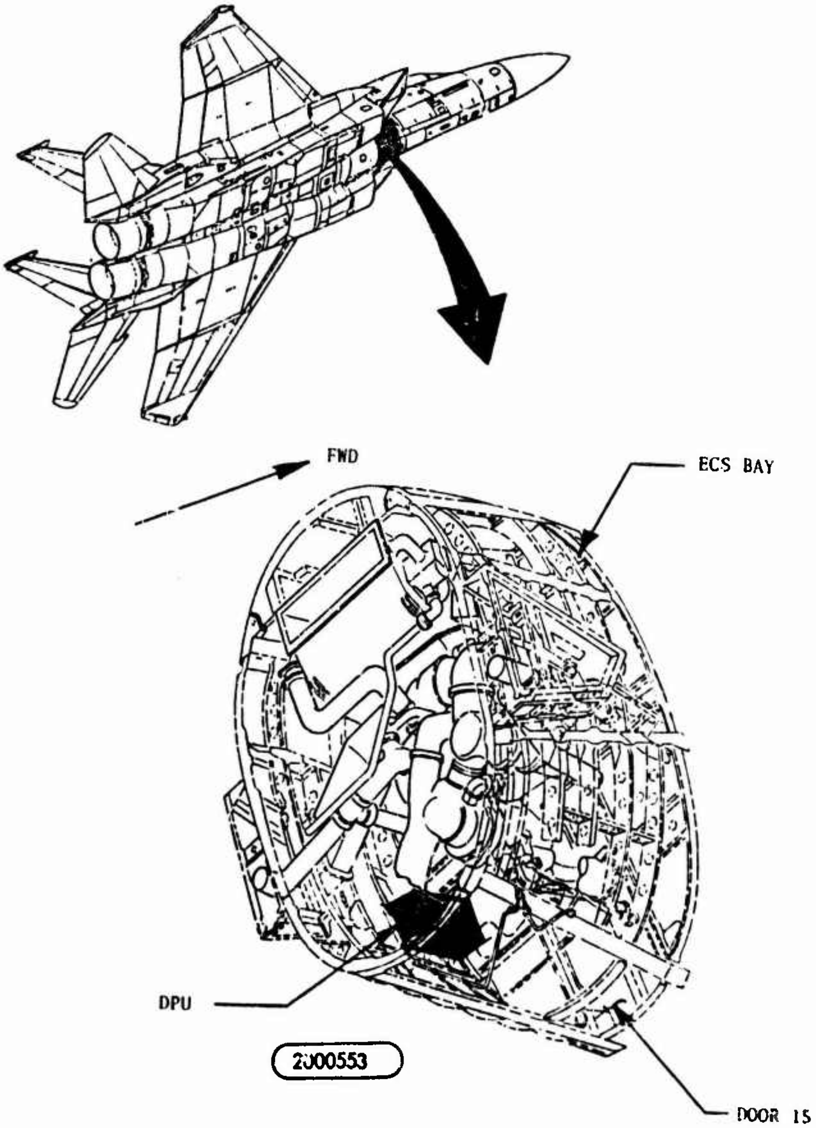


Figure 9. DPU Location - F-15 CSFDR System Configurations I and II

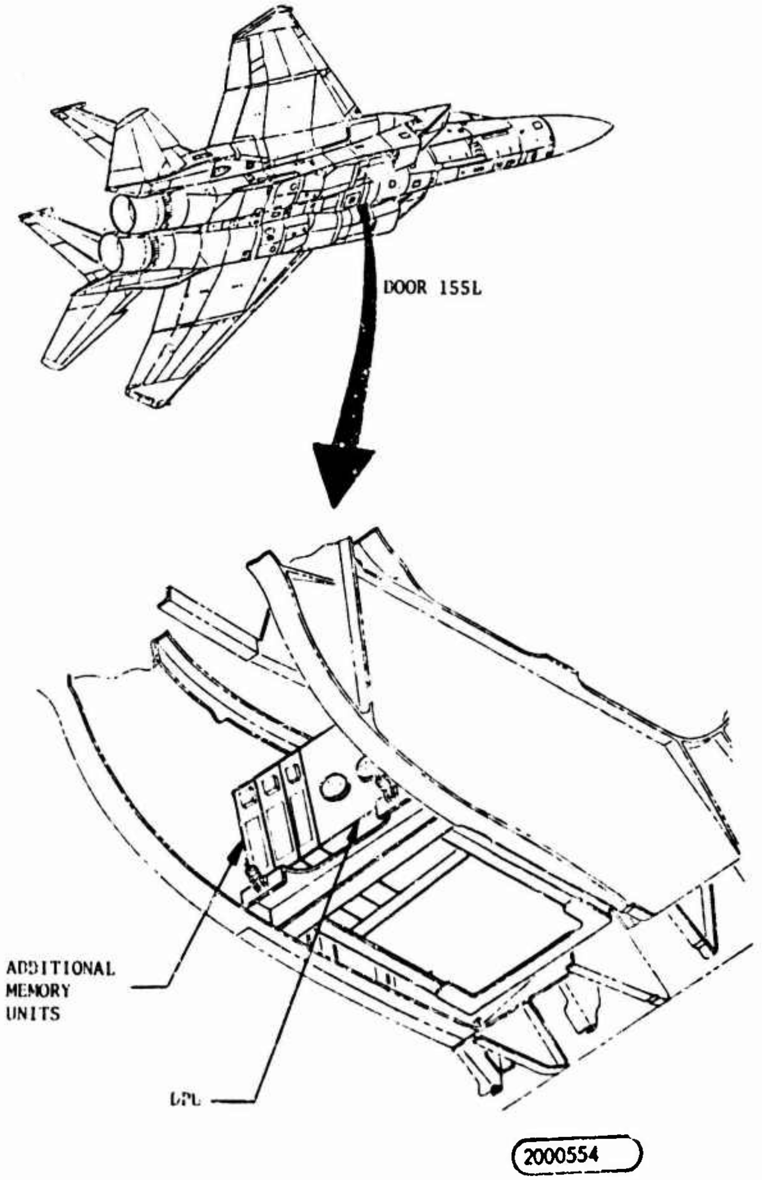


Figure 10. DPU Location - F-15 CSFDR System Configuration III

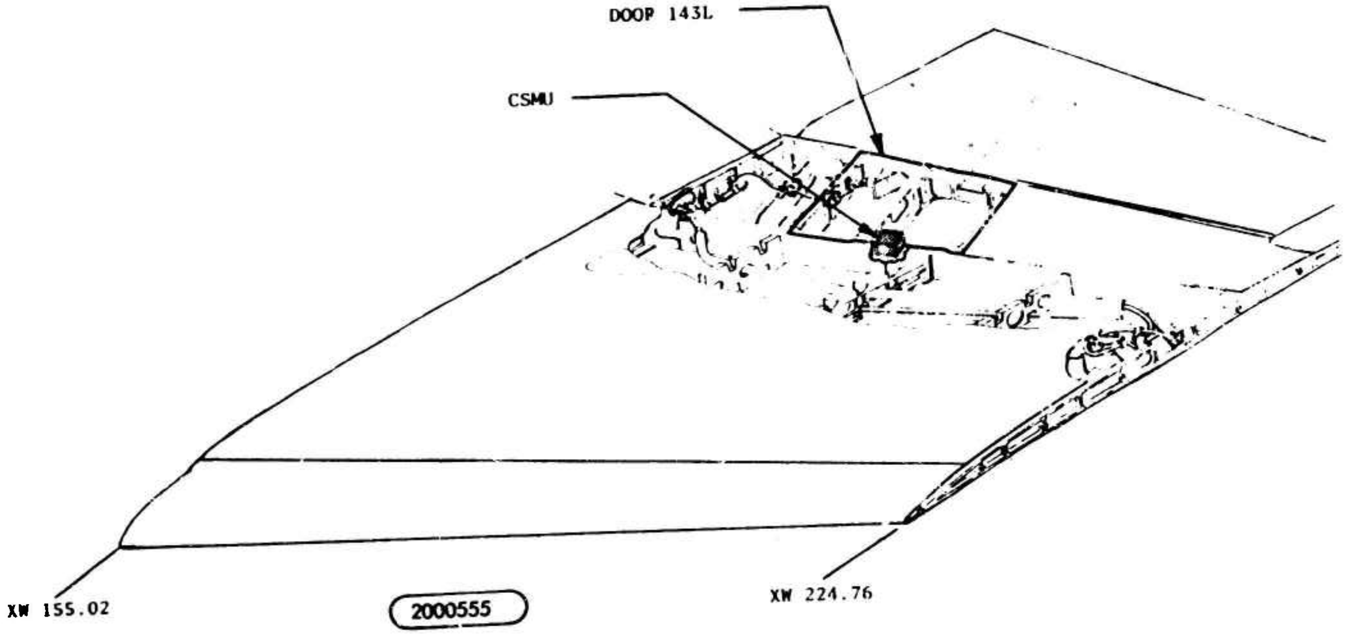


Figure 11. CSMU Location - F-15 CSFDR System, All Configurations

electrical cable runs and is integrated with CSFDR system cables whenever possible.

3.1.2.6 F-16 installation - The installations for the F-16 aircraft utilize existing aircraft space and existing aircraft installations to provide an optimum CSFDR system installation. The unit locations for Configurations I, II, and III are essentially identical. Unit locations for the three configurations were coordinated with the airframe manufacturer. The general installation for the three configurations is shown in figure 12.

The DPU for all three configurations is located in the aft equipment bay immediately aft of the cockpit (see figure 13). Access to this bay is through door 2101 on the left side of the aircraft and through door 2202 on the right side of the aircraft. For Configuration III, the DPU and the memory units for the aircraft structural integrity program, turbine engine health, and flight control monitoring replace the existing Signal Data Multiplexer Converter and the Signal Data Recorder on designated aircraft. The aft equipment bay location for the DPU provides easy access to data sources and easy access for data extraction. Because of the proximity of the M61A gun muzzle to the aft equipment bay, the DPU and the memory units may require vibration isolation due to the hostile environment created during gun firings. The aircraft to DPU interface cable is connected to the DPU in the aft equipment bay and branches out along existing electrical cable runs to the various data sources.

The DPU to CSMU interconnecting cable is routed from the aft equipment bay to the right side of the aircraft through the right-hand main landing gear wheel well to the right-hand shelf area forward of the stabilator. The CSMU is installed in the right-hand shelf forward of the chaff dispenser (see figure 14). This location for the CSMU was chosen based on the Air Force Class-A mishap data, limited available space in the airframe, and on discussions with the airframe manufacturer. The CSMU is located in the general plane of rotation of the F100 engine turbine section. However, because of the limited space available in the aircraft and the low survivability rate of other locations, this area is determined to be the optimum location for the CSMU. As an added precaution against turbine failure, additional armor plating is installed between the CSMU and the aircraft engine.

3.1.3 Crash-survivability investigation - The crash-survivability investigation is an extremely challenging engineering task. The investigation occasionally required judgemental evaluation and the prevailing belief of professionals and experts in lieu of hard facts and rigorous calculations. The very nature of severe A/F/T crashes is awesome. High-speed impacts result in total destruction of the aircraft and the variations possible are unlimited. No two accidents are identical and no single crash can be classified as genuinely typical.

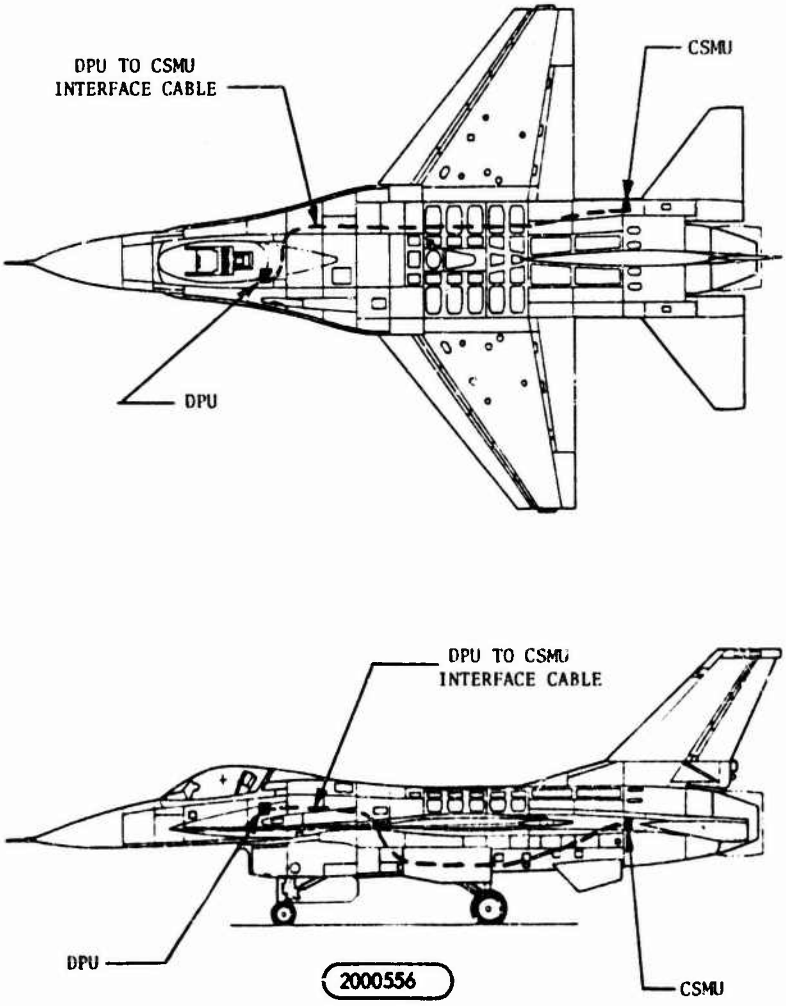


Figure 12. F-16 General CSFDR System Installation

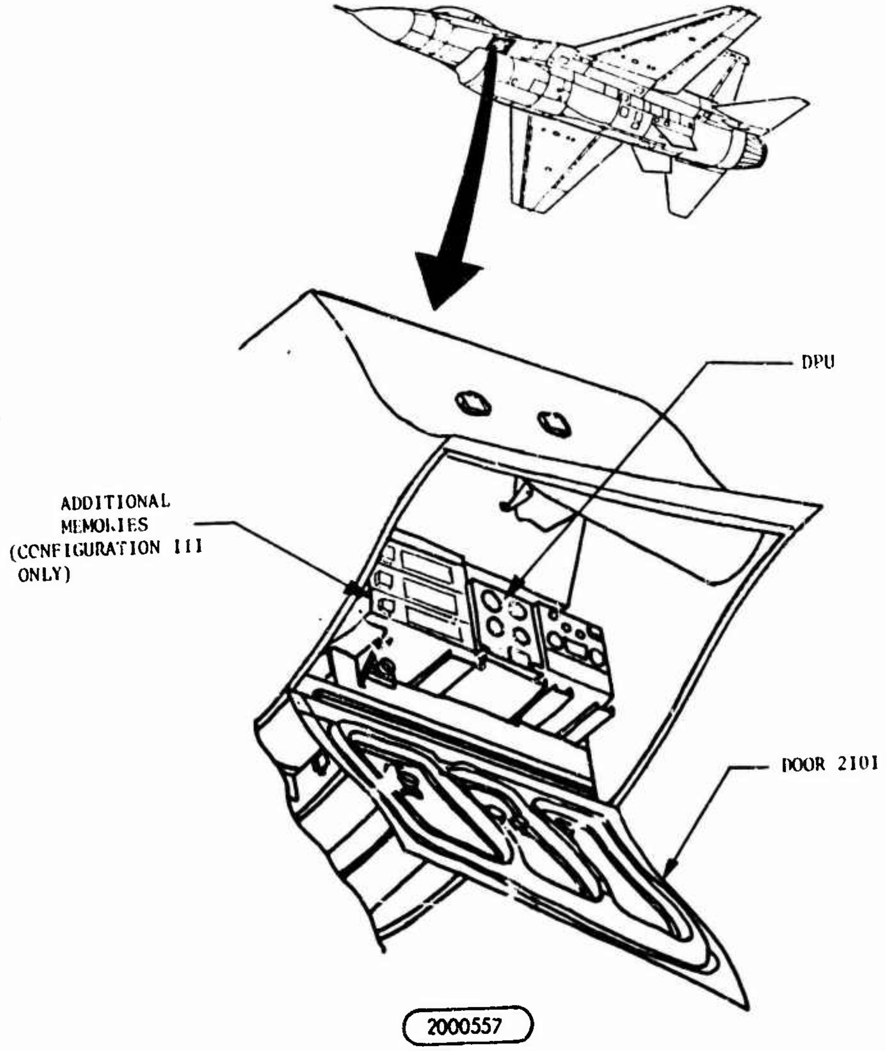


Figure 13. F-16 CSFDR System DPU Location

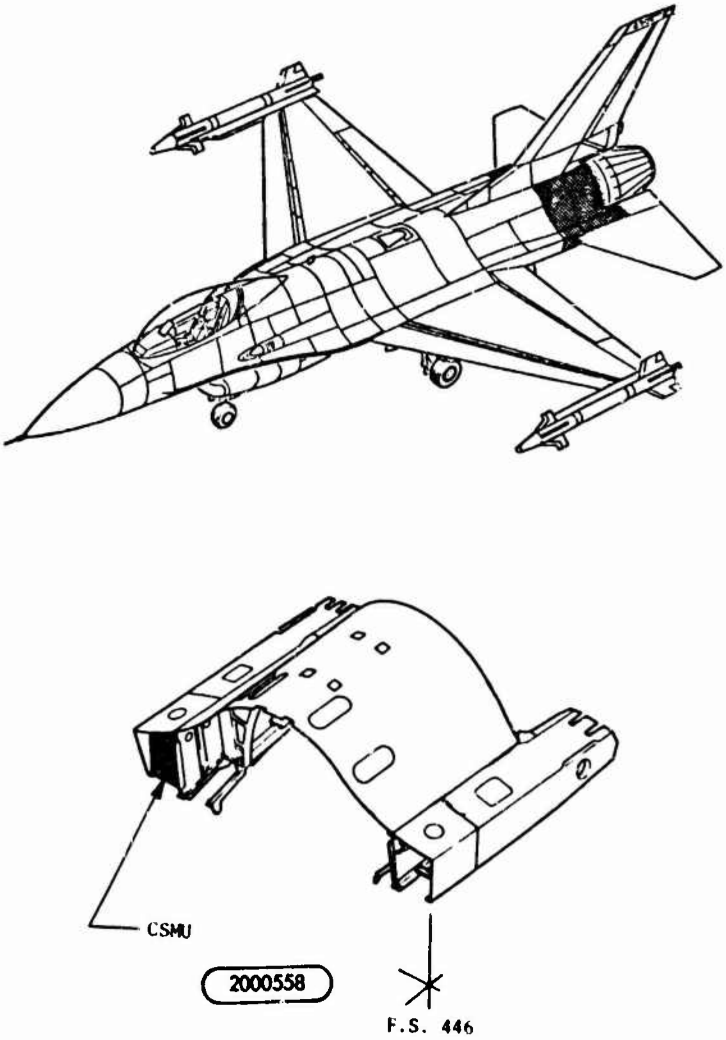


Figure 14. CSMU Location - F-16 CSFDR System, All Configurations

The results of the crash-survivability investigation will be critical to the success of the CSFDR program. Unreasonably severe crash requirements will result in unjustified equipment cost. Relaxed requirements will be equally disastrous, resulting in poor survivability performance.

The optimum CSFDR design will not survive 100% of the A/F/T crashes. The original goal was 90% survivability. However, as the study program progressed, it soon became apparent that greater than 96% survivability was possible using state-of-the-art digital memory technology. The proposed concepts are optimal designs, which have only recently become possible due to memory technological advances.

This portion of the study program involved six related tasks. Each task will be described in sequence as follows:

- A/F/T mishap data. The assembled military A/F/T mishap data will be summarized in the text, while an appendix will present supportive data and conclusions.
- Comparison of crash test requirements. The crash test requirements of TSO C51A will be compared with A/F/T aircraft mishaps to determine if the requirements should be altered.
- Recommended test conditions. Appropriate test conditions, which simulate crash conditions postulated for the CSFDR, will be recommended.
- Crash protection evaluation. Physical/mechanical/thermal control techniques are compared and evaluated, for the protection of the memory module, from the effects of A/F/T crashes.
- Recommended CSFDR packaging approach. The recommended packaging approach will be illustrated, along with external interfaces.
- Crash-survivability prediction. A prediction of the survivability of the crash-protected memory (CPM) data will be made based on USAF mishap history.

3.1.3.1 A/F/T mishap data - The research of available military A/F/T mishap data was undertaken early in the study program. The results were crucial to early program decisions and they are very evident in the recommended solutions. Not only did this research provide a basis for argument and deduction, but it also provided a wealth of sources possessing years of experience in the fields of accident investigation, aircraft safety, and crash environments.

Three sources of mishap data were pursued in order that an educated comparison could be made. The first was a literature search of available reports pertaining to crash-survivability data. Many study reports have been written, but all of them were for aircraft crashes in which the occupants could have survived. The wealth of analyses and data ends at crash severity levels which would be fatal to the occupants. Available data is for shallow impact angles (<15°) and low velocities (<160 fps).

The second source pursued was the opinion of aerospace experts, including consultants, Air Force, Navy, NTSB, NASA, and airframe prime contractor personnel. Again, for the most part, current thinking and experience was limited to low speeds and shallow impact angles. Several experts expressed their opinion as to the structural limits of A/F/T structures, but few would hazard a guess as to the resultant impact g levels. The most useful result of this inquiry was uncovering the equations used by missile engineers to predict g levels, depth of penetration, and the deceleration time period for missile and projectile ground impacts. These equations, the underlying assumptions, and the deduced results, will be shown and utilized throughout the crash-survivability text.

The third source of mishap data pursued was the wealth of data on file at the Air Force Inspection and Safety Center, Norton Air Force Base. Other data bank sources were pursued including the Army, Navy, and NTSB, but none of them materialized into such useful, pertinent data as that of the AFISC. Norton personnel were extremely cooperative and helpful in aiding this pursuit. An accident/mishap data questionnaire was transmitted to them. They compiled the data for 35 Class-A accidents involving A-10, F-15, and F-16 aircraft between January 1977 and August 1980. The responses to the questionnaire are shown in reference 6. A summary of the mechanical and fire damage for the cockpit, avionics bay, wing tips, vertical tail, and tail cone is presented in tables 16 and 17. Upon reviewing this data, an obvious conclusion is that the the wing tips, tail cone, and vertical tail are significantly more survivable regions of the aircraft than are the cockpit and avionics bay, in a post-mishap environment.

In addition, the Air Force computer printout of over 500 recent Class-A and -B accident reports were requested and two separate trips were made to Norton Air Force Base. On the second trip, a film of an A-10 crash was requested and researched for possible post-crash data. The film was analyzed with respect to 1) the chain of events transpiring, 2) the nature of the ensuing fireball, and 3) the impact deceleration phenomena.

Table 16. Mechanical and Fire Damage for 35 A-10, F-15, and F-16 Class-A Accidents

	Mechanical Damage						Fire Damage				
Relative Ranking	1	2	3	4	-		1	2	3	4	-
A-10 (17 accidents)											
Cockpit	29%	47%	-	12%	12%		-	12%	29%	6%	53%
Avionics Bay	47%	24%	6%	-	24%		6%	12%	24%	12%	47%
Wing Tips	9%	26%	18%	35%	12%		-	9%	21%	18%	53%
Tail Cone	12%	18%	24%	12%	35%		-	12%	12%	18%	59%
Vertical Tail	12%	18%	18%	29%	24%		-	12%	24%	24%	41%
F-15 (13 accidents)											
Cockpit	77%	8%	-	8%	8%		8%	-	8%	31%	54%
Avionics Bay	77%	8%	-	8%	8%		8%	-	8%	31%	54%
Wing Tips	23%	8%	12%	34%	23%		-	-	8%	46%	46%
Tail Cone	15%	-	8%	8%	69%		-	8%	23%	23%	46%
Vertical Tail	15%	15%	15%	38%	15%		-	8%	23%	23%	46%
F-16 (5 accidents)											
Cockpit	20%	60%	20%	-			-	20%	80%	-	-
Avionics Bay	20%	60%	20%	-	-		-	20%	60%	20%	-
Wing Tips	-	-	30%	70%	-		-	-	40%	60%	-
Tail Cone	-	-	40%	60%	-		-	-	40%	60%	-
Vertical Tail	-	-	-	100%	-		-	-	20%	80%	-

Table 16. Mechanical and Fire Damage for 35 A-10, F-15, and F-16 Class-A Accidents (Continued)

	Mechanical Damage						Fire Damage				
Relative Ranking	1	2	3	4	-		1	2	3	4	-
Summary A-10, F-15 and F-16 (35 accidents)											
Cockpit	46%	34%	3%	9%	9%		3%	9%	28%	14%	46%
Avionics Bay	54%	23%	6%	3%	15%		6%	9%	23%	20%	43%
Wing Tips	13%	16%	17%	40%	14%		-	4%	19%	34%	43%
Tail Cone	11%	9%	20%	17%	43%		-	9%	20%	26%	46%
Vertical Tail	11%	14%	14%	42%	17%		-	9%	23%	32%	37%

Col.	Mechanical damage	Col.	Fire damage
1	Total (many small pieces, not recognizable)	1	Total (major puddling)
2	Major (many medium pieces, some recognizable)	2	Major (burnthrough and some puddling)
3	Significant (some large pieces recognizable)	3	Minor (paint burn/ sooting)
4	Minor (relatively intact)	4	None
-	Unknown	-	Unknown

Table 17. Mechanical and Fire Damage Ranking of Possible CSFDR System Installation Locations

MECHANICAL DAMAGE								
Aircraft Section	Damage[1] Known	Total 1	Major 2	Significant 3	Minor 4	Average[3] Damage	Ranking	Mechanical Survivability of Location
Cockpit	32	16	12	1	3	1.72	4	poor
Avionics Bay	30	19	8	2	1	1.50	5	poor
Wing Tips	60[2]	9	11	12	28	2.98	2	good
Tail Cone	20	4	3	7	6	2.75	3	good
Vertical Tail	29	4	5	5	15	3.07	1	good

FIRE DAMAGE								
Aircraft Section	Damage[1] Known	Total 1	Major 2	Significant 3	Minor 4	Average[3] Damage	Ranking	Fire Survivability of Location
Cockpit	19	1	3	10	5	3.00	4	poor
Avionics Bay	20	2	3	8	7	3.00	4	poor
Wing Tips	40[2]	0	3	13	24	3.53	1	good
Tail Cone	19	0	3	7	9	3.32	3	good
Vertical Tail	22	0	3	8	11	3.36	2	good

[1] Extent of damage not known for all 35 of the analyzed A-10, F-15, and F-16 accident reports.

[2] Left and right wing data for each mishap were combined.

[3] Mathematical average of damage severity (i.e., $\frac{16(1)+12(2)+1(3)+3(4)}{32} = 1.72$).

The assembled data from actual accident reports is shown in appendix D. Tables D-1 and D-2 of appendix D show results similar to those presented in table 16. It should be noted that the impact velocity ranged from 0 to 550 fps and that the impact angles ranged from 0° to 70°. Shown in table D-3 is the range of dollar value and the crew ejection ratios for [illegible] of the 500 accidents. Twelve types of A/F/T aircraft were included as a typical cross section, while six other types were omitted.

This substantial accident data base was utilized throughout the crash-survivability investigation. The significant differences between the degree of damage to the forward portions of the fuselage, versus the tail cone and extremities, was paramount in the system design concepts and installation decisions. The latter locations are much less vulnerable to mechanical damage and less vulnerable to the resulting fire damage. Among the extremities, the crash environment in the wing tips is preferable, with the vertical tail a very close second, and the tail cone a not too distant third.

3.1.3.2 Comparison of crash test requirements - The five crash test requirements of TSO C51A are impact, penetration resistance, static crush, fire protection, and water protection. The requirements are compared with A/F/T aircraft mishaps in order to determine if the requirements should be altered.

a. Impact requirement (TSO C51A). TSO C51A impact shock requirement is 1000 g, half sine wave, applied to each orthogonal axis, and having a time duration of at least 5 milliseconds. This requirement is inadequate for the CSFDR program. We recommend 1) changing the pulse shape, 2) increasing the peak g level, 3) adding a second lower level, longer duration shock requirement, and in general, 4) removing the ambiguities and inconsistencies.

The impact shock pulse should be changed from a half sine wave to a terminal peak sawtooth shock. Half sine wave shock pulses are typically a result of elastic collisions in which one or both of the colliding objects do not exceed their elastic limit. That is definitely not the case during post-crash breakup of A/F/T aircraft. Widespread plastic deformations and structural failures are predominant.

An added benefit of terminal peak sawtooth pulses is that it is a more inclusive measure of the high frequency, short duration shock worthiness of the design. The higher frequencies receive greater excitation energy, without over exciting the lower primary frequency range. This point has been argued and proven repeatedly over the years by test engineers throughout the aerospace industry.

The peak level of 1000 g should be increased. Crash-protected memory only capable of surviving levels of 1000 gs will demonstrate unsatisfactory crash-survival rates. In the fifteen accident reports summarized in appendix D, four of the impact angles were between 16° and 62° and the aircraft velocities were 145 to 325 kias (245 to 550 fps). With these high impact angles and high speeds, the TSO C51A shock level will not be adequate, as will be shown by the following analyses.

In missile and projectile ground impact design, the Army uses the following equation to calculate g levels, depth of penetration, and time period of penetration. The equation assumes a rigid missile structure, which is not totally applicable for A/F/T impacts. However, the equation does establish an upper limit. The equation is a modified flow resistance equation (note the drag coefficient and the velocity squared term), which has been substantiated with actual missile testing. The projectile impact equation is as shown below with the parameters defined in terms of A/F/T impacts.

$$M\ddot{Z} = \left(\frac{1}{2} \cdot \frac{C_D \rho A}{g_c}\right) \dot{Z}^2 + \alpha A$$

where

M = mass of aircraft (lbm.)

$\ddot{Z}$ = deceleration (g)

C_D = drag coefficient = 2 (unitless)

ρ = density of impact media (lbm./cubic feet)

A = projected fuselage cross-sectional area (square feet)

g_c = gravitational constant, 32.174 (lbm.-ft./lbf.-sec.^{2})

$\dot{Z}$ = velocity at impact (ft./sec.)

α = bearing strength of media, α = 14,400 for sand (lbf./square feet)

The equation can be solved for $\ddot{Z}$ and then integrated twice, in closed form, in order to solve for depth of penetration Z and time period of penetration T.

$$\ddot{Z} = \frac{A}{M} \left[\left(\frac{C_D \rho}{2g_c}\right) \dot{Z}^2 + \alpha\right] , \ (g)$$

$$T = \frac{M}{A} \left(\frac{2}{C_D \rho g_c \alpha}\right)^{\frac{1}{2}} \Theta, \ (\text{sec.})$$

$$Z = \frac{M}{A} \ \frac{2}{C_D \rho} \ \ln \ \frac{1}{\cos \Theta} , \ (\text{ft.})$$

where

$$\Theta = \tan^{-1} \left[\left(\frac{C_D \rho}{2g_c \ \alpha}\right)^{\frac{1}{2}} V\right] , \ (\text{radians})$$

Note, because this equation is basically a flow resistance equation, it assumes the fuselage nose fully penetrates the surface of the media and the direction of $\ddot{Z}$ is parallel and directly opposite the velocity vector. The angle of impact is independent except that it must be high enough (>15° to 20°), such that the nose fully penetrates the surface of the media, and does not simply receive a glancing or deflected impact. The density of the impact media, which will be used, is 120 lbm./cubic feet (note, dry sand is 100 lbm./cubic feet, common black soil or wet sand is 125 lbm./cubic feet). The aircraft area density term (M/A) appears in all three equations, and in order to simplify the calculations, it was set equal to .0032 lbm./square feet for typical commercial aircraft (Boeing 747, 440/160,000 = .00275, small commuters 45/12,500 = .0036) and .0015 lbm./square feet for military A/F/T (A10, 52/35,000 = .00149). It should also be noted that the shock pulse shape, as predicted by the equations, will resemble an initial peak sawtooth pulse.

Using the projectile impact equations, table 18 was generated showing g level, period, and depth of penetration, for both commercial aircraft and military A/F/Ts at various impact speeds. As shown, 1000-g shock qualified hardware, will be shock worthy of impact velocities up to 418 fps. (250 knots). A 1700-g shock requirement will expand the range of coverage to 550 fps. (326 knots). In just the 15 A-10 and F-16

Table 18. Impact Velocity vs. Predicted G Level

	IMPACT VELOCITY V (ft/sec)	G LEVEL (g)	PERIOD T (sec.)	DEPTH Z (ft)	COMMENTS
Commercial Aircraft ($\frac{A}{M} = .0032$ lbm./ft^2)	135	263	.048	2.3	80 knots, slow approach
	240	733	.055	3.6	140 knots, fast approach
	283	1000	.057	4.0	TSO C51A g level
	540	3524	.061	5.7	320 knots, fast low-level cruise
Military A/F/T Aircraft ($\frac{A}{M} = .0015$ lbm./ft^2)	245	357	.118	7.8	145 knots, slow fighter approach*
	287	482	.121	8.6	170 knots, fast fighter approach*
	418	1000	.127	8.9	Mach .375, 250 knots
	514	1500	.129	11.8	Mach .46, 304 knots
	550	1713	.130	12.2	Mach .5, 326 knots
	781	3431	.133	14.1	Mach .7, 462 knots

*From F-4 approach velocity envelope data mishaps cited in appendix D, three of the fifteen (20%) had impact velocities greater than or equal to 250 knots. Those three accident reports listed indicated airspeeds of 250, 273, and 325 knots. Therefore it is recommended that the peak g level of the impact shock requirement be increased to 1700 gs.

The time period and depth of penetration has no real relevance to the impact shock requirement and its pulse duration because of the structural limitations of the airframe. Depth of penetration is only listed for comparison sake. It should be emphasized that the above calculations are for wet sand or common black soil. In desert sand, depth of penetration would be nearly 70% deeper. In addition, the impact velocity corresponding to 1700 gs is 775 fps. (470 knots, Mach .7) and 870-g level at 550 fps. (326 knots, Mach .5). Each calculation assumes a homogeneous impact media, without the presence of boulders, vegetation, and other dense foreign objects.

The structural limitations of an A/F/T will insure that the full g levels are not sustained throughout the entire period of ground penetration. The more significant time period is the time it takes the shock stress wave to travel the length of the aircraft and return.[7] Shock waves travel at the speed of sound in a stressed member. It will take 6.5, 7.65, and 5.4 milliseconds for an impact shock wave to travel twice the length of an all aluminum A-10, F-15, and F-16, respectively. These time period calculations assume that the aircraft structure can be treated as a single composite aluminum beam and the structure can dynamically support the initial build-up of stresses, until the peak stress levels are attained. The stress wave theory states that the maximum stresses will be attained 5-8 milliseconds after initial nose impact for a 42' to 67' long aluminum aircraft. This theory supports the argument that the shock impulse time duration should be specified as .005 to .008 seconds.

In order to be more inclusive, a family of shock pulse (g level, time duration) requirements should be imposed. Regardless of the g level and time duration specified, there will always be an A/F/T crash which will either subject the CSFDR system to high g levels for a shorter duration or lower g levels for a longer duration. Impact shock testing to an entire family of impulse shocks is not recommended and is totally unrealistic. However, a second lower g level, longer duration shock is recommended, and monitoring and recording the resultant high g level, short duration impulse, occurring during the penetration testing is recommended. Monitoring the resultant shock characteristics will provide a comparative measure of penetration test severity. It will also prove that an added high g level, short duration shock requirement will be somewhat redundant.

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[7] Raymond J. Roark and Warren C. Young: "Formulas for Stress and Strain", Fifth Edition, McGraw Hill, 1975, pp. 572-3.

A basic principle of shock pulse phenomena is that the shock pulse adequately excites all frequencies possessing a period which is less that twice the time duration of the input pulse. Therefore, with an impact shock pulse of .005 to .008 seconds duration, the frequencies above 62.5 to 100 Hz will receive significant excitation energy from the 1700-g shock pulse. However, the low g level, low frequency and the high g level, high frequency modes of impulse damage will not be subjected to sufficient shock test levels.

If a family of impact shock pulses were to be considered, the following three would be included:

•	Low g level, long duration	200 gs	15. msec
•	Primary impact shock requirement	1,700 gs	5.-8. msec
•	High g level, short duration	4,000-10,000 gs	<1. msec

The first would lower the range of significantly excited frequencies down to 33 Hz at 200 gs and the third would increase it to 500 Hz at 4,000 to 10,000 gs. As stated above, each of these can be encountered during a post-crash environment. An almost infinite number of combinations of aircraft speeds and density of impact media are possible. Additionally, in severe impacts where the aircraft literally shatters into many small pieces, the resulting debris collisions enter an expanded realm of possibilities. The CSMU could remain attached to a large portion of the aircraft, a moderate size piece of structure and skin, or it could even become a totally detached projectile. The low g level, long duration shock could result if the portion of structure were large and its impact velocity low. The high g level, short duration shock would be favored with a totally detached CSMU traveling at high speeds.

The 200-g, 15-millisecond duration shock requirement is recommended as an addition to the impact shock test requirement. It is selected because it is the realistic upper limit of standard aerospace shock test equipment. This requirement can be imposed with only a minor test cost impact for the CSFDR program. However, this requirement, or one similar, is essential to the program. Water-soaked wicks, resilient mounting material, flexible insulation, water filled bags and other relatively resilient material will be more susceptible to longer duration impulse shock. Hardware could easily pass the primary impact shock test, and yet fail miserably in a long duration, low g level test. This additional requirement is necessary in order to detect and correct a possible deficiency in the design worthiness of the crash-protected hardware.

The 4,000- to 10,000-g, less-than-1-millisecond shock level, is not recommended. If imposed, it would require very sophisticated shock test equipment. Possibly a test employing explosive charges would be needed to achieve this high g levels and short duration. Secondly, the penetration test could result in a shock pulse of similar magnitude and duration. A crude calculation for the penetration test indicates 8,000 gs for a .5-millisecond impact pulse. The penetration test impact pulse will be quite unrepeatable and uncontrollable, in both amplitude and duration. However, an accelerometer can be mounted to the CSMU which will be subjected to the crash-survivability testing. By doing so, the resultant impact shock magnitude and duration can be monitored and reported.

A final comment on the impact shock test requirement of TSO C51A is that, in general, the Technical Standard Order is much too ambiguous and inconsistant. For example, the time duration is specified as "at least five milliseconds" which would permit a 30-millisecond time duration at the supplier's discretion. The CSFDR impact shock requirement will need to be specified in a much more conclusive manner. MIL-STD-810C, figures 516.2 and 516.2-2 could be followed, in which the nominal value and tolerances are precisely specified for the pulse shape, its peak, and its duration. Each of the TSO C51A requirements suffer from similar ambiguities. They will need upgrading to military and Air Force standards.

b. Penetration resistance requirement (TSO C51A). TSO C51A penetration resistance requirement is specified as subjecting the memory package to "an impact force equal to a 500-pound steel bar which is dropped from a height of 10 feet to strike each side of the enclosure in the most critical plane". Additionally, the point of contact shall be no greater than .05 square inches (.25" diameter). Improvements in the penetration test can be made by 1) specifying the length, shape, and material of the impact point, 2) better specifying of the test setup which is to be utilized, and 3) reducing the mass of the steel bar from 500 to 100 pounds.

The mounting location of the CSMU is critical to the degree of penetration resistance which is necessary for adequate survivability in an A/F/T mishap environment. The forward portions of the fuselage and areas in the rotational plane of the engine turbine blades, will be the most severe locations. The turbine blades are thrown through the side of the aircraft following a severe mishap. Those mounting locations in their rotational path should be avoided if possible. In addition, the forward portions of the fuselage are frequently penetrated by structural members located in the aft sections of the aircraft. The wings, tail cone, and vertical tail will be less severe penetration environments.

The most glaring inadequacy of the TSO requirement is that the impact point is not specified. The length, shape, and minimum material properties of the impact point should be specified. The recommendation here is to simulate a .25-inch diameter, high-strength steel bolt. Its length should be long enough to reach the memory media, if the armor plate and insulation are fully penetrated. In the case of our CSMU, we recommend a blunt .25-inch diameter, high-strength steel cylinder, with the ends chamfered .030-.050 inches (at ≅45°), and with the cylinder protruding 1.1 inch out of the end structure of the drop weight. In addition, a compressive yield strength of the steel cylinder should be 200 ksi minimum and the cylinder should be securely attached to the drop weight. If second sourcing of recorders is anticipated, a standardized cylindrical point should be specified at this initial stage of the program. It should, therefore, have an increased length in order to accommodate a somewhat larger memory unit.

Details of the test setup to be utilized should be specified. The dimensions of the drop weight, the fixturing and guides necessary to insure a vertical freefall and impact, and details of the support media for the test article, should be specified and standardized as much as possible. An 18-inch base of fine sand in which the test article is placed with the impacted surface horizontal, within 1° in each axis is recommended. The maximum density and allowable grain size of the sand should be specified. The drop weight should be guided by a pair of guide rails, one on each side, with two guides (top and bottom) attaching the drop weight to each guide rail. The guides can be loose fitting eyebolts, as long as the top and bottom guides are separated as far as is practical from each other guaranteeing a vertical impact within a few degrees. The test should be standardized with specified dimensioning of a suitable drop weight.

The mass of the 500-pound steel bar, as specified by TSO C51A, should be reduced significantly. There are three basic reasons why this recommendation is proposed. The first is that the weight can be reduced without affecting the severity of the test. Secondly, the TSO requirement is overspecified for commercial recorders located in the aft sections of the aircraft. Thirdly, the armor thickness necessary is determined by this test requirement and a tradeoff between mechanical and thermal survivability is made, as the armor thickness is increased. With all arguments considered, a 100-pound drop weight is recommended.

The mass of the drop weight can be reduced without significantly lowering the severity of the test. If the CSMU test article were freely supported (i.e., its impact resistance provided only by its own inertia), the stresses in its armor would be completely independent of the impactor's mass. Only the impact area, its material properties, and the velocity of the impactor, would be relevant to the induced stress level. If rigidly mounted, the maximum stress would increase proportionally to

$1+(\mu+.667)^{\frac{1}{2}}$, where μ is the ratio of the mass of impactor to the mass of the impacted object (reference 7).

These relationships assume solid homogeneous impact materials. However, they are quite applicable to the recorder penetration testing. Table 19 summarizes the stress levels versus impactor weight for the existing commercial recorders and the proposed CSMU. It should be noted that even the proposed change to a 100-lbm. drop weight will result in higher stress levels in the CSMU armor, than the stresses in the armor of existing commercial recorders (weighing 20 lbm.), if both units are provided with the same degree of armor protection. This argument maintains that the relative stress severity is increased, even though one fifth of the drop weight mass is to be utilized.

The TSO penetration requirement is an overspecification for the commercial flight data recorders. The requirement was initially made to cover the option of locating commercial FDRs in the forward sections of the aircraft. Since the policy of locating the FDRs in the aft sections of the aircraft has been implemented, penetration damage to commercial FDRs has been minimal. In fact, no commercially available flight recorder has suffered detrimental penetration damage in the last ten years. With this in mind, even the 100-lbm. requirement may be too severe. In comparing the commercial to military mishaps, the higher velocities, higher impact angles, and higher structural density of the A/F/T aircraft will tend to increase the severity of the penetration environment. Conversely, the great decrease in recorder size and mass, the literal explosion of the A/F/T structure upon severe impact, and the proposed mounting locations for the CSMU, will all tend to lessen the chances of detrimental penetration damage.

The penetration requirement for the CSFDR system will determine the armor thickness necessary to pass the crash-worthiness qualification testing. Not only does the armor thickness add directly to the size and weight of the CSMU, but additional thickness adds to the quantity of insulation required for the same degree of thermal protection. As will be shown in the thermal performance section of the report, the maximum memory chip temperatures will be reached long after the post-crash flames are extinguished. The thermal justification for this phenomenon is that the armor plating stores up a tremendous amount of thermal energy because of its high thermal capacitance and high relative density. After the flame is extinguished, the thermal energy continues to be slowly conducted through the insulation, as well as being convected and radiated back to the ambient environment. For the recommended design, following a 15-minute equivalent flame test, the temperature of the memory chips will be 139°C when the flame is extinguished. Some 19 minutes later it will reach its maximum temperature of 253°C. As the armor

Table 19. Penetration Test Requirement - Stress Levels vs. Impactor Weight

Recorder freely supported $\sigma = [\frac{V}{a} E]$

Recorder rigidly supported $\sigma = [\frac{V}{a} E \; (1 + \sqrt{\mu + .667})]$

σ = compressive stress in impacted member, (psi)

V = velocity of impactor at time of impact, (ft/sec)

a = speed of sound in impacted member, (ft/sec)

E = modulus of elasticity for impacted member, (psi)

μ = mass of impactor/mass of impacted member, (unitless)

	IMPACTOR MASS (lbm.)	CSMU MASS (lbm.)	MASS RATIO μ	STRESS RATIOS DEPENDENT UPON IMPACTOR MASS		
				RIGID $(1+\sqrt{\mu+.667})$	FREE	AVERAGE RATIO
Commercial Flight Recorders	500.	20.	25.	6.07	1.0	3.53
	200.	20.	10.	4.27	1.0	2.63
Proposed CSMU	500.	2.8	178.6	14.39	1.0	7.69
	200.	2.8	71.4	9.49	1.0	5.24
	100.	2.8	35.7	7.03	1.0	4.02
	70.	2.8	25.	6.07	1.0	3.53

thickness is increased, this time delay will lengthen and the maximum temperature will rise slightly. Doubling the armour thickness will increase the memory thermal damage potential 30 to 40%. With this in mind, it is definitely not in the best interest of the program to over specify the penetration test. An adequate test level should be arrived at, but too severe a requirement will result in a size, cost, weight, and thermal performance penalty.

It should also be noted that in the proposed installation for the F-16, the CSMU will be adjacent to the engine turbine blades. An attempt was made to avoid this installation location, but it met with little success. In order to shield the CSMU from turbine blade penetration damage, the recommendation is to first mount an armor "guard plate" to the aircraft structure, and then mount the CSMU outboard of this plate. This added precaution should offset the added risk of mounting the CSMU in the rotational plane of the turbine wheel and blades.

c. Static crush requirement (TSO C51A). The TSO specifies a continuous force of 5,000 lbf. for 5 minutes, applied to each of the three main orthogonal axes, but not simultaneously. A strong argument can be made for reducing this requirement from 5,000 to 2,000 lbf., as well as a strong case for eliminating it entirely. However, it presents absolutely no design impact if included. It may be worth maintaining the requirement in the event that a structural deficiency, which is further weakened by the dynamic testing, is present in the packaging design or workmanship.

Since the engine, tail, wing, and main fuselage sections of an A/F/T are much lighter than a large commercial jet, a strong argument can be made for reducing the requirement from 5,000 to 2,000 lbf. In addition, any crash-protected memory enclosure, which can withstand both the penetration and impact test levels specified, will assuredly pass the static crush testing. In the CSMU design, the attached circuit board, dust cover, and connector will be destroyed in this test. However, the memory retention will be unaffected by the crushing loads. It is recommended that the level of the test be reduced to 2,000 lbf.

d. Fire protection requirement (TSO C51A). TSO C51A specifies a 15- or 30-minute test, dependent upon the mounting location of the recorder, in which 50% of the outside surface of the recorder is exposed to flames of 1100°C. The mishap data indicates that the severity of the fire protection requirement should be increased. A flame test should be avoided in the CSFDR program because any flame test literally defies standardization and an oven test will be recommended as a replacement. Since the vast majority of A/F/T post-crash fires last less than 5 minutes, a 15-minute oven test will be more than adequate.

As shown in table 16, total (major puddling) and major (burnthrough and some puddling) fire damage occur at a substantial rate. Using the summary table, listing the data from all thirty-five A-10, F-15, and F-16 accidents, total or major fire damage occurs in 4 to 15% of the mishaps, depending upon aircraft location. For each region of the aircraft listed, the following percentages apply: cockpit 12%, avionics bay 15%, wing tips 4%, tail cone 9%, and vertical tail 9%. These percentages are substantial enough that the fire protection requirement must simulate the equivalent of at least major fire damage in which burnthrough and some puddling occur.

The melting points of titanium (1800°C) and steel (1370°C) are significantly higher than that of aluminum (660°C). It can be assumed that the puddling and burnthrough phenomena occur totally to the aircraft aluminum members, in the vast majority of mishaps. It is our contention that the fire protection test should be severe enough so that if a piece of aluminum were subjected to the test, it would suffer major surface melting, if not total melt down. A CSMU design capable of passing such a test is feasible and practical at a reasonable cost, size, and weight. Any design not capable of passing such a requirement will suffer detrimental fire damage in 4 to 15% of A/F/T mishaps, as verified by mishap data. A design capable of surpassing the proposed requirement, and one which will be mounted in the wings or tail section of A/F/T aircraft, could possibly survive more than 99% of the fire damage mishap environments.

In order to evaluate the flame test requirement of TSO C51A and the post-crash fire environment of an actual A/F/T, flame heat transfer phenomena must be fully understood. A literature search was undertaken early in the program in order to attain an understanding of flame dynamics and heat transfer within a flame environment. Several references were in close agreement with each other and all proposed the same basic equations. The best and most thorough reference will be utilized throughout this section; it was supported by test data and it specifically dealt with JP-4 fuel fires.[8]

The energy balance equation for an object completely enveloped in a flame is as follows:

$$q_r + h\,(T_f - T) \quad = \quad \varepsilon\,\sigma\,(T^4)$$

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[8] J. R. Welker and C.M. Sliepcevich, "Heat Transfer by Direct Flame Contact - Fire Test - Phase I", final report prepared for the National Academy of Sciences, July 1971.

where,

q_r = radiant heat flux from the flame, (BTU/hr-ft^2)

h = convection heat transfer coefficient, (BTU/hr-ft^2-°F)

T_f = flame temperature, (°R)

T = surface temperature of enveloped object, (°R)

ε = surface emissivity of object, (unitless)

σ = Stefan-Boltzman constant, (BTU/hr-ft^2-°F) = .1714E-8

It is necessary to handle the flame heat transfer in such an unconventional manner because (1) the radiation heat flux from the flame to a solid object does not behave in accordance with a normal Stefan-Boltzman relationship, and (2) the flame is transparent to the radiation heat transfer from the object to its surroundings. In the above energy balance equation, the radiant heat flux term for JP-4 flames can be evaluated with the following equation:

$$qr = FA(1-e^{-bL})$$

where

F = view factor (unitless) = 1.0 for 100% envelopement and .5 for 50% envelopment

A = maximum possible heat flux, (BTU/hr-ft^2) = 31,000 for JP-4

b = extinction coefficient, (in.$^{-1}$) = .0186 for JP-4

L = diameter of flame, (in)

This equation states that a 20.6-foot diameter flame is necessary in order to attain 99 percent of the maximum possible radiant heat flux. A 3.1-foot diameter flame will emit 50 percent of the maximum radiant heat flux and a 6-inch diameter flame, 11 percent. The heat transfer coefficient for convection is 5 BTU/hr-ft^2-°F in a typical JP-4 flame, and the flame temperature (T_f) is 2450°F (1343°C).

As can be seen by the above equations, the temperature of an object completely enveloped by a flame will have a steady state surface temperature which is dependent upon the flame diameter and the emissivity of its surface. Figure 15 graphically shows the effect of emissivity and flame diameter on an object completely submerged and 50 percent envelopec by the listed JP-4 flame environments. A hasty conclusion can be drawn that aluminum with a low emissivity (0.02 to 0.3), will reach its melting temperature in most any JP-4 flame. The fallacy is that just small amounts of soot accumulation will drastically change the emissivity of a surface. With .001 to .002 inches of soot, the emissivity of stainless steel will increase through up to .99.[9] In addition, surface oxidation and temperature increases both tend to increase the emissivity. A conservative assumption for the emissivity of metals enveloped in a jet fuel fire with some soot accumulation present is that the ε is equal to .90.

As stated above, the A/F/T fire protection requirement should simulate at least major fire damage (i.e., burnthrough and some puddling). With this premise, figure 15 shows that a 13-inch diameter JP-4 fuel flame is necessary to produce some puddling of aluminum. The 15-minute oven test is an equivalent environment to that which exists when the CSMU is completely enveloped in a 13-inch diameter flame, for 15 minutes. This is a much more severe test than the TSO requirement. The TSO would allow the manufacturer to shield 50 percent of the surface area, and utilize a 6-inch diameter lower temperature flame to envelope the remaining 50 percent of the area. The proposed test will result in a CSMU maximum memory temperature which is 54° hotter than that encountered in a TSO type of requirement. In addition, the armor plate will reach 739°C as opposed to 489°C.

A flame test literally defies standarization. Just a few of the parameters which would effect flame test results are fuel flow rate, oxygen supply, soot accumulation, flame temperature measurement errors, fuel chemisty, atmospheric conditions, burner construction and adjustment, and countless others. With this in mind, a computer thermal analysis of the CSMU completely enveloped in a 13-inch diameter, JP-4 fuel flame was performed. The same computer model was used to arrive at an equivalent oven test, in which the time-temperature profile of the enclosed memory chips would be nearly identical. An oven temperature of 750°C (1382°F), for 15 minutes is recommended. It is necessary to increase the oven temperature 90°C above the melting point of aluminum, to account for the lower radiation and convection heat transfer rates which occur in an oven, versus a flame environment.

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[9] L.H. Russell and J.A. Canfield, "Experimental Measurement of Heat Transfer to a Cylinder Immersed in a Large Aviation Fuel Fire", Journal of Heat Transfer, Transactions of the ASME, August 1973, p. 399.

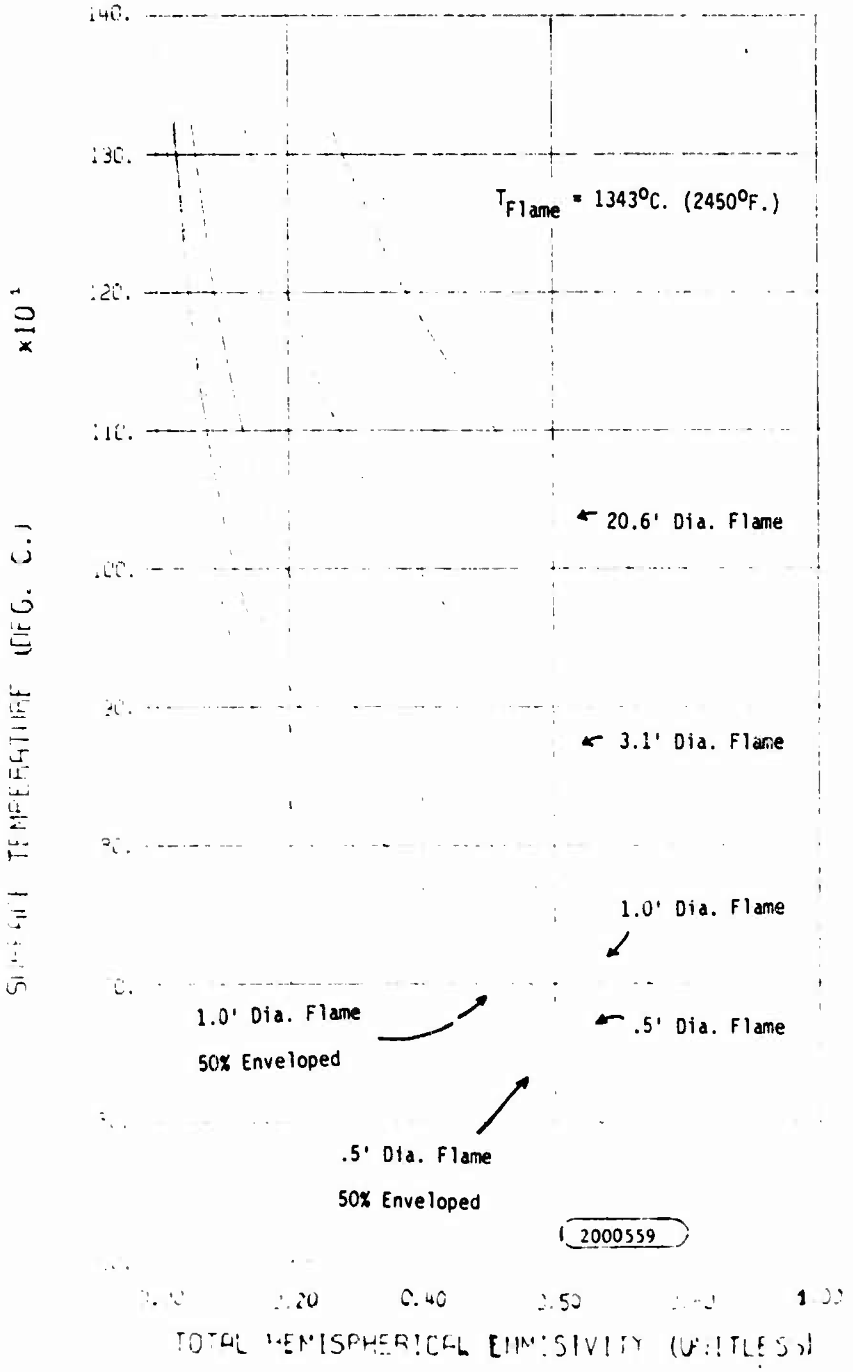

Figure 15. Steady State Surface Temperature versus Emissivity for Several Flame Environments

The recommended fire protection test for the CSFDR CSMU is the stabilizing of the unit at room temperature (21°C), within .3 minutes placing it in a 750°C oven, removing it after 15 minutes, and allowing it to naturally cool down, on an adjacent bench at room temperature (21°C). This is equivalent to operating the CSMU at 71°C, subjecting it to a 15-minute 13-inch diameter flame-enveloped ambience, and then allowing it to cool down naturally in a 71°C ambience. It is anticipated that the 15-minute test duration, as opposed to 5 minutes, will more than offset the 2-8 hour cool down period encountered in most actual A/F/T mishaps. This recommended test will be easily performed and easily standardized. It will result in a CSMU design which will demonstrate acceptable field fire protection performance.

e. Water protection requirement (TSO C51A). The FAA requirement is the "intelligence of the record medium shall be capable of remaining permanent and reproducible after the record medium has been immersed in seawater for 36 hours". Using IC memory technology, an extended life in saltwater immersion is easily attainable. A mandatory survival period of 36 hours in a salt bath is recommended for this program.

Specifying a longer test requirement will serve no purpose, while it will significantly increase test time, cost, and program schedule.

3.1.3.3 Recommended test conditions - Adequately specifying the details of the crash-survivability test conditions is as critical to the program as determining the proper requirement levels. Some of the details have been touched upon already and will not be repeated in their entirety, below. This section will be dealt with in six parts: the first deals with the recommended test sequence, and the last five deal with the specifics of each of the five basic crash-survivability test conditions.

a. Recommended crash-survivability test sequence. The hardware which will be subjected to crash-survivability testing should first be subjected to a simulated life test. Two test approaches are possible. The first would be to subject a CSFDR system to its qualification testing prior to the crash-survivability testing of the CSMU alone. A second approach would be to subject a qualification test system to qualification testing, while an additional CSMU would be provided for crash-survivability testing alone. This second approach would be desirable from several aspects, including program scheduling. If this parallel testing is initiated or if crash-survivability testing only is required (because of some redesign, proposed improvement, or memory expansion), the survivability test article should be subjected to simulated life testing initially.

It is recommended that the Air Force specify minimum requirements for the simulated life testing. The test methods of MIL-STD-810C should be followed. The requirements should include the following:

- Temperature shock - three complete temperature shock cycles from +71 to -57°C, with 4-hour stabilization periods, and 5-minute ambient shock excursions between the two extremes.
- Temperature-humidity-altitude - four 24-hour cycles including 0 to 50,000 feet, -54 to +65°C, and up to 95 percent RH exposure.
- Temperature-altitude - exposure to 0 to 70,000 feet altitude, -54 to +71°C continuous operation, +71 to +95°C intermittent operation, and -62 to +95°C non-operating environments.
- Salt fog - 48-hour exposure to a salt fog environment.
- Vibration - 1-hour endurance random vibration exposure in each axis is recommended, in accordance with MIL-STD-810C, figure 514.2-2A, with W_o equal to .2 g^2/Hz (16.4 G_{rms}).
- Humidity - 240-hour exposure to 85 to 95 percent RH and temperature cycling from 28 to 65°C.
- Rain or fresh water immersion (optional) - 2-hour rain exposure (MIL-STD-810C, Method 506.1, Procedure II) or a 2-hour immersion test (MIL-STD-810C, Method 512.1, Procedure I) could be optional simulated life testing requirements.

Low pressure, high temperature, low temperature, fungus, dust, explosive atmosphere, acceleration, shock, and gunfire vibration testing were all omitted from this simulated life testing. They will add very little to the intent of this test requirement and will be included as normal qualification test requirements.

The sequence to be followed in the crash-survivability testing is very important and should be specified by the Air Force. The following sequence is recommended:

(1) simulated life testing
(2) impact shock
(3) penetration resistance
(4) static crush
(5) fire protection
(6) water immersion

With the exception of the first test, this is the same sequence specified in paragraph 7.8 of TSO C51A. Humidity testing is included in a more realistic simulated life test requirement. The mandatory test sequence is a natural requirement. It follows the same sequence of events which may transpire during an A/F/T mishap.

The memory capacity of the CSMU should be stored, and verified, with data prior to the start of simulated life testing. At the conclusion of each of the six test requirements, the data should be retrieved and verified for accurate data retention. Care should be exercised so that the read/verify operation, does not in any way, recharge or restore the memory data retention capability. No repair or maintenance of the test article should be allowed. The Air Force should establish minimum pass/fail performance levels for crash-survivability testing. It would seem reasonable to allow for a small fraction of the bit locations to be randomly in error. Ground software can easily flag obvious discrepancies in actual stored mishap data. Regardless, minimum pass/fail performance levels should be clearly stated.

b. Impact shock test. The 200 to 250-g, 15-millisecond impact shocks should be performed first, followed by the 1700-g, 5 to 8-millisecond duration pulses. One pulse in each direction of each of the three mutually perpendicular axes, should be accomplished at the lower g level, before proceeding to the primary shock pulse requirement. This sequence of testing further justifies omitting a shock requirement from the simulated life testing.

As stated earlier, the shock levels should be specified similar to MIL-STD-810C, figure 516.2-1. Reasonable tolerance limits on each of the variables should be clearly stated. Terminal peak sawtooth shock pulses should be simulated in an accurate, repeatable test procedure, using high-quality shock test equipment.

Aerospace industry standard shock equipment can be utilized for the low-level, long duration shock pulse. The primary shock pulse will require an elastic shock cord accelerated drop testing rig, an air cannon, or a jet sled-barricade impact apparatus. The cheapest testing alternative will be exercised, while maintaining the shock pulse accuracies specified. Accurate monitoring equipment and accelerometers will be utilized. Complete and accurate test documentation should be required.

c. Penetration resistance test. Two drop tests are required, one in each direction of the most critical plane. An attempt should be made to standardize this test by specifying the following:

- Impact point material, size, shape, and length.

- Construction and design of the drop weight, including its size, length, and acceptable impact point structural attachment.

- Test fixturing guidelines should be determined for the guide/guide-rail assembly, the quick release drop mechanism, and the impact measurement equipment.

- Support media for the test article - allowable sand density, grain size, cross-sectional area, and depth.

- The requirement to monitor the resultant shock pulse should be specified (an accelerometer attached to one of the unused mounting flanges will suffice).

It will be important to clearly specify a test requirement of this nature. The Air Force deserves the hardware penetration worthiness which they are expecting and the suppliers will be able to arrive at a truely optimum design. Test standardization is essential if the design worthiness of competitive designs and the design worthiness of multiple sources, are to be realistically compared.

d. Static crush test. The static crushing load will be applied for 5 minutes sequentially, in each of the three mutually perpendicular axes. A materials tensile/compression test machine can be utilized. The apparatus will be fixtured so that the applied loads are uniformly distributed over the primary flat surfaces in each direction. The crushing loads will not be applied to the projected mounting feet, connector, or heads of screws attaching the cover. If the crushing loads are to be applied to these protruding physical features of the chassis, it should be clearly stated. The proposed design will pass either test but a memory readout will be more difficult if the connector is damaged in the static crush test.

e. Fire protection test. The uncontrollable and unstandardizable nature of flame testing, mandates the need to specify an oven test. Industry studies have arrived at this same conclusion, "...all such recorders must be tested under identical conditions. This can only be effected by establishing a more definitive standard test method, thus eliminating variations in testing procedures as exist at present.... A suitable and uniform test method...would be insertion of the complete recorder for 30-minute duration in an electric furnace operating at 1600°F."[10] The oven test is recommended as an essential change.

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[10] Thomas Rust, Jr and Paul N. Boris, "Fire Test Criteria For Recorders", NAFEC, Atlantic City, N.J. Final report prepared for the FAA (Report No. FAA-DS-70-16), July 1970, pp. 2, 34.

A 15-minute oven test is adequate, based on the fact that the vast majority of A/F/T post-crash fires are extinguished in less than 5 minutes. The additional 10 minutes of test will adequately account for the post-fire, cool-down temperature profile, which exists as the aircraft wreckage gradually cools down to the outside ambience. The 750°C (1380°F) is based on mishap fire damage data, and its determination is well supported in the previous section above. If the crash-protected memory unit were to be installed in the cockpit or avionics bay of an A/F/T, where equipment is much more prone to fire damage, the 870°C (1600°F) oven temperature is probably warranted.

The proposed test is as follows:

(1) Stabilize the CSMU temperature at room temperature (21°C).

(2) Place the unit in a 750°C preheated oven for 15 minutes duration.

(3) Remove the CSMU from the oven and allow it to naturally cool down at room temperature (21°C).

(4) Upon returning to near room temperature stabilization, a minimum of 1 to 3 hours later, the data retention should be verified.

The test specification and testing procedures should also state the following limitations. An electric furnace is desirable. It should be well insulated, and capable of a quick response in recovering from the temperature drop induced as the test article is transferred into the oven. The transfers should be accomplished as quickly as possible (within .2 to .3 minutes) and the oven should be back up to 750°C, within the first minute of the 15-minute test period. The oven air temperature should be maintained at 750-775°C and all six walls of the furnace exposed to the test article, should be within 25°C of the air temperature. The unit should be placed in the center of the furnace, in a normal mounting orientation, and be supported by a perforated metal shelf. During the room temperature cool down, artificial cooling should not be allowed, such as quenching or impingement of moving air. Again, a perforated shelf or metal grate is recommended as a support shelf.

f. Water protection test. This test should simulate seawater immersion of the recorder for a period of 36 hours. A seawater solution of a specified salt concentration, PH level, and room temperature should be prepared. The test article should be immersed in the solution, so that its uppermost point is at least 36 inches below the surface. The test should be conducted at a reasonably low altitude, with ambient atmospheric pressure.

3.1.3.4 Crash protection evaluation - Physical, mechanical, and thermal control techniques are compared and evaluated for the protection of the memory module from the effects of A/F/T crashes. The following sections will deal with the crash protection schemes considered during this study program. The sections are (1) remote memory mounting, (2) memory module design concept, (3) thermal protection/insulation evaluation, (4) mechanical protection/armor evaluation, and (5) memory locating aids.

a. Remote memory mounting. The single most distinctive, and ultimately the most superior feature of the design approach is the remote memory mounting of the CSMU. The CSMU was designed to be installed in a remote location on the aircraft. The processor (DPU) can be installed in the avionics bay where the signals are readily available, while the crash-protected memory is located in the more crash-benign extremities of the aircraft. There can be no argument with the conclusions drawn from the mishap data. The wings, tail, and tail cone of the aircraft receive a much lower level of fire and mechanical damage.

Thus, the remote memory concept is absolutely essential to an optimum CSFDR system design. Installing an entire system, processor and memory, in the avionics bay will either decrease its survivability or increase the size, weight, and cost of the mechanical and fire protection required. Installing both in the extremities will increase cabling weight, increase installation cost, and decrease accessability to the hardware.

The remote memory concept came under consideration very early in this study program. The functional breakdown between the DPU and the two sections of the CSMU were important in optimizing this concept. The CSMU contains a crash-protected section, in which only the crash-protected memory (CPM) is mounted, and the non-survivable timing and control section, contained on a single printed circuit board. With this functional breakdown, the interconnect between each of the three sections is minimized. There are only 14 assigned signal lines between the DPU and the CSMU, which minimizes cable size and weight.

Early in the study program, an evaluation was made of a multiple semi-hardened CSMU configuration. In this concept a single processor would feed data to several CSMU designs. They would contain little or no thermal protection and a minimum amount of mechanical protection. Several semi-hardened CSMUs would be installed in each aircraft, in the hope that at least one would survive. Potential installation locations included the canopy rail, ejection seat, wing tips, and vertical tail. The real drawback to such a design is (1) cost to install multiple memories, (2) cable weight and cost to interconnect multiple memories, and (3) cost impact with multiple CPM modules. Just the CPM module, by itself, is a significant portion of the total CSFDR system hardware cost. The memory components themselves are very expensive. Figure 16 shows a design concept sketch of the semi-hardened CSMU design. Each unit would be less than 13 cubic inches in size, and a weight of 1 pound would be a reasonable design goal.

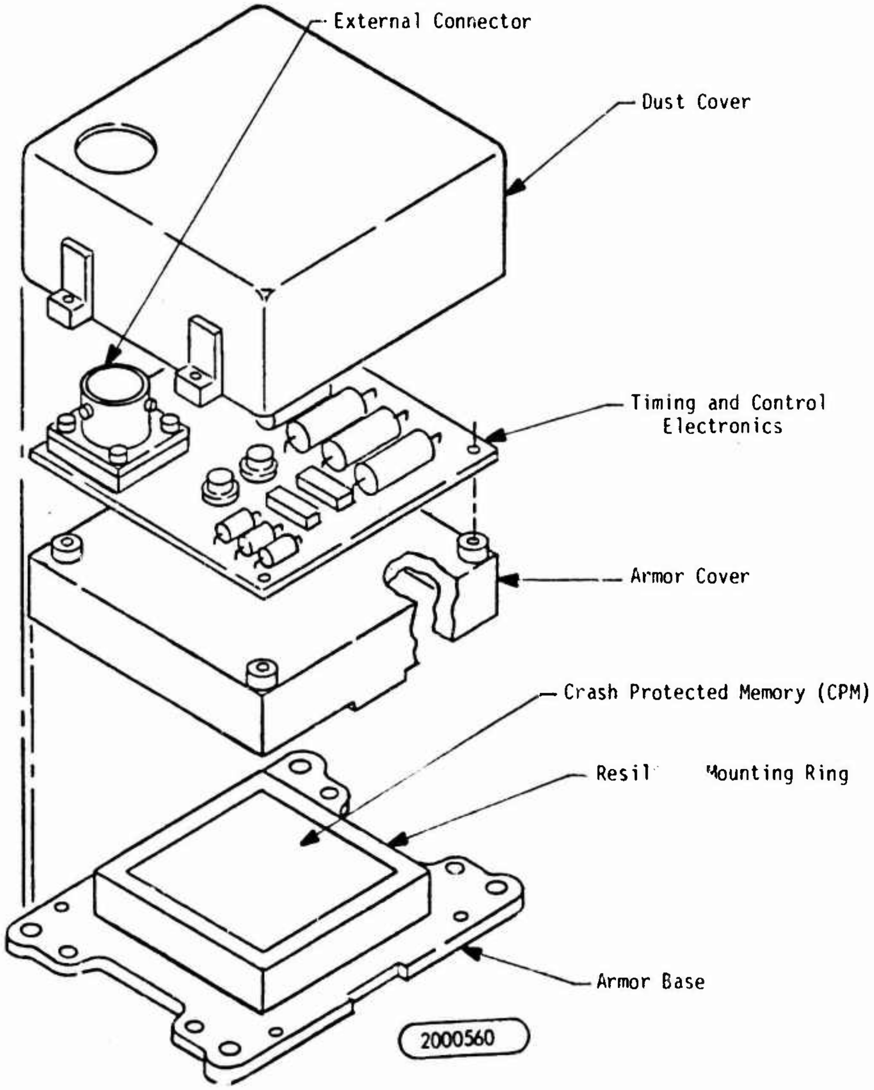


Figure 16. Multiple Semi-hardened CSMU Concept

A single, fully crash-protected and remotely mounted CSMU does not suffer from any of these shortcomings. Hardware and installation cost, size, and weight are minimized, while maximum survivability is attained.

The point cannot be over-emphasized: the remote memory mounting is a very effective survivability protection feature. Minimizing the severity of the post-crash environment is a very attractive alternative to added insulation and increased armor thickness.

b. Memory module design concept. The design of the CPM module was critical to the overall crash-protection design of the CSMU. In order to aid the overall thermal and mechanical worthiness of the design, the CPM had to be as rugged and as small as possible, and yet be cheap to build in large volume production. Three CPM designs received considerable consideration. They were (1) a cubical stacking design, (2) a fluid-filled module design, and (3) a single card design.

Early in the study program, it became obvious that the size and shape of the CPM, its protective insulation, and its armor enclosure were to be important considerations. For a given memory capacity requirement, the needed volume to package alternately-shaped CPM modules is not constant. Some shapes, and their resulting packaging concepts, lend themselves to higher packaging density and more efficient volume utilization. However, if the following assumptions are true, some very interesting conclusions can be drawn.

- Assume that a spherical, cubical, and rectangular CPM design can be packaged in the same volume.
- Assume that the insulation and armor enclosure thicknesses are identical in all three designs.
- Assume that the insulation and armor adopt the same shape and aspect ratios as the module they are encompassing.

With these assumptions, the conclusions are as follows:

- The thermal time constant of the sphere-shaped design would be the longest, followed by the cube, and then the rectangular design. This is because the volume to surface area ratio of a sphere is the highest. When subjected to a flame or oven ambient, the sphere would be the slowest to increase its temperature. However, upon removal, it would also be the slowest to cool down. A more rigorous thermal analysis would show a slight thermal performance advantage for the sphere, because of its smaller outside surface area and lower armor thermal capacitance.

- The static-crush and penetration resistance of the sphere would be the highest, followed by the cube, and then the rectangle. The spherical armor has much more strength and toughness because of its localized three-dimensional nature, while the cube has shorter, unsupported spans than the rectangular prism.

- The total volume of the insulation and armor are smallest for the sphere, followed by the cube, and then the rectangular prism. If a 1-cubic-inch CPM module is assumed and if the insulation and armor thicknesses are .8 inches and .125 inches, respectively, the following volumes would result. For the spherical concept, the CPM would have a diameter of 1.24 inches, the outside diameter of the armor would be 3.09 inches, and its total volume would be 15.5 cubic inches. For a 1-inch cube CPM, the armor would be 2.85 cubic inches, and its total volume would be 23.2 cubic inches. For the rectangular concept, if the CPM is 2x2x.25 inches, the armor would be 3.85x3.85x2.10 inches, and its total volume 31.1 cubic inches.

If only thermal performance, mechanical strength of the armor, and total volume were to be considered, the proposed design would definitely be spherical in shape. The cubic concept would be a second choice and the rectangular a distant third. However, total cost, packaging inefficiencies, interconnect problems, aircraft installation considerations and countless other considerations have to be examined.

The spherical CPM was not given further consideration, as was noted above. The CPM packaging density would be tremendously reduced in order to accommodate the spherical shape. The CPM volume could easily approach 2 cubic inches, raising the outside diameter 3.5 inches and the total volume to 22.5 cubic inches. The volume, thermal, and even weight advantages would be negated by inefficient space utilization. Existing automated manufacturing and assembly equipment could not be employed, resulting in exorbitant cost figures for high-volume production. Advanced and totally unproven packaging and manufacturing technologies would be required in order for the spherical concept to become even reasonably competitive from a CPM cost standpoint. Another problem is the inefficient utilization of aircraft space. The rectangular design, with its smallest dimension being only 2.1 inches, can be installed in more of the available aircraft locations than a spherical unit with a 3.5-inch minimum dimension. Wing tip and vertical tail installations would be difficult or impossible.

The stacked and fluid-filled CPM module designs were both conceived as cubic configurations. These two concepts solve many of the shortcomings of the spherical configuration and yet they are still less than optimum designs.

The stacking design involves assembling the CPM module by vertically stacking several flat, square modules. Its advantages include modular memory expansion accomplished by adding layers to the stack, multiple use of identical modules, and ease of servicing. The insurmountable problem with this design is the module-to-module interconnect requirement. Memory circuit interconnect demands are extremely high. Even the most exotic and advanced connection schemes possible resulted in utilizing 50 percent of the total CPM volume for module-to-module interconnect. An inherent risk with these module interconnect schemes is their questionable gas-tight qualities and their unproven reliability. The interconnect problems were insurmountable without introducing significant program risk. This stacking CPM design concept is not recommended.

The second CPM concept pursued was mounting the memory components directly to a printed flexible circuit, folding the assembly into a desirable shape, and installing it in a fluid-filled sealed enclosure. The fluid-filled module would be non-repairable and inaccessible for maintenance and trouble shooting. The memory component to flex circuit mounting is an unproven process, with possible susceptibility to mechanical damage, during thermal shock and cyling. The major shortcoming of this design is the cost to seal the enclosure with enough strength to withstand the impact shock requirements and the high temperature excursions, with resultant pressure buildup.

The CPM design concept which is recommended is the single flat card design. This design utilizes existing technology and proven processing techniques. The design is simple, repairable, low-cost, and extremely rugged. The design efficiently utilizes available volume and the interconnect scheme is extremely reliable and proven.

Parallel to the study program, a considerable effort was undertaken to arrive at an optimum design utilizing this single flat card concept. In all three concepts, the use of discrete, hybrid, or custom monolithic microcircuit technologies were seriously considered. The recommended design is a very creative solution which solves memory interconnect problems, minimizes CPM power dissipation, minimizes the critical size parameters, and still features some very attractive data retrieval and repairability features. While exhibiting these distinctive and essential qualities, our CPM design utilizes existing technology, rugged mechanical performance is assured (see appendix E), and the assembly cost will be low. The CPM component cost, while not inexpensive, will be lower or competitive with other designs and configurations which utilize similar or alternate technologies.

c. Thermal protection/insulation evaluation. The search for an optimal CSMU thermal insulation included both vacuum super-insulations and ambient pressure insulations. Thermal protection schemes considered included thermoelectric coolers, intumescent thermal protection coatings, heat-fuseable leads, mechanically-shearing leads, a bimetalic heat column, capacitive heat sinking material (including water-soaked wicks, water-permeated mineral fiber, and water bags), heat pipes, and high thermal capacitance potting gels or fluids. The proposed design, using solid ambient pressure, Johns-Manville Min-K-1301 insulation is the best solution. It provides the maximum protection, while minimizing cost, maintainability, simplicity of design, size, and weight.

The thermal conductivity of Johns-Manville Min-K-1301 insulation is .0208 BTU/hr-ft-°F (.036 W/M-°C) at 800°F (425°C). There are available vacuum super-insulations which have thermal conductivities which are 10 to 1000 times lower than Min-K. However, they must be maintained in a vacuum ambience to exhibit their super insulation qualities. At normal ambient pressures, their thermal conductivity exceeds that of Min-K. A vacuum insulation scheme is not recommended.

Over the life time of an A/F/T, any vacuum design would lose its vacuum and require recharging. Even metals slowly pass molecules of gas through their thickness. Even worse, these insulations (which are constructed of multi-layered metal foils, vacuum deposited on thin films of Mylar, Kapton, or similar plastics) slowly outgas and contaminate their own ambient vacuum environment. Expensive designs would need to be employed to absorb these contaminants.

Regardless of the other problems, the cost increment imposed by an evacuated hermetically sealed CSMU chassis enclosure would be cost-prohibitive in itself. Glass-sealed Kovar feed-throughs would be required to electronically connect the CPM with the timing and control electronics. The penetration and impact shock protection required of the armor plating would have to be upgraded. Not only would the structure have to survive impact and penetration damage, the hermeticity of the enclosure would have to be maintained. In extremely small quantity production, vacuum insulations could possibly become competitive. In the large quantity productions required of the CSFDR program, the technical problems and cost impact seem insurmountable. The insulation thickness savings could easily be offset by the added mechanical protection required.

Considering only ambient pressure insulations, Min-K is unsurpassed in insulation qualities at the CSFDR high temperatures, ranging from 400 to 800°C. (750-1470°F). In addition, Min-K is a moldable solid insulation possesing outstanding mechanical strength and durability. Its 5% compression strength is 95 psi, while its 8% value is 190 psi. As will be shown in a later section, a .8-inch thickness of Min-K, will adequately protect the selected MNOS memories during the vast majority of A/F/T crashes.

Intumescent thermal protection coating was considered for the CSMU. The molded Min-K insulation surrounds the CPM. The insulation and CPM are enclosed in an armored housing, made of high-strength steel or titanium. An initial concept featured an intumescent coating applied to the outside of the armor. Intumescent coating is a paint derivative, which swells 5 to 50 times its original thickness when exposed to high temperatures (350° to 500°F) or flame. In swelling, the material forms a charred insulation layer. The typically cured virgin material has a density of .051 lbm./cubic inches and a thermal conductivity of .200 BTU/hr-ft-°F, while the char properties are .022 and .040, respectively. The char thermal conductivity is twice that of Min-K, making it a very good insulation, itself. However, the real, attractive feature of intumescent coating is it's self-healing qualities. If penetration and impact shock were to locally damage the insulation, the swelling would tend to fill any resultant voids.

A computer thermal analysis of the proposed CSMU with and without intumescent coating was performed. The characteristics of the coating were accurately modeled from data in available literature. The virgin thickness of the coating was .020 inches, while the char thickness was .100 inches, a conservative expansion ratio. At the time the flame was extinguished, the CPM memory was 45°C cooler with the coating than without. This difference expanded to 85°C, 8 minutes after the flame was extinguished. However, 21 minutes after flame extinction, the resultant CPM temperatures crossed and the CPM with coating attained a maximum temperature of 10°C hotter than without. What is even worse, the higher CPM temperatures were maintained for longer periods of time. In comparing the total time-temperature damage to the MNOS memory chips, the thermal performance of the one with coating incurred 30% more thermal damage to the memories. The damage life factors are 3.3 and [illegible].0, respectively.

This thermal phenomenon is easy to understand. The coating is a tremendous aid during the flame-exposure, heat-up phase, but it becomes an even bigger penalty during the cool-down phase. The thermal energy, stored in the high thermal capacitance armor plating, is retained for longer periods of time, forcing more heat energy to trickle through the insulation to the CPM. The intumescent coating must be moved inside the armor enclosure to be effective. Since it is a poorer insulation than Min-K, it is not included in our recommended configuration. The self-healing features still make it an attractive alternative. If preliminary impact and penetration testing of the proposed configuration indicate that significant damage to the Min-K is incurred, incorporation of intumescent coating, applied to the inside surface of the armor enclosure, is an easy design improvement to make.

The normal power dissipation of the proposed CPM is 9.1 mW. This extremely low power dissipation is essential to an optimum thermal design. Since the CPM requires exceptional thermal insulation to survive the fire protection requirement, it also stands the risk of overheating during normal operation. However, at 9.1 mW, the thermal rise during normal operation will be .8°C from the memory junction to the CSMU ambient. At extremely high data storage rates, this temperature rise could possibly double to 1.6°C.

Many of the thermal protection schemes mentioned above were considered as possible solutions, if the electrical interconnect to the CPM became a significant thermal path through the MIN-K insulation. As it turns out, with only 10 interconnect lines required, the thermal resistance of the flex circuit is 28:1 greater than the total thermal resistance of the insulation. The thermal conductivity of copper is 11,100 times larger than Min-K. However, the effective cross-sectional area is 311,000 times smaller.

The combination of low thermal conductivity of the interconnect and the extremely low power dissipation of the CPM, eliminates the need for thermoelectric coolers, heat fuseable leads, shearing leads, heat columns, and heat pipes. Normal operating temperature rise of the CPM and the thermal shorting of the insulation by the interconnect are not significant problems in the design concept.

Capacitive heat sinking material received serious consideration, but each had serious objections, including cost, weight, and durability. Water soaked wicks and water bags present a serious sealing problem and their durability to survive low level, long duration impact shocks is questionable. The durability of water permeated mineral fiber, through repeated temperature cycling, above and below the freezing point of water, is doubtful. High thermal capacitance potting gels and fluids are attractive, if employed inside the insulation layer and surrounding the CPM. However, insulation contamination with moisture and enclosing the material in a sealed containment barrier, becomes difficult and expensive.

Two layers of insulation were also considered. A high temperature/low thermal capacitance insulation surrounding a lower temperature/high thermal capacitance insulation, has some thermal performance advantages. The problems are 1) the thermal capacitance ($\rho \times C_p$, Btu/in^3-°F) of insulations do not exhibit a wide spread in value, and 2) the cost of each layer will nearly equal the cost of a single layer, while handling, storage, assembly, and maintenance cost are increased. The optimum and simplest thermal design solution is a single layer of Min-K insulation.

d. Mechanical protection/armor evaluation. As stated earlier, the penetration resistance requirement of the CSMU determines the armor thickness required. An armored enclosure, which survives the penetration test, will surely perform adequately in static crush and impact shock. High strength steel (9 Ni-4 Co steel, in accordance with AMS 6524) and weldable titanium (TI-6 Al-4V, in accordance with MIL-T-9046) are the two most promising armor enclosure materials. High-strength-reinforced plastic composites have received some consideration, however, the high temperature fire protection demands exceed their maximum service temperature.

In penetration testing, the drop weight will be traveling 25.38 fps at impact, if released from 10 feet and air resistance is ignored. If the CSMU is placed on 18 inches of dry sand (on its 3.95-inch x 3.8-inch surface), the projectile sand penetration equations predict the decelerations and drop weight will be 16.63 g. if a 100 lbm. weight is used. The peak force on the armor plate will be the mass of the weight times its negative acceleration, or 1663 lbf., applied over a .25-inch diameter circular area. If a factor of safety of 1.5 is introduced by increasing the designed load from 1663 lbf. to 2500 lbf., the armor thicknesses required will be .153 inches for 9 Ni-4Co steel and .180 inches TI-6Al-4V titanium (reference 7). The tensile ultimate strengths of both of the materials were those listed in MIL-HDBK-5B, namely 220 and 160 ksi, respectively. It should be noted that these calculations agree closely with the maximum stress levels calculated using the equations from table 19. Using the calculated average stress ratios between rigid and freely supported recorders, the maximum stress levels for a 9Ni-4Co steel bar would be 176 to 337 ksi. For a Ti-6Al-4V bar it would be 100 to 191 ksi. In each case, the lower value is for a 100-lbm. drop weight and the higher values for a 500-lbm. drop weight.

All factors considered, the proposed CSMU configuration has an armor thickness of .153-inch-thick 9Ni-4Co steel or .180-inch-thick Ti-6Al-4V titanium. These are currently the recommended armor thicknesses and they will be the initial thicknesses subjected to preliminary crash testing. Both materials are weldable and both have their advantages. Titanium has the advantage of lower thermal capacitance and lighter weight while steel is less expensive to purchase and process. It has a size advantage in that a thinner plate can be utilized. Steel has a higher ultimate strength but titanium a higher specific strength.

e. Memory locating aids. TSO C51A, paragraph 8.0, specifies that the exterior of the recorder must be finished in either bright orange or bright yellow, to aid in locating the device amongst the post crash debris. It is recommended that the requirement be carefully considered by the Air Force along with two other feasible locating aids. They are magnetizing a portion of the armored enclosure or doping the enclosure with low level radiation. These would allow the use of either a magnetic or radiation detector to locate the CSMU.

It should be noted, that bright distinctive coating requirement has three possible disadvantages. First, it is not in agreement with standard Air Force case finishes specified in MIL-E-5400. Secondly, it would impose a minor thermal impact since the emissivity is low and the increased thickness and lower conductivity of a durable bright coating would be less than desirable. Third, industry studies on commercial recorders have met with mixed success as to the crash/fire durability of even the best and most expensive coatings available. Air Force direction is required as to the desirability of alternate locating aids.

3.1.3.5 Recommended CSFDR packaging approach - The recommended CSFDR packaging approach will be illustrated along with external interfaces. The physical description, packaging approach, thermal survivability performance, and related issues will be described. The subsections are (1) Hardware Description/Standard Design Requirements, (2) MNOS High-Temperature Memory Retention, (3) CSMU Fire Protection Worthiness/Thermal Evaluation, and (4) CSMU Armor Enclosure Design.

a. Hardware description/standard design requirements. The hardware description and the standard qualification requirements of the CSMU and DPU will be described below. The crash-protected portion of the CSMU will be qualified to the crash survivability requirements of the program. However, the remainder of the system should be required to pass standard qualification requirements for military airborne electronics. The applicable specification levels of MIL-E-5400 and the test procedures of MIL-STD-810C are recommended. Since it is desired to install the DPU and CSMU in any A/F/T, wherever a suitable location is available, the design requirements must be stringent enough to maintain this flexibility.

The 10-g sinusoidal vibration requirements of MIL-E-5400R, figure 2, Curve IVa, is recommended for both the CSMU and DPU. The curve is for equipment installed in the rear half of the fuselage or wing area of jet aircraft. A random vibration requirement in accordance with MIL-STD-810C, figure 514.2-2A, with $W_o = .2\ g^2/Hz$ (16.4 G_{rms}) would also be acceptable. The CSMU and DPU design concepts are worthy of passing either of these design vibration requirements. Either the random or the sinusoidal vibration requirements should be specified.

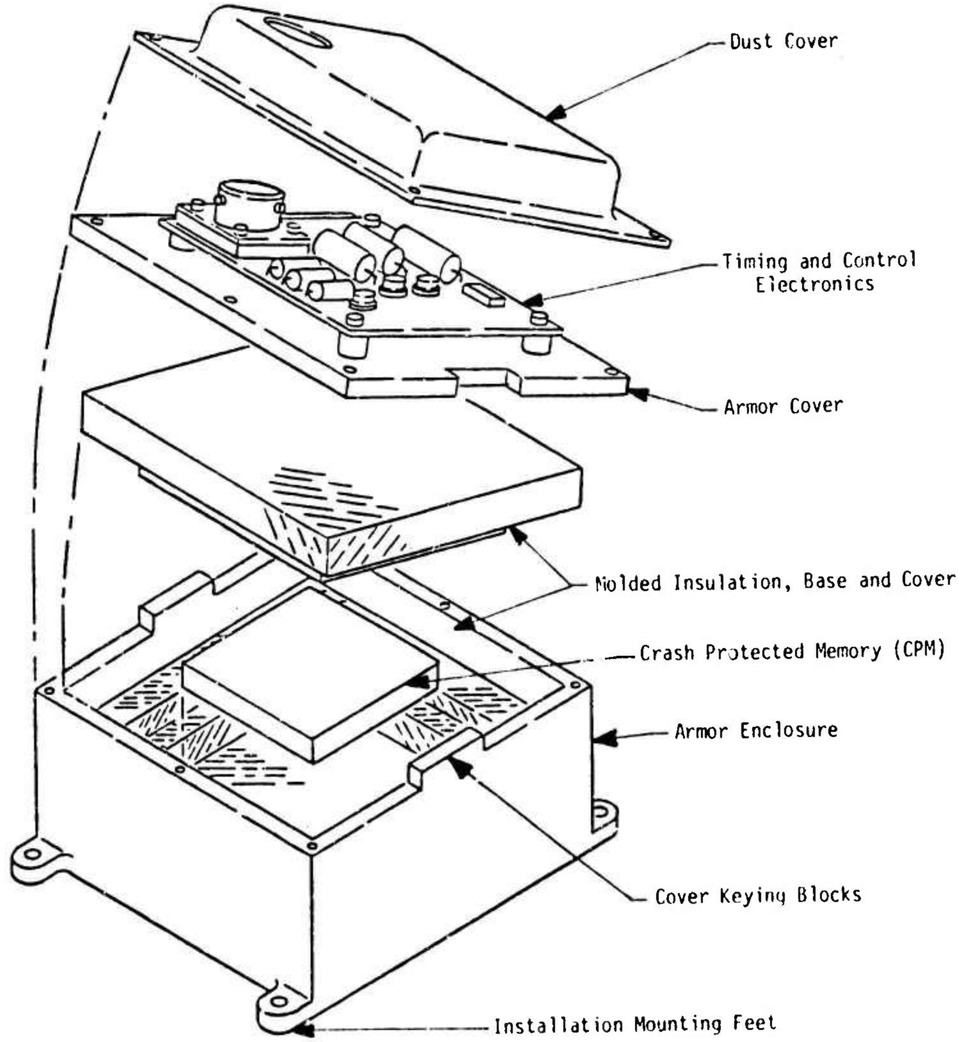
The basic design shock requirements of MIL-STD-810C, figure 516.2-1 are recommended. Terminal-peak sawtooth shock pulses of 20 g peak and 11-millisecond duration are suggested. In addition, reasonable requirements for crash safety and bench handling should be specified.

The temperature-altitude environments of MIL-E-5400, Class 2 are recommended. They include the design requirement to operate in a continuous temperature ambient of -54 to +71°C and a 30-minute intermittent operation at +95°C. In addition, the altitude range is from sea level to 70,000 feet. This requirement will allow for the needed installation flexibility on A/F/T aircraft. Both the CSMU and the DPU are capable of reliable performance in this environment without employing a cooling fan or other added cooling aids.

In addition to these three, the full complement of normal qualification design requirements for airborne electronics should be employed. These requirements include altitude, high temperature, low temperature, temperature shock, humidity, fungus, salt fog, dust, explosive atmosphere, acceleration, and temperature-humidity-altitude. Standard and proven design procedures and manufacturing processing will assure a quality design of the DPU and CSMU, which will be capable of reliable performance at these qualification test levels.

The DPU will have a bolt-on front panel with military standard connectors. The unit retention hardware will include a rear wedge retainer and two front panel ARINC-style hold-down hooks, facilitating a quick disconnect and removable feature. Configurations I and III will require an additional printed circuit board. The Configuration II descriptions, below, will be presented within parentheses. The chassis dimensions of the DPU will be 7.38 inches x 5.75 inches x 5.00 inches (7.38 inches x 5.35 inches x 5.00 inches). The envelope volume will be 212 (197) cubic inches and weight of 8.4 (7.6) lbm. is estimated. The unit will contain seven (six) printed circuit boards. Two power supply assemblies and a power transformer will be required, which account for nearly 2 pounds of the total weight. A design concept DPU sketch is shown in figure 55.

The CSMU design concept sketch is shown in figure 17. The CSMU .050-inch-thick aluminum dust cover will be removable by extracting four screws, while an additional two screws will remove the armor cover. Five standoffs and screws mount the timing and control electronics board to the armor cover and two screws attach the external connector to the printed circuit board. The CPM and circuit board assemblies will be easily tested and repairable. The molded Min-K insulation consists of two half shells, which mate with an offset interlocking seam, forming a close-tolerance, high-thermal-resistant interface. The CPM will be completely enclosed within .8-inch-thick insulation. The molded insulation seam will be designed with a passage in which the interconnect will be contained as it passes through the insulation. Molded Min-K half shells have been successfully employed in similar applications, protecting electronics on manned spacecraft, aircraft, and other high-temperature applications.



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	L (in)	W (in)	H (in)
Configuration I	3.95	3.80	2.80
Configuration II	3.80	3.30	2.86

Figure 17. CSMU Design Concept Sketch

The CSMU will be equipped with one shell-size-12 military standard connector. The unit will be installed in the aircraft with four bolts. Configurations I and III will require 8K x 16 bits of crash-protected memory, while Configuration II is a smaller unit with only 4k x 16 bits. The CSMU is 3.95 inches x 3.80 inches x 2.80 inches (3.80 inches x 3.30 inches x 2.80 inches), for a total volume of 42 (35) cubic inches, and the CSMU will weigh 2.8 (2.4) lbm. As stated earlier, the armor will be either .153-inch-thick steel or .180-inch-thick titanium.

b. MNOS high-temperature memory retention. MNOS memory chips, like all IC memory technologies, are susceptible to high temperature damage. The data retention phenomena is related to the temperature exposure level as well as the time period at that level.

The physical phenomenon of this time/temperature memory retention damage is that a stored "0" is entered as a zero or low-voltage potential across a nitride-oxide interface. A stored "1" is entered as a higher potential. At low and moderate temperatures, the entered voltage potentials are maintained for a very long time period, making MNOS a nonvolatile memory. At higher temperatures, two voltage loss mechanisms called "tunneling and thermal excitation of stored charge" become significant, and memory retention is affected. An excellent study report on this subject was presented to the IEEE in 1979[11] and the time/temperature results are summarized in figure 18. As shown, memory retention time versus temperature is a straight line on log-log paper with a slope of -.736 dB/decade. This time/temperature data is for a typical MNOS memory chip and not for our proposed MNOS EE-PROM, which is a much more current design Every indication is that as MNOS technology matures, the maximum number of read cycles and the time/temperature performance will only improve.

The data shows that the memory can take 1 minute of exposure at 350°C, 1 hour at 258°C, 1 day at 200°C, and 1 month at 160°C. The exposure during a fire test will be a time/temperature profile, not a single temperature level for a given time. To account for this, Miner's Law of Cumulative Fatigue Damage is utilized. This basically takes a summation of the damage at each temperature level encountered, by summing the ratios of time spent at a given temperature to the memory retention time at that same temperature. If the sum of the ratios is less than 1.0, the memory is retained; if greater than 1.0, the memory was lost. As an added factor of safety, 0.7 is taken as the pass/fail criterion, in accordance with Miner's Law. In equation form, the pass/ fail criterion is calculated as follows:

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[11] Kjell O. Jeppson and Christer M. Svensson, "Retention Testing of MNOS LSI Memories", <u>IEEE Journal of Solid State Circuits</u>, Vol. SC-14, No. 4, August 1979, p 723-9.

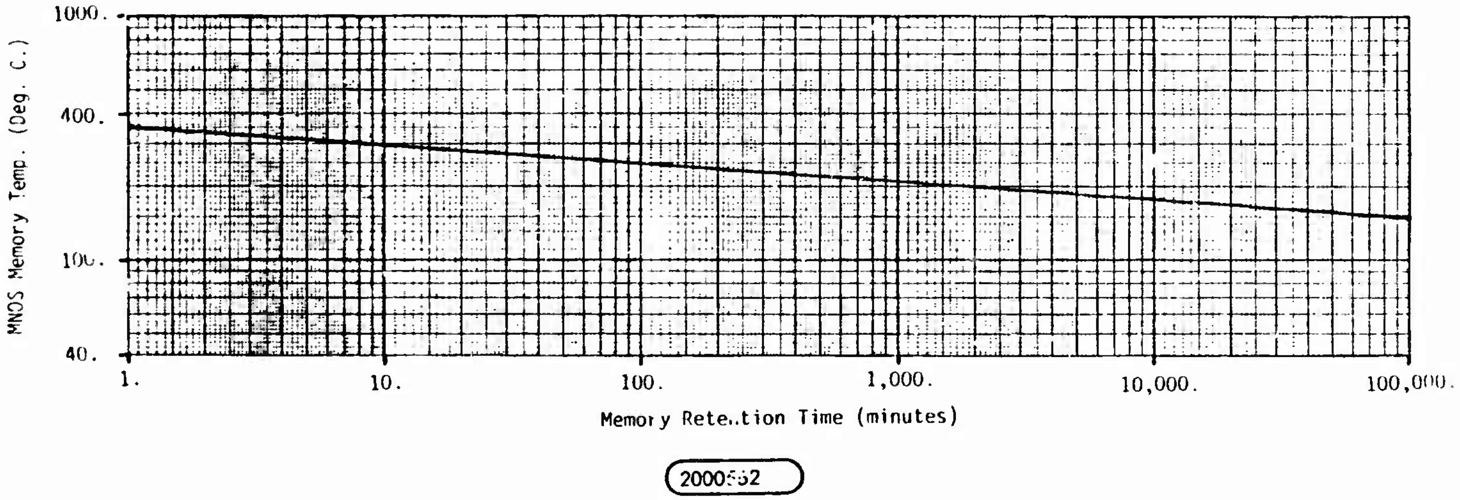

Figure 18. MNOS Memory Retention
(Time versus Temperature)

$$N = \Sigma \frac{t_x}{t_{xa}} \leqq 0.7 \text{ for acceptable data retention}$$

where

N = damage life factor (unitless)

t_x = time exposure at the temperature of x°C (minutes)

t_{xa} = memory retention time at x°C,

The damage life factor of the proposed design when subjected to the 750°C, 15-minute duration oven test is N=0.30 (a factor of safety of .7/.3 = 2.33).

c. CSMU fire protection worthiness/thermal evaluation. The fire protection worthiness and thermal evaluation of our proposed CSMU design was accomplished using a finite differencing transient thermal analysis. The analysis was performed using an IBM-370 computer. Output time/temperature profile Calcomp plots were generated displaying the results of each run.

An eight-node thermal model of the CSMU was utilized. Initial temperatures, boundary conditions, flame heat flux, thermal capacitance of each node, and the thermal resistances between adjacent nodes were calculated and input for each thermal run. The eight nodes used for each run were as follows:

Node number 1 - CPM node

Node number 2 - Inside .3-inch thickness of Min-K insulation

Node number 3 - Middle .2-inch thickness of Min-K insulation

Node number 4 - Outside .3-inch thickness of Min-K insulation

Node number 5 - Armor enclosure (9Ni-4Co steel, .125 inch thick)

Node number 6 - External CSMU surface temperature

Node number 7 - Flame node or oven air temperature

Node number 8 - Surrounding ambient or oven wall temperature

In each run, the 8k x 16-bit CSMU was analyzed, since it is worst case; the smaller CSMU will exhibit better thermal performance. Each run included a steady state solution to arrive at initial temperatures, followed by either a simulated oven or flame exposure period. It was concluded by a sufficient cool-down period so that the CPM had time to reach its maximum temperature and begin to cool off.

Tables 20 and 21 summarize the complete set of thermal runs in the chronological order in which they were made. Shown are modeled input properties, the significant results, and comments. Runs number 1, 2, 3, and 4 modeled the CSMU completely enveloped by a large JP-4 fireball. The proposed CSMU cannot survive 10 minutes of exposure to this environment. However, 3 to 6 minutes would be survivable. Run number 2 was modeled with intumescent coating outside the armor. Runs number 3 and 4 varied the thickness of Min-K insulation to prove that .8 inches was a near optimum thickness. Very little thermal performance is gained by increasing the thickness above .8 inches. Run number 5 decreased the size of the JP-4 fire to a 3.6-foot diameter flame and the CSMU survived 10 minutes of exposure to this environment.

In runs number 6, 7, and 8, flame environments in accordance with TSO C51A were simulated, to show how benign these environments are. In run number 7, the flame temperature was raised from 1100°C to 1343°C, while in number 8, 100% envelopment was modeled. In run number 9, the flame was increased so that aluminum present would undergo significant melting. Run number 9 showed that Min-K-1301 was entirely adequate, with a maximum service temperature of 1300°F (705°C). In the remaining analyses, Min-K-1301 was modeled. Min-K-1301 is a slightly superior insulation with lower thermal conductivity and better compression strength than Min-K-2000. The vendor states that its transient exposure service temperature is much higher than 1300°F. Run number 10 showed that -1301 insulation lowers the CPM maximum temperature 9°C, while lowering the damage life factor from .36 to .28.

Runs number 11 through number 14 modeled a simulated oven test in order to recommend a test level equivalent to that encountered during the flame exposure in run number 10. Room temperature initial conditions were chosen for ease of testing. It will take less time to stabilize at room temperature prior to the oven exposure, and a second oven at 71°C will not be required. In run number 14, the thermal capacitance of the armor was doubled in order to observe its impact.

Table 20. Summary of CSMU Thermal Analyses in a JP-4 Flame Environment

RUN NO.	INSULATION THICKNESS (in.)	POSURE TIME (min.)	PERCENT ENVELOPED (%)	MODELED FLAME CHARACTERISTICS			MAX. TEMPERATURE RESULTS				DAMAGE LIFE FACTOR N	COMMENTS
				q_r, FLAME RADIANT HEAT FLUX (BTU/hr-ft^2)	DIA. (ft.)	MAX. TEMP. (°C)	ARMOR		CPM			
							TEMP. (°C)	TIME (min.)	TEMP. (°C)	TIME (min.)		
1	0.8	10	100	31,000.	21.	1343.	922	10.3	310	28.6	3.3	Severe flame test
2	0.8	10	100	31,000.	21.	1343.	934	10.3	319	38.6	5.+	With .020"-thick intumescent coating
3	0.5	10	100	31,000.	21.	1343.	923	10.3	415	17.6	high	105°C hotter than No. 1
4	1.0	10	100	31,000.	21.	1343.	921	10.3	288	30.6	1.4	22°C cooler than No. 1
5	0.8	10	100	17,000.	3.6	1343	766	10.3	249	30.6	.19	Memory survives a 3.6' flame for 10 minutes
6	0.8	15	50	3,273.5	.5	1100.	489	15.3	200	35.6	.01	Per TSO C51A
7	0.8	15	50	3,273.5	.5	1343.	531	15.3	215	35.6	.02	Same as #6, except hotter flame
8	0.8	15	100	3.273.5	.5	1343.	592	15.3	239	34.6	.11	100% enveloped
9	0.8	15	100	6,584.5	1.07	1343.	646	15.3	262	33.6	.36	*Recommended equivalent test level
10	0.8	15	100	6,085.5	1.07	1343.	646	15.3	253	34.6	.28	Min-K-1301 modeled instead of -2000

*The Min-K insulation will be subjected to temperatures no hotter than the armor: 646°C (1195°F). Since Min-K-1301 has a maximum steady state service temperature of 130[illegible], and it is a slightly better insulation (i.e., lower conductivity) than Min-K-2000, it was decided to recommend the -1301. The maximum steady state service temperature of the -2000 is 1093°C (2000°F).

Table 21. Summary of CSMU Thermal Analyses in a Simulated Oven Test

RUN NO.	INSULATION THICKNESS (in.)	EXPOSURE TIME (min.)	PERCENT ENVELOPED (%)	INITIAL TEMP. (°C)	OVEN TEMP. (°C)	FINAL TEMP. (°C)	MAX. TEMPERATURE RESULTS				DAMAGE LIFE FACTOR N	COMMENTS
							ARMOR		CPM			
							TEMP. (°C)	TIME (min.)	T.	TIME (min.)		
11	0.8	15	100	71	650	21	634	15.3	243	37.6	≃.15	71°C SS at start
12	0.8	15	100	70	732	21	721	15.3	277	36.6	≃1.2	71°C SS at start
13	0.8	15	100	21	750	21	739	15.3	254	38.6	.30	Recommended oven test
14	0.8	15	100	21	750	21	710	15.3	255	45.6	≃.40	Armor thickness double to .25 inches

In all 14 runs, the emissivity of the CSMU was assumed to be .90, because of the soot formation mentioned above. Convection heat transfer coefficients were calculated as accurately as possible. The interconnect conductivity was modeled; however, the insulation seam effects were not included. In both the oven and flame analyses, .3-minute transition periods were modeled for flame ignition and extinguishment or for transfer into and out of the oven.

Figures 19 and 20 show the computer-generated Calcomp plots of all eight nodes in runs number 6 and 10, respectively. The over and under shoots shown for node number 7 are caused by a second-order curve-fitting routine. Notice that the y-axis is scaled from 0 to 1400°C, while the x-axis is scaled from 0 to 50 minutes.

Figure 21 is a Calcomp plot of only node number 1, the CPM module temperature for runs number 1, 3, 4, 5, 6, 10, 13, and 14. They are presented for ease of comparison between the resultant performances, with more resolution of the temperature scale (0 to 350°C).

The recommended CSMU will exhibit excellent survivability in the post-crash-fire environments of A/F/T aircraft. The chosen Min-K insulation is the best non-vacuum, high-temperature insulation on the market. Firm quotes have been received from Johns-Manville for unit prices, ranging from $72 in high quantities to $92 in moderate quantities, for both pieces. This price does not include modest tooling and set-up charges and it was for an initial insulation design. However, the costs are representative.

d. CSMU armor enclosure design. The base of the armor enclosure was designed so that it could be cast in high volume production and yet machined and welded in the initial low volume phase. As shown by analysis above, the enclosure will pass the penetration testing. The armor cover is a simple flat plate which will be machined in most production volumes.

The cover keying blocks, shown in figure 17, serve two purposes. First of all, one of the two blocks protects the CPM interconnect as it passes out of the armor enclosure and into the dust cover-protected chassis volume. Secondly, the keying blocks support the armor cover against any shear forces attempting to dislodge the cover. The six screws attaching the armor cover are sized only to resist the modest tensile loads which will occur during a crash environment. The large compressive and shearing loads will be resisted by the top edge of the base and the keying blocks, respectively.

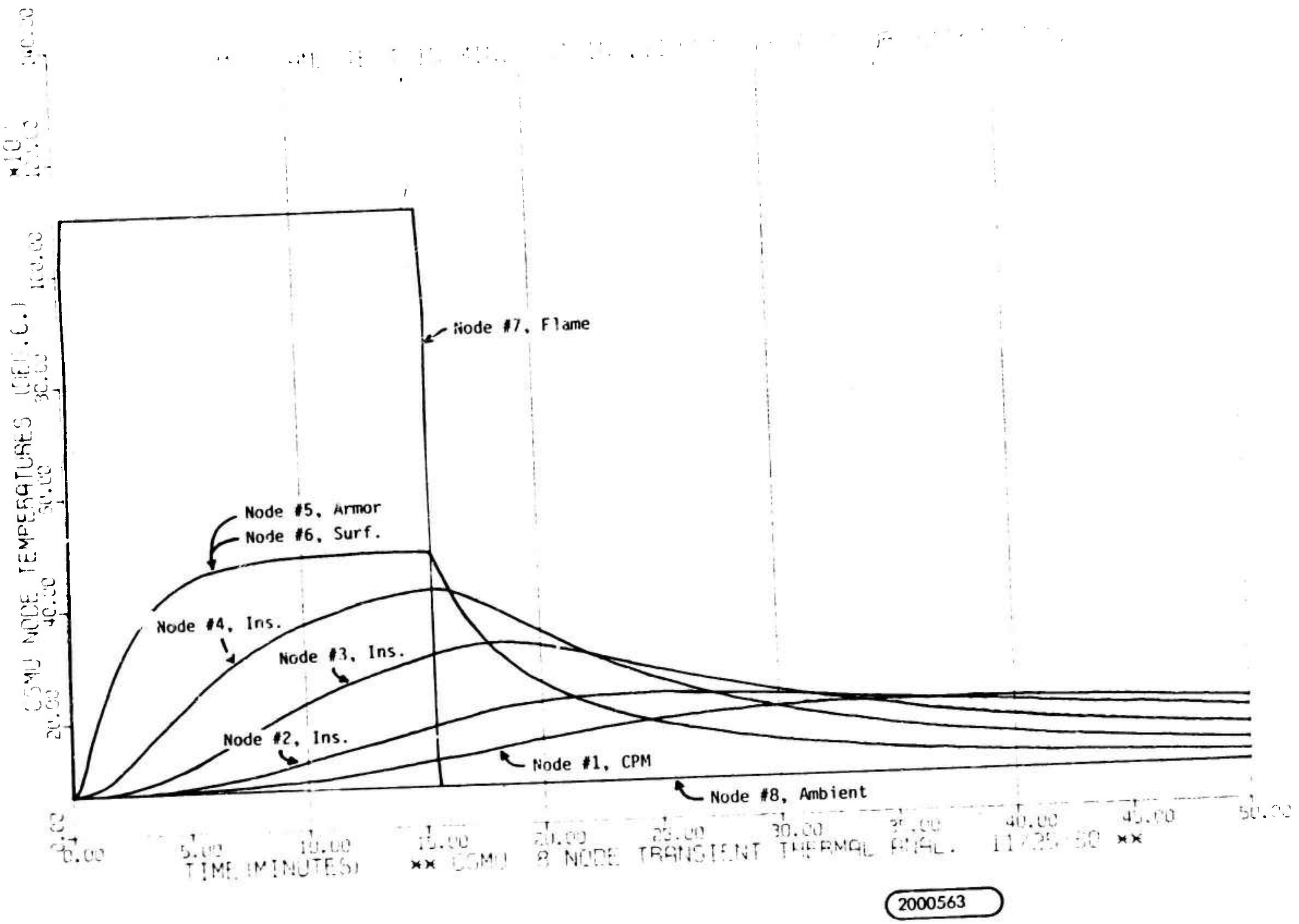

Figure 19. CSMU Flame Test per TSO C51A (Run No. 6)

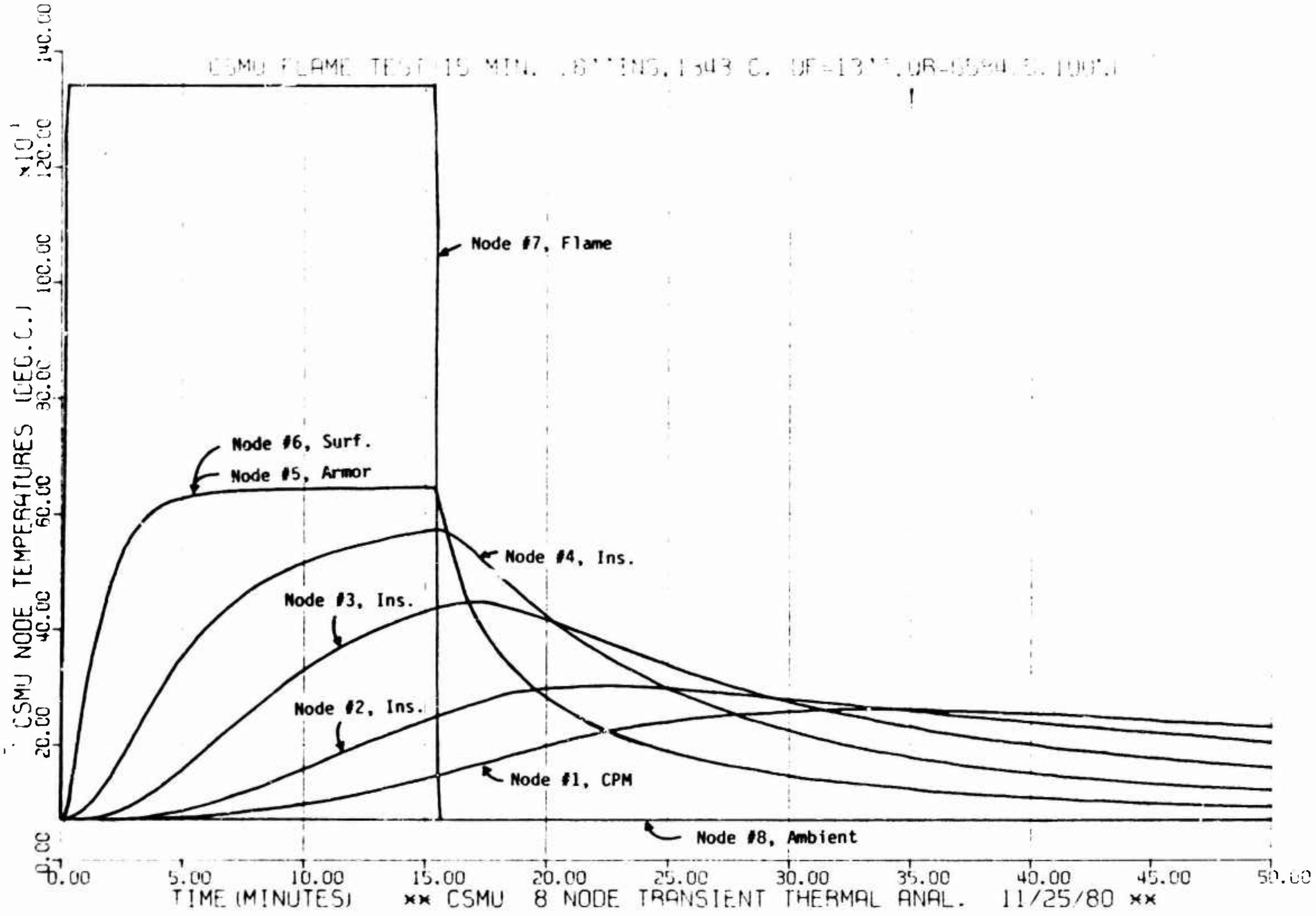

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Figure 20. CSMU Severe Flame Test (Run No. 10)

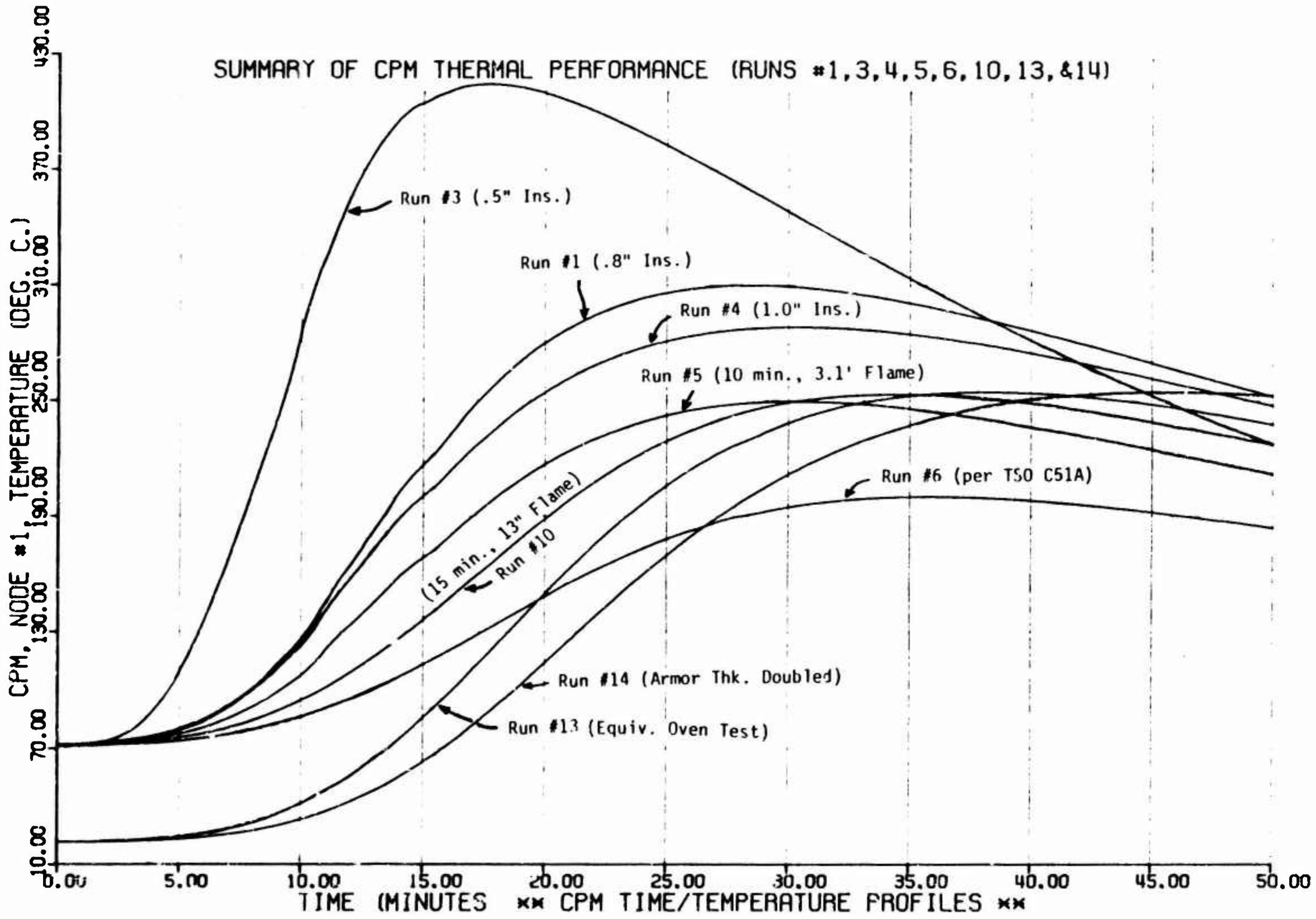

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Figure 21. CPM Thermal Performance

The four mounting feet and attachment bolts are not intended to keep the CSMU attached to the aircraft structure following a severe crash. There is no need for it to remain attached to the structure, which itself is undergoing major mechanical damage, and fracture into many small pieces. The survivability of the CSMU will be enhanced as impact durations are shortened and the kinetic energy ($\frac{1}{2}MV^2$) will be lower, assuming identical velocities but lower projectile mass. The CSMU armor enclosure will exhibit adequate mechanical protection for the CPM and the Min-K insulation.

3.1.3.6 Crash-survivability prediction - A prediction of the survivability of the CPM data, based on USAF mishap data, is an extremely challenging task. Regardless of the conclusions, they can be easily criticized and refuted. The very nature of the problem allows for the utilization of little but one's best engineering judgement. Assuming that the CSMU will surpass the test requirements recommended in 3.1.3.2, the following A/F/T crash survivability rates are predicted.

a. Mechanical damage. With the CSMU mounted in the wing or tail cone areas, total mechanical damage will be incurred only 11 to 13 percent of the time; major mechanical damage only 9 to 16 percent of the time (based on the 35 A-10, F-15, and F-16 accidents reported in table 16). Our CPM should survive intact, 100 percent of the major and at least 80 percent of the total mechanical damage crashes. This gives a non-survivability rate of only 2.2 to 2.6 percent, in which the CPM did not survive intact. Of this 2.2 to 2.6 percent, an additional retrieval effort will allow the data to be read out nearly 100 percent of the time. Fly lead damage, and possibly silicone memory die damage, may reduce this lower level data retrieval success rate to 90 percent. Therefore, the data failure rate will be at most .3 percent.

b. Fire damage. With the CSMU mounted in the wings or tail cone, total fire damage occurs zero percent of the time and major fire damage 4 to 9 percent. Since the CSMU can survive a 15-minute test in which significant or total aluminum meltdown will occur, 99.9 percent survivability is predicted.

c. Combination of mechanical and fire damage. The mishap data in appendix D, where actual accident files were reviewed, indicates that severe mishaps initiate both severe mechanical and severe fire damage sequentially. Therefore, if the CSMU is only 80 percent survivable when total mechanical and major fire damage occur, at most the failure rate will be 1.8 percent (20 percent times 9 percent, the maximum rate of major fire damage).

The crash survivability requirements will guarantee passage of most of these combined environments.

d. Other. There will, without a doubt, be CPM data survival failures which cannot be attributed to fire and mechanical damage. The largest share of these could possibly be due to a malfunctioning CSFDR system or a bad sensor signal received by the system, caused by a normal in-flight failure. However, if the system operability is mandatory as a GO/NO-GO pre-flight requisite, this failure mode should be less than .5 percent. Another cause of failure could be an abnormally weak memory chip which goes undetected and fails in either the mechanical or the fire damage environments. This would result in the loss of a portion of the CPM data. Still another possibility is that the data completely survives the crash and then somehow suffers abuse prior to retrieval. However, assuming that proper Air Force and supplier procedures are in effect, all of these failure modes should not amount to a 1 percent failure rate.

e. Conclusions. The failure rates listed above are: mechanical damage .3 percent, fire damage .1 percent, fire and mechanical damage 1.8 percent, and other damage 1 percent, for a total failure rate of 3.2 percent. With this in mind, it would seem safe to guarantee a better than 96 percent survival rate and to expect the actual survival rate to approach 98 percent. On the other hand, if the CSFDR system were to be designed to meet only the TSO C51A requirements, an 80 to 85 percent survivability, at best, could be expected.

3.2 Technical approach

3.2.1 Tri-service standardization investigation - The primary purpose of this section is to make a specific recommendation concerning the potential for standardization among Air Force, Navy, and Army applications. In order to complete this task, conflicting requirements, if any exist, must be identified and analyzed. The primary vehicles for identifying Navy and Army requirements are the ULAIDS (Universal Locator Airborne Integrated Data System) and AIRS (Accident Information Retrieval System) programs, respectively. Additional data was obtained via questionnaires directed to Navy and Army personnel concerned with military aviation safety.

3.2.1.1 ULAIDS program - This program attacks crash-survivable flight data recording from the Navy viewpoint. Its' system includes two recorders: 1) an AHMR (Aircraft Health Monitoring Recorder) and 2) a FIR/UL (Flight Incident Recorder/Universal Locator) package. Currently, the AHMR is a tape unit. The FIR is being approached from both the tape and solid-state electronic memory technologies. Additionally, the ULAIDS system includes the following equipment:

- Two Signal Acquisition and Conditioning Terminals
- Master Monitor Display
- Data Entry Panel
- Two Multiplex Terminal Units
- Interconnecting Cables

Production targets for total system weight, size, and power are 89 pounds, 5121 cubic inches and 358 watts, respectively.

Additionally, a maximum of 374 sensor/parameters can be recorded. Two unique features related to ULAIDS are 1) the FIR/UL is an ejectable package, and 2) one of the parameters required is voice (audio).

3.2.1.2 AIRS program - This program attacks crash-survivable flight data recording from the Army viewpoint. A solid-state, non-ejectable recorder is used for recording, in which the actual data module is designed to survive requirements in excess of TSO-C51a. Production targets for total system weight, size, and power are 7.62 pounds, 190.5 cubic inches, and 25 watts. Also, a capability of multiplexing 18 analog and 18 discrete signals exists within the AIRS recording unit. A unique feature of the AIRS design is its capability of surviving impacts up to 150 gs for a duration of 10 milliseconds. This feature permits acceleration of the crew-space area to be measured during impact, and consequently, design improvements for crew safety can be made. However, an additional accelerometer package is required to provide this capability since most aircraft are not equipped with accelerometers that have the 150-g range.

3.2.1.3 Tri-service requirements

a. Flight parameters. Navy and Army parameter lists were reviewed. These lists included the proposed F-18, A-7E, AN/ASH-20, NPS-1, NPS-2, ULAIDS, minimum AIRS, intermediate AIRS, and recommended AIRS. The USAF recommended CSFDR can handle all of the parameters reviewed with two exceptions.

(1) Audio as required by the ULAIDS list.

(2) Three axes of impact gs in the ± 150-g range for the AIRS lists.

Neither of these two parameters (audio or impact gs) are recommended for the USAF list. This does not imply that these two parameters are not useful in their intended applications. However, keeping in mind that the CSFDR system primary design constraints for the A/F/T problem include size, weight, and LCC, these additional parameters are not recommended for the USAF. The audio parameter has a severe impact on the size, weight, and cost due to the separate audio conditioning unit and expanded memory required (5.5 million bits to store 15 minutes of audio). The desire to record impact accelerations requires that a separate accelerometer package be located near the cockpit area, and that the recorder electronics remain functional through the first ± 150 gs of impact. This requirement also adversely affects size, weight, and LCC and appears to be of limited value to the A/F/T problem.

b. Installation. The Navy- and Army-required installations do not pose a problem to the recommended CSFDR design. The Navy desires an ejectable memory pack which has the added capability of floating after aircraft impact with water. It is felt that this approach is the best one for the Navy because of the high percentage of accidents which occur at sea. Since the recommended CSFDR system design has a separate memory pack (CSMU), it is a relatively simple task to package the CSMU on an ejectable air foil and provide the Navy with this needed capability.

The Army does not require an ejectable memory pack and since the impact accelerations of an Army helicopter are quite low when compared to those of an A/F/T aircraft, no problem is envisioned for CSFDR installations for Army applications.

c. Crash survivability and packaging. The A/F/T crash-survival requirements are the most severe in the entire avionics industry. This is due to the smaller overall dimensions of the aircraft, and the severity of high velocity/high impact angle crashes. In the case of the Navy, where an ejectable pack is required, the crash environment is relatively benign in terms of impact, penetration, static crush, and fire. Obviously the water immersion requirement is very important. however, the proposed CSFDR system meets the Navy water immersion requirement.

In the case of the Army, the impact, penetration, and static crush requirements are typical of commercial airline requirements. However, because of the lower velocities and unique construction of Army helicopters, the probability of the CSMU remaining in the post-crash fire is increased somewhat. This potential problem can be offset by locating the CSMU away from the fuel tank areas. The Army water immersion requirement of four weeks is compatible with the equivalent recommended CSFDR system requirement.

Thus, in summary, the Navy and Army survivability and packaging requirements do not pose a problem to the CSFDR system.

d. Crash-protected memory required. The CPMs for Configurations I and II are 8K x 16 bits and 4K x 16 bits, respectively. The recommended memories for the ULAIDS and AIRS recorders are approximately 6,000,000 bits and 32,000 bits, respectively. If the requirement to record audio is removed from the Navy system, only 500,000 bits ar required, and if a bit compression ratio of 10/1 can be achieved for the Navy data, a CPM of 50,000 bits would be sufficient. Therefore, both the Army and Navy requirements could be satisfied by the Configuration II CPM of 4K x 16 bits (65,536 bits), even though these systems are configured to nominally retain the last 30 minutes of data (and in the case of the Navy, 15 minutes of audio).

Thus, the projected USAF CSFDR system crash-protected memory ranges are adequate for the Army and Navy applications.

Note: It must be remembered that not all Navy paramter lists include audio, and therefore, audio is not viewed as a firm requirement, even though it is a highly desirable one for the Navy.

e. Data/conversion data processing/data compression. The data conversion functions are extremely similar for all three services, even though the actual parameters may be unique. For example, the Navy FIR list includes arresting hook position as a parameter. This parameter is sensed as a discrete. The CSFDR system DPU samples and converts discretes regardless of what the discretes represent. Similarly, the Army lists include rotor RPM as a parameter. This parameter is sensed as a frequency input. The CSFDR system DPU samples and converts frequencies to digital words regardless of what the frequencies represent.

The CSFDR system DPU data conversion modules contain the following types of capabilities:

- Synchro/resolver/LVDT to digital
- DC to digital
- AC to digital
- Frequency to digital
- Discrete to digital
- Aircraft MUX Bus Interface (standard 1553, and non-standard)

The Army system, for helicopters, requires only 18 analog and 18 discrete inputs. This is well within the CSFDR system capability. Also, the Navy system requires a typical signal capacity of 72 discretes and approximately 71 analog inputs. The multiplexing capability designed into the CSFDR system is also adequate for these conversions.

Also, of extreme importance, is the fact that all three services are going to the MIL-STD-1553 aircraft MUX bus architectures. Thus, the MUX bus interface of the CSFDR system is directly applicable to the tri-service problem, and as modern aircraft approach an all-digital type, the aircraft integration of a tri-service CSFDR system will become a relatively easy task.

The actual data processing/data compression functions of the CSFDR system are very comparable to those that would be required for the Navy recording system. For example, the F-15 throughput and compression ratios would be very similar to those of the F-18. Also, the dp/dc functions of the CSFDR system are more than adequate for the Army system since the number of signals and resulting data rates are much lower. It should be noted, however, that parameter labels, limits, and aperture sizes may vary within the tri-service applications and threfore some minor software changes will be required. However, it must be emphasized that the CSFDR system is programmable and reprogramming is not a problem. (The CSFDR system must be programmable even for the USAF programs because, as aircraft age, it may become desirable to reprioritize the parameters and add or delete parameters as desired by accident investigators.)

Thus, in summary, the data conversion, data processing, and data compression routines are adaptable to the tri-service problem.

f. Ground readout facility and associated software. The ground readout facility and associated software should reside at a separate location for each service. Since DOD 5000.31 specifies Fortran IV as an acceptable language for ground-based machines for all three services, it is recommended that this language be used for all three services to assure maximum compatibility.

However, a tri-service readout facility is not recommended. The NTSB is not currently staffed or equipped to handle a tri-service readout capability. Additionally, their definition of transportation does not include military operations. The Navy's North Island facility is planned for Navy readouts, and this facility is not recommended for the USAF.

In summary, we feel that each service should maintain its own readout facility because of the frequency/demand relationship and independent locations of accident/ mishap data which are already in existence.

g. Security protection of data. Security protection is discussed in 3.2.5 for the USAF. The Navy applications require data encryption standards. We also recommend these standards for the Army applications, although they are not currently required. Once the security protection features have been integrated into the CSFDR system, they are also directly applicable to the Navy and Army problems. Because this feature is easily incorporated into the recorder systems, it is recommended for all three services.

h. Military directives. Appendix F shows the Cross-Reference of Military Directives Related to Aircraft Accident Safety Investigations and includes the NTSB and Coast-Guard directives. Although the definitions, procedures, methods of recovering data, etc. vary from service to service, no conflicting requirements were found which could potentially arise out of the implementation of these directives insofar as the recorder and use of its data were concerned. In fact, in the case of a mishap involving military aircraft from two or more services, a common recorder would be beneficial to the joint mishap board since the resulting formats of data presentation would be common.

i. Expanded recording function. In terms of conversion, processing, and compression, the DPU can handle the expanded recording functions of ASIP, TEH, and FC monitoring for the USAF applications. However, separate solid-state, non-survivable memories were recommended for these functions. This separation of the non-survivable memory is recommended for the USAF; however, it is required for the Navy AHMR function since the Navy policy is to separate the "maintenance data" from the flight incident data. A common processor, however, can be used for both functions.

Expanded recording functions are not required for the Army recorder, however, if they become a requirement in the future it is recommended that a separate, non-survivable memory package be used for these functions.

Thus, the approach taken for the USAF CSFDR program is not in conflict with the expanded recording requirements of the other services.

j. Large-scale standardization. Large-scale standardization is desired by all three services. A classic example is the standardization of the Navy FIR/UL for the P-3 and A-7 aircraft. The approach recommended for the USAF CSFDR system does not present a conflict in terms of large-scale standardization for other services.

k. Summary of tri-service standardization investigation. Table 22 shows the areas of investigation for tri-service standardization along with the recommended USAF CSFDR approach. Areas, in which the recommended approach agrees with or conflicts with Army and Navy concepts, are also shown in the table.

3.2.1.4 Conclusions of tri-service standardization study - The design approach recommended for the USAF CSFDR system permits a tri-service standard recorder to be produced if potentially conflicting requirements are resolved. The first potentially conflicting requirement is that of recording audio information. The desire to record audio has a negative impact on volume, weight, and LCC of the installed recording system. Additionally the initial area of crash-survivable memory is adversely affected and the required memory for compressed audio is approximately two orders of magnitude over and above that required for compressed data. The desire to record audio also implies microphone station integration and a separate audio conditioning unit. However, this discussion does not imply that audio data is not useful in an accident investigation. Moreover, the desire to record audio in the Navy systems is not a firm requirement at this time. This fact is evident in the recent parameter list for the F-18. Thus, on a temporary basis, until the state-of-the art for digitizing audio and related memory densities each improve, we recommend that audio not be included as a firm requirement for tri-service standardization involving A/F/T aircraft.

The second potentially conflicting requirement is that of recording impact accelerations during a catastrophic mishap. Although such data can be of great value in designing the crew space area for low velocity aircraft, the adverse effects on weight, size, and LCC of carrying this capability through to all production units does not seem realistic. Therefore, we do not view this capability as a requirement for production units in any of the services.

Therefore tri-service standardization is feasible and compatible with the recommended USAF CSFDR system approach if audio and impact recording are not firm requirements. The Navy desire for "deployable and floatable" memory packs is justified and does not present a conflicting requirement to the recommended approach because the CSMU is a separate module and may be packaged on an ejectable air foil.

The LCC of a tri-service standardization program for crash-survivable flight data recording would be less than three individual programs (one for each service). For a tri-service program, resulting in production quantities of 30,000 recording systems, the LCC cost savings of 50% is estimated based upon similarity to existing programs within DOD. However, once the decision has been made to develop a tri-service standard, provisions should be made for a primary and a secondary source from the very onset of the program.

Table 22. Summary of Findings for the Tri-service Standardization Investigation

AREA OF INVESTIGATION	USAF CSFDR RECOMMENDATION	COMPATIBLE WITH USN CONCEPTS	COMPATIBLE WITH USA CONCEPTS
Flight parameter	Configuration I, Configuration II lists	no (audio desired)	no (impact gs desired)
Installation	Separate memory packages	yes	yes
Crash-survivability and packaging	Exceeds TSO C51, separate memory pack	yes (ejectable memory)	yes (non-ejectable)
Crash-protected memory	131,072 bits/ 65,536 bits	yes (6,000,000 bits with audio but, 50,000 bits with data compression for flight data only)	yes (32,000 bits with data compression)
Conversion/ processing/ compression	All signal types/ microprocessor adequate/compression used	yes/yes/yes	yes/yes/yes
Ground readout facility	Three choices	Need separate facility(s)	Need separate facility(s)
Security protection	Optional, but design concept feasible	yes	yes
Military directives	Compatible with USAF regulations and manuals	yes	yes
Expanded recording	Separate mass storage unit	yes	yes
Large-scale standardization	yes	yes	yes

3.2.2 Use of the CSFDR system on future A/F/T aircraft - The basic CSFDR system will provide maximum adaptability for application to future A/F/T aircraft such as the next generation trainer, the B-52 Companion Trainer, Stealth derivative aircraft, and forward swept wing fighter. Figure 22 shows the general procedure which will enhance usage of the CSFDR system on future A/F/T aircraft while incorporating new technologies as they become available. The procedure begins with an analysis of the existing sensors on the aircraft under consideration. The accuracy, type, range, dynamic characteristics, and availability of signals will be determined. Since MIL-STD-1553 is extremely likely to be implemented on future aircraft, it is also likely that the vast majority of required parameters will be available on the data bus. The list of required and desired parameters for accident/mishap investigation developed in 3.1.1 will be compared to the parameters available on the aircraft. If the sensors and parameters are not sufficient to conduct an accident/mishap investigation, a list of new sensors required will be made. This list will include the required sensor characteristics and the total cost associated with their integration on the aircraft in a format similar to that given in 3.1.1.

The next step required is a data conversion analysis. This step may not be required if the MIL-STD-1553 bus is available and contains the required parameters. All sensor data can be conditioned and formatted, as well as providing the data from degraded modes as failures occur, by integrating CSFDR system requirements into the aircraft central computer and outputting words on the data bus. The recorder is then treated as an additional terminal. In the event that some of the required signals are not on the 1553 data bus, the analog-to-digital conversion, digitization, discrete-data conversion, and multiplexing requirements will have to be identified. If such is the case, the I/O adequacy of the CSFDR system will have to be determined. If new I/O functions are required, they will be defined and total cost for their incorporation will be computed. However, in view of the broad multiplexing capabilities of the DPU, it is very unlikely that new I/O functions will be required.

The data conversion analysis is followed by a data-processing analysis in which the airborne program is examined for application on the new aircraft. In this step, the parameter list, recording rates, data compression subroutines, and other special requirements such as built-in test, warning flags, and readout capability are examined for adequacy. If they are not adequate for the new aircraft, the required software modifications will be outlined and the cost of these modifications will be computed. Correspondingly program changes and associated costs for modifying the readout facility software will be defined and computed respectively. The cost of this step is minimal since the CSFDR system is programmable and is not operating near its saturation levels.

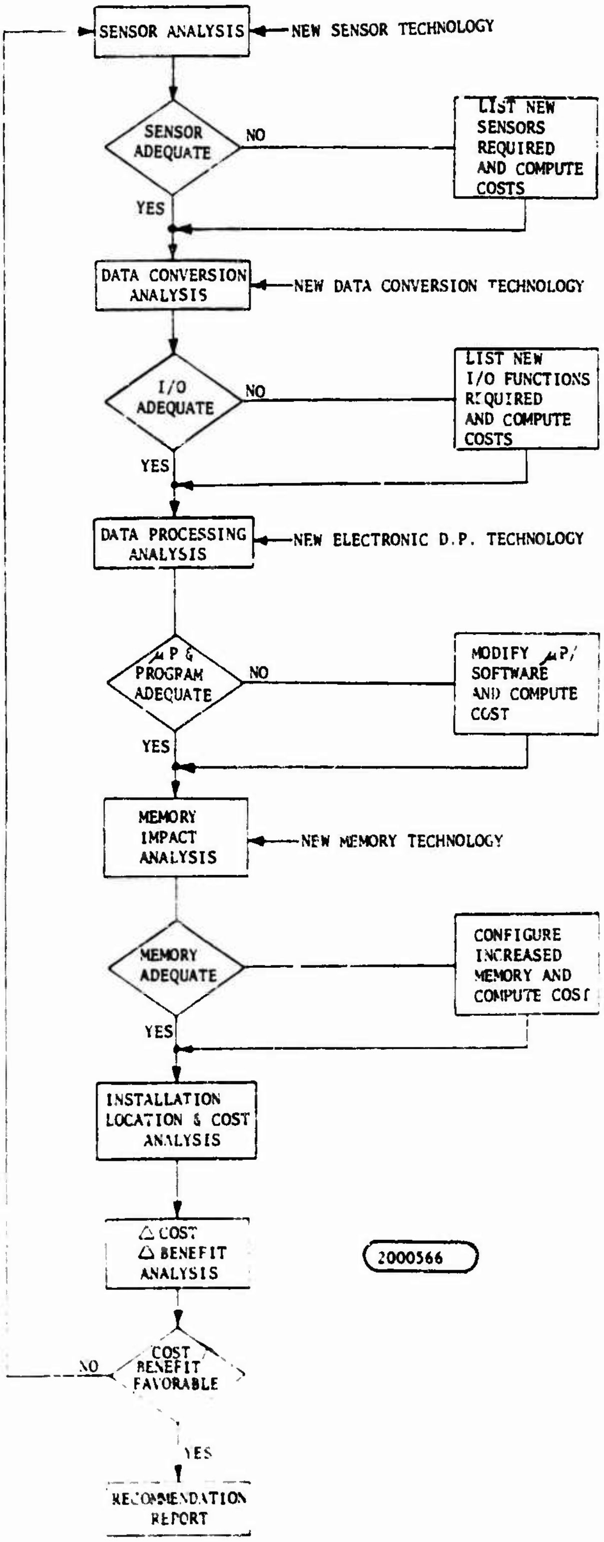

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Figure 22. Future A/F/T Application Procedure

The fourth and most important step of figure 22 is the crash-survivable memory impact analysis. Here the memory size, required to support the recording as determined in the preceding steps, will be determined and compared to the existing CSFDR system memory. If a memory expansion is required, new and improved memories will be examined and traded off against expansion of the survivable memory with the existing technology. Costs for the recommended approach will be identified.

An installation analysis is the next step. Mounting locations for the CSFDR system (DPU, CSMU, and cable routing) on future A/F/T aircraft are unknown at this time. The CSFDR system and installation will be tailored to each aircraft based on aircraft design, mission, and specific CSFDR requirements. The aircraft design will be reviewed and potential DPU and CSMU locations will be selected as well as potential routes for electrical cabling. The potential locations will then be analyzed with respect to existing and projected accident/mishap data, aircraft mission and CSFDR system requirements, and an installation concept will be selected to provide maximum system performance and survivability. Also included in the analysis will be weight and balance impact, cable lengths, and mounting requirements. Installation costs will be computed at this point The installation cost will be relatively small based on the CSFDR system being installed as original equipment during manufacture of the airframe. Installation of the CSMU in an aircraft extremity is very likely.

The next step consists of making a cost/benefit summary for application of the standard FDR to the new aircraft under consideration. All of the costs associated with the previous steps will be tallied, and the resultant LCC computed. Then, the projected accident rate for the new aircraft will be calculated with and without the CSFDR system to determine the expected accident rate reduction due to the CSFDR system. The accident rate reduction can then be translated into dollar savings during the useful life of the aircraft fleet. The total dollar savings include the cost of aircraft saved, the cost of accident investigations, the cost of salvaging the crashed aircraft, and the cost of replacing lost aircrews. Such a cost/benefit analysis will be performed in the same manner as the analysis in 3.5 of this report. If the cost/benefit analysis results are not favorable, all of the above analyses will be repeated as shown in figure 22 until a favorable cost/benefit summary is obtained. In the unlikely event that a favorable cost/benefit cannot be obtained after a few iterations of the process in figure 22, the results of the analysis will be summarized and a recommendation will be made based on the results.

Once a cost/benefit summary is obtained, a recommendation report will be prepared and delivered to the Air Force program manager of the subject aircraft. Contained in the recommendation report will be a proposed CSFDR system tailored to the new aircraft to provide maximum system performance and survivability. The report will also include summaries of all the analyses shown in figure 22 as well as a summary of the cost/benefit analysis.

Figure 22 is designed to handle all cases and the reader should not be alarmed when reviewing it. The recent success of MIL-STD-1553, advances in microprocessor capability, and incorporation of growth capability into the standard FDR functions, lead us to believe that the majority of decision blocks in figure 22 will be executed on the "yes" branch and the Δ cost computed will be very small in relationship to the value of benefits.

The impact of incorporating future technologies such as improved sensors, improved signal conditioning and I/O hardware building blocks, improved microprocessors, improved RAM and PROM technologies, and improved crash-survivable memories will be made evident in the cost/benefit summary. During each of the analyses in figure 22, incorporation of new technologies will be considered. Corresponding costs and data will be incorporated in the procedure. By designing standard hardware building blocks, standard instruction sets, and growth capability into the standard CSFDR system, a significant performance improvement can be achieved at minimal cost impact through incorporation of new technical advances. Figure 22 is a general procedure which will enhance the use of the proposed standard FDR on future A/F/T aircraft while maintaining the flexibility required for the injection of new technology.

Advances in survivable memory technology are easily incorporated into the CSFDR system concept. This is due to the fact that the survivable memory (CSMU) is designed as a separate building block and communicates with the DPU over a standardized bus. Thus, new survivable memories can be incorporated into the system without affecting the standard DPU design.

Configuration III is the recommended configuration for future aircraft. Procurement of Configuration III will eliminate the need for additional recorders, and all of the recording requirements will be satisfied under a single, standardized recording concept.

3.2.3 Large-scale standardization investigation

3.2.3.1 Need for large-scale standardization - Standardizing the CSFDR system for A/F/T has a significant effect on the LCC and resulting cost/benefit ratios. Therefore, broadening the scope of standardization to include bombers, cargo, transport, and helicopter aircraft should have an additional positive effect on the LCC and overall cost/benefit ratios.

Additional need for large-scale standardization is evident in the Statement of Need.[3] Paragraph 4.g of the MENA states that "there should be sufficient standardized capability to permit adaptation of the CSFDR system to larger aircraft and/or helicopters should the mishap data for those aircraft support later incorporation." However, it should be noted that many large aircraft in the DOD inventory now use FDRs. Examples are the C-141, C-5A, P-3, S-3, and B-1 aircraft.

3.2.3.2 Time from critical event to mishap - In 3.3.2 (data processing/data compression), the assumption is made that the vast majority of A/F/T mishaps can be resolved by retaining the last 15 minutes of flight in the CSMU. Indeed, discussions, with safety personnel indicate that the last 5 minutes is often adequate and in many cases the last minute is sufficient for A/F/T mishap investigations. This assumption, of retaining the last 15 minutes of flight, thus appears to be more than adequate for the A/F/T problem, however, it is not a valid assumption for larger, lower performance aircraft.

Figure 23 shows the percentage of accidents (for commercial-type aircraft) which can be resolved by retaining variable amounts of pertinent recording times. This data is based upon NTSB and USN ULAIDS studies and is applicable to aircraft such as the Boeing 727 and the Lockheed P-3C. This figure shows that in order for the recorder to be beneficial in over 95 percent of mishap investigations for larger aircraft, a pertinent recording time of 30 minutes is a better assumption. Therefore, for the larger, lower performance aircraft, it is recommended that the data processing/data compression techniques permit a nominal time of 30 minutes of data to be retained before memory wraparound occurs. This will provide an adequate margin of safety for turbulent flights in which memory wraparound could occur in less than 30 minutes.

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[3] Ibid.

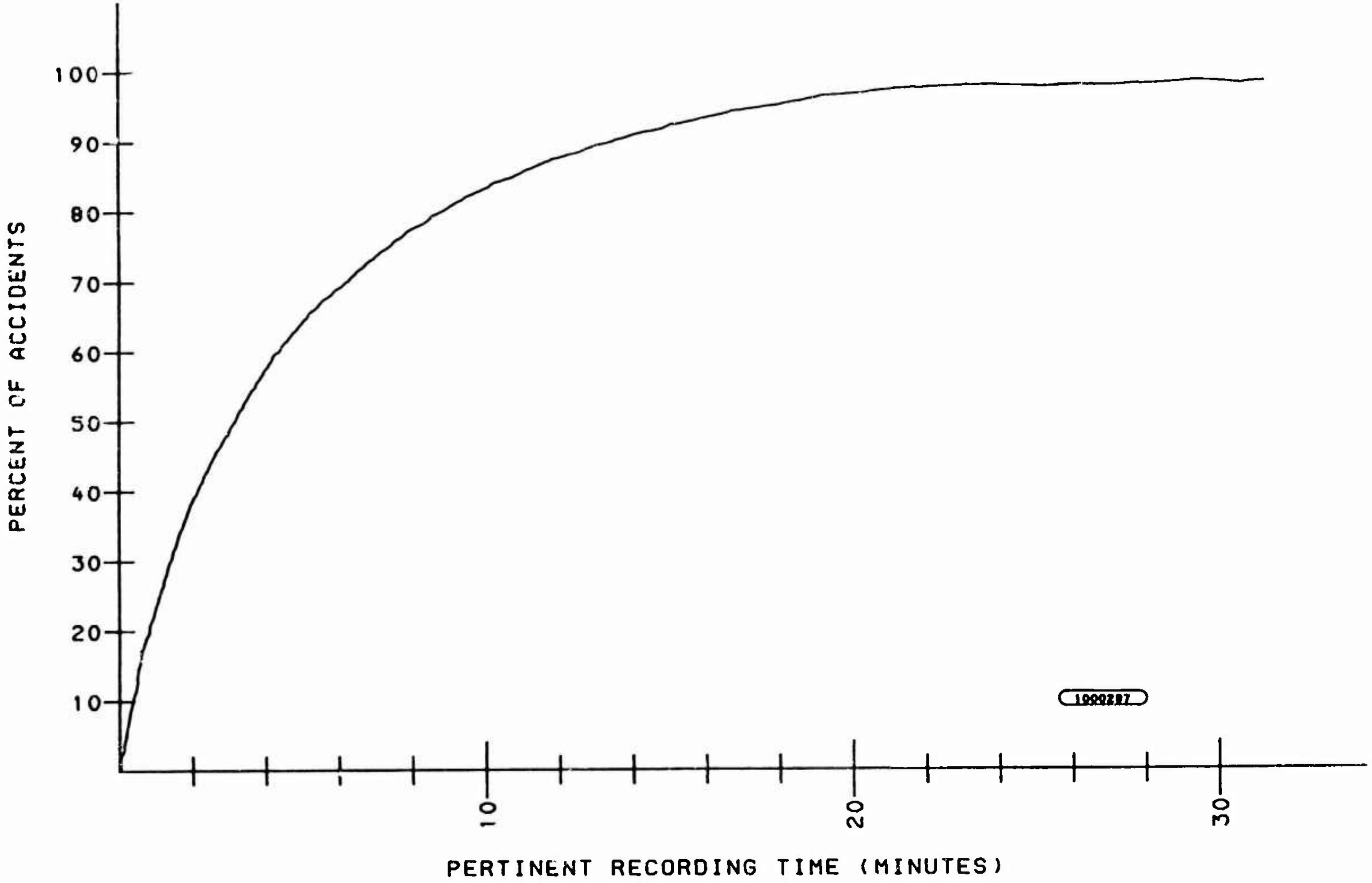

Figure 23. Pertinent Recording Time Distribution for Large Aircraft

3.2.3.3 Parameter lists for large aircraft and memory required - A very wide range of parameter lists exists for the larger military aircraft. These lists vary from the very simplified list associated with metal foil type recorders, which are comprised of about 5 to 10 basic parameters, to the very comprehensive lists associated with tape FDRs, such as the B-1 bomber list which is comprised of 40 basic parameters over a 30-minute recording interval. However, these lists do not pose a problem to the selected CSFDR system concept. As was shown in 3.1.2, the decision was made to separate the CSMU from the DPU. This separation allows a family of CSMU modules to operate in conjunction with a single DPU. Therefore, a separate CSMU is recommended for application to large aircraft which require comprehensive parameter lists for extended recording times. This CSMU shall operate in conjunction with the standard DPU.

Based upon our review of parameter lists, it is recommended that the expanded CSMU be capable of recording 120 signals (approximately 40 to 60 parameters) for a nominal time period of 30 minutes. Based upon the data processing/data compression techniques of 3.3.2, this translates to a requirement for the CPM of 16K x 16 bits/word (262,144 bits).

3.2.3.4 Installation on large aircraft - Installation on large aircraft is straightforward, and, in fact, easier than on A/F/T aircraft. This is primarily due to the relaxing of the size and weight restriction and to the larger availability of space on these aircraft. Moreover, a requirement for a deployable unit can be satisfied by simply packaging the CSMU on the ejectable package (air foil or other), if a deployable unit is desired.

Historically, recorders for these aircraft have demonstrated a higher degree of survivability when the recorders were installed at or near the tail sections of the aircraft. The recommended approach of separating the CSMU from the DPU would permit the CSMU to be installed in or near the tail section and would minimize the overall weight impact to the aircraft since the sensor input lines would not have to run to the tail section, but only to the DPU.

3.2.3.5 Crash survivability for large aircraft - The environment for helicopter, cargo, transport, and bomber aircraft tends to be less severe in the impact area, and more severe in the areas of penetration and static crush. This is a direct result of the slower moving, more massive aircraft. Historically, TSO-C51A has been adequate for these aircraft, especially when the recorder is located in the tail section. Therefore, the CSMU for the large aircraft should be designed to meet the crash-survivability specifications of TSO-C51 with a slight increase in the flame test time to allow for application to helicopters which historically have localized post-crash fires. Therefore, the crash-survivability specification recommended for the large-scale integration CSMU is as shown in table 23.

Table 23. Summary of Major Crash-Survival Requirements for Large-Scale Integration CSMU

Impact	1000-g half sine wave for 5 msec
Penetration	500-lb weight dropped from 10 feet on 0.05-square inch area
Static crush	5000-lb continuous
Fire	1100°C on 50% of outside area for 24 minutes
Water	Immersed in sea water for 4 weeks (or equivalent accelerated test)

3.2.3.6 Data conversion/data processing/data compression for large-scale integration applications - In general, the discussions of the conversion, processing, and compression functions in 3.3.2 are also applicable to the large-scale integration aircraft. The full range of signal types can be converted within the DPU signal conditioning subsections. In some cases, certain parameters may have to be rescaled. For example, an eight-bit word is used to provide a 30,000-pound range with a resolution of 117 pounds for the A/F/T applications. For some large-scale applications the same eight-bit word would provide a 225,000 pound range but only to a resolution of 879 pounds (the KC-135A has a total net fuel capacity of 203,288 pounds). The processing and compression functions used for the A/F/T applications are also directly applicable to the large-scale integration aircraft. In fact, in most cases, better bit compression ratios would be attained, although this would not necessarily be true for higher performance bombers such as the B-1. Some aperture sizes could be widened in order to achieve better bit compression ratios while maintaining enough accuracy to conduct meaningful accident investigations. These minor changes in DPU functions are easily achieved because of two factors.

- The DPU is reprogrammable.
- The processor resident within the DPU is operating at approximately 10 percent of its throughput for the A/F/T application and, therefore, easily accommodates new functions.

3.2.3.7 Multiple recorders - In order to achieve extremely high reliabilities and survival rates, some large-scale integration candidates such as the B-52 may desire two recorders on board. Totally independent data buses may also dictate that some aircraft have two recorders on board. This concept is easily achieved in either of two ways:

- Use a separete DPU and CSMU for each recording system.
- Use a single DPU to drive multiple CSMUs.

3.2.3.8 Expanded recording functions for large-scale integration - Expanded recording functions for the large-scale integration applications are also feasible. In fact, in many cases, these functions have less of an impact on the CSFDR system than corresponding requirements for the A/F/T configurations. For example, in the case of ASIP functions, the B-52 requires fewer parameters than either the A-10, F-15, or F-16, although longer time histories are involved. In general, the expanded recording functions for the large-scale integration aircraft are comparable to those of the A/F/T class.

3.2.3.9 Large-scale integration recommendation - The recommended approach is compatible with the concepts of large-scale standardization. However, this requires an additional building block module for the family of CSFDR system configurations. The additional module is a new CSMU over and above that required for A/F/T standardization applications.

3.2.4 Expanded recorder functions (Configuration III) - Expanding recorder functions to include turbine health parameters and ASIP parameters has only a modest effect on increasing the computing capacity requirements of the CSFDR recorder system. Signal conditioning and preprocessing requirements increase in proportion with quantity and type of added parameters. Engine health recording is considered first, followed by a discussion of incorporating ASIP recording.

If engine health recording is added to the CSFDR Configuration I, then very little addition is needed for ASIP incorporation. The need for adequate ground readout equipment at each base would already be established. Compiling ASIP data, removed with engine data, would require only a small simple addition to the ground readout equipment. One additional non-protected memory in the aircraft could serve both functions. The added memory would require about double the capacity of the engine recorder alone and could be sized according to engine quantity and flight durations.

If engine health recording is not done in the CSFDR, and ASIP only is added, the memory size will be made larger to decrease the readout interval which reduces the frequency of recording media removal and handling. ASIP is trend data and is used basically in long-term planning in airframe life maintenance or extension. A more complicated data handling would result from lack of a local readout capability and a need to send paperwork and recording media to a central data facility. An added ASIP-only solid-state memory with a 15-hour capacity and requiring many units per aircraft to fill the mailing system pipeline would raise the total system cost. In combination with the engine health recording, ASIP data could be accumulated on computer cassette tape for monthly transmittal to the data processing center, or printouts could be forwarded directly to the ASIP office, effecting considerable time and savings.

This concept looks particularly inviting where new engine health programs are being considered anyway. Pertinent programs are the requested TEMS (turbine engine monitoring system) for the A-10 and the EDS (engine diagnostic system) for the F-100 engine used in F-15 and F-16 aircraft. These systems will be discussed further in paragraphs dedicated to the specific aircraft.

A Configuration III system with both engine health recording and ASIP recording is practical. It is a modestly expanded Configuration I system with an added non-volatile memory (non-survivable memory). A Configuration II system is too limited and, if chosen, should be "stand alone" with engine health and ASIP recorders.

A Configuration III system, unlike I or II, will require recording during ground operation as well as when airborne. The crash-protected memory will still record only as in Configurations I or II.

3.2.4.1 Engine health - The existing engine health recorders can be of the ETTR type (engine time/temp. recorder) which gives time duration that a critical temperature parameter exceeds preset temperature thresholds (such as a low temperature for engine ON time, an intermediate temperature for continuous normal operation, and a high temperature for maximum power time). The TEMS type (turbine engine monitoring system) provides, in addition to a time/temperature history, rpm (N_1, N_2), turbine high pressure output (ahead of combustor), bearing temperatures and vibration, oil temperature, throttle position, BUC and other status, oil pressure, I.T.T., nozzle position as applicable, chip detector, and selected others.

If the minimum CSFDR configuration system is chosen for A/F/T aircraft, addition of the engine health parameters would not be practical because of the necessary added sensing points on the engine and the need for support equipment for daily data dump and readout. The Configuration I system will already record those engine parameters available to the cockpit area. The addition of the remaining desired parameters is relatively easy if it is decided to equip the aircraft with a TEMS or EDS type of system minus the individual processors and recorders. The combined system makes much more economical use of space, hardware, and ground processing equipment than three stand-alone systems.

The additional signals can be processed and compressed in the same manner as the other CSFDR signals except for engine vibration sensors. These signals need a very high sampling rate to reconstruct their signature. The signature only needs recording, however, when changes occur. Certain types of preprocessing, such as use of octave band filters, and RMS level thresholds on these bands, would permit lowering of the sample rate and still permit monitoring of vibration changes.

For engine health, ASIP, and flight control monitoring, a total of 15 hours of recording in a 256 K mass memory (electrically alterable) is assumed and used for later cost analysis to cover all possible applications (including the B-52). If only engine health for a single-engine aircraft, or only ASIP, which is required on only every fifth airplane, is chosen for a Configuration III application, considerably less total memory is required. So many variations exist that only the most comprehensive is used in the model to demonstrate effectiveness.

a. A-10. The A-10 presently has only an ETTR system on-board but is a candidate for a TEMS system, hopefully in the near future. Engine instrumentation designed or installed for a TEMS system can just as easily be recorded in the augmented CSFDR system providing common usage of on-board equipment and ground processing equipment. The specific parameters needed for the proposed TEMS, in addition to those already monitored by the Configuration I system are:

(1) Compressor discharge pressure

(2) Oil temperature

(3) Bearing temperature (probably temperature of four oil scavenge lines)

(4) Vibration sensors (two quadrature pairs or triplets, three to six sensors)

(5) Chip detectors (up to 5) (DC threshold)

(6) Engine serial number (and location)

(7) Aircraft serial number (Date and time can be added upon readout)

The sensors are mostly DC analog type (such as thermocouples) and possibly a synchro AC analog output. The vibration sensors would have outputs similar to microphone outputs which will require preamplifiers and special processing previously mentioned.

The total increase in signals to record is approximately 33 (both engines).

The total number of parameters to record in the mass memory is 46.

b. F-15. The F-15 presently uses an ETTR type of recorder with electromechanical counters showing time/history of low cycle fatigue, hot section time level I, hot section time level II, and engine time. It contains electromechanical indicators for over-temperature, hot start, N_1 overspeed and N_1 sensor fault.

The time/temperature data provides immediate information on probable operating time before replacement, and the indicators provide an immediate no-go status. Much information needed is not available, such as the number of stalls or stagnation durations. This need (and the on-going F-100 engine stall susceptibility) has led to the EDS program. The Engine Diagnostic System program evaluation model is presently on board an F-15 in its validation phase (April '80 - June '81). In addition to the engine parameters presently available in the cockpit and on the ETTR, EEC parameters are monitored and 21 sensors are added. These include a 3-axis vibration sensor on the gear box, four each of scavenge pump oil temperature and pressure sensors, with the seven FTIT probes monitored separately to cover the maximum/minimum temperature spread. Other existent pressure and temperature sensors are recorded.

The data is recorded in a 64-K EAROM and evaluated after every flight during validation (probably daily in operation). A maintenance advisory panel located inside door 48L displays, seven no-go conditions, and seven maintenance advisory parameters. A multiplexer is located on the engine to reduce the wire runs to the recorder. The system uses an 8080 family microprocessor

It is understood that all parameters monitored on the validation system may not be required in a production system. That information should be available at completion of EDS system evaluation. The engine retrofit is extensive enough to make it non-interchangeable with non-equipped engines. Of some concern is that such a system may not go aboard F-15s at all, but only on F-16 and perhaps later designs. Cost effectiveness is yet to be proven in respect to whether all or only some aircraft should be equipped.

Consequently there are several ways any effort to integrate engine health recording into the Configuration III CSFDR system could go.

On the assumption that the F-15 is too far downstream and the cost of an EDS by itself is too high to warrant retrofit, the ETTR parameters and certain selected added parameters could result in a cost effective, reduced scale EDS when integrated with the CSFDR Configuration III recorder.

The following parameters are considered added for Configuration III (the results of the EDS validation will provide the real determination) for the purposes of this study.

(1) P_{T_6} pressure probe

(2) CIVV position (resolver)

(3) Oil temperature (sensor may be present)

(4) Four oil scavenge return temperatures and pressures (very tentative)

(5) Vibration sensor triad on gear box

(6) Chip detector status (4?)

(7) Fan exit temperature (thermocouple)

(8) T_{T2} (inlet temperature thermocouple)

(9) V_{MAX} (switch closure discrete)

(10) Possibly FTIT separation to seven outputs)

(11) Engine serial numbers and location

(12) Aircraft serial number

The above list constitutes the maximum parameters added above those engine parameters already in the Configuration I list.

The total added for two engines, therefore, becomes approximately 57 additional signals to record.

The total parameters to be recorded in the mass memory module is 71.

c. F-16. Most of the foregoing general discussion of the EDS system also applies to the F-16. The odds favor installation of such a system on F-16 blocks yet to be built. Retrofit of those built is more questionable. But if not, it would once again brir, up the problem of engine interchangeability.

If the same parameter assumptions are made as for the F-15, then the same 29 signals (one engine) plus N_1 and an actual nozzle position parameter should be recorded for a total of 31 maximum added for engine health data. The total to be recorded in the mass memory is 37 parameters. If the assumption is made that the entire EDS system parameters will be implemented, then an addition of about 15 more parameters would be made.

The use of a multiplexer on the engine reduces the wire bundle size necessary to go to the recorder (which is probably necessary, particularly for the F-16), but does appear to limit the options for data compression as indicated by the EDS 64-K memory size. The tradeoff between preprocessing for compression ahead of multiplexing would have to be made against the cost of the larger memory required. Preprocessing ahead of the MUX may allow the addition of engine health parameters to an otherwise standard Configuration I processor resulting in overall standardization improvements.

3.2.4.2 ASIP functions - The aircraft structural integrity program presently monitors selected parameters for nearly all aircraft types in the active inventory. These parameters are selected to permit long-term monitoring for analyzing and predicting airframe stress and fatigue life. By monitoring the operational environment, the aircraft can be repaired as required in an orderly and scheduled manner, thus allowing minimum unscheduled down time and the elimination of potentially dangerous conditions. The program is intended to provide safe aircraft throughout the design life span.

The requirements for this program are spelled out in AF regulation 80-13 and in military standard MIL-STD-1530A(11).

Various recorder systems are used, such as the ASH-28 on the F-15, and the MXU-553/A on the A-10 and F-16. Input parameters are obtained in various manners in the three aircraft. Generally speaking, most data is obtained from added sensors. This is a good approach where only every fourth to sixth airplane is equipped with the recorder and no standard source of data is already common to the various aircraft. Added accelerometers and gyros are costly.

Table 24 is included to show the ASIP parameters currently recorded for 15 types of aircraft. Flight durations can be from an hour to 15 to 18 hours. Typically this has required tape transports to cover the data for the full duration. On short flight A/F/T types, the 15-hour duration has proved useful in requiring only 2 to 4-week tape cartridge changes. The Configuration III CSFDR version augmented to include engine health and ASIP functions can be configured in many variations.

The parameters to be added to Configuration I for covering the ASIP requirement are few. The cost impact on the Configuration I system is minimal. The greatest variable is in sourcing the body axis dynamics inputs and in obtaining the control surfaces inputs. An effort has been made to obtain these from existing sources where possible, such as the IMU, central computers, and the flight control system. Dynamics data, other than the flight control system, is from the MUX bus; hence, it requires minimum added wiring.

The greatest cost addition of ASIP to the Configuration I CSFDR (without EHR) is found in added mass memory and in the ground processing equipment necessary to extract the data and transfer it to less costly tape for transmittal to data processing centers.

Some similar associated data is obtained from the existing accelerometer counter set on each airplane. This data is presently manually read and recorded on report forms from the data recorded on the face of the unit (A8K-17/A37J-8). This same data could easily be recorded on all aircraft using Configuration III.

As stated in 3.2.4.1, Configuration III can appear in many forms. The one used for cost tradeoffs in this study is just one of these several, and assumes the 256-K memory version with ASIP data retrieved after 15 flight hours (or simultaneous engine parameter recording with daily data retrieval).

A decision on combining engine health recording with CSFDR is important to the ASIP decision.

Table 24. Parameter List (MXU-553/A and AN/ASH-28)

PARAMETER	AIRCRAFT															EVENT CODE	
	A-10	A-37	B-52	C-130	C/KC-135	C-141	E-3	F-5E/F	F-15	F-16	F-100	F-105	T-37	T-38	T-43		
ECU type	68	68	66	67	66	67	67	68	-		68	68	68	68	67	A	Store drop (left)
Airspeed	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	B	Store drop (fus)
N_z	X	X	X	X	X	X	X	X	X	X	X	X	X	X	(1)	C	Store drop (coded)
N_y	X	X				X	X	X	X	X	X	X	X	X	X	D	Takeoff
N_x									X	X						E	Weight on wheels
Altitude	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	F	Store drop-pylon L1
Fuel flow		X	X		X							X	X			G	Store drop-pylon L2
Roll rate	X	X						X	X	X	X	X	X	X		H	Store drop-pylon L3
Angle of attack									X							I	Store drop-pylon L4
Pitch rate	X	X		X		X	X	X	X	X	X	X	X	X		J	Store drop-pylon R1
Yaw rate	X	X		X		X	X	X	X	X	X	X	X	X		K	Store drop-pylon R2
Roll accel.									X	X						L	Store drop-pylon R3
Elevator		X		X		X	X	X	X	X	X		X	X		M	Store drop-pylon R4
Rudder		X		X		X	X	X	X	X	X		X	X		N	Refueling
Aileron		X							X	X	X		X			O	Gunfire
Speed brake	X															P	Ground cals
Time	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Q	Boom contact
Fuel totalizer	X		X		X				X	X	X				X	R	Flaps retract
No. of strains	1	1	4	6	4	5	5	1		1	1		1	1		S	Flaps extend
Flaps				X		X	X	X		X				X		T	Autopilot on
Nose gear steer.				X		X	X									U	Speedbrake deployed
Rate of climb									X							V	Refuel door open
Ground speed				X			X									Y	6 RPM antenna rotation
Engine RPM										X						Z	1/4 RPM antenna rotation
Cabin pressure				X		X										AA	Reserve tank valve (L)
Event code:																AB	Center tank pumps (L)
1	O	F	E	AC	E	AC	E	C	U	E	O	(2)	D/E	P	E	AC	Ldg. gear down
2	S	G	Q	E	T	E	Y	C	AC	AC	E	(2)				AD	Ramp door open
3	E	H	R	AD	S	U	Z		AD	C	F	(2)				AE	Weapon count
4	F	I			U		AA		AF		G	(2)				AF	Config. identification
5	G	J			V		AB				H	(2)					
6	H	K					T				J	(2)					
7	I	L					V				K	(2)					
8	A	M									L	(2)					
9	B	E/N												D			

Note: (1) Both gust and maneuver N_z derived by analog filter on N_z

(2) Information not obtained

If the engine health systems are added to Configuration I (making Configuration III) and the ground equipment is added for after-flight or daily readout, then the ASIP functions are a miminum add-on.

Configuration I would monitor about 90% of the ASIP program needs as is. It is relatively simple to add the needed parameters. The data recording period and readout needs are different from either the crash recorder needs or the engine health needs. ASIP data is trend data and does not need to be collected more than once a month or every 15 flying hours. The solid-state recorder memory, to be most practical, should be dumped at the end of each flight (or day) at the same time that the engine health data is removed. At these times, it could easily be stored on a cassette and accumulated for the desired time or printed out on a printer. This eliminates the long time on-board storage capacity for ASIP data.

The advantages of recording both engine health and ASIP data on a common recorder is that all parameter identification data, dates, times, A/C identification, etc., can all be conveniently printed out using one common ground data processing unit at each base. Many laborious and error prone hand-written forms could be eliminated. Data could then be transmitted in digital form or by mailed printouts directly to the user organizations. In other words, ASIP and engine data can be added for little more than engine data alone.

Therefore, from the standpoint of ASIP recording program costs, the decision to add engine health recording is important.

Again, as with the engine health requirements, the CSFDR system Configuration II is not compatible with the ASIP needs, mainly from the point of view of ground data readout and handling.

Assuming that existing aircraft with ASIP recorders have the CSFDR system added and the choice is to use Configuration II, then it is recommended that the ASIP stay as is.

Combining the ASIP functions with the CSFDR system and engine health recording would relieve some space presently occupied by ASIP boxes providing space for the common recorder and, in the F-16, allowing the VTR to be returned to the present ASIP designated aircaraft.

The following paragraphs delineate the specific changes or additions to the parameter list of Configuration I to perform the complete ASIP functions.

a. A-10. For the A-10, only the following parameters need be added to the Configuration I version:

(1) Strain gauge (1) and amplifier

(2) Aircraft serial number and squadron number

(3) Date (month, day, year)

Parameters in Configuration I that will be available for ASIP:

(1) Angle of attack

(2) Right elevator position

(3) Left elevator position

(4) Right aileron position

(5) Left aileron position

(6) Right rudder position

(7) Left rudder position

(8) Leading edge slat position

The total number of parameters that may be recorded for ASIP is 31.

b. F-15. For the F-15, only the following parameters need to be added:

(1) Longitudinal acceleration

(2) Roll acceleration

(3) Strain gauge and amplifier

(4) Ramp door open

Flaps data is available if desired.

Four parameters are added to the Configuration I CSFDR list. A total of 20 ASIP parameters will be recorded on the mass memory. (One of these parameters, Weapons Configuration and Status, consists of 18 digital words in the Configuration I list.)

The existing ASH-28 ASIP recorder contains its own sensors for the above first two parameters. If combined with the CSFDR, the two sensors will need to be added, or the data can be derived from inertial data. Other ASH-28 self-contained sensors have equivalent signals from other sources already in the Configuration I list.

c. F-16. For the F-16, only the following parameters need to be added:

(1) Strain gauge and amplifier

(2) Longitudinal acceleration (could be computed from inertial data)

(3) Roll acceleration

(4) Aircraft serial number and squadron number

(5) Date (month, day, year)

Five parameters are added to the Configuration 1 CSFDR list. A total of 23 parameters will be recorded in the mass memory.

3.2.4.3 <u>Flight control monitoring</u> - Some flight control monitoring is done in Configuration II, such as the primary control surfaces and pilot inputs, as well as critical CAS warning discretes. Comprehensive monitoring is done in the Configuration I version which includes Configuration II parameters plus many more status and fail discretes.

Only the F-16 has more detailed data on the FCS which is recorded on the ejection seat recorder. It is believed that those parameters necessary for crash analysis are recorded on the survivable memory in Configuration I, but if all of the signals presently on the seat recorder are desired, they can easily be accommodated by picking up existing wiring from the ECA and from the FLCC connector to the present seat recorder. If the monitoring electronics continue to be produced in the ECA and FLCC, then acquiring FCS status parameters from this source would be preferred over the individual discrete sources shown in the F-16 Configuration 1 list because they will all be available on Manchester coded data buses. The ECA and FLCC output a total of 96 fail or status bits and provide good repair or troubleshooting diagnostics.

For the A-10 and F-15, a fair amount of FCS data is recorded. More discretes could easily be added if required.

3.2.5 Security of recorded data - The purpose of the study for this section is to (1) determine the depth of any potential data security problems which could arise from CSFDR system use and (2) state feasible solutions to the problems.

3.2.5.1 Parameter lists and associated intelligence - A mishap resulting from flight over enemy territory could result in enemy recovery of the CSMU. Recovery of the expanded memory modules used for ASIP, TEH, and FC recording cannot generally be used to produce readouts since these memory modules are not crash-survivable. Moreover, these modules are easily accessible, and can, therefore, be easily removed prior to flight over enemy territory. Therefore, the discussion of security of recorded data is restricted to the CSMUs associated with Configurations I and II. This further implies that the parameter lists associated with these two configurations must be reviewed in order to determine whether or not enemy knowledge of their time histories is a critical problem.

Table 25 shows the information which could be deduced from the time histories of the Configuration I and II parameter lists. It must be remembered that complete time histories of these parameters will not be available because of the memory wraparound which will typically occur. (Typically, memory wraparound occurs after 29 minutes and 19 minutes for Configurations I and II, respectively.)

Aircraft capability and performance limitations could be deduced from time histories of relative time, airspeed, altitude, attitudes, attitude rates, fuel quantities, fuel rates and velocities. In general this information would be available for unclassified aircraft in various technical orders, magazines, and other publications. However, an accumulation of data from a series of mishaps could provide the enemy with an approximation of aircraft capability and performance limitations if some of the flights operated at or near the performance limit.

Pilot tactics and maneuvers, and weaknesses therein, could be deduced from the time histories of the same parameters listed in the previous paragraph. A good example would be the case where a fighter aircraft engaged in dogfight maneuvers entered an uncontrolled spin and crashed in enemy territory. The conditions which caused the departure of controlled flight could be well-defined and recorded in the CSMU. Accumulation of this type of data could result in a very thorough knowledge of pilot tactics and maneuvers.

Base locations could possibly be deduced from a time history of airspeed and heading or velocities. Altitude would supplement this information. Because of the expanded time histories in Configuration I, this configuration is the more susceptible one to this problem. With memory wraparound occurring more frequently in Configuration II, it is not likely that base locations can be deduced directly from its CSMU. Also, it is highly unlikely that actual base numbers can be deduced from either configuration.

Table 25. Intelligence Which Could Be Derived from CSMU Data

INTELLIGENCE	DEDUCED FROM CONFIGURATION I CSMU	DEDUCED FROM CONFIGURATION II CSMU
Aircraft capability and performance	Yes, to the extent recorded and accumulated	Yes, to the extent recorded and accumulated
Pilot tactics and maneuvers (and weaknesses therein)	Yes, to the extent recorded and accumulated	Yes, to the extent recorded and accumulated
Base locations/ numbers	Sometimes/no	Rarely/no
Routes flown	Sometimes	Rarely
Equipment on board and associated reliability	Yes/rarely, if ever	Yes/rarely, if ever
Altitude profiles	Yes	Yes
Numbers of aircraft being used locally	No*	No*
Temporary rendezvous points	Sometimes	Sometimes
Armament carried	Yes	No

*Especially true if audio is not recorded.

Similar comments to those in the above paragraph apply to the deduction of routes flown.

The equipment on board can be deduced from the associated status word(s) monitored and recorded by the CSFDR, although thorough examination of the wreckage and unclassified literature could be used to obtain the same information in may cases. Also, through an accumulation of status word information over a period of time, it is possible that the relative reliability of various aircraft subsystems could be deduced.

Altitude profiles vs. time can be deduced directly from CSMU data. This problem is particularly critical for classified aircraft.

The actual numbers of aircraft being used for various missions cannot be obtained from CSMU data. However, if audio were a recorded parameter, then it would be possible to deduce numbers of aircraft from the recordings of airborne radio transmissions.

Temporary rendezvous points could be derived if they were within approximately 19.4 minutes (Config. II) or 29.4 minutes (Config. I) of flight time from the mishap site. These points could be derived from airspeed, altitude, and heading information or velocity and altitude information.

3.2.5.2 Need for security - The preceding section pointed out some of the needs for security for CSFDR system information. In addition to the above rationale presented in that section, there are two other needs for security. These are

- Potential application to classified aircraft and RPVs
- Potential tri-service standardization

Since the design concept presented in this study is for a standard CSFDR system, the future aircraft, in which the CSFDR system will be used, are not known at this time. Therefore, it is conceivable that classified aircraft and RPVs could use the CSFDR system. Security is vital to these types of aircraft.

Additionally, the Navy desires security for its airborne recorded information. Thus, the concept of the tri-service standardization dictates that security be considered.

3.2.5.3 Potential methods of preventing or minimizing data loss to the enemy - The potential methods of preventing or minimizing data loss to the enemy are shown in figure 24. They are subdivided into operational, hardware, software methods, and documentation methods.

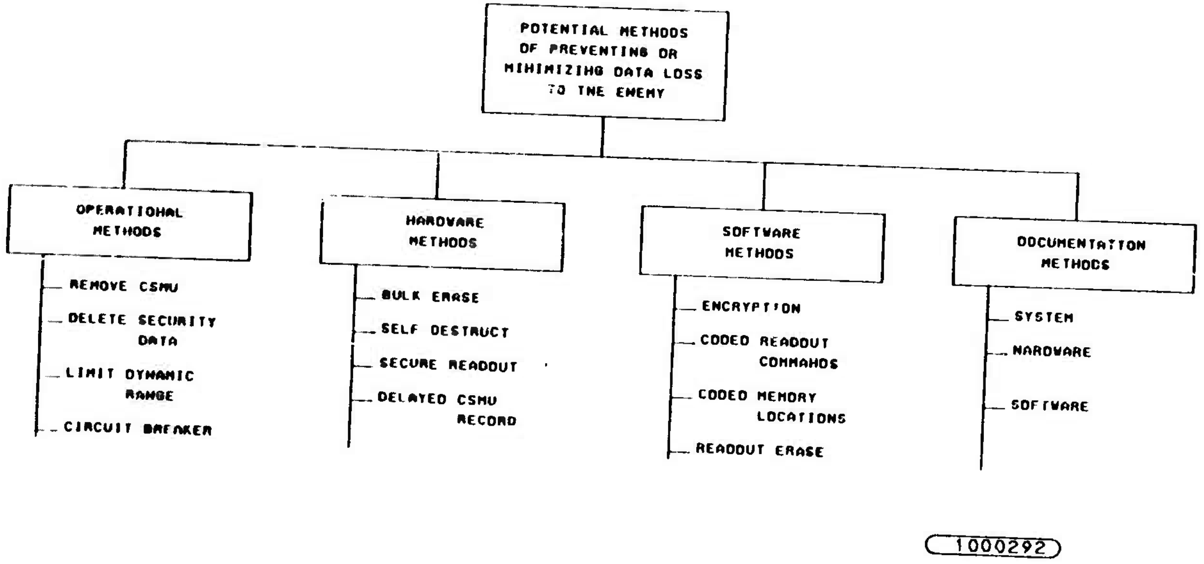

Figure 24. Potential Methods of Attaining Security

a. Operational methods. The first operational method which could be used would be that of removing the CSMU from the aircraft. However, the CSMU is not as accessible as the MSU of Configuration III. This stems from the fact that survivability and accessibility are usually conflicting goals. Moreover, the CSMU is a very small and light unit and does not pose an operational penalty in these areas. Also, the combined person-hour penalty which would result from removal and reinstallation would be significant. Therefore, the removal method is not recommended.

Other operational methods are to delete security-sensitive data and to limit the dynamic range of certain data when operating near or over enemy territory. These two methods require additional manual inputs to the CSFDR system and the possibility of inadvertently or incorrectly applying such inputs discourages these techniques.

Similarly, the circuit breaker method is discouraged since it may be inadvertently left open during normal peacetime operations.

Therefore, none of the operational methods is recommended.

b. Hardware methods. The first potential hardware method is that of a bulk erase feature within the CSFDR system readout process. The weakness in this method is the possibility of an inadvertent bulk erase during normal readouts. Similar weaknesses are present in the self destruct (pyrotechnical/electrical) method and the secure readout method which alters the data if it is not accessed properly.

The delayed CSMU record technique would involve storing the critical data in the scratchpad memory and inhibiting transfer to the CSMU when operating near or over enemy territory. Again, the weakness in this method would be the possibility of inadvertently changing the CSFDR system to and from the inhibit mode when it is not desired to do so. Also, additional hardware is required to perform this function.

Therefore, none of the hardware methods is recommended.

c. Software methods. The first software method discussed is that of encryption. Once the airborne software has determined that data would be recorded in the CSMU, the microprocessor loads this data into an encryption chip. Here the data is encoded and returned to the microprocessor bus within several microseconds. Following this step, the encoded data is transmitted to the CSMU. Only those data words which have been determined to be nonredundant by the airborne software require encoding. This minimizes the impact on the data processing functions. The encoding chips are explained in more detail in the next section and will meet the Data Encryption Standards defined by the National Bureau of Standards. Of all the security protection techniques reviewed, this one offers the most promise for the CSFDR system, and is, therefore, the recommended technique.

Another software method is that of coded readout commands. In this method, the CSMU would not respond unless the proper encoded readout commands were sensed in the read/ write electronics of the CSMU. This technique is not recommended for the CSFDR system because the CSMU can be disassembled, thereby permitting the read/write electronics to be bypassed, and ultimately a direct read off the memory chips could be made.

A third software method is that of using coded memory locations in the CSMU. This technique is not compatible with the CSFDR system architecture and is not recommended.

The final software method considered was that of readout erase. With the nonvolatile solid-state memories selected for the CSMU, this technique would not be practical or effective.

d. Documentation methods. The first potential method of achieving security protection via documentation methods is that of controlling all CSFDR system documents. This technique has been used effectively for avionics systems where small numbers of classified systems were involved. However, since it is desired to use the standard CSFDR system on many aircraft, this method would be awkward, expensive to implement, and would probably not be effective over a long time period.

The technique of controlling only the hardware documentation would not be effective. This is due to the fact that the CSMU memory map and software are sufficient to reconstruct the parameter profiles.

Controlling the software (both airborne and ground-based) documentation would be partially effective. Without a knowledge of the data compression software, if would be difficult to reconstruct the parameter profiles. However, is must be remembered that not all flight incidents are catastrophic in nature, and, therefore, the DPU may survive some incidents over enemy territory. Since the data compression program is resident in the DPU, a DPU which survives a minor incident could be used to extract the entire airborne software program. Thus, controlling the software documentation does not guarantee security of the actual software program. Therefore, this technique is only recommended as an alternate to that of encryption.

e. Recommended method. The easiest and most effective method of securing the CSFDR system data is that of encryption. The microprocessor selected for the CSFDR system is compatible with data encryption techniques and these techniques have minimal hardware and software impacts on the overall system design. Moreover, the actual code used is exceedingly difficult to break if the DES-type algorithm is used. It is estimated that it would take a ground-based mainframe computer approximately 6 months of processing time to break the DES-type code.

Many companies have developed integrated circuit chips to implement the NBS DES. Table 26 lists the manufacturer, chip nomenclature, and rough prices for the chips, in production quantities required for the CSFDR system.

Table 26. Summary of Survey for Data Encryption Devices Which Meet NBS DES Requirements

MANUFACTURER	CHIP NOMENCLATURE	APPROXIMATE PRICE PER CHIP ($)
Burroughs	MC884	$40
Fairchild Semiconductor	9414 set	$30
Intel	8294	$15
Motorola	MC6859	$40
Western Digital	WD2001 2002	$50 - $100

The Motorola MC6859 offers great promise for the CSFDR system application. It is available as a monolithic IC in a 24-pin DIP. The device is already designed to operate in conjunction with a microprocessor. It utilizes an 8-bit I/O bus and a 12-bit address/control bus. Additional ICs are required to adapt this device to the CSFDR microprocessor and it would add one-half a card of "real estate" to the CSFDR system. This added "real estate" will not increase the size of the unit, however, since this expansion capability is designed into the CSFDR DPU. Actual security of this approach lies in the key. To meet the DES, a 64-bit word is scrambled into another 64-bit word, using a 56-bit key to determine the coding. The multi-trillion combinations possible by this key makes decoding, without knowledge of the key, almost impossible. However, the MC6859 goes one step further in that it uses a second key to protect the first. In this two-key system, the primary key is used to encrypt the secondary key and the secondary key is used to encrypt the subsequent message. This technique would provide the needed security for the CSFDR system.

In summary, we recommend the software technique of data encryption as the technique to secure the CSFDR system data. Additionally, we recommend a two-key system for encryption.

3.2.6 Data readout facility - The data readout facility and its associated equipment represent the lowest risk portion of the entire CSFDR system program. Several low technology risk approaches were uncovered during this phase of the study and these approaches include maximum use of equipment already existing within the USAF inventory. Therefore, the output of this phase of study is a prioritized ranking of the choices available to the USAF.

3.2.6.1 Ground-based facilities - This analysis began by compiling a list of feasible facilities for CSFDR system readouts. These were:

- Norton AFB existing EDP center and special interface equipment.
- Data Transfer System ground terminal, located at Norton AFB, and special equipment.
- Tinker AFB EDP center and special interface equipment.
- NTSB existing readout facility and special interface equipment.
- Universal Ground Terminal Unit developed for ULAIDS, located at NAFB.

These facilities were analyzed in terms of minimum cost impact to the overall CSFDR system program.

a. NTSB facility. Although the NTSB facility at Washington D.C. appeared to be a logical choice based upon past history, it was immediately eliminated from the list after interviews were held with key NTSB personnel. There are four basic reasons why it was eliminated.

(1) The NTSB operates under the strict definition of "transportation" and currently reports directly to Congress. (In the past, the NTSB was coupled with the FAA and both reported to the Department of Transportation.) Military operations, which include training missions, and delivery of military hardware do not fit the NTSB classical definition of transportation and it would require Congressional approval for the NTSB to broaden their definition of transportation to include military operations on a full-time basis.

(2) The NTSB is currently staffed only for commercial accident investigations. The higher frequency of military accidents would require an expanded staff, especially if all three services requested support.

(3) Use of the NTSB could cause potential security problems where classified missions/aircraft were involved in a mishap.

(4) Due to the nature of commercial accident investigations and their legal aspects, it is unlikely that the legal representatives of commercial airlines would accept simultaneous services to both commercial and military readouts.

Based upon these reasons, we eliminiated the NTSB facility as a viable readout facility.

b. UGTU facility. The Universal Ground Terminal Unit (UGTU) developed for the Navy ULAIDS program was also reviewed for applicability to CSFDR system readouts. This system is an excellent ground-based system capable of processing data collected by various Navy airborne data management systems and includes:

FIR (tape and solid-state memory) Playback Interface Unit (PIU)

AHMR tape PIU

A-7E Integrated Engine Condition Monitoring System Tape (IECMS) PIU

F-18 Maintenance Data Recorder Magazine (MDRM) PIU

Data entry/display terminal

Line printer

Computer

Mass storage (2-1.2 million-word disks)

Tape drive

The UGTU was also eliminated as a candidate readout facility for the following reasons:

(1) With the one exception of the solid-state FIR PIU, the UGTU is oriented to reading out airborne tape units and this is in conflict with the recommended CSFDR approaches which are all solid-state memory oriented.

(2) The line printer, computer, mass storage, and tape drives are a functional duplication of similar devices in the USAF inventory at Norton AFB, and Tinker AFB.

Thus the Navy UGTU was eliminated as a viable CSFDR system readout facility.

The remaining three candidate facilities are all feasible and acceptable for the CSFDR system configurations.

c. Norton AFB EDP facility. The Headquarters Air Force Inspection and Safety Center is located at Norton Air Force Base, California. Mishap statistics and related data are now maintained on file at the Norton EDP center, which makes this facility the most logical choice for CSFDR system readouts. The accumulated CSFDR system data will augment the existing AFISC data base.

The Norton EDP facility utilizes a standard IBM 370/155 mainframe computer and standard OS/VS1 operating system. Additionally, this facility services/interfaces EDP centers at WPAFB, Langley AFB, Tinker AFB, Kelly AFB, and many other AFBs. Interface with other safety centers within DOD is also provided.

The primary languages now used at Norton are Fortran IV and COBOL. Both of these languages are on the DOD 5000.31 approved standard language list. Of the two languages, Fortran IV is the more applicable one for the readout facility software required to support the CSFDR systems. Therefore, all of the ground-based software described in 3.3.3.4 will be provided in Fortran IV. Additionally, the Norton AFB EDP center has the capability for placing the mishap data on a secure disk file, which is a highly desirable feature.

The only additions required to this facility are:

(1) The Data Processor Retrieval Unit which interfaces the CSMU with the 370/155 mainframe and provides three levels of readout capability (see 3.2.6.2.b)

(2) A plotter and plotter interface unit to provide parameter plots as described in 3.3.3.4.

(3) A ground support software package as described in 3.3.3.4.

(4) The capability to make the area secure during CSMU readouts.

In summary, we recommend that the existing EDP facility at the NAFB, with the above additions, be considered as the primary ground readout facility.

d. Norton AFB DTS facility. In the event that the USAF should elect not to use the IBM-370/155-based EDP facility at Norton, an alternate capability designed around the Data Transfer System can be located at Norton AFB for CSFDR system readouts. This ground-based system is already in the USAF inventory and utilizes a standard HP 1000 series general purpose computer system. This system includes a disk drive, two display stations, a line printer, and receptacles for Data Transfer Modules. The same additions as for the Norton AFB EDP facility are required for the Norton AFB DTS facility. The ground-based software described would be resident on the HP-1000 and would be written in Fortran IV. This system is described in reference 12.

e. Tinker AFB EDP facility. A third choice for the readout facility is also available and practical for CSFDR system readouts. This is the existing EDP center at Tinker AFB, which is now used to process the ASIP tapes. These tapes contain up to 15 hours of flight data, and approximately 600 tapes are processed each month. The EDP center uses an IBM-360/65 standard system with card/tape/disk/printer and controller capabilities. The ASIP tapes now processed at Tinker must be reformatted (transcribed) before they can be processed on the mainframe. Tinker AFB represents a logical choice for CSFDR system readouts because of the tie-in to the ASIP functions (configuration III) and their interface with Norton AFB. The same additions would have to be made to the Tinker facility as for the Norton facility to provide full CSFDR system readout capability since a plotter is not currently available. (Note: The Tinker facility is being updated and procurement of a plotter is planned. If this facility is selected as the CSFDR system readout facility, the updated facility should be reviewed and incorporated into the CSFDR program.)

3.2.6.2 <u>Data readout hardware description</u> - Often overlooked in the initial stages of crash recorder design are the requirements for readout at various levels of recorder system damage. The fact that the recorder memory media survives the mishap does not guarantee a direct readout via external connectors. There are many cases on record where the recorder had to be literally sawed in half with a hack saw, or equivalent, following a mishap, in order to retrieve the memory. Moreover, the external connectors are frequently damaged mechanically or thermally, thereby eliminating a direct readout. This problem is not unique to the USAF CSFDR system, but is a common problem in basic crash recorder design. We have, therefore, chosen to divide the readout categories into four basic levels as follows:

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[12] LSI brochure entitled "Shirt Pocket Precision: The LSI Data Transfer System", LSI Publication No. ID-028-0280.

Level I - CSMU recovered and undamaged - readout made directly via the chassis connector on CSMU.

Level II - CSMU recovered and partially damaged - readout accomplished by mechanically connecting to the internal interconnect of the CSMU.

Level III - CSMU recovered and damaged externally - readout made directly via the memory integrated circuits (ICs).

Level IV - DPU and CSMU totally intact and on aircraft-readout made directly through DPU connector without removing any part of recorder system.

These methods and the needed equipment are described in the next two sections.

a. Level IV - DPU and CSMU intact and on aircraft.

This method of readout would occur following a minor mishap or when a non-catastrophic incident occurred during flight and was followed by corrective actions which resulted in an uneventful landing. In these cases, a very small portable unit would be carried out to the aircraft for data retrieval.

The system block diagram for this portable Data Retrieval Unit (DRU) is shown in figure 25. In operation, the Data Processor Unit on this aircraft recalls the data from the Crash-Survivable Memory Unit (also on the aircraft) and loads it into the Data Transfer Module contained in the receptacle of the DRU. This process is initiated after the cable is connected and the START push button is depressed. When the microprocessor in the DPU receives this interrupt its normal program will be halted and the retrieval program will be executed. The microprocessor illuminates the BUSY indicator lamp on the DRU to inform the operator while the data is being loaded. A BIT procedure is incorporated to read each word back from the DTM and compare it with the word just loaded to check integrity of the Data Retrieval Unit. A bad word compare is signaled by blinking the BUSY indicator lamp.

The Data Retrieval Unit hardware and carrying case are shown in figure 26. The case will house a DTM receptacle and provide storage for two DTMs which are already in the Air Force inventory. (See reference 12 for information on DTM hardware.) The interface cable is stored in the cover of the carrying case. Power for the DRU is provided by the Data Processor Unit via the standard I/O bus.

This method provides a very inexpensive approach, which maximizes USAF inventory hardware, to provide level IV type readouts. After the data has been loaded into the solid-state DTM, it can be mailed to any desired USAF facility for further analysis.

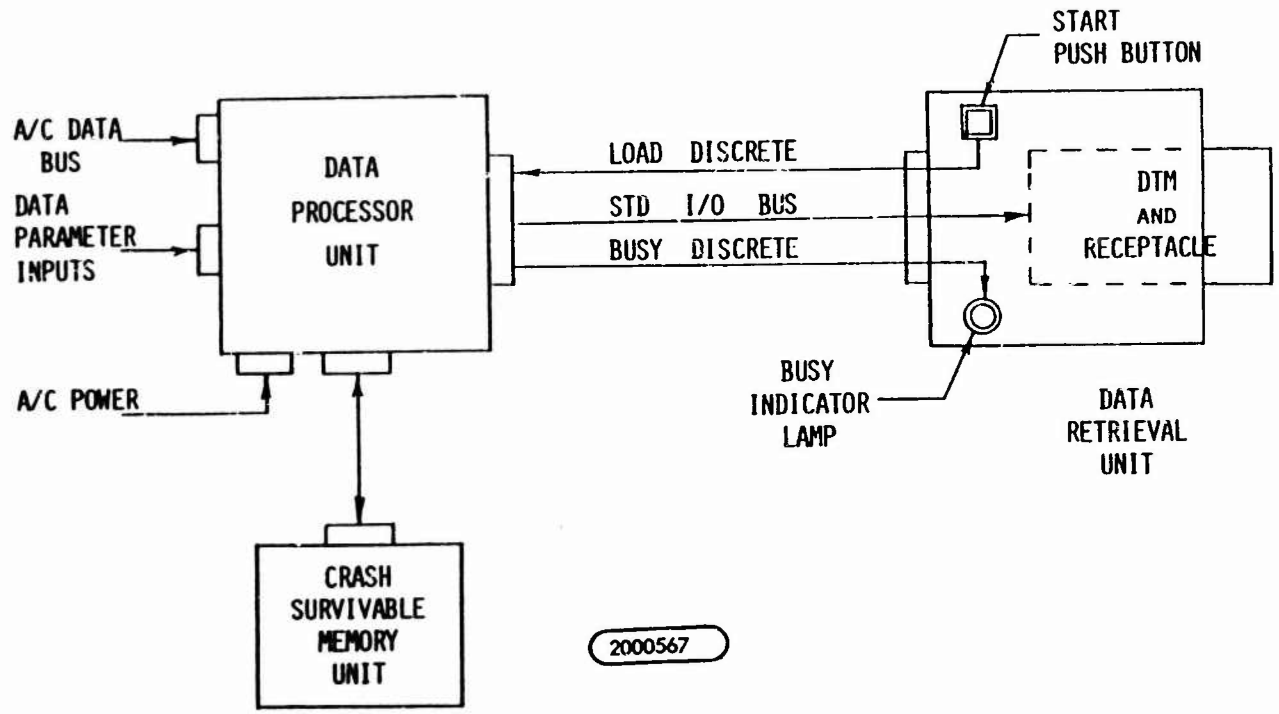

Figure 25. Data Retrieval Unit System Block Diagram

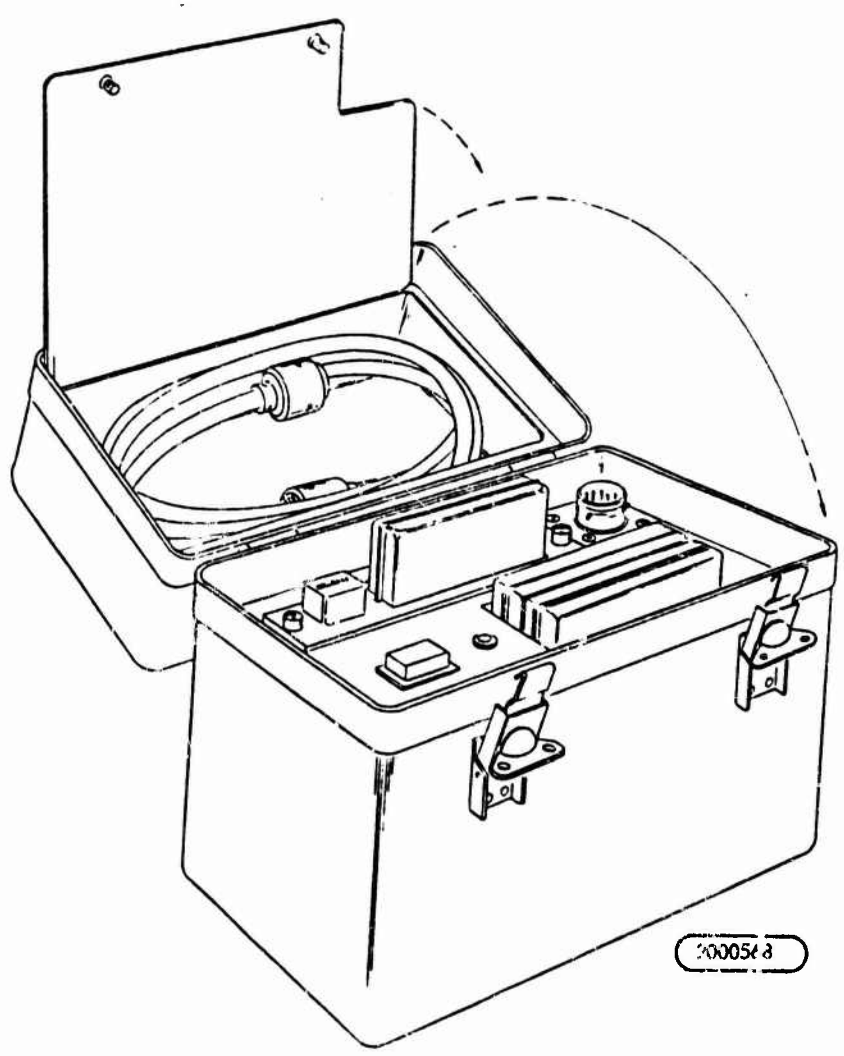

Figure 26. Data Retrieval Unit

The minimum cost DRU can be located at each airbase or as deemed necessary.

b. Levels I, II, and III - CSMU Recovered Separately. The second category requires a more comprehensive machine to interrogate the equipment after damage has occurred. The Data Processor Retrieval Unit (DPRU) would be located, for instance, at Norton AFB.

The Data Processor Retrieval Unit system diagram is shown in figure 27. This equipment can extract data from the CSMU at three levels of mishap severity. This equipment consists of a Lear Siegler ADM-3A CRT terminal, the DPRU and cable/interface for the three levels of interrogation. The operator controls the hardware functions via the CRT terminal. The data is read out of the CSMU by the DPRU and loaded into the Data Transfer Module (DTM). After data retrieval is completed, the information can subsequently be transferred from the DTM to the IBM 370 system. This process requires that the data be recalled from the DTM, reformatted to RS-232 and transmitted to the IBM-370 ground-based system. Now the post-incident analysis can be carried out via the ground-based system.

Likewise, any DTM sent to NAFB from level IV readout incidents are plugged into the DPRU in order to transfer mishap data to the IBM-370 system.

At level I the CSMU is intact and the interface cable is attached to the chassis connector. The read command is entered on the CRT terminal keyboard. The data is then read out of the CSMU and loaded into the DTM which is inserted in the DPRU. The various operations at the three levels of interrogation are controlled by a microprocessor within the DPRU. In order to achieve the maximum degree of standardization possible within the overall CSFDR system, the microprocessor hardware will be identical to that within the airborne DPU.

At level II the mechanical connection is with the internal circuit interconnect. This is the interface to the read/write logic housed within the protected subassembly. The data interface at level II is still serial in nature with approximately ten conductors in the circuit interconnect.

At level III interrogation is directly with the EE-PROM memory ICs. At this level a parallel interface must be provided to the memory ICs. There are several ways to do this. One way is to remove the read/write logic gate-array from the memory substrate. Then attach it to the metalization interface of the memory IC array. A mechanical substrate holder is used to connect to the metalization interconnect. Another approach is to remove each memory IC package. Each memory IC would be read individually when installed in a mechanical holder that connects to the package leads. The data processor retrieval unit would store, organize and then load the information into one or more DTMs. Multiple copies of the data can be made at all levels.

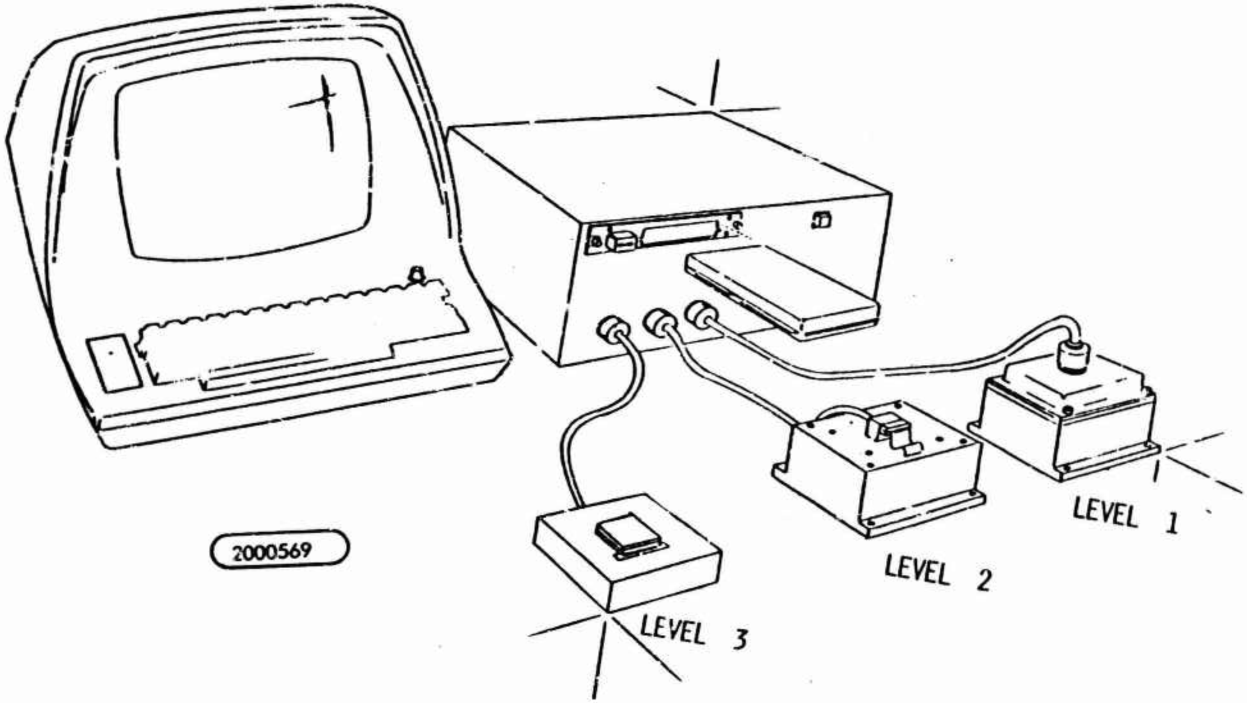

Figure 27. Data Processor Retrieval Unit System Diagram

Note that this approach also is of minimum cost because the DTMs are in USAF inventory. The processor resident within the DPRU is identical to that of the airborne DPU thereby reducing processor hardware and software design.

3.2.6.3 Prioritized ranking of data readout facilities - Ranking of potential readout facilities is as follows:

(1) Norton AFB existing EDP center with DPRU station to provide all levels of readout.

(2) Data Transfer System, stationed at Norton AFB, based upon existing USAF inventory HP-1000 system and DPRU to provide all levels of readout.

(3) Tinker AFB existing EDP center with DPRU station to provide all levels of readout.

Note that a DPRU is required in any case. Also, based upon a review of Class-A mishaps, it is envisioned that levels I and II would be the most frequently used levels of readouts.

3.2.6.4 Data readout hardware for mass memory unit - Configuration III requires data retrieval hardware to transfer information from the Mass Storage Unit (MSU) to magnetic tape. This hardware consists of two pieces of equipment: an MSU Data Retrieval Unit and a Tape Recorder Unit. In operation, the MSU-DRU is carried out to the aircraft and attached to a connector provided on the Data Processor Unit (DPU). The data is recalled from the Mass Storage Unit by the DPU and transmitted to the MSU-DRU. The Data Retrieval Unit reformats the data and sends it to the Tape Recorder Unit for recording.

3.2.7 Recommended technical approach - The technical approach for CSFDR system design recommended in this section is based upon the results of sections 3.1 (determination of requirements), 3.2 (technical approach), and 3.3 (areas of special emphasis).

There are five primary driving functions which must be optimized in order to assure a CSFDR system capability for A/F/T aircraft:

a. Minimize the total volume (size) of the CSFDR system because space (real estate) is at a premium for A/F/T aircraft.

b. Minimize the total weight (including all cables, brackets, and CSFDR components) impact to the aircraft because weight is also critical for A/F/T aircraft.

c. Minimize the LCC of the CSFDR system.

d. Crash protect and install the protected memory to survive A/F/T Class-A mishaps.

e. Design the CSFDR system to operate throughout the high-g maneuvers which are typical of A/F/T profiles.

These driving functions are satisfied if the following technical approach is taken.

a. Separate the survivable memory pack from the remainder of the CSFDR sytem electronics.

b. Use a solid-state memory in conjunction with state-of-the art techniques for data conversion/data processing/data compression.

A brief discussion of how this technical approach will satisfy the primary driving functions follows:

Separating the survivable memory from the CSFDR system electronics minimizes the overall weight added to the aircraft because the sensor lines need only to run to the processor unit and not the full length or width of the aircraft. For example, if all CSFDR system modules were packaged within a single box and this box were located in the tail cone, then every sensor line would have to run to the tail cone. The technical approach taken, allows the processing and conversion functions to be located as close as is practical to the sensors and, therefore, eliminates long, heavy cables. Conversely, to mount a single unit in a centralized fuselage bay to save wiring, requires more recorder size and weight to achieve satisfactory survivability rates.

Survivability and installation are also improved by separating the memory from the processor. This follows because a small package containing the survivable memory chips can be remotely located in an extremity of the aircraft, and it is an established fact that extremities of the aircraft exhibit greater survivability characteristics. Additionally, it is easier to find space for two smaller units than for one larger unit on A/F/T aircraft. This is especially true for aircraft like the F-16.

Use of a solid-state memory is also critical in satisfying the primary driving functions. Solid-state devices allow continual operation of the CSFDR system through high-g maneuvers. This is not true of electromechanical type recorders. For example, "tape bunching" is a common problem where tape units are installed on high performance aircraft. Experience also shows that many tape recorders will completely cut out during a +7-g (or greater) maneuver. Solid-state memories eliminate these problems.

The LCC is also minimized by going to solid-state devices. This is a direct result of eliminating the reliability problems and maintenance overhead problems associated with recorders having moving parts. Also, solid-state memories, when used with data compression techniques, permit a smaller overall package.

Table 27 shows the recommended design goals of each configuration.

Table 27. Characteristics of Configurations I, II, and III

Completely solid-state system - Data Processor Unit (DPU) and Crash-Survivable Memory Unit (CSMU)

Expanded recording functions - Via Mass Storage Units (MSU)

CSMU and MSU separable from DPU - Installed as single unit or in combinations of DPU plus remotely located memories

Low-power Crash-Protected Memory (CPM) - Very low power, solid-state, non-volatile

Microprocessor controlled - Data conversion, processing, and compression, including BIT

CSMU survivability - Per recommended A/F/T crash-survivability specification

Characteristic		DPU	CSMU	MSU	TOTAL
Size:	I	212 in^3	42 in^3	---	254 in^3
	II	197 in^3	35 in^3	---	232 in^3
	III	212 in^3	42 in^3	108 in^3	362 in^3
Weight:	I	8.4 lbs	2.8 lbs	---	11.2 lbs
	II	7.6 lbs	2.4 lbs	---	10.0 lbs
	III	8.4 lbs	2.8 lbs	6.0 lbs	17.2 lbs
Power:	I	40 watts	1 watt	---	41 watts
	II	35 watts	1 watt	---	36 watts
	III	40 watts	1 watt	10 watts	51 watts
Average Flight Time Retained:	I	---	29 min	---	---
	II	---	19 min	---	---
	III	---	29 min	15 hrs	---
Memory Required:	I	---	131,072 bits	---	131,072 bits
	II	---	65,536 bits	---	65,536 bits
	III	---	131,072 bits	256Kx16 bits	264Kx16 bits

Table 27. Characteristics of Configurations I, II, and III (Continued)

Characteristic		DPU	CSMU	MSU	TOTAL
MTBF:	I	5,258 hrs	63,613 hrs	---	4,856 hrs
	II	5,580 hrs	89,047 hrs	---	5,251 hrs
	III	5,258 hrs	63,613 hrs	3,400 hrs	2,000 hrs
Maint. MN/HRS per 1000 operating hours:	I	2.899 hrs	0.204 hrs	---	3.103 hrs
	II	2.733 hrs	0.146 hrs	---	2.879 hrs
	III	2.899 hrs	0.204 hrs	3.823 hrs	6.926 hrs
Program Memory:	I	3,140 WDS	---	---	3,140 WDS
	II	3,000 WDS	---	---	3,000 WDS
	III	3,400 WDS	---	---	3,400 WDS
Random Access Memory:	I	2,000 WDS	---	---	2,000 WDS
	II	2,000 WDS	---	---	2,000 WDS
	III	2,000 WDS	---	---	2,000 WDS

3.2.8 Reliability and maintainability

3.2.8.1 Reliability - A reliability analysis was performed on the Data Processor Unit (DPU), Crash-Survivable Memory Unit (CSMU), and the Mass Storage Unit (MSU) which are a part of the CSFDR system. The results are summarized in table 28 for all configurations.

A mean time between failures (MTBF) of 4856 hours was predicted for the Configuration I system using MIL-HDBK-217C notice 1 in an airborne uninhabited fighter environment with an ambient temperature of 71°C. Since most of the circuitry is existing design, actual component stress values were used and a realistic estimate was made by the Thermal Analysis Group for board temperature rises. Military temperature range components with the quality factors summarized below will be used:

Resistors and capacitors	MIL-SPEC
Semiconductors (discrete)	JANTX
Integrated circuits	MIL-STD-883 Class B

Similarly, the MTBFs for Configuration II and III are computed to be 5251 hours and 2000 hours, respectively.

3.2.8.2 Maintenance concept

a. Configuration I and II

(1) O-level (flight line) maintenance. The Data Processor Unit maintains a modular design with a microprocessor controlling all the functions. This allows the microprocessor to efficiently and comprehensively perform a self-test check on the DPU hardware, using the built-in test (BIT) subroutine. The microprocessor can also interrogate the CSMU on the two-way standard I/O bus to confirm read/write capability to the EE-PROM.

Within the DPU, the analog conversion hardware is checked by including two reference voltage inputs on the analog MUX board. The BIT subroutine commands the A/D converter to sample and convert these positive and negative references on a periodic basis. A watchdog timer is used to detect software hangups and other periodic-function failures.

A BIT failure signal is provided from the DPU to annunciate the Master Caution/Telelight Panel if a failed condition is detected. Additional failure indicators can be mounted on the DPU to differentiate between a DPU and CSMU failure. This BIT capability will eliminate the need for O-level test equipment.

Table 28. CSFDR System Reliability Prediction

DPU	F.R x 10^{-6} hrs	MTBF (hrs)
Conf. I & III	190.20	5257.62
Conf. II	179.20	5580.36
CSMU		
Conf. I & III	15.72	63613.23
Conf. II	11.23	89047.20
MSU		
Conf. III	294.1	3400.20
CSFDR Total		
Conf. I	205.92	4856.25
Conf. II	190.43	5251.27
Conf. III	500.02	2000.00

(2) I-level (base shop) maintenance. The Data Processor Unit Test Set is shown in figure 28. This test set is used at the intermediate (I-level) test facility to fault isolate to the board level. The equipment consists of:

- CRT/keyboard terminal
- Test interface board
- DPU test panel
- Cables and board extractors

The test operator interfaces with the test set via the CRT/keyboard terminal and switches located on the DPU test panel. The test procedure is semi-automatic. The operator initiates each test segment and waits for a GO/NO-GO condition response. The CRT terminal will provide visual display to indicate modes of opertaion, patterns and indications of failure.

The Test Interface Board plugs into a card slot provided in the Data Processor Unit. This board contains a Universal Asynchronous Receiver Transmitter (UART) to interface between the CRT terminal's RS-232 channel and the microprocessor's parallel data bus. The PROM containing the self-test program (STP) of about 6K words is located on the interface board. The scratchpad RAM used by the DPU microprocessor while executing the STP is also contained on the interface board.

The DPU Test Panel is basically a sensor simulator and digital wraparound tester. The sensor simulator section provides analog AC, DC signals and discrete inputs to the DPU. The Test Panel provides wraparound of the two standard I/O bus channels. The Test Panel receives data on one of the standard I/O channels and wraps around to the A/C data bus (e.g., 1553) input. A circuit board in the test panel generates the interface needed for the A/C data bus channel.

The Crash-Survivable Memory Unit (CSMU) can be attached to a working Data Processor Unit for test purposes. The self-test program will exercise the EE-PROM in the CSMU by read/writing to each location. The power will be supplied to the CSMU separately so that the power monitor in the CSMU can be checked by the DPU Test Panel for the low voltage condition. The CSMU will be returned to depot for repair.

(3) Depot level maintenance. The depot-level test equipment will include the following items:

- Data Processor Unit Test Set
- Gen Rad 2270 (analog cards)
- Gen Rad 1796A (digital cards)
- CSMU Tester

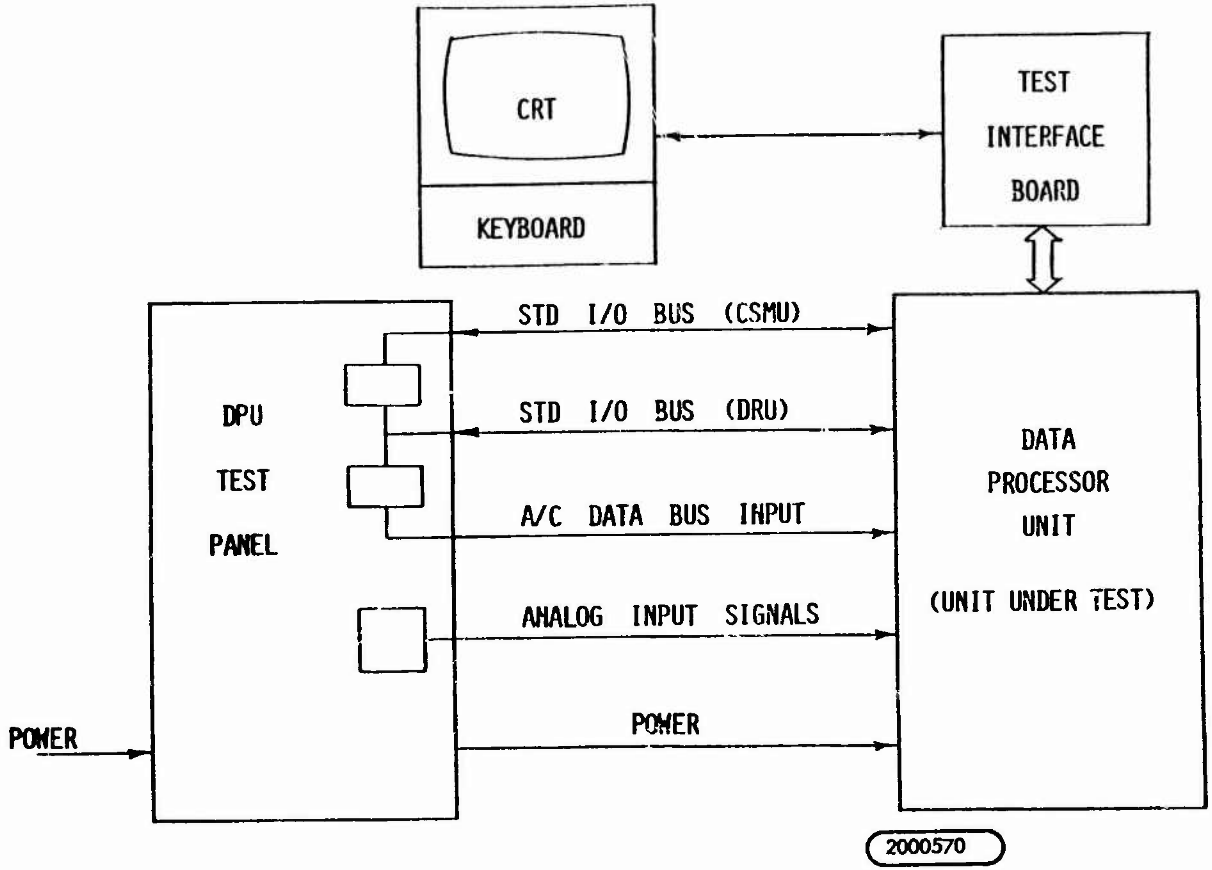

Figure 28. Data Processor Unit Test Set

The Data Processor Unit Test Set (figure 28) will fault isolate any returned DPU to the board level. Automatic Test Equipment (ATE) will be used to fault isolate the DPU circuit cards to the component or group of components level. The Gen Rad 2270 ATE is used to fault isolate the analog cards. The digital cards are fault isolated using the Gen Rad 1796A ATE.

The CSMU Tester is shown in figure 29. This equipment has been previously proposed for depot level testing of a similar product, the Data Transfer Module. The CSMU Tester is a semi-automatic test station providing all required power and signals to operate and exercise the CSMU. The tester also provides visual display to indicate modes of operation, patterns and indications of failure.

The tester is made up of the following items which are depicted in figure 29.

Item 2 - Computer, Data General NOVA 4/S
Item 3 - Terminal, LSI ADM 3A
Item 4 - Interface Panel Assembly
Item 5 - Diskette Subsystem, Data General 6030
Item 6 - CSMU Adapter Assembly
Item 7 - Digital Interface Board (DIB) Adapter Assembly
Item 8 - Oscilloscope, Tektronix Model 453, Mod 703K

b. Configuration III. In Configuration III the DPU and CSMU maintenance concepts are the same as for Configurations I and II. Maintenance of the MSU, at each level, will be handled in a manner similar to that of the CSMU.

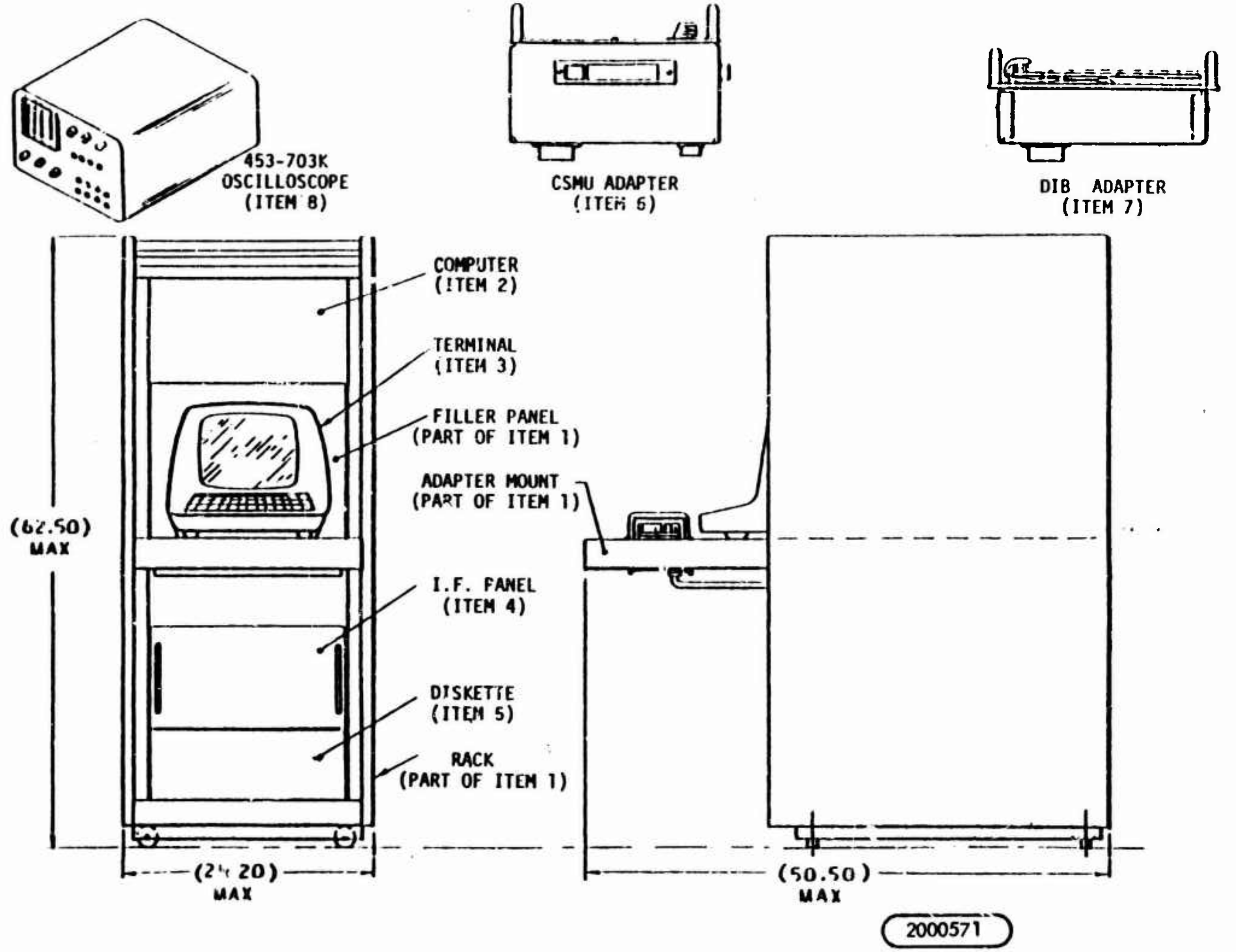

Figure 29. CSMU Tester

3.3 Areas of special emphasis

3.3.1 Memory technology survey - In order to complete the memory technology survey, potential candidates for the data storage medium were divided into three basic groups:

(1) Electromechanical	Oscillographic Digital tape Disc Drum	
(2) Nonsolid-state electronic	Core Plated wire	
(3) Solid-state electronic	MNOS EAROM MNOS BORAM MNOS/SOS TTL (static) I^2L (static) I^3L (static) CMOS CMOS/SOS	NMOS (static) NMOS (dynamic) MNOS EE-PROM NMOS EE-PROM PMOS (static) VMOS ECL CCD Bubble

In the initial stages of the memory technology survey, all of the above technologies were considered as potential candidates in order to eliminate any possible bias towards a particular technology. Characteristics associated with each of these technologies are given in table 32.

3.3.1.1 Electromechanical group - Four basic electromechanical technologies are considered in this group: 1) oscillographic, 2) digital tape, 3) disc, and 4) drum. The first two technologies are currently used in crash recorders for transport, cargo, and patrol aircraft.

a. Oscillographic. Oscillographic recording technology is currently used in crash survivable flight data recorders for intermediate-sized aircraft. These recorders are generally designed to ARINC Characteristic No. 542[13] entitled "Airborne Oscillographic Flight Data

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[13] ARINC Characteristic No. 542, "Airborne Oscillographic Flight Data Recorder", Aeronautical Radio, Inc.

Recorder", and meet the crash-survivability requirements of FAR 37.150, TSO-C51a[14].

The basic concept of oscillographic recording is shown pictorially in figure 30. A metal foil is used to minimize the amount of heat protection required and the foil is usually coated with a thin layer of high temperature opaque adhesive to provide a good contrast of the recorded information. The recording styli remove ("scratch") the coating thereby engraving the value of the parameter on the metal foil. The styli, or scribers, are driven by the actual sensor signals. Time is automatically provided by time scribes or perforations based upon a constant rate drive of the foil. Including time, recorders using this technology record at least five parameters, and some variations have an expanded recording capacity of up to ten parameters. An additional requirement of recorders using this technology is that the metal foil and associated magazine be easily replaceable and/or removable because of the limited recording time and necessary replenishment of the foil itself. Table 29 shows the major characteristics associated with recorders utilizing oscillographic technology.

Table 29. Characteristics of Typical Oscillographic Recorders

Size	1/2 ATR long (4.88"x19.52"x7.62") (726 cubic inches)
Weight	18 - 25 pounds
Operating temperature	-55° to +70°C
Recording time	200 - 400 hours
Number of parameters	5 basic (time, pressure altitude, vertical acceleration, airspeed, heading) expandable to 10
Type	Non-ejectable (type I or type II)
Service life	1000 hours minimum for electrical and mechanical assemblies
Approximate cost (low quantity)	$15,000

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[14] U.S. Federal Aviation Regulation, Part 37.150, "Aircraft Flight Recorder", TSO-C51 a.

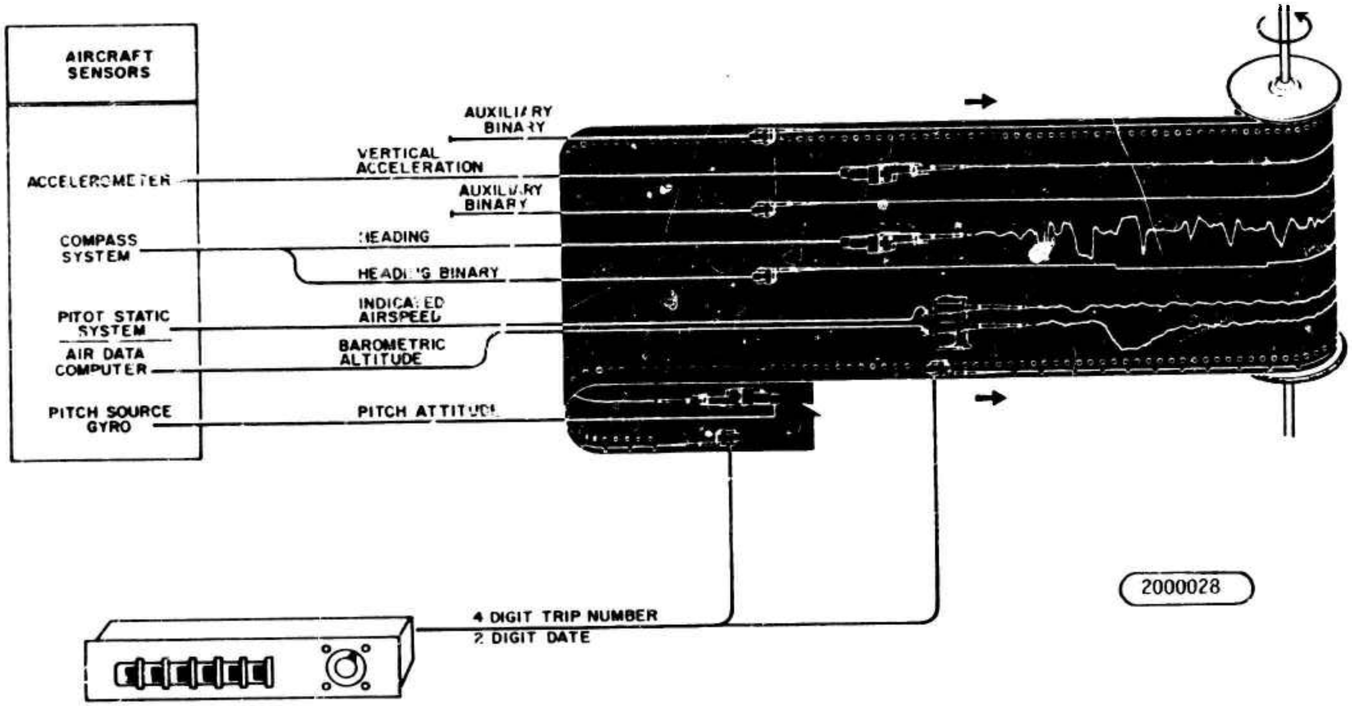

Figure 30. Basic Concept of Oscillographic Recording

The oscillographic recording technology does have some advantages. First, the coated metal foil used can withstand temperatures well beyond that of semiconductor memories thereby minimizing the amount of heat protection required to withstand a post-crash fire. There is also some inherent protection from mechanical and thermal damage due to the concentric layers of the foil itself. Moreover, the time at which a catastrophic incident takes place will be easily identified on the foil and markings beyond this point can be ignored in the readout process. Finally, it is important to note that this recording technology is fully developed and has been used in over 500 accident investigations related to commercial airlines.

However, this recording technology is not suitable for the A/F/T aircraft category. Size and weight are excessive, only a limited number of parameters can be recorded, it is not easily reprogrammable, it has a relatively low reliability because of the many moving parts, the foil must be replenished frequently, it cannot be relied upon to record faithfully during high g maneuvers when recording is extremely important for A/F/T aircraft, it has relatively "sluggish" data transfer rates, and it has a high maintenance overhead penalty. The high maintenance penalty is associated with foil replacement, check and calibration of styli, lubrication of moving parts, and replacement of worn parts.

b. Digital Tape. Digital tape recording technology is also currently used in crash-survivable flight data recorders. This technology is used on all wide-bodied commercial aircraft, some large military aircraft, and some narrow-bodied commercial aircraft. Recorders using this technology are generally referred to as digital flight data recorders (DFDRs) and are designed to ARINC Characteristic No. 541[15] entitled "Airborne Magnetic Flight Data Recorder" and meet the crash survivability requirements of FAR 37.150, TSO-051a. Parameters recorded by the DFDRs are identified in ARINC Characteristic 573-7[16] entitled "MARK 2 Aircraft Integrated Data System (AIDS MARK 2)". Additionally, the DFDRs are used in a recording system configuration employing a flight data acquisition unit to access analog data from aircraft sensors and transmitters and convert the data to digital form for transmission to the DFDR.

The basic concept of crash-protected digital tape recording is shown in figure 31. A metal tape ("Vicalloy") is used to minimize the amount of heat protection required and temperatures in the proximity of 650°C can be experienced by the tape without a total loss of recorded data.

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[15] ARINC Characteristic No. 541, "Airborne Magnetic Flight Data Recorder", Aeronautical Radio, Inc.

[16] ARINC Characteristic No. 537-7, "Mark II Aircraft Integrated Data System", Aeronautical Radio, Inc.

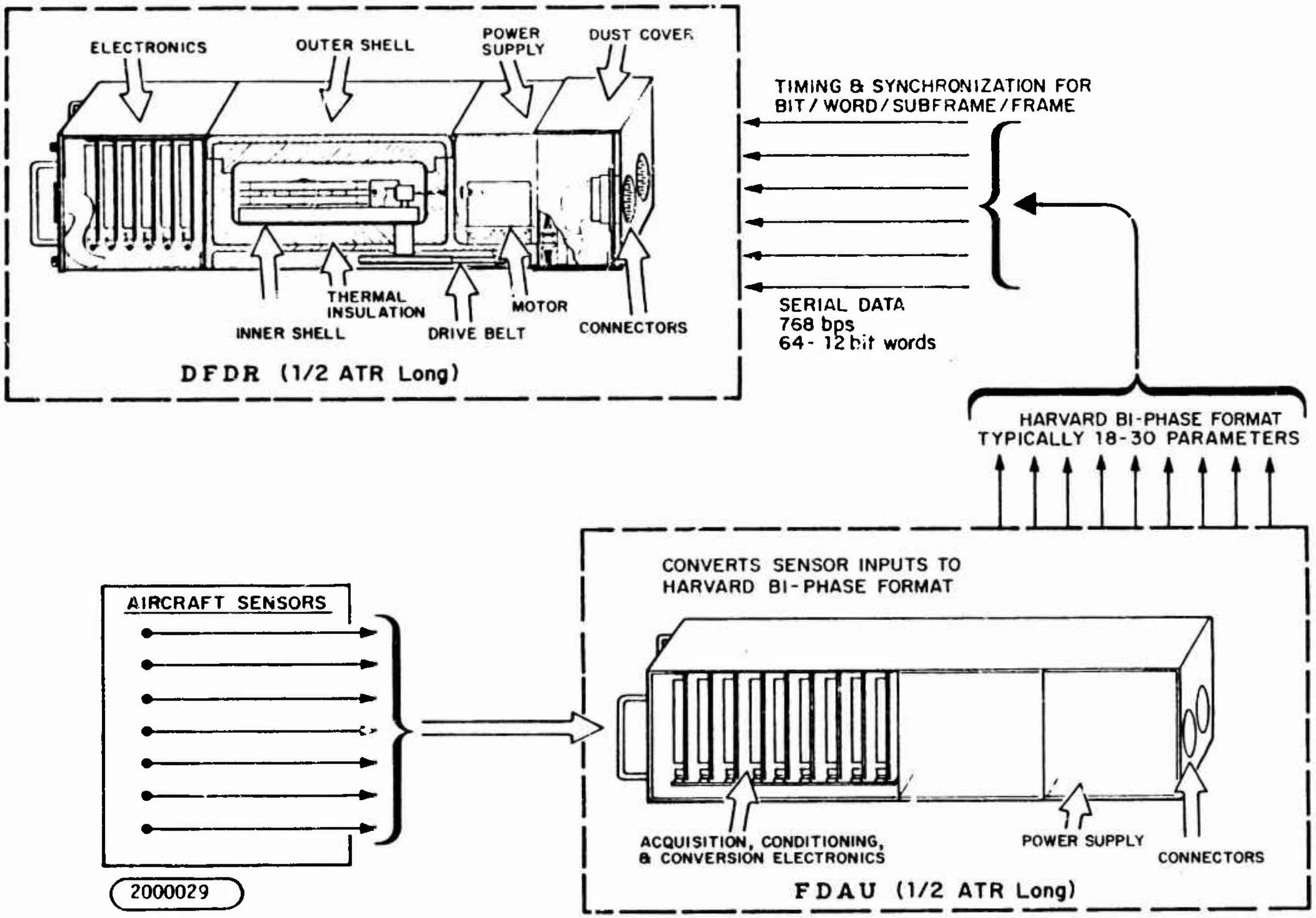

Figure 31. Basic Concept of Crash-Protected Digital Tape Recording

A typical DFDR can record over 25 hours of data before writing over previously recorded data. Multiple track tapes are used to achieve the 25-hour requirement. For example, a six-track tape will record over 4 hours of data on each track before rewriting in an old track. In this case, tracks 1, 3, and 5 would be recorded in the forward direction and tracks 2, 4, and 6 in the reverse direction. After all six tracks have been used, and more than 25 hours of data have been stored, recording is resumed on track 1, erasing the old data. Four-track tape units are also frequently used, but in either case, the requirement to store the last 25 hours of data at the rates specified in ARINC 541 implies a storage capacity of $69x10^6$ bits or greater.

Typical DFDRs require an FDAU which generates the timing signals required to define bit, word, subframe, and frame times.

Each frame of data contains four subframes, and each subframe contains 64 12-bit bytes representing one second of digital data. The first word of each subframe is a synchronization word, provided by the FDAU, and this word signals the start of a new subframe. The FDAU also converts the data to a Harvard Bi-phase format, and transmits it to the DFDR in a serial form.

DFDRs typically have the transport contained within an enclosure constructed to protect the tape against crash environments. However, the capstan motor is mounted outside the thermal insulation to prevent motor heat from destroying the transport. In the early days of crash recorders, prototype recorder memories were occasionally destroyed due to the internal heat generation of the motor itself.* Thermal expansion/contraction problems are solved by using compatible materials. For example, mechanical housing and and shafts are constructed of compatible material to maintain adjustment throughout the operating temperature range. Table 30 shows the major characteristics associated with crash-protected recorders utilizing digital tape technology.

Including time, DFDRs typically record at least 18 parameters and some variations have an expanded recording capacity of up to 30 parameters. (One variation found had a capacity of up to 110 parameters.) An internal status monitoring capability for indicating when inadequate power is being received, and a means for preflight checking of the recorder for proper tape movement are generally provided. Cooling is usually provided by a combination of radiation and convection from outside surfaces. Forced air cooling is usually not employed by DFDRs because of the dust problems it creates with respect to the moving parts and forced air cooling of the outer surface is usually not required.

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*This is a classic problem in crash recorder design. The requirement to crash-protect the memory creates a double problem with respect to the insulation technique used. The memory must be insulated well enough to survive a post-crash fire, but it must also allow for heat dissipation during normal operation.

Table 30. Characteristics of Typical DFDR

Size	1/2 ATR long (4.88"x19.52"x7.62") (726 cubic inches)
Weight	20 - 25 pounds
Operating temperature	-55° to +70°C
Recording time	25 hours or greater
Number of parameters	18 - 20 (expandable to 110)
Storage	69×10^6 bits or greater
Service life	1000 hours minimum for electrical and mechanical assemblies
Format	Harvard Bi-phase
Track density	1600 - 1800 bpi per track
Tape speed	0.43 - 0.46 inches/second
BIT error rate	10^{-3} to 10^{-4}
Recording medium	Mylar magnetic tape or "Vicalloy" metal tape
Separate FDAU	1/2 ATR long, 15 - 20 pounds
Approximate cost (low quantity)	\$15,000 for recorder \$10,000 for FDAU

Since DFDRs require periodic maintenance actions to check the recording quality, clean the read/write heads, clean the tape, and extract data approximately every 500 hours, the maintenance overhead for these units is considerable, although not as high as the maintenance overhead for oscillographic recorders. Data monitoring outputs of DFDRs help to reduce the maintenance overhead.

The digital tape technology does offer some advantages for crash survivable recording systems. As with oscillographic recorders, the recording medium can withstand temperatures well beyond that of other memory media thereby minimizing the amount of heat protection required to withstand a post-crash fire. Concentric layers of tape provide some mechanical and thermal protection. Memory expansion is relatively inexpensive (about 0.001 to 0.007 cents/bit) thereby permitting an expanded parameter list potential at a very low cost. Also, the time at which a catastrophic event takes place will be easily identified on the tape and the possibility of writing over pre-accident information is remote. Finally, it is important to note that this recording technology is fully developed for crash-survivable recording and has been used in accident/mishap readouts with excellent success world wide.

Although smaller and lighter DFDR systems are being offered, this technology is not suitable for the A/F/T aircraft category. Size and weight are excessive. The device has a relatively low reliability because of the moving parts, the tape must be replaced periodically when recording quality degrades, it cannot be relied upon to record faithfully during high-g maneuvers when recording is extremely important for A/F/T aircraft*, and it has a high maintenance overhead penalty. The maintenance overhead penalty stems from the need to continually check recording quality, clean the read/write heads, clean the tape, lubricate the moving parts, extract data, and replace worn tapes and parts.

c. Disc. Disc memory systems are not currently used for crash-survivable flight data recorders. However, one vendor surveyed offers a very small airborne memory disc which could be made crash-survivable. This airborne memory disc is currently used on several intermediate-sized and wide-bodied commercial aircraft. It is also used on one fighter aircraft in the USN inventory. The disc also meets a wide range of military specifications including operating temperature, power, shock, vibration, altitude, sand/dust, salt spray, humidity, and EMI.

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*Experience with DFDRs installed in high performance military aircraft for foreign countries shows that tape bunching during high-g maneuvers is a very common problem.

The concept of how this disc memory system would be used for the crash-survivable flight data recorder is shown in figure 32. Parallel data is transferred bidirectionally across the standard memory bus under control of the data processing electronics. Disc-related electronics are functionally divided into 1) the required interface logic for bidirectional transfer of parallel data, control lines, and status lines, 2) serial-to-parallel/parallel-to-serial code conversion, data formatting, and error detection, and 3) read/write and memory select circuitry. Storage is on the small plated disc which utilizes fixed heads for surface magnetization and magnetization detection. A common power supply would drive the recording system elements. High density storage is achieved via a microscopically thin nickel-cobalt alloy on an aluminum substrate. Characteristics of a projected crash-protected disc system utilizing this technology are shown in table 31.

The digital disc technology would offer some advantages for the CSFDR system. The read/write access time is in the 10-millisecond range and is therefore considerably faster than typical tape units. This access time is comparable to the write cycle access time associated with MNOS solid-state memories and therefore is compatible with digital data compression techniques. Also, the reliability of the disc system is expected to be very good (approximately 10,000 hours), due to 1) the use of extremely low mass heads, 2) tough coatings over the smoothest surface, 3) massive gyro precision bearings, and 4) hermetically sealed enclosure. Also, the capability for 54 minutes of continuous recording is attractive. Finally, the endurance of the disc media is an excellent characteristic for the A/F/T application, with the disc life exceeding the aircraft life itself.

However, because of the numerous disadvantages of the disc system for the A/F/T problem, we do not recommend this technology. The volumetric storage density is only about 25K bits/cubic inch as compared to about 100K bits/cubic inch for tape units. Also, the disc system is an electromechanical device requiring periodic maintenance actions. Additionally, the cost of the disc system would be relatively high when compared to other systems, the size of 465 cubic inches is too large, the weight of 15 pounds is too heavy, and the survivability rate of the disc is not expected to be as good as other memory media for the A/F/T application. Finally, it is important to note that the disc memory now in production has the motor mounted in the disc's center and therefore would have to be redesigned for the A/F/T application. This redesign is due to the high power of the motor and the two-way insulation problem associated with crash recorders in general.

Table 31. Projected Characteristics of a DFDR Utilizing Disc Storage

Size	1/2 ATR short (4.88"x12.52"x7.62") (465 cubic inches)
Weight	15 pounds
Operating temperature	-54° to +71°C
Recording time	0.905 hours (54.3 minutes)
Number of parameters	18 - 30 (expandable to 110)
Storage	2.5x10^6 bits
Service life	3000 hours
Format	Serial
Density	6000 bpi
Disc speed	6000 rpm
Bit error rate	10^{-7}
Recording medium	Cobalt-nickel alloy disc
Data transfer rate	10x10^6 bps
Approximate cost (low quantity)	$15,000 - $20,000

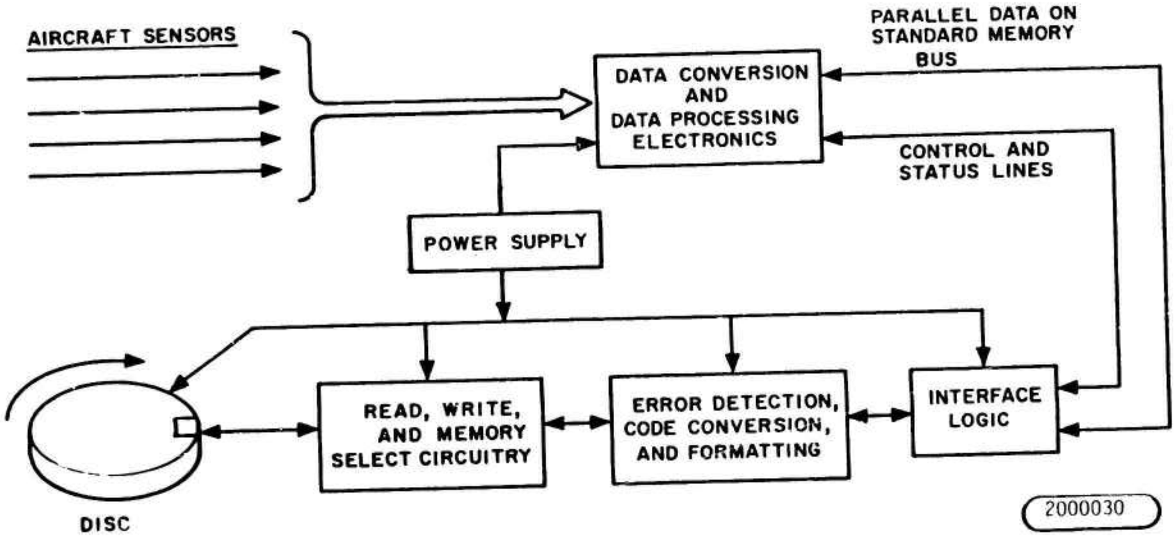

Figure 32. Memory Disc System Used for Flight Data Recording

d. Drum. Drum memory systems are not currently used for CSFDRs, but are ideal for situations where large stores of information must be available for reading, concurrent with input of enormous quantities of data for processing. Drum memory systems are used on the USN S-3A and P-3C aircraft. They are also used on the AWACS and B-1 aircraft. None of these units are crash-protected. Drum memory systems have been used on high performance aircraft such as the A-6 and F-111. The results have been discouraging in the areas of reliability, maintainability, and performance through high g maneuvers because of the inherent electromechanical nature of the drum system. Fifteen megabit drum systems using a cobalt-nickel finish, packaged in a single ATR long configuration, and meeting military specifications, have been delivered. These units would have to be repackaged to meet crash survivability specifications. Utilizing such repackaged units for the A/F/T application would result in severe penalties in the following areas:

- size
- weight
- initial cost
- LCC (because of high $\bar{R}$ and $\bar{M}$ costs)

Moreover, no major technological advances are known at this time that would significantly improve these critical areas. Size, weight, and costs would have to be reduced by a factor of two for the A/F/T application. Therefore, we do not recommend this memory technology for the CSFDR system.

3.3.1.2 Nonsolid-state electronic group - Two basic memory technologies are considered in this group: 1) core, and 2) plated wire.

a. Core. Magnetic core memories have been considered for severe environment flight recorders in the past[17]. Previously, this technology has continued to be more cost effective and more reliable than many challenging technologies. This has been due to improvements in cores, planar stack design, and semiconductor sense/drive circuits. In military applications, where volatility is a major concern (this is especially true for the CSFDR), magnetic core has offered the most viable approach for RAM where semiconductor with battery backup is not acceptable. Other advantages of core include fast access time, fast write cycle time, infinite data retention, and infinite endurance. However, the size, weight, and operating power requirements for a crash-protected core memory system would consume the major portion of the budgets assigned to these parameters for the entire CSFDR system. Note the following data for a projected 4Kx16-bit crash-protected core memory system:

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[17] Trageser, James H., "Non-Volatile Memory System for Severe Environment Flight Recorders", Technology, Inc., Dayton, Ohio, May 18, 1978.

Operating Power	68 watts
Size	150 cubic inches
Weight	8 pounds

The operating power number becomes particularly bad for this application when the two-way insulation problem is superimposed onto the design. Additionally, the cost/bit of approximately 5 cents for core memory systems is not particularly attractive. Thus, we do not recommend core memory technology for the CSFDR application.

b. Plated Wire. Plated wire is one of a very few memory technologies which has exhibited nonvolatile storage capabilities during circumvention. For this reason it has historically been an excellent candidate for memory system applications requiring radiation hardening. However, with a memory system cost of approximately 80 cents/bit it cannot be considered as a viable candidate for the CSFDR system.

3.3.1.3 Solid-state electronic group - Seventeen solid-state electronic memory technologies were reviewed for application to the crash survivable memory portion of the CSFDR system. Five of these technologies were found to be viable candidates.

All of the solid-state electronic memory technologies reviewed are briefly described in the following paragraphs.

a. MNOS (metal-nitride-oxide-semiconductor). MNOS devices are solid-state memories which can retain stored data when power is removed. They can be erased and programmed by applying an electrical pulse of about 25 to 30 volts to the programming pins without wiping out the rest of the memory.

These devices are relatively slow in the write cycle[18] and have costs (in the hybrid configurations) which range between those of core memory and plated wire. Since they provide almost infinite store times, they have become popular in a host of new applications where non-volatile devices are required. The hybrid MNOS EAROM memory systems are available from several sources with excellent system bit densities.

MNOS technology is similar to that of typical P-channel MOS transistors. The major difference is the nitride layer placed above the gate region between the gate metal and oxide layer. Figure 33 indicates the cross section of an MNOS transistor.

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[18] Hnatek, Eugene R., "An Overview of Advanced LSI Technology", Monolithic Memories, Inc., Sunnyvale, California, 1977.

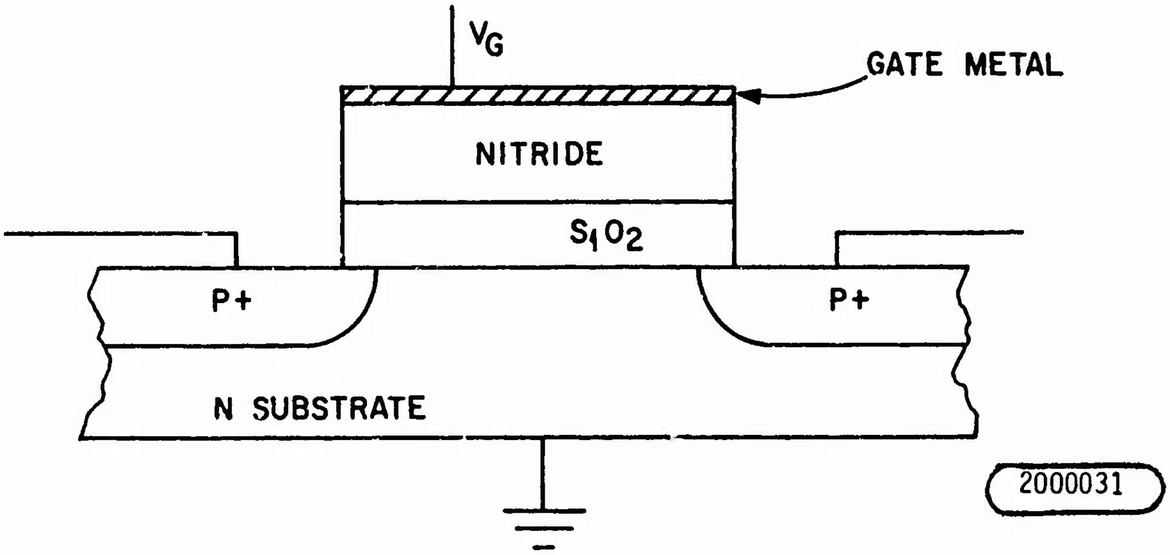

Figure 33. MNOS Cross Section

The function of the nitride layer is to provide the ability to vary the threshold voltage of the transistor. The variation in threshold voltage is accomplished by trapping a positive or negative charge in the nitride layer by application of a write or clear voltage to the gate. Application of a clear voltage (typically 25 to 30 volts positive) results in movement of a negative charge from the substrate into the nitride layer. This has the effect of reducing the magnitude of the negative voltage which must be applied to the gate to turn the transistor on. Application of a write voltage (typically 25 to 30 volts negative) has the opposite effect, i.e., movement of a positive charge from the substrate into the nitride layer which increases the magnitude of the negative voltage which must be applied to the gate to turn the transistor on. Both the nitride layer and oxide layer are insulators. However, the write or clear voltage amplitude is sufficiently great to effectively break down the oxide, allowing the charge to move into the nitride layer. Once there, it remains trapped until application of a write or clear voltage, thereby providing the non-volatility characteristics of an MNOS transistor. When used as a memory cell, the shift in threshold voltage is used to designate a logic "zero" or "one".

One excellent quality of MNOS memories for the CSFDR system application is the ability of these devices to retain data for long periods of time at elevated temperatures[11]. This is a requirement because the survivable memory module must be able to withstand the elevated temperatures encountered in a post-crash fire while utilizing a minimum amount of insulation. (The minimum insulation is required in order to keep the overall size, weight, and cost as low as possible.) Retention testing of MNOS LSI memories has been studied in great detail. Retention times of 60 years at 70°C (constant) and 2 years at 125°C are expected. Retention times of 8 hours at a constant storage temperature in the 150°C to 175°C range are projected. These retention times are adequate for the CSFDR system application when state-of-the-art insulation techniques are considered.

The read cycle time of less than 1 microsecond is compatible with the CSFDR system. Recent improvements in MNOS technology have reduced the erase/write cycle time to 100 microseconds. Although this erase/write cycle is slow when compared to the read cycle, it is compatible with a CSFDR system memory hierarchy when a "scratchpad" memory is used for data compression. Additionally, read/write power dissipations in the 100 microwatt range, retention in excess of 30 years, and endurance of 10^6 cycles, make this technology a good candidate for the CSFDR system crash-protected memory when used in the hybrid package configurations.

b. MNOS BORAM (block-oriented random access memory). Militarized MNOS BORAM is available via two USA electronics houses and one foreign country electronics house. In all three cases, the 8-kilobit chips are available. The US Air Force, Army, and Navy have continually funded MNOS BORAM developments during the past decade because of its tremendous potential where non-volatility is required[19].

A primary difference between standard MNOS EAROM technology and MNOS BORAM is the data transfer rate achievable via block operations. The required data for a block transfer is read in parallel into shift registers and then multiplexed onto the system I/O bus as required. Conventional shift registers provide the external storage to accomplish this function as shown in figure 34.

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[11] Ibid.

[19] Belt, Ronald A., "Advanced Memories for Military Systems", NAECON Record, 1976.

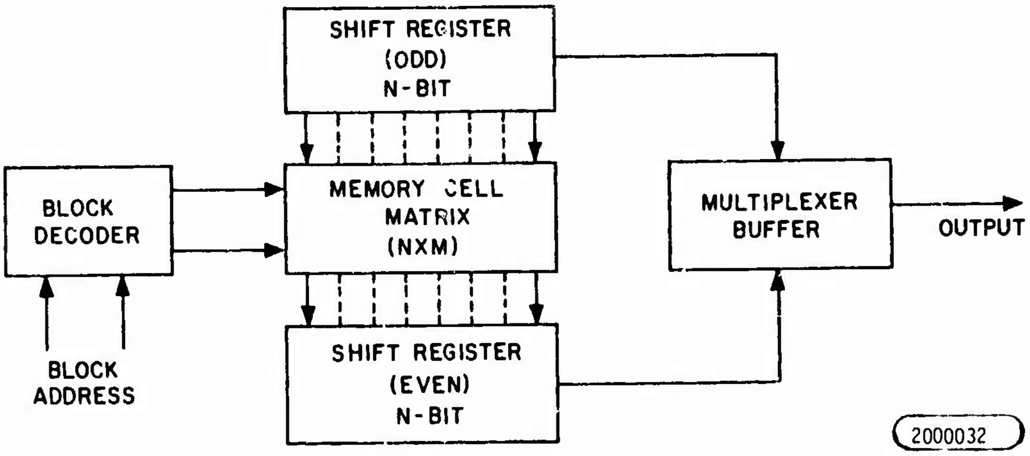

Figure 34. MNOS Array Block Diagram

In either a read or write mode, the block address is applied to the block decoder which accesses the memory cell matrix column M bits long. Data is then transferred M bits in parallel, between the matrix and the N-bit shift registers, the direction of data flow being determined by the operating mode (read or write). Data transfer between the memory array shift register and the internal BORAM data bus is accomplished through the multiplexer buffer. Extensive use of hybrid packaging techniques would provide the extremely high densities required by the CSFDR system applications.

The MNOS BORAM is an excellent candidate for the CSFDR system survivable memory. It has all of the advantages of MNOS EAROM technology. Additionally, it has an improved data transfer rate (5/2 improvement), and a full military operating temperature range, both of which are improvements over MNOS EAROM.

c. MNOS/SOS (metal-nitride-oxide-semiconductor/silicon-on-sapphire). Silicon-on-sapphire for use in the military/aerospace community is confined to one manufacturer of integrated circuits. (Other companies developing SOS technology have not introduced integrated circuits to the general marketplace at this time.) Although this technology offers one of the best speed power products of any technology in the semiconductor industry, it is not recommended for the CSFDR system survivable memory. This is primarily due to the high processing costs and lack of a second source.

d. TTL (Transistor Transistor Logic). Bipolar TTL integrated circuit memory is basically characterized as high speed devices with 35- to 100-nanosecond access time. They require only a +5 volt power supply and their output levels are compatible with the industry's most popular logic family. However, they have the disadvantages of high power dissipation, low bit density, relatively high cost, volatility, and do not provide for reduced voltages for data retention. For these reasons, TTL is excluded as a CSFDR system survivable memory candidate technology.

e. I^2L (integrated injection logic). Bipolar I^2L memories have many excellent features. They exhibit high bit densities, relatively low power dissipation, access times in the 50- to 100-nanosecond range, and low data retention power. In spite of the relatively low power consumption of these devices, they can consume more power during operation than CMOS devices when the read/write data rates become high. Also, this is a volatile memory technology. Therefore, we do not recommend this technology for the CSFDR system survivable memory.

f. I^3L (isoplanar integrated injection logic). The isoplanar process substitutes thermally grown oxide for the P-type diffusions that isolate active elements of conventional bipolar devices. This process permits a very small die size (11,716 mil^2) which is smaller than many competetive devices. Thus, it provides a higher density, higher yield, and lower cost than competitive MOS devices. Higher speeds are also achieved because the smaller die size results in faster parts since parasitic capacitances are reduced. These devices, however, are volatile and currently available from only one source. Therefore, they are not recommended for the CFSDR system.

g. CMOS (complementary metal oxide semiconductor). CMOS is a mature, proven semiconductor technology and has been qualified for use in severe military environments. High reliability has been established and manufacturers routinely supply devices to military specifications for operation over a temperature range of -55°C to +125°C. Advances over the last few years in the fabrication processes have resulted in improved bit densities. These same improvements have also resulted in improved operating speed and reduced power consumption.

It should be emphasized that 1) the power dissipation of most types of volatile semiconductor memories is too high to allow a reasonable size battery to retain the data for the desired length of time following the crash, and 2) CMOS is a volatile technology. However, the power dissipation of the new CMOS devices is so low that these devices are attractive for the CSFDR system survivable memory. CMOS memories with battery backup are being used to provide a non-volatile memory system in a number of military/aerospace applications and multiple sourcing is not a problem. Battery backup in the power-down mode must be an inherent part of the memory system design if CMOS is used. Moreover, the size, weight, and cost of the battery must be included in any comparison of volatile and non-volatile memory technologies.

Most available batteries do not have the required operation and shelf life qualities for the temperature ranges to be encountered in the CSFDR system application. One notable exception is the lithium solid-state battery. This battery is capable of operation and storage over the required temperature range with no measurable self-discharge. Cells have been stored at temperatures up to 100°C for a period of one year with no measurable loss in capacity and its estimated shelf life exceeds 20 years. The only characteristic which has limited their use in more applications is the relatively low current capability of these cells at low temperatures. However, with CMOS memory this is not a valid limitation. The data retention current for CMOS memory devices in the power-down mode is primarily the leakage current of reverse biased silicon diodes which exhibits a positive exponential characteristic. Thus, as the battery's ability to supply current is reduced for decreasing temperatures, the current demand by the memory is also reduced by an equal or greater amount. The solid-state lithium battery has an energy density between 5 and 10 whr/cubic inches. For a 4Kx16-bit memory system using CMOS, a single 3.8 volt, solid-state battery having an approximate size of 1.2" diameter x .25" long would have the capacity to support the memory in the power-down mode.

Therefore, based upon the preceding considerations, we must regard CMOS memory technology coupled with a specialized lithium solid-state battery design as a viable candidate for the CSFDR system survivable memory.

h. CMOS/SOS. One company is developing CMOS/SOS circuits under contract to the Office of Naval Research for use in air-to-air missiles. As with the case of MNOS/SOS, the high processing costs and lack of second source make this technology unattractive for the CSFDR system.

i. NMOS (N-channel metal-oxide semiconductor). Both the static and dynamic NMOS chips have advantages over some semiconductor technologies for this application. They have excellent bit densities, relatively fast write cycle times, have recently been tested over full military temperature ranges, and have excellent costs per bit. However, because of their volatility and relatively high read/write power (approximately 10/1 over CMOS) these devices would create severe thermal problems when packaged in an insulated crash-survivable memory module. Therefore, neither the static nor dynamic NMOS is recommended.

j. MNOS EE-PROM (electrically erasable programmable read-only memory). Two types of EE-PROM devices have recently been announced. 1) MNOS based[20], and 2) NMOS based[21]. Each device has excellent qualities for the CSFDR system application.

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[20] Johnson, W.S., "16-K EE-PROM Relies on Tunneling for Byte-Erasable Program Storage", Electronics, February 28, 1980.

[21] Shelton, E.K., "Low-Power EE-PROM Can Be Reprogrammed Fast", Electronics, July 31, 1980.

The MNOS based EE-PROM is a 16,384-bit fully static device and is either byte or chip erasable. It is non-volatile. The device meets the goals of high density, long-term retention, high performance, and endurance required by the CSFDR system. Figure 35 shows the MNOS EE-PROM memory cell.

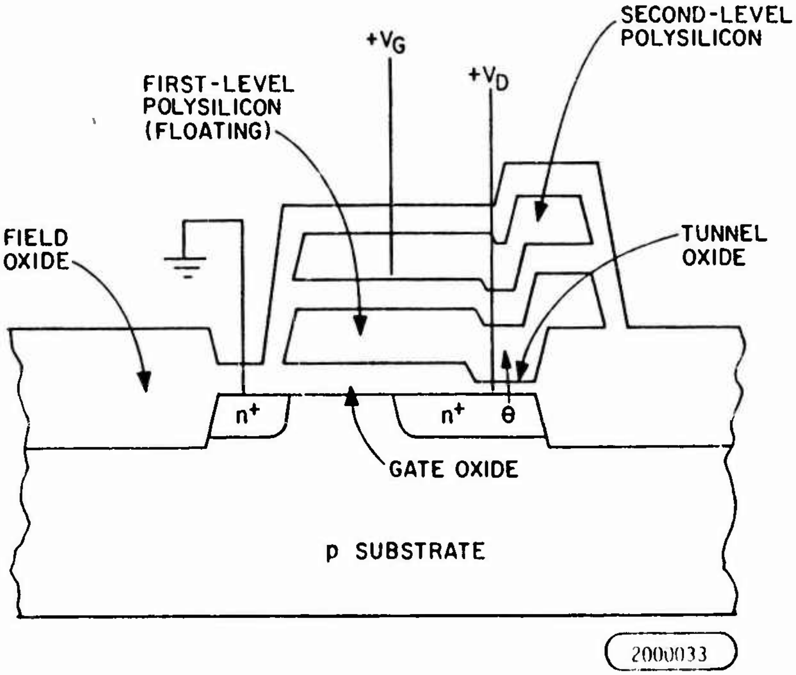

Figure 35. MNOS EE-PROM Memory Cell

The heart of this device relies upon electron tunneling through thin oxide to charge and discharge a floating gate. The floating gate is capacitively coupled to a positive potential when a voltage (V_G) is applied to the top gate and when the drain voltage (V_D) is at 0 volts. Electrons are then attracted through the tunnel oxide to charge the floating gate. Applying a positive potential to the drain and grounding the gate reverses the process to discharge the floating gate. Thus, a very simple, reproducible means for programming and erasing a memory cell is provided.

This technology is expected to become the standard form of non-volatile storage in microprocessor-based systems of the future. It is considered a viable candidate for the survivable memory of the CSFDR system.

k. NMOS EE-PROM. EE-PROMs can also be built using NMOS technology[21]. When used in conjunction with CMOS peripheral circuitry, a non-volatile memory system requiring very little power results. An 8,192-bit chip has recently been introduced. This device requires only 25 milliwatts during programming and erasing, and 10 milliwatts during reading. Only 17 volts are required for programming this device, as opposed to 25 volts for MNOS EE-PROMs. Memory retention is estimated at 10 years at elevated temperatures of 125°C. The memory cell is shown in figure 36.

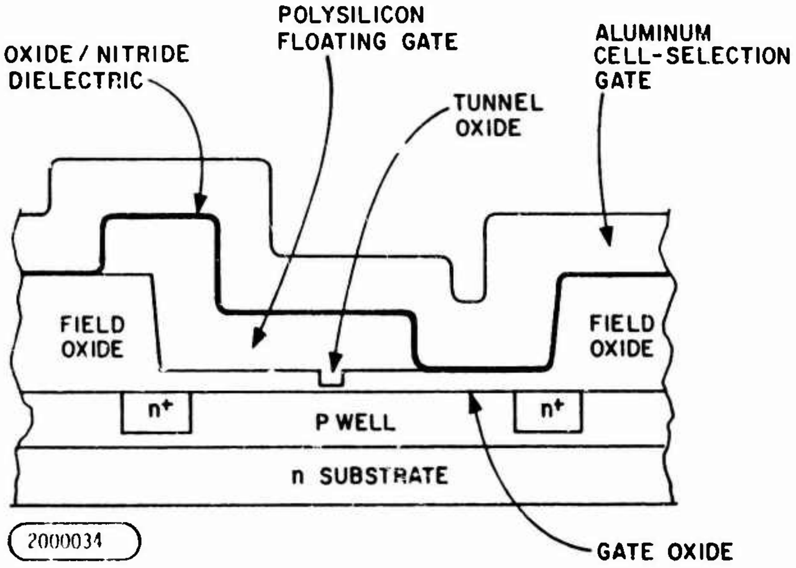

Figure 36. NMOS EE-PROM Memory Cell

The memory cell consists of a single transistor having a split-gate structure. The left side of the transistor contains the dual-gate storage portion of the cell, formed by a polysilicon floating gate overlaid by an aluminum control gate. The aluminum layer also extends to the right, thereby serving as a cell selector gate.

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[21] Ibid.

The polysilicon floating gate is isolated from the MOS channel by the tunnel oxide and the normal gate oxide. It is isolated from the control gate above it by a nitride-oxide sandwich. This thin dielectric sandwich is crucial because it ensures a strong capacitive coupling between the gates permitting 17 volts to charge and discharge the floating gate.

The erasing and storage operations are initiated by raising the supply voltage pin to the +17-volt programming voltage and then applying TTL-level signals to the chip-enable and output-enable lines.

An internal voltage detector monitors the power supply voltage level. If this voltage is elevated above about +8 volts, the detector automatically throws the chip into the erase-and-program mode. A logic low pulse on the output-enable lines now causes bulk erasure of the memory, and a logic low pulse applied to chip-enable programs the byte at the location selected by the address bus with the information present on the data bus. During erasure or programming, the output bus drivers are automatically turned off so that the raised supply voltage does not damage any devices connected to the EE-PROM.

In summary, the low power, good endurance retention at high temperatures, good chip density, non-volatility, and excellent cycle times make this technology an excellent candidate for the survivable memory portion of the CSFDR system.

l. PMOS (P-channel MOS). PMOS is the most mature semiconductor technology reviewed for this study. It derives its name from the fact that the conducting channel between source and drain of the MOS FET is P-type material. Multiple power supplies are usually required because the threshold level on PMOS memory cells is relatively high and a negative gate to source voltage is necessary. Unfortunately, the read/write power dissipation is very high (approximately 25 to 50 times greater than CMOS). Because of these two negative features (high power and volatility), this technology does not warrant consideration for the CSFDR system.

m. VMOS (V-groove MOS). VMOS is basically an N-channel MOS logic structure integrated on a three-dimensional surface rather than in two dimensions. Although this technology has some interesting features, its high power dissipation (625 microwatts) eliminates it as a viable CSFDR system candidate.

n. ECL (emitter-coupled logic). Bipolar emitter-coupled logic memories operate in the transistors' linear region. This allows extremely high speed because the time required to bring the transistor out of saturation is eliminated. However, these devices, like the bipolar TTL devices, have very high power dissipation, relatively high cost, and are volatile. Thus, they are not nearly as attractive for the CSFDR system application as other solid-state technologies.

o. CCD (charge-coupled devices). CCD memory fills a need: it fits into the gap between other semiconductor and magnetic media. Chip organization is important, and there are three ways to organize a CCD memory chip: synchronous, serial-parallel-serial, and line-addressable RAM.

Available CCD memories are either serial-parallel-serial types or line-addressable RAMs. In the serial-parallel-serial organization, parallel lines of data move simultaneously to a row-end detector, shortening access time; but this is more complex to build and dissipates more power. Finally, the line-accessible organization, in which each line of data is accessed at random, is the fastest and dissipates relatively low power.

A basic CCD cell occupies 60% of the area of a 1-transistor MOS RAM cell. In addition, the CCD memory has less overhead requirements, all tending to increase density.

To store digital data in these devices, charge signals must be periodically refreshed or regenerated. Overall design of different CCD memory chips reflects the emphasis placed on one or more of the following: clock power, access time, chip overhead for peripheral circuits, frequency ranges, temperature range, and the number of CCD clock phases.

CCD memories are considerably slower than MOS or bipolar memories and have reduced operating temperature ranges. For these reasons they are not recommended for the CSFDR system.

p. Bubble. Magnetic bubbles are formed in thin sheets of certain magnetic oxides by applying a biasing magnetic field perpendicular to the plane of the sheet. They are not semiconductor devices, but are an LSI technology and deserve consideration for the CFSDR system.

A bubble represents a "1" and the absence of a bubble means "0". The tiny bubbles, measuring just 5 microns across (a micron is a millionth of a meter), are actually cylindrical magnetic islands polarized in a direction opposite from that of the film. The tiny bubbles appear, disappear, and move around on the surface of the crystalline chip under the control of a magnetic field. See figure 37.

Bubbles are non-volatile with a slow serial speed, but system throughput may approach the highest speed silicon RAMs where associative and parallel processing can be used.

Magnetic-bubble memories unite most of the outstanding capabilities of solid-state and electromechanical storage.

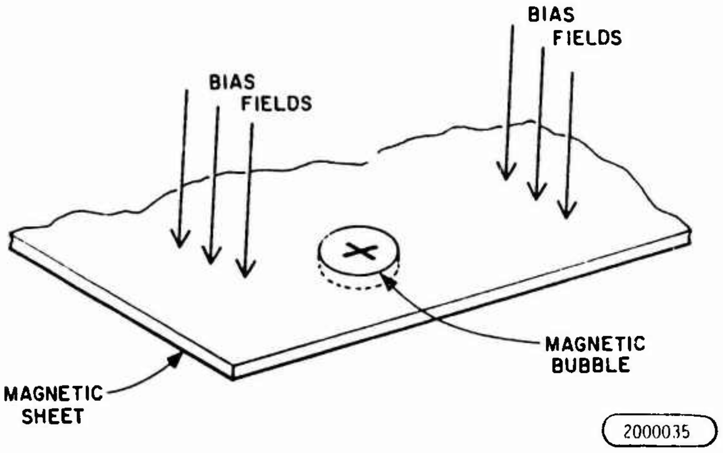

Figure 37. Bubble Memory Device

In comparison with fixed-head and floppy disks, bubbles have a higher reliability and a lower error rate since they employ no moving parts. Other assets are a faster access time, less power consumption, smaller physical size, simple interfacing, and a lower entry price, all resulting from the elimination of mechanical elements.

One-megabit devices are available which operate over the -30° to +80°C temperature range, and standby over the -50° to 100°C temperature range. Chip densities are excellent and the data retention is unlimited for all practical purposes. Thus, the magnetic bubble memory technology is a viable candidate for the CSFDR system survivable memory module.

3.3.1.4 Data storage characteristics table - The characteristics of each memory technology surveyed are shown in table 32. This table includes four electromechanical memories, two nonsolid-state electronic memories, and seventeen solid-state electronic memories.

3.3.1.5 Analysis of prime candidates - A review of the rationale presented in the previous paragraphs and the associated table 32, shows that there are six technologies which warrant further consideration for the survivable memory module: 1) MNOS EAROM, 2) MNOS BORAM, 3) CMOS with special solid-state lithium battery, 4) MNOS EE-PROM, 5) NMOS EE-PROM, and 6) bubble memory. A comparison of the read and write power for MNOS EAROM and MNOS BORAM clearly shows MNOS BORAM as having a significant advantage. Power dissipation is an extremely important parameter for the survivable memory. Therefore, MNOS EAROM is eliminated. Similarly, when MNOS EE-PROM is compared with NMOS EE-PROM, we find that NMOS EE-PROM has a significant advantage in the power dissipation category. Therefore, we also eliminate MNOS EE-PROM from the list in favor of NMOS EE-PROM. Thus the basic list of four electromechanical memories, two non-solid-state electronic memories, and seventeen solid-state memories is reduced to the following four prime candidates:

Table 32. Data Storage Characteristics for Memory Technologies Surveyed

	CHARACTERISTIC												
MEMORY TECHNOLOGY	READ ACCESS TIME	WRITE CYCLE TIME	TRANSFER RATE	READ-OUT	VOLA-TILITY	OPERATING TEMPERATURE RANGE	SYSTEM COST/BIT	READ POWER/BIT	WRITE POWER/BIT	RETEN-TION	ENDURANCE	VOLUMETRIC OR AREA BIT DENSITY	SECOND SOURCE AVAILABLE	BIT ERROR RATE
Oscillographic	min	N/A	N/A	NDRO	NV	-55 to +70	N/A	N/A	N/A	∞	16.6 days	N/A	yes	N/A
Digital tape	sec	sec	10Mb/s	NORO	NV	-55 to +70	0.0001¢	2µw av.	2µw av.	∞	1/3 yr	$10^5 b/in^3$	yes	$10^{-3}-10^{-4}$
Disc	10ms	10ms	10Mb/s	NDRO	NV	-54 to +71	0.08¢	7µw av.	7µw av.	∞	1/2 yr	$2.5x10^4 b/in^3$	yes	10^{-7}
Drum	10ms	10ms	10Mb/s	NDRO	NV	-20 to +55	0.05¢	8µw av.	8µw av.	∞	1/2 yr	$2x10^4 b/in^3$	yes	10^{-7}
Core	350ns	700ns	1Mb/s	DRO	NV	0 to +70	5¢	3mw	3mw	∞	∞	$3x10^3 b/in^3$	yes	10^{-8}
Plated wire	350ns	800ns	5Mb/s	NDRO	NV	-55 to +85	80¢	200µw	100µw	∞	∞	$\frac{5x10^3}{in^2}$	yes	10^{-8}
MNOS EAROM	700ns	100µs	2Mb/s	NDRO	NV	-55 to +100	30¢	100µw	100µw	30yrs	10^6cys	$\frac{3x10^4}{in^2}$	yes	10^{-9}
MNOS BORAM	1µs	20µs	5Mb/s	NDRO	NV	-55 to +125	1¢	0.8µw	0.8µw	30yrs	10^6cys	$\frac{6.5x10^4}{in^2}$	yes	10^{-9}
MNOS/SOS	350ns	100µs	5Mb/s	NDRO	NV	-55 to +125	30¢	100µw	100µw	30yrs	10^6cys	$\frac{6.5x10^4}{in^2}$	no	10^{-9}
TTL (static)	60ns	60ns	10Mb/s	NDRO	V	-55 to +125	80¢	500µw	500µw	∞	∞	$\frac{6.5x10^3}{in^2}$	yes	10^{-9}
I^2L (static)	50ns	100ns	10Mb/s	NDRO	V	-55 to +125	10¢	100µw	100µw	∞	∞	$\frac{1.2x10^5}{in^2}$	yes	10^{-9}
I^3L	35ns	70ns	10Mb/s	NDRO	V	-55 to +125	7¢	0.5µw	0.5µw	∞	∞	$\frac{2.5x10^5}{in^2}$	no	10^{-9}
CMOS	700ns	700ns	2Mb/s	NDRO	V	-55 to +125	25¢	10µw	10µw	5yrs w/bat	∞	$\frac{1.2x10^4}{in^2}$	yes	10^{-9}
CMOS/SOS	350ns	350ns	7Mb/s	NDRO	V	-55 to +125	25¢	5µw	5µw	∞	∞	$\frac{6.5x10^4}{in^2}$	no	10^{-9}
NMOS (static)	200ns	350ns	10Mb/s	NDRO	V	-55 to +125	1¢	100µw	100µw	∞	∞	$\frac{6.5x10^4}{in^2}$	yes	10^{-9}
MNOS EE-PROM	250ns	1ms	5Mb/s	NDRO	NV	-55 to +125	0.4¢	50µw	100µw	>10yrs	$10^{-5}-10^6$cys	$\frac{4x10^5}{in^2}$	yes*	10^{-9}
NMOS EE-PROM	600ns	100µs	5Mb/s	NDRO	NV	-55 to +125	0.5¢	0.2µw	0.5µw	>10yrs	10^5-10^6cys	$\frac{2x10^5}{in^2}$	yes*	10^{-9}
PMOS (static)	1µs	1µs	1Mb/s	NDRO	V	-55 to +125	25¢	250µw	250µw	∞	∞	$\frac{6.5x10^4}{in^2}$	yes	10^{-9}
VMOS	50ns	65ns	10Mb/s	NDRO	V	-55 to +125	0.7¢	625µw	625µw	∞	∞	$\frac{10^5}{in^2}$	yes	10^{-9}
ECL	50ns	60ns	10Mb/s	NDRO	V	-55 to +125	60¢	500µw	500µw	∞	∞	$6.5x10^3$	yes	10^{-9}
CCD	100µs	100µs	5Mb/s	NDRO	V	0 to +85	0.03¢	2µw	2µw	2ms	∞	$\frac{10^5}{in^2}$	yes	10^{-9}
BUBBLE	40ms	50ms	800Kb/s	NDRO	NV	-30 to +80	0.03¢	1µw av.	1µw av.	∞	∞	$\frac{2x10^6}{in^2}$	yes	10^{-9}
NMOS (dynamic)	200ns	450ns	7Mb/s	DRO	V	-20 to +85	0.3¢	100µw	100µw	2ms	∞	$\frac{6.5x10^4}{in^2}$	yes	10^{-9}

*Second sources projected as being available within the CSFDR time frame; first sources already available.

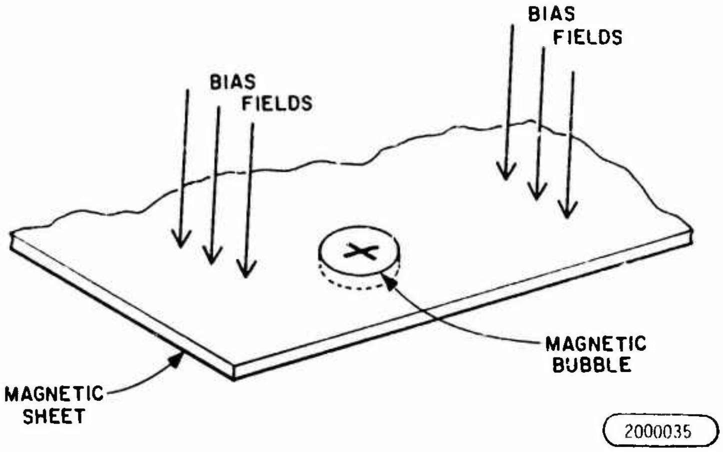

Figure 37. Bubble Memory Device

In comparison with fixed-head and floppy disks, bubbles have a higher reliability and a lower error rate since they employ no moving parts. Other assets are a faster access time, less power consumption, smaller physical size, simple interfacing, and a lower entry price, all resulting from the elimination of mechanical elements.

One-megabit devices are available which operate over the -30° to +80°C temperature range, and standby over the -50° to 100°C temperature range. Chip densities are excellent and the data retention is unlimited for all practical purposes. Thus, the magnetic bubble memory technology is a viable candidate for the CSFDR system survivable memory module.

3.3.1.4 Data storage characteristics table - The characteristics of each memory technology surveyed are shown in table 32. This table includes four electromechanical memories, two nonsolid-state electronic memories, and seventeen solid-state electronic memories.

3.3.1.5 Analysis of prime candidates - A review of the rationale presented in the previous paragraphs and the associated table 32, shows that there are six technologies which warrant further consideration for the survivable memory module: 1) MNOS EAROM, 2) MNOS BORAM, 3) CMOS with special solid-state lithium battery, 4) MNOS EE-PROM, 5) NMOS EE-PROM, and 6) bubble memory. A comparison of the read and write power for MNOS EAROM and MNOS BORAM clearly shows MNOS BORAM as having a significant advantage. Power dissipation is an extremely important parameter for the survivable memory. Therefore, MNOS EAROM is eliminated. Similarly, when MNOS EE-PROM is compared with NMOS EE-PROM, we find that NMOS EE-PROM has a significant advantage in the power dissipation category. Therefore, we also eliminate MNOS EE-PROM from the list in favor of NMOS EE-PROM. Thus the basic list of four electromechanical memories, two non-solid-state electronic memories, and seventeen solid-state memories is reduced to the following four prime candidates:

Table 32. Data Storage Characteristics for Memory Technologies Surveyed

MEMORY TECHNOLOGY	CHARACTERISTIC												
	READ ACCESS TIME	WRITE CYCLE TIME	TRANSFER RATE	READ-OUT	VOLA-TILITY	OPERATING TEMPERATURE RANGE	SYSTEM COST/BIT	READ POWER/BIT	WRITE POWER/BIT	RETEN-TION	ENDURANCE	VOLUMETRIC OR AREA BIT DENSITY	SECOND SOURCE AVAILABLE	BIT ERROR RATE
Oscillographic	min	N/A	N/A	NDRO	NV	-55 to +70	N/A	N/A	N/A	∞	16.6 days	N/A	yes	N/A
Digital tape	sec	sec	10Mb/s	NDRO	NV	-55 to +70	0.0001¢	2μw av.	2μw av.	∞	1/3 yr	10^5b/in^3	yes	10^{-3}-10^{-4}
Disc	10ms	10ms	10Mb/s	NDRO	NV	-54 to +71	0.08¢	7μw av.	7μw av.	∞	1/2 yr	2.5x10^4b/in^3	yes	10^{-7}
Drum	10ms	10ms	10Mb/s	NDRO	NV	-20 to +55	0.05¢	8μw av.	8μw av.	∞	1/2 yr	2x10^4b/in^3	yes	10^{-7}
Core	350ns	700ns	1Mb/s	DRO	NV	0 to +70	5¢	3mw	3mw	∞	∞	3x10^3b/in^3	yes	10^{-8}
Plated wire	350ns	800ns	5Mb/s	NDRO	NV	-55 to +85	80¢	200μw	100μw	∞	∞	$\frac{5x10^3}{in^2}$	yes	10^{-8}
MNOS EAROM	700ns	100μs	2Mb/s	NDRO	NV	-55 to +100	30¢	100μw	100μw	30yrs	10^6cys	$\frac{3x10^4}{in^2}$	yes	10^{-9}
MNOS BORAM	1μs	20μs	5Mb/s	NDRO	NV	-55 to +125	1¢	0.8μw	0.8μw	30yrs	10^6cys	$\frac{6.5x10^4}{in^2}$	yes	10^{-9}
MNOS/SOS	350ns	100μs	5Mb/s	NDRO	NV	-55 to +125	30¢	100μw	100μw	30yrs	10^6cys	$\frac{6.5x10^4}{in^2}$	no	10^{-9}
TTL (static)	60ns	60ns	10Mb/s	NDRO	V	-55 to +125	80¢	500μw	500μw	∞	∞	$\frac{6.5x10^3}{in^2}$	yes	10^{-9}
I^2L (static)	50ns	100ns	10Mb/s	NDRO	V	-55 to +125	10¢	100μw	100μw	∞	∞	$\frac{1.2x10^5}{in^2}$	yes	10^{-9}
I^3L	35ns	70ns	10Mb/s	NDRO	V	-55 to +125	7¢	0.5μw	0.5μw	∞	∞	$\frac{2.5x10^5}{in^2}$	no	10^{-9}
CMOS	700ns	700ns	2Mb/s	NDRO	V	-55 to +125	25¢	10μw	10μw	5yrs w/bat	∞	$\frac{1.2x10^4}{in^2}$	yes	10^{-9}
CMOS/SOS	350ns	350ns	7Mb/s	NDRO	V	-55 to +125	25¢	5μw	5μw	∞	∞	$\frac{6.5x10^4}{in^2}$	no	10^{-9}
NMOS (static)	200ns	350ns	10Mb/s	NDRO	V	-55 to +125	1¢	100μw	100μw	∞	∞	$\frac{6.5x10^4}{in^2}$	yes	10^{-9}
MNOS EE-PROM	250ns	1ms	5Mb/s	NDRO	NV	-55 to +125	0.4¢	50μw	100μw	>10yrs	10^{-5}-10^6cys	$\frac{4x10^5}{in^2}$	yes*	10^{-9}
NMOS EE-PROM	600ns	100μs	5Mb/s	NDRO	NV	-55 to +125	0.5¢	0.2μw	0.5μw	>10yrs	10^5-10^6cys	$\frac{2x10^5}{in^2}$	yes*	10^{-9}
PMOS (static)	1μs	1μs	1Mb/s	NDRO	V	-55 to +125	25¢	250μw	250μw	∞	∞	$\frac{6.5x10^4}{in^2}$	yes	10^{-9}
VMOS	50ns	65ns	10Mb/s	NDRO	V	-55 to +125	0.7¢	625μw	625μw	∞	∞	$\frac{10^5}{in^2}$	yes	10^{-9}
ECL	50ns	60ns	10Mb/s	NDRO	V	-55 to +125	60¢	500μw	500μw	∞	∞	6.5x10^3	yes	10^{-9}
CCD	100μs	100μs	5Mb/s	NDRO	V	0 to +85	0.03¢	2μw	2μw	2ms	∞	$\frac{10^5}{in^2}$	yes	10^{-9}
BUBBLE	40ms	50ms	800Kb/s	NDRO	NV	-30 to +80	0.03¢	1μw av.	1μw av.	∞	∞	$\frac{2x10^6}{in^2}$	yes	10^{-9}
NMOS (dynamic)	200ns	450ns	7Mb/s	DRO	V	-20 to +85	0.3¢	100μw	100μw	2ms	∞	$\frac{6.5x10^4}{in^2}$	yes	10^{-9}

*Second sources projected as being available within the CSFDR time frame; first sources already available.

1) MNOS BORAM
2) CMOS and special solid-state lithium battery
3) NMOS EE-PROM
4) Bubble

These four leading memory technology candidates are now analyzed in greater detail. Potential crash-survivable memory configurations, utilizing these technologies, are listed in table 33. These configurations cover the range of crash-protected memory modules required for CSFDR system configurations I, II, and III. Because of the numerous and overwhelming advantages of a microprocessor in the system, all memory configurations are assumed to operate in conjunction with a microprocessor.

Table 33. Matrix of Prime Memory Technology Candidates For CSFDR Crash-Protected Memory Module

MEMORY SIZE	MEMORY TECHNOLOGY			
	MNOS BORAM	CMOS & BATTERY	NMOS EE-PROM	BUBBLE
65,536 bits	A	B	C	D
131,072 bits	E	F	G	H
262,144 bits	I	J	K	L

It should be noted that all four memory technologies can be used in a crash-survivable system. The problem is, therefore, reduced to selecting the best memory technology of the four, keeping in mind that size, weight, and LCC are principle constraints for the A/F/T applications.

Note the relative ranking of these four memory technologies in table 34.

a. MNOS BORAM configuration. Table 34 shows this technology to be outstanding in terms of transfer rate, readout, volatility, operating temperature range, bit-error rate, and qualification. MNOS BORAM chips are available from two national sources and one foreign source. Chip densities of 8Kx1 bit are available. Thus, 8, 16, and 32 chips are required for memory configurations A, E, and I, respectively, and no size/weight penalty would result from the use of this technology. The only negative characteristic of this technology is the slight cost penalty per bit when compared to bubble or NMOS EE-PROM.

Table 34. Relative Rank of Four Prime Memory Candidates for Each Pertinent Characteristic

CHARACTERISTIC	TECHNOLOGY			
	MNOS BORAM	CMOS & BATTERY	NMOS EE-PROM	BUBBLE
Read access time	3	2	1	4
Write access time	2	1	3	4
Transfer rate	1	3	1	4
Readout	1	1	1	1
Volatility	1	4	1	1
Operating temperature range	1	1	1	4
System cost/bit	3	4	2	1
Read power/bit	2	4	1	3
Write power/bit	2	4	1	3
Retention	2	4	3	1
Endurance	2	1	2	1
Density (chip)	3	4	2	1
Second source availability	2	1	4*	2
Bit error rate	1	1	1	1
Qualification	1	2	3	4
Production lead time	3	4	1*	2

*Projected by mid 1981 calendar year.

b. CMOS & solid-state lithium battery configurations. Table 34 shows this technology to be outstanding in terms of write access time, readout, operating temperature range, endurance, second source availability, and bit error rate. However, this technology is volatile and a special solid-state lithium battery would have to be designed. The battery, in turn, increases the technological risk, reduces the reliability, increases the volumetric density, and increases the production lead time. (No off-the-shelf battery surveyed had the reliability, maintainability, and shelf-life features desired for the CSFDR system application.) Additionally, the cost per bit of this technology makes configurations B, F, and J the highest priced configurations in table 33. Thus, due to the adverse LCC effects of the special battery and relatively high memory prices, this technology is the least attractive of the four prime candidates.

c. NMOS EE-PROM configurations. Although this technology is called "NMOS", a nitride layer is used to achieve non-volatility in a fashion very similar to "MNOS". The resulting technology is outstanding in terms of read access time, transfer rate, readout, volatility, operating temperature range, read/write power, bit error rate, and projected production lead times. Additional features which make it attractive for the CSFDR system application are its good price per bit, good endurance, and good density. One of its primary advantages over the competing technologies is its unusually low power dissipation of .2 to .5 microwatts per bit. Because of the two-way insulation problems inherent in the crash-protected memory module design, low power devices are essential. Additionally, these devices cost only about one-half as much as MNOS BORAM devices and a mere one-fiftieth of CMOS/battery devices. Therefore, configurations C, G, and K are expected to have the highest reliability, lowest total weight, and lowest total volume of any corresponding configuration in table 33. Moreover, the electronics industry is projecting this technology as the standard form of storage for microprocessor-based systems of the future. Therefore, second source availability and production lead times are anticipated as being very good in the time frame envisioned for the CSFDR system. Both 8K and 16K chips are available now. Therefore, 8, 16, and 32 chips would be required for configurations C, G, and K, respectively. In summary then, we rank this technology as the best technology available for the crash-protected memory of the CSFDR system.

d. Bubble memory configurations. Excellent qualities of the bubble memory configurations are its readout, volatility, system cost per bit, retention, endurance, chip density, and bit error rate. However, the low chip density does not result in the lowest overall crash-protected memory volumetric density. We caution those who would use this technology in a crash-protected memory that a host of support circuitry is required in addition to the bubble module itself. This support circuitry includes coil drivers, function drivers, sense amplifiers, and timing/control circuitry. Therefore, in spite of the excellent chip density of bubble memories, configurations D, H, and L would be larger and heavier than any of the corresponding technologies in table 33. Additionally, the bubble devices have reduced operating temperature ranges. Therefore, we do not consider this technology as good as NMOS EE-PROM or MNOS BORAM for the CSFDR system application.

e. Final rank of memory technologies. It is technically feasible to use any of the four prime candidate memory technologies in the crash-survivable module. However, we feel that the numerous advantages of NMOS EE-PROM make it the leading candidate for the crash-survivable module of the CSFDR system. The four candidates are ranked as follows:

Table 35. Final Rank of Prime Memory Candidates For The Crash-Survivable Memory

I.	NMOS EE-PROM
II.	MNOS BORAM
III.	Bubble Memory
IV.	CMOS & special solid-state lithium battery

3.3.2 Data processing/data compression.

3.3.2.1 Analysis of available techniques to process data and reduce memory requirements - This is an extremely important aspect of the CSFDR system study. Since memory is a primary cost driver of the recording system, the most effective method of converting, formatting, and compressing the data must be determined in order to minimize the amount of solid-state memory required. However, the data processing/data compression effort must not lose sight of the the fact that an acceptable level of data fidelity must be retained after compression and ground read-out in order to be beneficial in an accident/mishap investigation. The options are:

(1) Reduce the number of recorded parameters (eliminate dependent parameters without losing information).

(2) Open up the tolerances for the reconstructed parameter profiles, thereby reducing the number of bits per word required.

(3) Retain less flight time prior to the incident.

(4) Sample all parameters, but record only if outside established boundaries.

In any case, the delicate balance between the number of parameters recorded and the size of the solid-state crash-protected memory must be established. This is especially true for Configuration II.

a. Data word organization. The data word organization within the data processor/data converter unit and crash-protected memory unit must be sufficient to allow their use in an accident/mishap investigation. Thus, after ground readout, the capability of accurately reconstructing or reducing the following is required:

- aircraft ground track and altitude vs. time
- aircraft attitude/attitude rates vs. time
- aircraft velocities/accelerations vs. time
- aircraft control system and surfaces vs. time
- aircraft engine parameters vs. time
- pilot inputs vs. time (primarily rudder pedal, throttle, and stick)

- status of various aircraft systems vs. time including aircraft peculiar systems

Thus, the required word lengths and sample rates must be established first.

b. Required data word lengths. The CSFDR system input parameters are converted at the required sampling rate to digital form via the data conversion electronics cards and associated data conversion subroutines. The conversion electronics cards and conversion subroutines are functionally modular in order to permit maximum standardization of these items. The optimum data word lengths for conversion and processing are determined as follows:

- Compute number of bits needed to give required accuracy for each parameter

- Compute the total number of bits required to cover the dynamic range of each parameter

The data word lengths for typical parameters or parameter groups are determined in the following paragraphs:

(1) Relative time. Although relative time is not strictly classified as a flight parameter, it is an extremely important parameter because the recorded data are required as a function of time for the accident/ mishap investigation. Absolute time (GMT), if available, could be used to compute elapsed or relative time. However, this is unnecessary because, if elapsed time is recorded, the absolute time can be determined from flight records, or by extrapolating forwards or backwards in time from the known absolute time of well-defined events. Moreover, absolute time is not always necessary to establish the cause of an accident/mishap. Thus, it is sufficient to record relative time via the internal clock of the CSFDR system. Additionally, it is not necessary to record time continuously, but simply to time tag, in an optimum way, the recorded data. The resolution required is 0.25 seconds for the data sampled at the higher rates. The maximum range for elapsed time is a function of the flight profile. Although, on the average, Configuration II will store the last nineteen minutes of data, in highly turbulent flight profiles, the CPM will be filled in less than nineteen minutes of flight and data wraparound will occur. Moreover, if the flight is lengthy, as is the case where air-to-air refueling occurs, it will be necessary to know which cycle the CPM is operating in. Thus, a total of 16-bits are required for relative time. This will give a resolution of 0.25 seconds and total elapsed time in excess of 4.55 hours.

The required 16 bits may also be divided into 8 bits for a synchronization frame (at the rate of one frame per minute) and 8 bits for the relative time tag between synchronization frames. In this case, a total of 16 bits will provide 4.28 hours of time, with a resolution of 0.25 seconds.

(2) Calibrated airspeed (CAS). The accuracy required for CAS is five knots. The required range is 1,000 knots. With eight bits, a range of 1,000 knots with a resolution of 3.9 knots is achieved.

(3) Fuel flow. Military aircraft achieve very high rates of engine fuel flow for relatively short periods of time. A good generalized range for this parameter is 110,000 PPH. With eight bits a range of 110,000 PPH with a resolution of 430 PPH (0.119 PPS) is achieved for each engine.

(4) Altitude. The required range for altitude is -1,000 to 80,000 feet. The organization of this parameter is a function of the type of sensor used. For the majority of cases the air data computer is the assumed altitude source. Although modern aircraft have several sources, these other sources of altitude are not required to be operational for flight. When available, however, these alternate sources provide excellent accuracies and could be used. Therefore, two altitude formats are recommended.

- Coarse altitude - 11 bits provides a range of -1,000 to 80,000 feet with a resolution of 78.1 feet (one bit reserved for sign).
- Fine altitude - 16 bits provides a range of -1,000 to 80,000 feet with a resolution of 2.44 feet (one bit reserved for sign).

(5) Engine RPMS. Core and fan RPMS require a generalized range of 120%. Seven bits gives the complete desired range with a resolution of 0.93%.

(6) Aircraft attitude parameters. High performance military aircraft are capable of achieving the full range (360°) of aircraft attitudes in normal flight operations. The general desired range for these parameters is, therefore, ±180°. Thus, nine bits are required for a range of ±180° with a resolution of 0.7°.

(7) Aircraft attitude rates. A/F/T aircraft are capable of achieving relatively high attitude rates, especially roll rate. For roll, a rate of ±360°/second, with a resolution of 2.81°/second can be recorded with an eight-bit word.

For pitch and yaw, rates of ±180°/second, with resolutions of 2.81°/second can be recorded with seven-bit words.

(8) Throttle position (power lever angle). This parameter can be recorded in terms of percentage for each engine. A maximum range of 150% is recommended. With seven bits, the full range of 150% can be recorded with a resolution of 1.2%.

(9) Exhaust gas temperature. A range of up to 1055°C is adequate for this parameter. An eight-bit word will give a 4.12° resolution which is adequate for mishap investigation purposes.

(10) Aircraft accelerations. Vertical, lateral, and longitudinal accelerations have a wider range for high performance military aircraft than for commercial aircraft. The recommended range for vertical acceleration is -5g to +10g. This range can be achieved with an eight-bit word having a resolution of 0.08g. For both lateral and longitudinal accelerations a range of ±5g is recommended. A seven-bit word having a resolution of 0.08g can be used for lateral and longitudinal accelerations.

(11) Control surface positions. Primary control surfaces and secondary trim surfaces can be represented within a full scale range of ±70°. An eight-bit word will provide this range with a 0.55° resolution.

(12) Fuel quantity and individual tank quantity. For the A/F/T aircraft surveyed, a maximum range for fuel load of 30,000 lbs. is adequate. This load is calculated assuming JP-4 at 6.5 lb./gal. and JP-8 at 6.7 lb./gal. An eight-bit word gives the 30,000 lb. range with a resolution of 117 lbs, which is adequate for this parameter.

(13) Stick position or force. Units for stick position/force can be expressed in 1) inches of travel, 2) degrees of movement, or 3) pounds of force. Thus, it is recommended that this parameter be recorded as a percentage of full scale. An eight-bit word for both lateral and longitudinal stick position, will yield the desired range of travel with a resolution of 0.8%.

(14) Angle of attack. A range of ±40° is adequate for this parameter. An eight-bit word gives the desired range with a resolution of 0.3°.

(15) Heading (true or mag). Full heading range is 360°. A single eight-bit word will provide a 1.4° resolution which is sufficient when an analog air data computer is used. If more accurate heading sources are available, a ten-bit word can be used to provide a resolut of 0.35°.

(16) Hydraulic pressure (main and utility). The aircraft surveyed in this study have hydraulic pressure systems in the 0 to 5000 PSIG range. An eight-bit word allows a resolution of 19.5 PSIG.

(17) Oil pressure. The recommended range for oil pressure is 0 to 100 PSIG. A six-bit word permits a resolution of 1.5 PSIG.

(18) Rudder pedal (position or force). This parameter can be expressed as 1) inches of travel, 2) degrees of movement, or 3) lbs. of force. For this reason, we recommend recording it as a percentage of full scale. With one bit reserved for the sign, an eight-bit word will provide a resolution of 0.8%. Thus, if full scale corresponds to +3.5 inches of travel, as is the case with the A-10 aircraft, a resolution of 0.0273 inches is achieved.

(19) Mach number. Resolutions for Mach number should be at least 0.1. With five bits a Mach number of 3.2 can be recorded with a resolution of 0.1.

(20) Afterburner positions. The desired range is 0 to 100%. Resolution does not have to be high in order to use this parameter in an accident investigation. A resolution of 12.5% can be achieved with a four-bit word. Typical ranges are from -10° to +100°.

(21) Sideslip angle. Emphasis within DOD on control configured vehicles (CCV) broadens the requirement for recording sideslip angle. For yaw pointing, or cockpit pointing, a range of ±30° is required for sideslip angle. An eight-bit word gives the desired range with a resolution of 0.23°.

(22) Generator/inverter/alternator output. For accident investigation purposes these parameters can be treated as discretes which are valid when within specified limits and invalid when outside these limits. Typical ranges are as follows:

Signal	Valid Range
AC primary	112 - 118 V
AC emergency	108 - 122 V
DC primary	22.0 - 30.0 V
DC emergency (battery)	18.0 - 25.0 V

Generator failure/trip/warning, transformer rectifier warning, and emergency generator signals are available as discretes on many aircraft. These discretes are useful for accident investigation purposes. However, for expanded recording purposes it is recommended that actual AC and DC voltage levels be recorded. For AC voltages, a range of 0 to 230 volts and a resolution of 0.9 volts can be achieved with an eight-bit word. For DC voltages, a range of 0 to 30 volts and a resolution of 0.94 volts can be achieved with a five-bit word.

(23) Fan turbine inlet temperature (FTIT). FTIT can be recorded via an eight-bit word. For a range of 0-1200°C a resolution of 4.68°C results.

(24) Velocities. Vertical, lateral, and longitudinal velocities can be represented with a nine-bit word. This would provide a range of ±2500 fps with a resolution of 9.7 fps.

(25) Outside air temperature/indicated air temperature. The desired temperature range is ±100°C. An eight-bit word will permit full range recording of this parameter with a resolution of 0.78°C.

(26) Cabin pressure. For accident investigation purposes the cabin pressure warning discrete is adequate. However, for expanded recording and trend analysis the pressure range should be recorded. A range of 0 to 50,000 feet equivalent pressure altitude can be recorded via an eight-bit word having a resolution of 195 feet equivalent pressure altitude.

(27) Wing sweep angle. USAF aircraft such as the F-111 and B-1 require recording of the wing sweep angle. Since this parameter does not change frequently it does not have a large effect on memory size. A range of wing sweep angles from 10° to 75° can be recorded with a six-bit word. This provides a resolution of 1.01° which is more than adequate for accident investigation purposes.

(28) Cabin temperature. A cabin temperature discrete is adequate for accident investigation purposes. For expanded recording, the temperature range should be recorded. A range of -35°C to +55°C can be recorded via a seven-bit word providing a resolution of 0.85°C.

(29) Discretes. The following parameters are typical of those parameters which can be recorded as discrete signals (on/off, go/no-go, valid/invalid, etc.):

- Master caution light
- Augmentation system status signals
- Fire warning

- APU/EPU/EEC/JFS status
- Transmitter keyed
- Paddle switch
- Autopilot on/off
- Altitude/attitude hold, turn rate or heading hold
- Gear position
- Squat switch
- Cabin temperature low/high
- Cabin pressure low
- Marker beacon passage
- FCC status

These discretes can be packed into a single sixteen-bit word.

c. Required sample rates. The maximum allowable sampling rate must be established for each parameter. Even though a particular parameter may not actually be recorded for a relatively long period of time, it must be sampled at predetermined rates or it will not be possible to reconstruct the parameter waveform to the desired degree of accuracy.

Many flight parameter lists were reviewed during this study. These lists include both commercial and military flight data recorders. Five of these lists have been selected to demonstrate typical sample rates required by crash-protected flight data recorders. The selected lists are 1) B-1 Bomber, 2) ULAIDS FIR, 3) AIRS, 4) Commercial MINI FDR program, and 5) commercial DFDR list for wide body aircraft. The sample rates are shown in table 36.

A review of table 36 shows the following with regard to sample rates:

(1) Aircraft attitude and attitude rates are sampled at higher rates for high performance military aircraft as expected.

(2) Aircraft accelerations must be sampled at rates greater than 1/second in order to reconstruct the waveform without missing peaks and troughs. A rate of four samples/second is common for aircraft accelerations.

Table 36. Sampling Rates Required by Existing Crash Survivable Flight Data Recording Systems

PARAMETER	SAMPLING RATE (SAMPLES PER SECOND)				
	B-1 BOMBER	ULAIDS FIR (A-7E)	AIRS	COMMERCIAL MINI FDR (PROPOSED LIST)	COMMERCIAL DFDR
Relative time	-	1	4	-	-
CAS	1	1	1	1	1
Fuel flow	1	1	-	-	-
Altitude	1	1	1	1	1
Engine RPMs	1	10	1	-	
Aircraft attitude	Pitch - 4 Roll - 4	Pitch - 2-10 Roll - 2-10	Pitch - 1/2 Roll - 1/2	Pitch - 1 Roll - 1	Pitch - 1 Roll - 1
Attitude rates	Pitch - 8 Yaw - 8 Roll - 8	Pitch - 2-10 Yaw - 2-10 Roll - 2-10	-	-	-
Throttle position	1	4	-	1	1/4
EGT	-	-	1/2	-	-
Aircraft accelerations	Vertical - 4 Lateral - 4 Longitudinal - 4	Vertical - 4 Lateral - 4 Longitudinal - 4	Vertical - 4 Lateral - 4 Longitudinal - 4	Vertical - 4 Lateral - 2 Longitudinal - 2	Vertical - 4 Lateral - 4
Control Surface position	Rudder - 4 H. Stab. - 4 Flaps - 1 Spoiler - 8	Rudder - 4 Elevator - 4 Flaps - 1/4 Spoiler - 1 Aileron - 4 Slats - 1 Speed Brake - 1	-	Elevator - 1 Stab. - 1 Aileron - 1 Spoiler - 1 Rudder - 1 Trim - 1/2 Flaps - 1/2	Pitch Surface - 1 Yaw Surface - 2 Flaps - 2 Trim - 1/2

Table 36. Sampling Rates Required by Existing Crash Survivable Flight Data Recording Systems (Continued)

PARAMETER	SAMPLING RATE (SAMPLES PER SECOND)				
	B-1 BOMBER	ULAIDS FIR (A-7E)	AIRS	COMMERCIAL MINI FDR (PROPOSED LIST)	COMMERCIAL DFDR
Fuel quantities	For CG - 1	1/10	-	-	-
Stick (pos or force)	4	4	-	-	Wheel - 1
AOA	4	1	-	1	2
Heading	1	1	1/2	1	1
Hydraulic pressures	1	- *	- *	- *	-
Oil pressures	1	1	-	-	-
Rudder pedal	4	1	-	-	2
Mach number	-	1	-	-	-
Afterburner pos.	-	2	-	-	-
Sideslip	-	2-10	-	- *	-
Gen/alt/inv	1	- *	-	- *	-
FTIT	-	-	-	-	-
Velocities	-	Vertical - 1	-	-	-
OAT/IAT	1	1/4	-	1/2	-
Cabin pressure	-	1	-	- *	-
Wing sweep angle	1	1	-	-	-
Cabin temperature	-	1/4	-	-	-
Landing glideslope	-	-	-	1	-
Discrete events	1	As they occur.	1	1	-

* Monitored and recorded as discrete event

(3) Control surfaces are sampled at higher rates for high performance military aircraft. This is required because many control surfaces can be changed 100% within a single second.

When variable apertures are used for compressing data (as will be recommended in a later section), an additional measure of the sample rate is the maximum rate of the parameter in terms of limit increments per sample. For example, if airspeed has a 10-knot aperture a 16.8 ft/sec^2 longitudinal acceleration will have one limit increment per sample rate at one sample per second. If the longitudinal acceleration is greater than 16.88 ft/sec^2, the uncertainty of the airspeed between samples will increase.

If it is determined that higher sample rates are necessary, this can be accomplished with little impact on the system cost.

It must be remembered that the sample rates required are determined by the waveform accuracy needed to analyze the accident/mishap. As with word size, range, and resolution, the optimum cost profile will be obtained by meeting the needs of accident investigations without adding unnecessary complexity to the system. The word size, parameter range, tolerance, resolution, and sample rates recommended for the CSFDR system are shown in table 37.

d. Memory reduction techniques. The memory reduction technique to be selected for the CSFDR system is extremely critical in that it affects the required memory size and input power. The required memory size is directly proportional to initial system cost. The power dissipation of the survivable memory affects package size, insulation technique, and reliablity. Thus, the power dissipation of the survivable memory is proportional to the CSFDR LCC. Therefore, the memory reduction technique has two primary purposes:

- Optimize the amount of information contained in a specified memory size.
- Optimize the information transfer rate from the "scratchpad" memory (buffer memory) to the survivable memory.

The microprocessor will be used to reject redundant and unneeded data. The advantage of using the microprocessor to perform this function, is that the users (accident investigators) can set the criteria for data rejection and therefore aid in the memory reduction effort. Thus the CPM will receive only those data samples conveying the most information about the behavior of the parameter to be recorded. Since all samples will not be bused to the CPM, some error in the compressed signal is to be expected. Moreover, any two consecutive samples which are received need not be consecutive in real-time. Therefore, it is necessary to include some sort of timing information so that the relative positions of bused data may be established.

Table 37. Recommended Word Sizes and Sample Rates

PARAMETER	BITS REQUIRED	RANGE	RESOLUTION	SAMPLE RATE (TIMES/SECOND)	TOLERANCE FOR RECORDING
Relative time* a) minute	8	4.28 hours	1 minute	1/60	1 minute
b) 1/4 second	8	64 seconds	0.25 seconds	4	0.25 seconds
Calibrated airspeed*	8	1000 knots	3.9 knots	1	10 knots
Fuel flow*	8	110,000 PPH	430 PPH	1	500 PPH
Altitude* (coarse)	11	-1,000 to 80,000 feet	78.1 feet	1	100 feet
(fine)	16	-1,000 to 80,000 feet	2.44 feet	1	100 feet
Engine RPMs*	7	120%	0.93%	1	5%
Aircraft attitude (roll)*	9	±180°	0.7°	4	5°
(pitch)*	9	±180°	0.7°	4	2°
Aircraft attitude rates (roll)*	8	±360°/second	2.81°/second	8	20°/second
(pitch)	7	±180°/second	2.81°/second	8	5°/second
(yaw)*	7	±180°/second	2.81°/second	8	2°/second
Throttle (PLA)*	7	150%	1.2%	1	5%
EGT	8	1055°C	4.1°C	1	50°C
Aircraft body accelerations (vertical)*	8	-5g to 10g	0.08g	4	0.25 g
(lateral)*	7	±5g	0.08g	4	0.5 g
(longitudinal)	7	±5g	0.08g	4	0.5 g
Control surface positions (primary)*	8	±70°	0.55°	4	2°
(flaps)	4	0 - 45°	2.8°	1	2°
(slats)	Discrete	out/in	-	per event	-
(speedbrake)	Discrete	out/in	-	per event	-
Total fuel*	8	30,000 lbs.	117 lbs.	1	500 lbs

* High Priority Parameter

Table 37. Recommended Word Sizes and Sample Rates (Continued)

PARAMETER	BITS REQUIRED	RANGE	RESOLUTION	SAMPLE RATE (TIMES/SECOND)	TOLERANCE FOR RECORDING
Stick (pos. or force)*	8	100%	0.8%	4	5%
AOA*	8	±40°	0.3°	4	2°
Heading (true or magnetic)*	8	360°	1.4°	1	2°
Hydraulic pressures	8	5000 PSIG	19.5 PSIG	1	50 PSIG
Oil pressure	6	100 PSIG	1.5 PSIG	1	5 PSIG
Rudder pedal (pos. or force)*	8	100%	0.8%	4	5%
Mach number	5	3.2	0.1	1	0.1
Afterburner position	4	100%	12.5%	2	15%
Sideslip angle	8	±30°	0.23°	2	2°
Generator/alternator/inverter*	8 5	230 VAC 30 VDC	0.9 VAC 0.94 VDC	1 1	10 VAC 3 VDC
FTIT*	8	1200°C	4.7°C	1	100°C
Velocities* (X, Y, Z)	9	±2500 FPS	9.7 FPS	1	8.3 FPS
OAT/IAT	8	±100°C	0.78°C	1	5°C
Cabin pressure	8	50,000 feet	195 feet	1/4	500 feet
Wing sweep angle	6	10° + 75°	1°	1	2°
Cabin temperature	7	-35°C + 55°C	.85°C	1/4	5°C
Discrete events* (packed)	16	-	-	per event	-

* High Priority Parameters

Additionally, an important aspect is the manner in which the sampled data is bused to the CPM. Because the selected non-redundant data samples arrive at non-periodic intervals, a "scratchpad" or storage buffer is required so that the data samples can be transferred at a rate which will allow for adequate power dissipation. This aspect is extremely important in that it affects the reliability of the CPM. This additional buffering requirement must be weighed against the savings in power and MTBF of the overall CSFDR system.

The following paragraphs describe the data compression techniques surveyed for this study. The general field of data compression normally divides the compression methods into "telemetry" techniques and "video" techniques. The "video" techniques are interesting; however, they do not lend themselves to application in the CSFDR system. Therefore, only the "telemetry" techniques are discussed in the following paragraphs.

Using telemetry techniques, the CSFDR system samples parameters, converts these parameters to digital form, performs logical operations on the parameters, and buses the parameter values to the CPM when required. The performing of logical operations and the busing of information from the "scratchpad" memory to the CPM can be viewed as a telemetry technique. If the data compression method selected is classified according to the effect it has on the data packed into the CPM, then the relevant compression methods fall into one of three basic categories:

- Direct data compressors
- Transformation compressors
- Parameter extraction compressors

In the Direct Data Compressors (DDC) the actual value of the sampled parameter or the sampled value within a tolerance window is recorded when the required logical conditions are met. Predictors and interpolators are the most common methods used for DDC's. In each method, polynomial curve fitting has been used to approximate the parameter at all sample points over a finite interval. It is represented over this interval by its sample points as $f(i)$, where $i = 0, 1, \ldots n$. An n^{th} order polynomial is then used to approximate the parameter to any accuracy desired. The accuracy criterion may be stated as

$$|f(i) - \sum_{k=0}^{n} a_k t^k (i)| < K \text{all } i,\ 0 \leqq i \leqq n \qquad (1)$$

where K is the tolerance and the a_k are determined by solving n + 1 equations in n + 1 unknowns which result by inserting all values of i in (1). If the tolerance is zero, the compressor introduces no additional error to the quantized parameter. The order of the compressor is simply the order of the approximating polynomial.

The interpolator achieves compression by transmitting values at each end of a finite time interval such that the polynomial which results by connecting these transmitted points will pass within the required tolerance of all intervening sample values. The predictor uses the polynomial obtained from the n + 1 sample values as an estimate for future sample values in the hope that these values will not deviate from the polynomial by more than the tolerance. Compression is achieved if the polynomial is valid for more than the n + 1 sample values used. In either case, a time word is needed in addition to the data word in order to indicate the length of time over which the approximation is valid.

In the case of the predictor, the polynomial is extrapolated one unit at a time by means of a finite difference technique. A prediction equation results as

$$Y_t^* = Y_{t-1} + \Delta Y_{t-1} + \Delta^2 Y_{t-1} + \dots\dots\dots + \Delta^n Y_{t-1} \qquad (2)$$

where

Y_t^* = predicted value at time t

Y_{t-1} = value of data one sample period prior to t

$\Delta^{n+1} Y_t$ = $\Delta^n Y_t - \Delta^n Y_{t-1}$

ΔY_t = $Y_t - Y_{t-1}$

(1) Direct data compressor using zero-order polynomial predictor. For the zero-order predictor, equation 2 becomes

$$y_t^* = Y_{t-1} \qquad (3)$$

The simplest type of data compressor using this technique is called the fixed-aperture predictor. A set of fixed tolerance windows called apertures is used to divide the range of the parameter into equal parts. The aperture width is 2K, from equation (1), and is typically three or four times greater than the binary resolution of the digitized signal. The tolerance can be established by the user by merely truncating the last few bits from the binary data word. The first sampled parameter will fall into one of the apertures, and, if subsequent values for this parameter fall into the same aperture, they are considered redundant and will not be recorded in the CPM. If subsequent samples fall into an aperture, other than the preceding one, they are considered non-redundant and are recorded in the CPM. Reconstruction of the recorded values in the ground computer takes place by assuming the value of the parameter to be valid over the sample period. This gives the plotted parameter waveform a step appearance. Figure 38 shows the operation of a direct data compressor using the fixed aperture zero-order polynomial predictor. In addition to demonstrating the technique, this figure shows the need to select the proper sample rate for each CSFDR system parameter. Note, the error in predicted sample number 13, due to the relatively long sample time.

A more complex version of the direct data compressor, using the zero-order polynomial predictor, is that of the floating aperture technique. In this technique the first sample value is recorded in the CPM and an aperture of fixed width is placed around it. If subsequent samples fall within this aperture they are not recorded. If a subsequent sample falls outside the aperture, then this sample is recorded and an aperture is placed around it. Thus the aperture "floats" with the last recorded value for the parameter. Figure 39 illustrates this method.

A zero-order offset predictor is also possible. The floating aperture technique may be modified by combining a zero-order and first-order polynomial method. The zero-order predictor takes advantage of trends in the data by offsetting the predicted sample by a specified amount. The sign of the offset is in the direction of the last offset sample. Therefore, the predicted parameter value is equal to the last recorded sample, plus or minus the offset value. This predicted value becomes the center for a new aperture and the process continues as in the basic floating aperture technique.

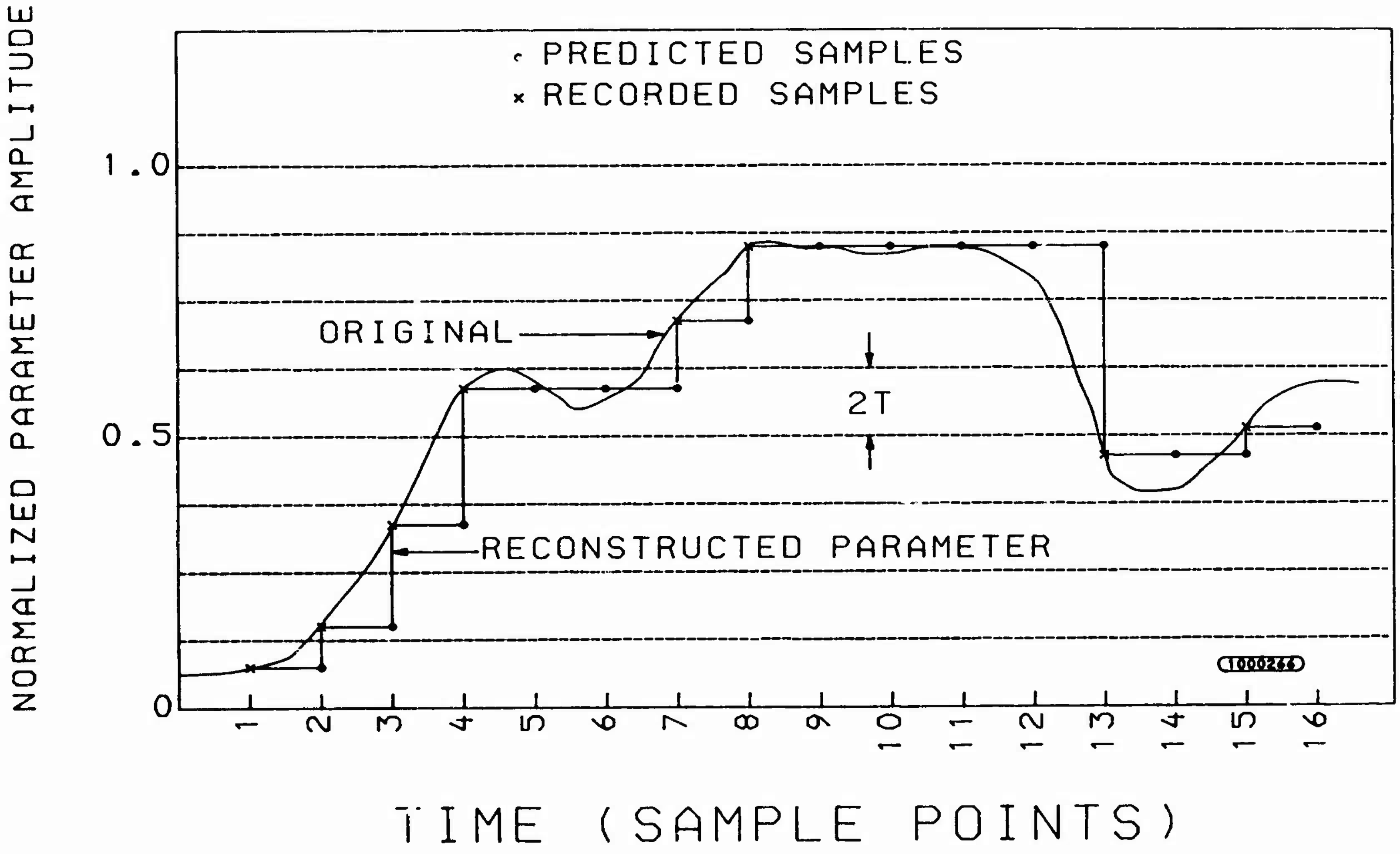

Figure 38. Direct Data Compressor Using Fixed Aperture Zero-Order Polynomial Predictor

All of the zero-order predictors are easily incorporated into microprocessor-based recording systems. They require storage only of the present sample, a future predicted sample, and the size of the aperture. If the zero-order offset is used, the value of the offset must also be stored in the program memory.

(2) Direct data compressor using zero-order polynomial interpolator. Interpolators differ from predictors in that the sample values between the last recorded sample value and the present sample value affect the interpolation. Interpolators are very useful when the data changes rapidly and a predictor may not be sufficient. If future and past samples are used in the redundancy elimination technique, then it is possible to eliminate a larger percentage of samples. This so-called after-the-fact polynomial approximation is termed interpolation.

The zero-order interpolator also approximates the data in a step-like reconstruction, but differs in that the sample actually selected for recording is determined at the end of a redundant set. With a predetermined aperture width, the first sample outside the aperture causes a value to be recorded which is the average of the highest and lowest sample values between the current and last recorded sample. Thus, it is possible to record a value which did not really occur since the last recorded sample. If the aperture is chosen to be zero, then the zero-order predictor and interpolator are equivalent. Figure 40 shows the zero-order interpolator for the same source parameter as was used for the zero-order predictor. As the comparison of the two figures (figures 39 and 40) shows it is apparent that the interpolator is valid over a longer period of time, but requires a more complex airborne computer program than the predictor.

(3) Direct data compressor using first-order polynomial predictor. First order data compressors approximate parameter values by a series of straight lines. These data compressors are best suited for parameters which have long monotonic increasing or decreasing sample sequences. Zero-order compressors would not be effective for such parameters because consecutive samples would be continuously exceeding the aperture width.

Letting n = 1 in equation (2) gives us the first-order predictor equation:

$$Y_t^* = Y_{t-1} + \Delta Y_{t-1} = 2Y_{t-1} - Y_{t-2} \qquad (4)$$

Thus, the predicted sample value is the last value plus the same change as the last value changed from the one before it. This technique is similar to the zero-order offset technique except the offset is variable rather than fixed.

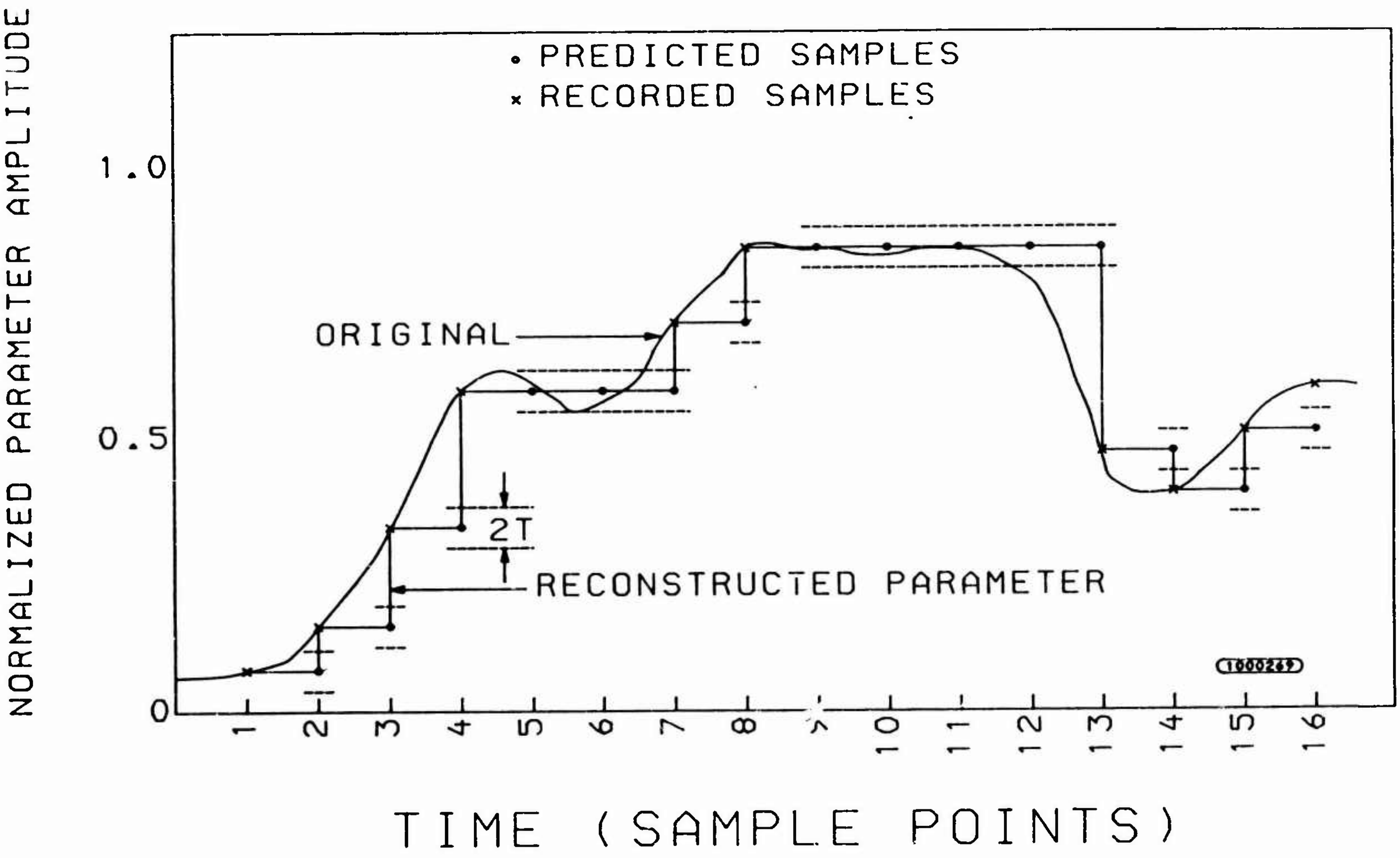

Figure 39. Direct Data Compressor Using Floating Aperture Zero-Order Polynomial Predictor

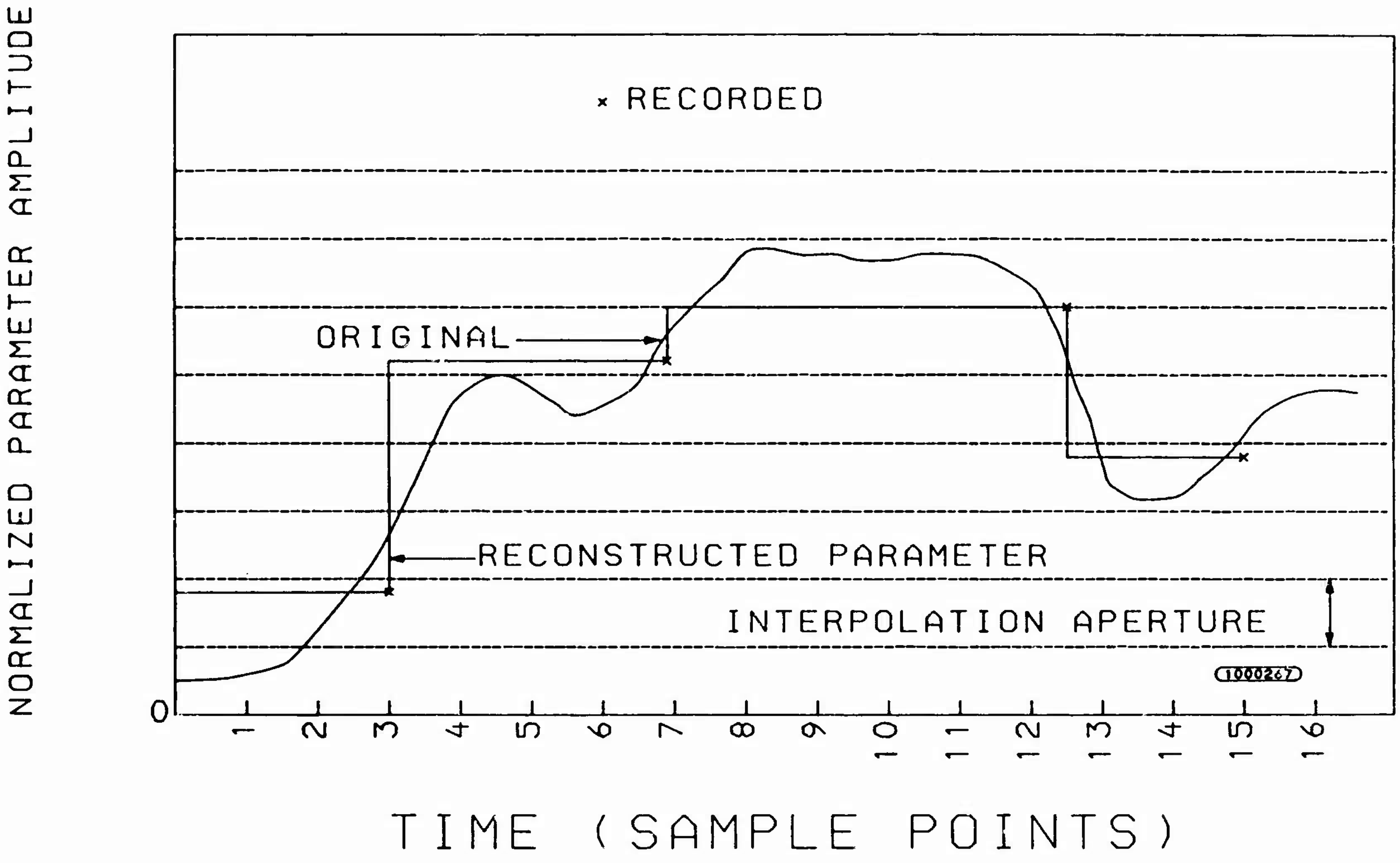

Figure 40. Direct Data Compressor Using Fixed Aperture and Zero-Order Polynomial Interpolator

The compressor records the first two sample values thereby defining a straight line and the third sample is predicted to lie on this line. An aperture of fixed width is then positioned around the predicted sample. If the third sample value is in the aperture then that sample is not recorded. The fourth sample is then predicted to lie on the line and the aperture is positioned around this new value. In the event that the third sample fails to lie in the aperture, it is recorded and it and the previus sample value form the basis for the new prediction line. Figure 41 shows the operation of the first order predictor.

A modified first order prediction method has also been used in past data compression programs. In this technique the slope of the prediction line is established as described above.

However, each in-tolerance data sample is held until the test is made on the next data sample to determine whether it is in-tolerance. When a sample fails to lie in the aperture and, hence is out of tolerance, the previous in-tolerance sample is recorded in addition to the sample which fell out of tolerance. The new prediction line is determined by the sample just recorded and the current sample. In this way, whenever an out-of-tolerance sample follows an in-tolerance sample, the prediction line is defined by two actual sample values rather than a sample value and a predicted value.

(4) Direct data compressor using first-order polynomial interpolator. The first order interpolator is very similar to the zero order method except that the interpolations are made with respect to slope. Therefore, straight line segments connecting recorded values will approximate the mean slope of data samples over the time interval represented and will be such that no intervening data sample deviates more than the pre-set tolerance from the straight line.

This method begins by recording the first data sample. A straight line is then drawn between the first and third samples. If the second sample is within an acceptable aperture of the interpolated value, then a straight line is drawn between the first and fourth samples.

The second and third samples are now checked to determine if each of these values is within the prescribed aperture. If at the Nth sample value after the last transmitted data point, a line is drawn and the interpolated value differs by more than the allowed tolerance, then the (N - 1)th sample is considered non-redundant and is recorded. Figure 42 illustrates the first-order interpolator.

(5) Direct data compressor using adaptive techniques. The previous methods described use a fixed procedure for removing redundant information. An adaptive predictor responds to changes in the data and adapts itself accordingly to provide whatever compression is possible under the prescribed ground rules.

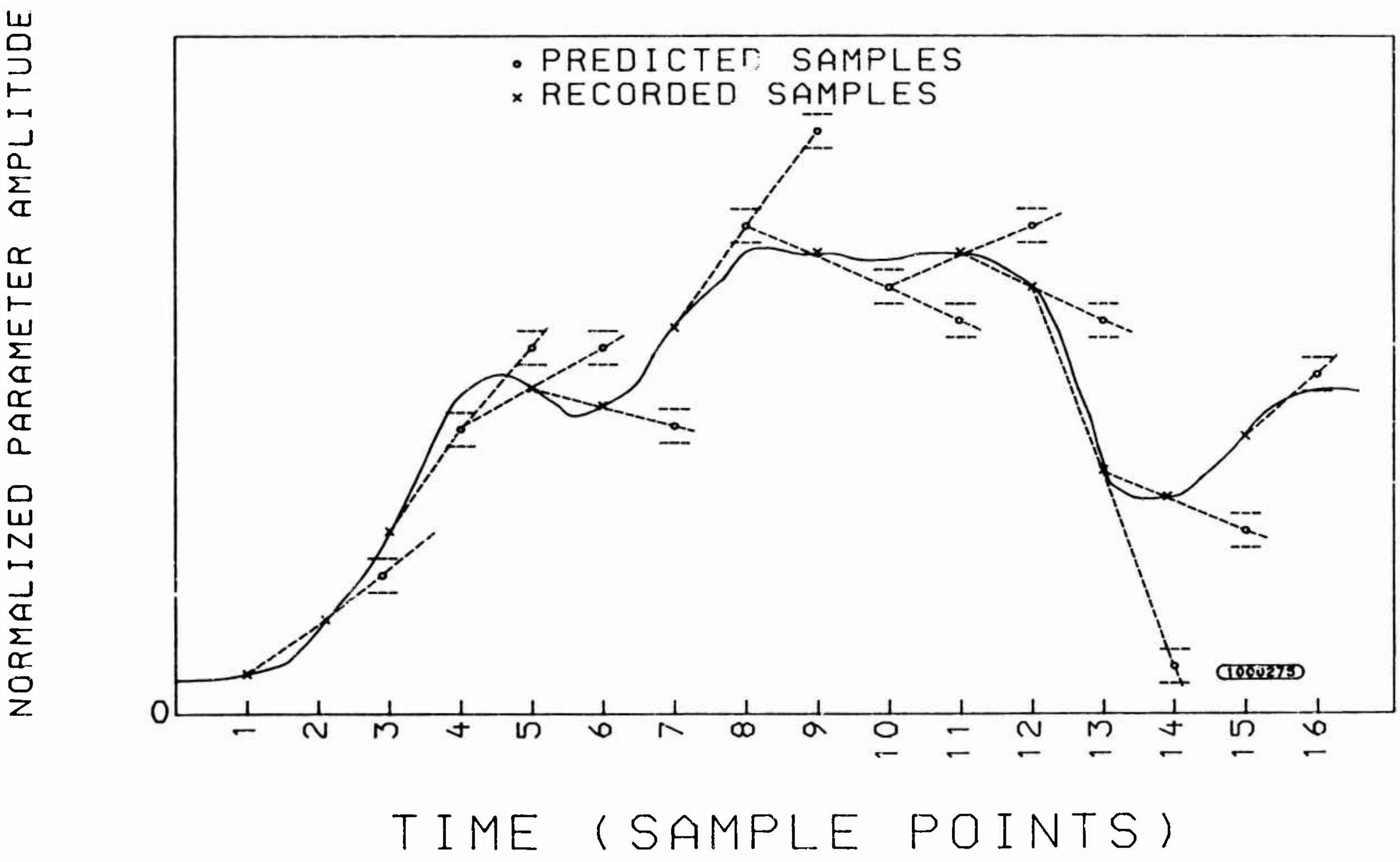

Figure 41. Direct Data Compressor Using First-Order Polynomial Predictor

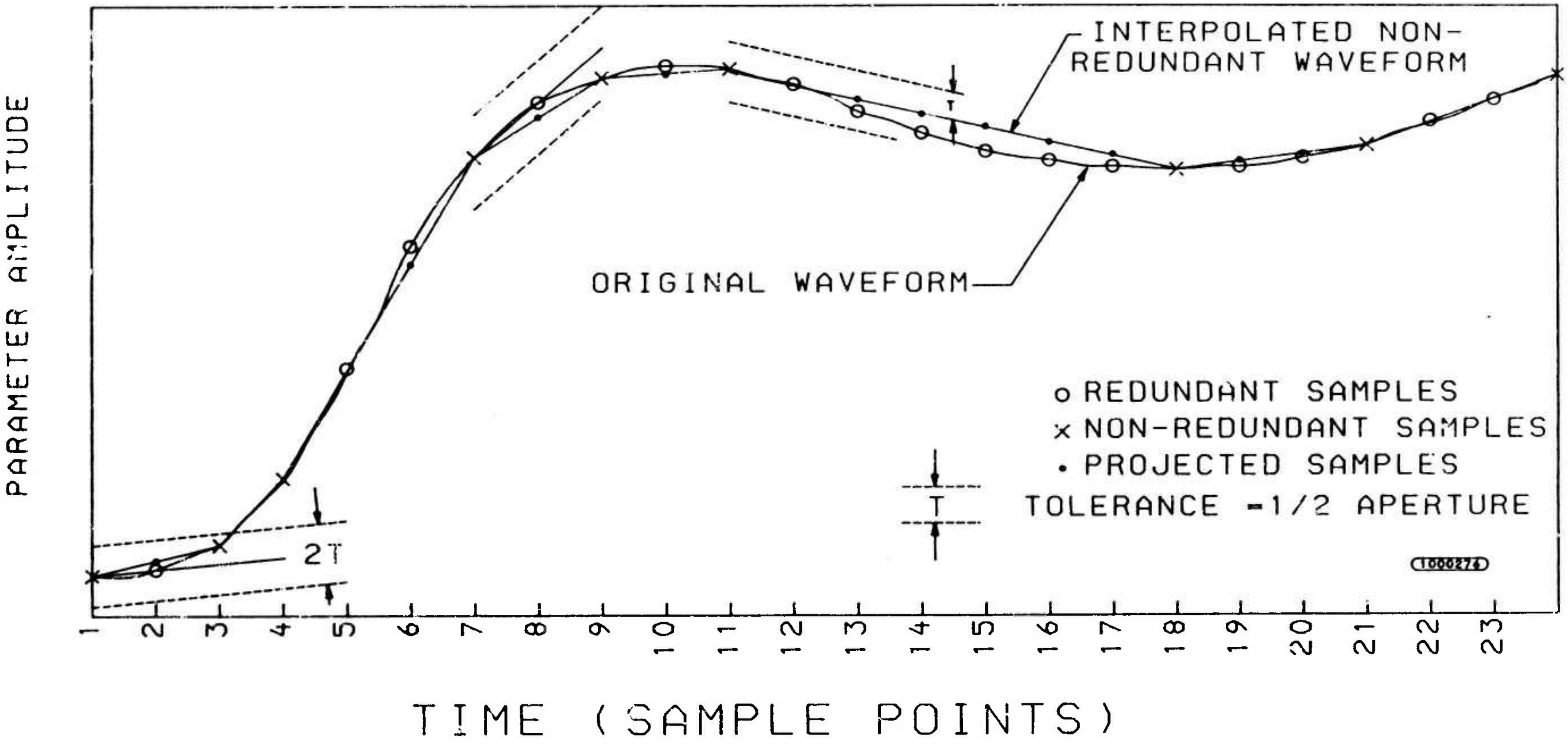

Figure 42. Direct Data Compressor Using First-Order Polynomial Interpolator

Adaptive compressors have been used to solve the buffer memory overflow problem. In periods of high data activity, there would be a large number of non-redundant samples which would be bused to the memory for storage. If the buffer memory was not large enough, then more of the data samples would be lost. An adaptive system would correct this problem by measuring buffer occupancy and adjusting the aperture accordingly. Thus, when the buffer is nearing overflow, the aperture is increased to produce fewer non-redundant samples. The penalty for applying this technique is an increase in the end-point to end-point error for the recorded parameters unless a combining of data derived from dynamically related parameters is used to maintain the required accuracy. Keeping in mind the fact that aperture sizes used in the previously described data compressors are established by the accuracy required to perform the accident investigation, use of the adaptive data compression techniques are recommended only if the reconstructed signal accuracy is maintained. Retention of the required accuracy can be achieved by coupling of dynamically related parameters. For example, altitude can be recorded using an aperture size of 200 feet unless vertical velocity (from an accurate source) exceeds 500 feet/minute. In this case altitude can be recorded using an aperture width of 1000 feet and vertical velocities can be integrated to obtain altitude during the portion of the flight in which vertical velocity exceeds 500 feet/minute.

(6) Transformation compressor using Fourier filter. The Fourier filter method evaluates the Fourier transform from a large number of sample points and has some merit for single channel processing. For multiplex systems, as in the case of the CSFDR system, this method is not considered practical because of the tremendous number of additions and multiplications necessary to determine the coefficients.

(7) Transformation compressor via Karhunen-Loeve method. This method is a generalization of the Fourier-filter technique. Instead of using sines and cosines as the basis by which to expand a function, an optimum set (in the sense of minimum number of functions needed to describe a signal for a given RMS error) is chosen. If the signal is uniformly sampled at a frequency 1/T, then the data points are given by:

$$X(T), X(2T), \ldots, X(nT)$$

and a set of functions are desired such that

$$x(nT) = \sum_{i=1}^{M} a_i \phi_i (nT) \qquad (5)$$

where

$x(nT)$ = reconstructed data point

a_i = coefficient to be transmitted

ϕ_i = eigenvectors of the autocorrelation matrix of the x's

The M eigenvectors chosen to represent the data in equation (5) are those which have the largest eigenvalues. The coefficients a_i can be found by taking the inner product of the data points and the eigenvectors. While the method is esthetically interesting, the prohibitive number of additions and multiplications for any reasonable mean-square error make it impractical, particularly for the CSFDR system.

(8) Data compression via parameter extraction. This form of data compression is different from the other two categories in that the original signal cannot be reconstructed from the recorded values. One such technique is the quantiles technique in which estimations of the mean and standard deviations can be made from the recorded data. Parameter extraction techniques are not considered as viable data compression techniques for the CSFDR system application.

e. Data frame organizations. The previous paragraphs which describe the possible data compressors are applicable to compression of individual parameter waveforms. Additional memory reduction can be achieved by optimizing the organization of the data in the CSMU once it is determined via software that the data should be recorded.

Commercial crash-survivable recorders, which utilize digital tape technology, record fixed-frame formats at full sample rates for standard parameter lists in a continuous recording mode. This fixed-frame format is not acceptable for the A/F/T problem because of the very high amount of memory required to store the parameters. For example, if a fixed-frame format is applied to the parameter list in table 37 at the sample rates shown, a crash-survivable memory for the CSFDR system would exceed 58,612.5 words x 16 bits per word to hold 15 minutes worth of data. (This translates to a requirement for a 0.937 million-bit memory.) In terms of size, weight, and cost impact, the CSFDR system cannot tolerate a CPM memory requirement of this magnitude.

There are basically five kinds of data frame organizations possible. These are:

- Fixed frame
- Multiple level fixed frame
- Variable (random) frame
- Multiple level variable frame
- Combined fixed frame and variable frame

These data frame organizations have been studied for all three services[22,23,24], and there is no need to duplicate these efforts. The results of these efforts, however, along with a brief description of the techniques, are summarized in table 38.

The important point to glean from table 38 is that some variation of a variable (random) frame format must be used to achieve the data compression ratios required for the CSFDR system. Thus, the analysis to determine the optimum memory reduction technique for the CSFDR system reduces to selecting the best combination of data compressor (for individual waveforms) and data frame organization.

Although a variable frame organization is required to achieve the necessary data compression ratios, it is difficult to maintain signal status and compare parameters within the same time frame when using a pure variable frame. Therefore, a periodic fixed frame, at the rate of one total frame per minute, is recommended.

f. Measures of data compression efficiency. Two methods for measuring data compression efficiency are commonly used:

- Sample compression ratio.
- Bit compression ratio.

The sample compression ratio relates the number of non-redundant samples to the total number of samples.

$$CR_s = \frac{S}{S_C} \tag{1}$$

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[22] Lloyd N. Baetz, "Study and Design of Flight Data Recording Systems for Military Aircraft", Master's Thesis, NPS Monterey, California, June 1976.

[23] Department of t' Army, "Accident Information Retrieval System (AIRS)", Final Report, AVRADCOM, August 1977.

[24] Department of the Air Force, "Development and Evaluation of L/ESS Data Compression Techniques", Final Report, University of Dayton Research Institute, Dayton, Ohio.

Table 38. Summary of Potential Frame Formats

FRAME FORMAT	BRIEF DESCRIPTION	DATA COMPRESSION IMPACT	ADVANTAGES	DISADVANTAGES
Fixed frame	Records entire frame of parameter if any given parameter exceeds its aperture, even if other parameters don't change.	2.3/1 to 4.0/1	Simplifies data processing. Simplifies time correlation of data. Simplifies ground data reduction.	Low data compression ratios. Inefficient use of CPM.
Multiple level Fixed frame	Only records full frame when a given parameter exceeds its aperture by a specified amount; otherwise, partial frames are recorded (multiple level of representation of the data).	3.0/1 to 5.3/1	Reduces memory more than fixed-frame technique.	Ground data reduction process is slightly more complex than for fixed-frame technique. Resolution reduced.
Variable (random) frame	Only records the parameters when they exceed their apertures.	8.1/1 to 27.0/1	Increases data compression ratios significantly.	Must identify each parameter. Must time tag each parameter. Complex ground data recovery. Difficult to maintain signal status of unrecorded signals.

Table 38. Summary of Potential Frame Formats (Continued)

FRAME FORMAT	BRIEF DESCRIPTION	DATA COMPRESSION IMPACT	ADVANTAGES	DISADVANTAGES
Multiple level variable frame	Only records parameters when they exceed their apertures by specified amount (record most significant bits when needed, otherwise record bits of lower significance).	8.9/1 to 28.1/1	Minor gain in data compression ratios.	Complex airborne program. Complex data recovery. Heavy overhead penalties.
Combined fixed frame and variable frame	Records parameters when they exceed their aperture and supplements this recording by recording a fixed-frame at periodic intervals.	6.2/1 to 22.1/1	Permits signal status to be reviewed periodically. Acceptable data compression ratios.	Can't achieve the data compression ratios possible via pure variable frame technique. Complex ground data recovery.

where

CR_s = sample compression ratio

S_c = number of samples transmitted with compression (identifier included)

S = number of samples transmitted without compression (identifier included)

The sample compression ratio is useful in determining the efficiency of a particular data compression technique for a given waveform.

The bit compression ratio takes into account the timing information, which must be sent along with the data, and is a true indication of overall system performance. It is defined as:

$$CR_b = \frac{B}{B_c}$$

where

B = number of bits transmitted without compression

B_c = number of bits transmitted with compression

The relationship between the two compression ratios is:

$$CR_b = \frac{n_d}{n_d + n_t} CR_s$$

where

n_d = number of bits per data word

n_t = number of bits in time tag

It is important to note that both compression ratios are a function of the observation period and the type of signal being recorded. Obviously, during periods of high turbulence, the data compression ratios for the CSFDR system will be lower than those for the non-turbulent periods. Thus, for highly turbulent flights, the time history of the recorded parameters will be shorter than the nominal 19 minutes, and for non-turbulent flights, the time history of the recorded parameters will be considerably longer than the nominal 19 minutes. (See figure 51.)

g. Evaluation of direct data compression techniques. In order to evaluate the efficiency of the direct data compression techniques described previously, A/F/T sample records for the important parameters listed in table 37 were obtained. The sample compression ratios were then computed for these parameter recordings. The results, advantages, and disadvantages are summarized in table 39. A variable frame format was assumed in all cases, however, no adaptive data compression techniques were assumed at this point although these techniques will ultimately be used in the finally recommended data compression technique.

As table 39 shows the first-order techniques provide the highest sample data compression ratios. However, these techniques are not recommended due to the disadvantages listed in that table. These techniques require high sample rates. In the case of roll rate, for example, a sample rate of 20 times/second would be required to use the first-order techniques. Additionally, these techniques require more complex airborne computer programming than the zero-order techniques and are awkward to use where the signals are noisy. An additional program memory and scratchpad memory of 100 words and 3,000 words, respectively, would be required for these techniques.

The fixed aperture/zero-order polynomial interpolator is also not recommended for the CSFDR system. This is primarily due to the fact that it has no significant advantages over the floating aperture/zero-order predictor and it does not record actual sample values. This technique also requires a relatively complex ground data reduction program.

Therefore, the direct data compression technique recommended for the CSFDR system is the floating aperture/zero-order predictor. As will be shown in the following sections, this technique can easily be coupled with a variable frame, periodic fixed frame, and adaptive compressor to achieve the data compression ratios required for the CSFDR system. Using the adaptive technique with dynamic coupling produces results very similar to those of the first-order techniques.

Figures 43 through 46 show original and reconstructed profiles using this technique. Figures 44 and 45 are magnified portions of figure 43. Note that the reconstructed profiles are step-like in nature.

h. Recommended memory reduction technique and memory required. Based upon the results of the preceding sections, the following memory reduction technique is recommended for the CPM:

Aperture technique - Floating

Fundamental equation - Zero-order polynomial

Table 39. Summary of Sample Compression Ratios for A/F/T Parameter Profiles

DIRECT DATA COMPRESSION TECHNIQUE	DATA COMPRESSION RATIOS FOR TYPICAL FLIGHT PORTION	DATA COMPRESSION RATIOS FOR TURBULENT FLIGHT PORTION	ADVANTAGES	DISADVANTAGES
Fixed Aperture/ Zero-order Predictor	5.6 to 10.2	3.9 to 6.0	Simplifies airborne software. Simplifies ground data reduction.	Not good for monotonically increasing/decreasing parameter profiles. Gives modest data compression ratios.
Floating Aperture/ Zero-Order Predictor	4.4 to 14.2	3.9 to 6.7	Relatively simple airborne software. Relatively simple ground data reduction.	Average data compression ratios.
Fixed Aperture/ Zero-Order Interpolator	9.0 to 13.8	4.1 to 7.0	Good data compression ratios.	Does not record actual samples. Relatively complex ground data reduction.
Floating Aperture/ First-Order Predictor	10.5 to 20.0	5.45 to 6.2	Excellent data compression ratios. Good for monotonically increasing/decreasing profiles.	Requires high sample rates. Complicated airborne program. Not good for noisy signals.
Floating Aperture/ First-Order Interpolator	19.5 to 30.5	4.2 to 6.7	Good for monotonically increasing/decreasing profiles. Excellent data compression ratios.	Requires very high sample rates for accuracy and stability. Complicated airborne program. Not good for noisy signals.

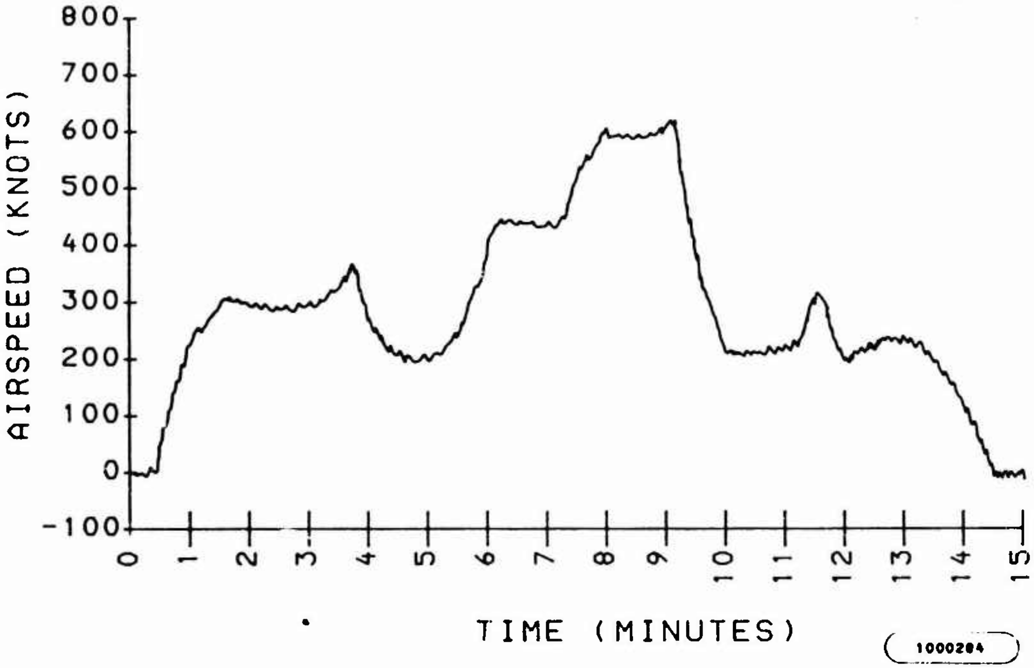


Figure 43. Airspeed Versus Time for Fifteen-minute Flight

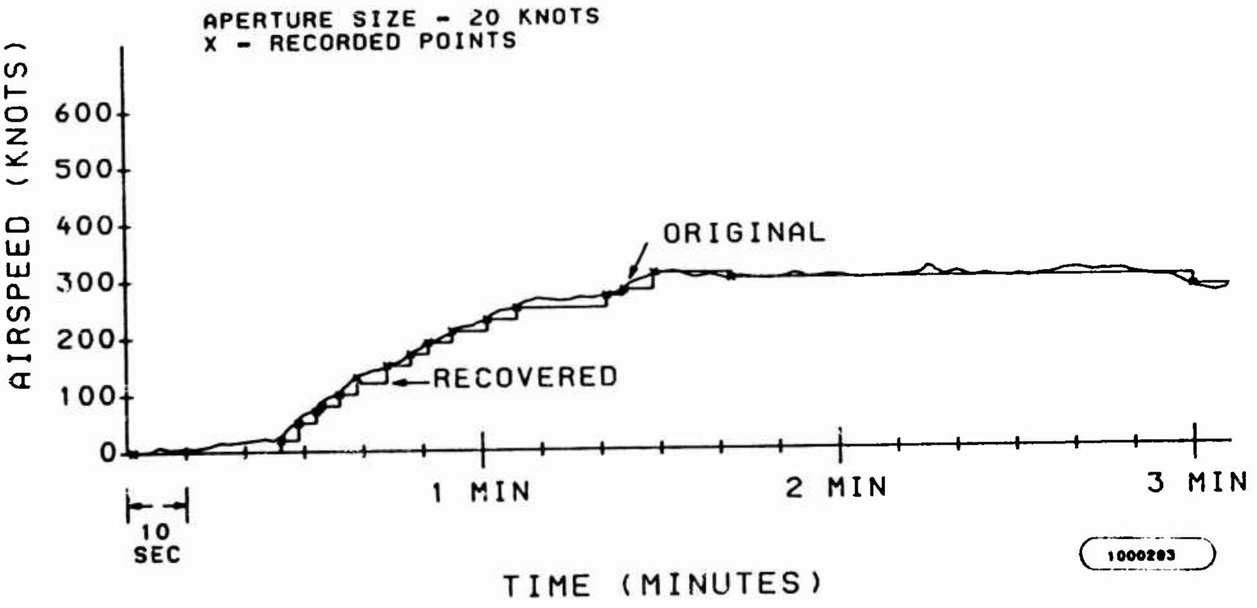


Figure 44. Direct Data Compression Using Floating Aperture and Zero-Order Predictor for First Three Minutes of Airspeed Profile

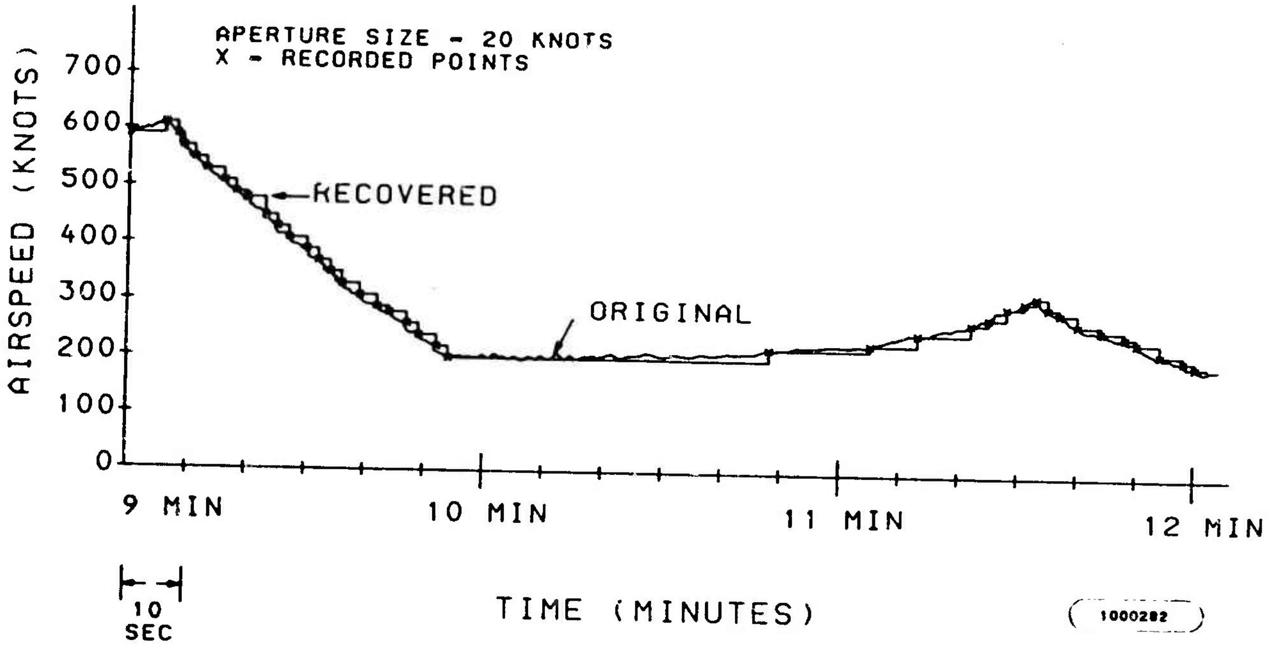


Figure 45. Direct Data Compression Using Floating Aperture and Zero-Order Predictor for Minutes Nine through Twelve of Airspeed Profile

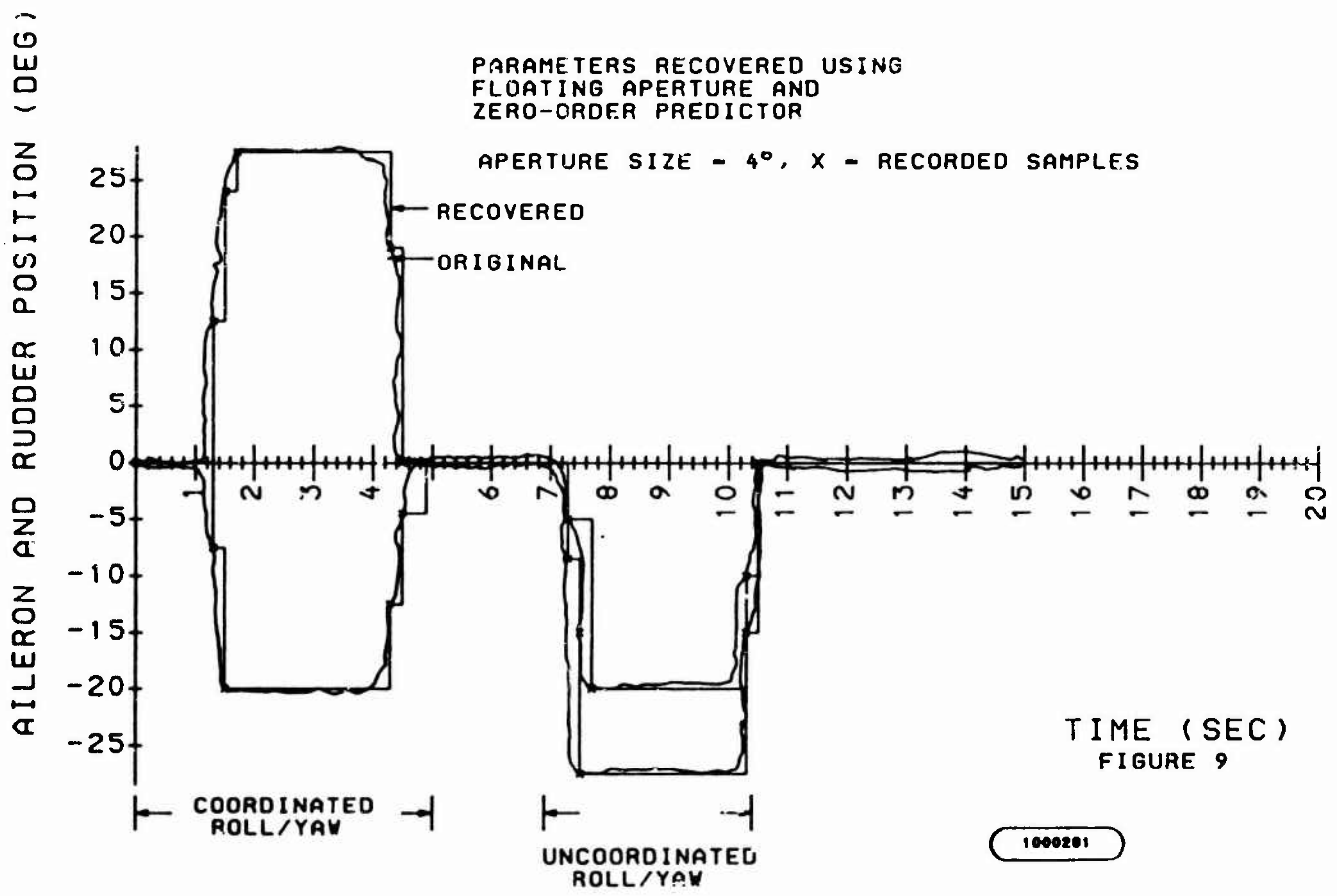


Figure 46. Aileron and Rudder Versus Time

Non-redundancy method - Predictor

Aperture sizes - Variable and adaptive to flight conditions (but always within limits required for accident investigation)

Parameter coupling - Coupling of dynamically related parameters to further reduce memory required and provide data compression effects of first-order prediction

Frame organization - Variable frame organization with time and label tags where necessary coupled with fixed frame once/minute to maintain signal status and integrity

In order to complete the memory reduction analysis, parameter profiles for a severe turbulent mode of flight for an A/F/T were obtained. These parameters are shown in figures 47 through 50 and the above recommended memory reduction technique was applied to these parameters. The parameters represent a low angle-of-attack spin mode experienced when full and abrupt coordinated roll, yaw, and elevator controls are incorrectly applied. As the curves show, a snap-roll is experienced in the 2-10 second portion of the flight. Following this period, a spin is fully developed with rapid loss of altitude and inertial yaw rates in the 50 degrees per second range. Actual aircraft flight path is approximately vertical as indicated by the summation of angle-of-attack and pitch angles throughout the spin. The bit compression ratio obtained for these profiles, using the recommended memory reduction technique was 4.972 over the 40-second interval shown. Since the profiles represent a turbulent mode, this ratio is acceptable. Application of the memory reduction technique to the same parameters for a non-turbulent flight condition yielded a bit compression ratio of 16.8. This further emphasizes the fact that compression ratios are a function of time and flight profile.

A typical Configuration I parameter list would be comprised of all the parameters listed in table 37. The recording time/memory relationship is determined by computing the number of bits required for the full Configuration I list, assuming a two-engine aircraft. This results in 56 signals. Calculations for the pure turbulent, typical, and pure cruise modes for the Configuration I parameter list are as follows:

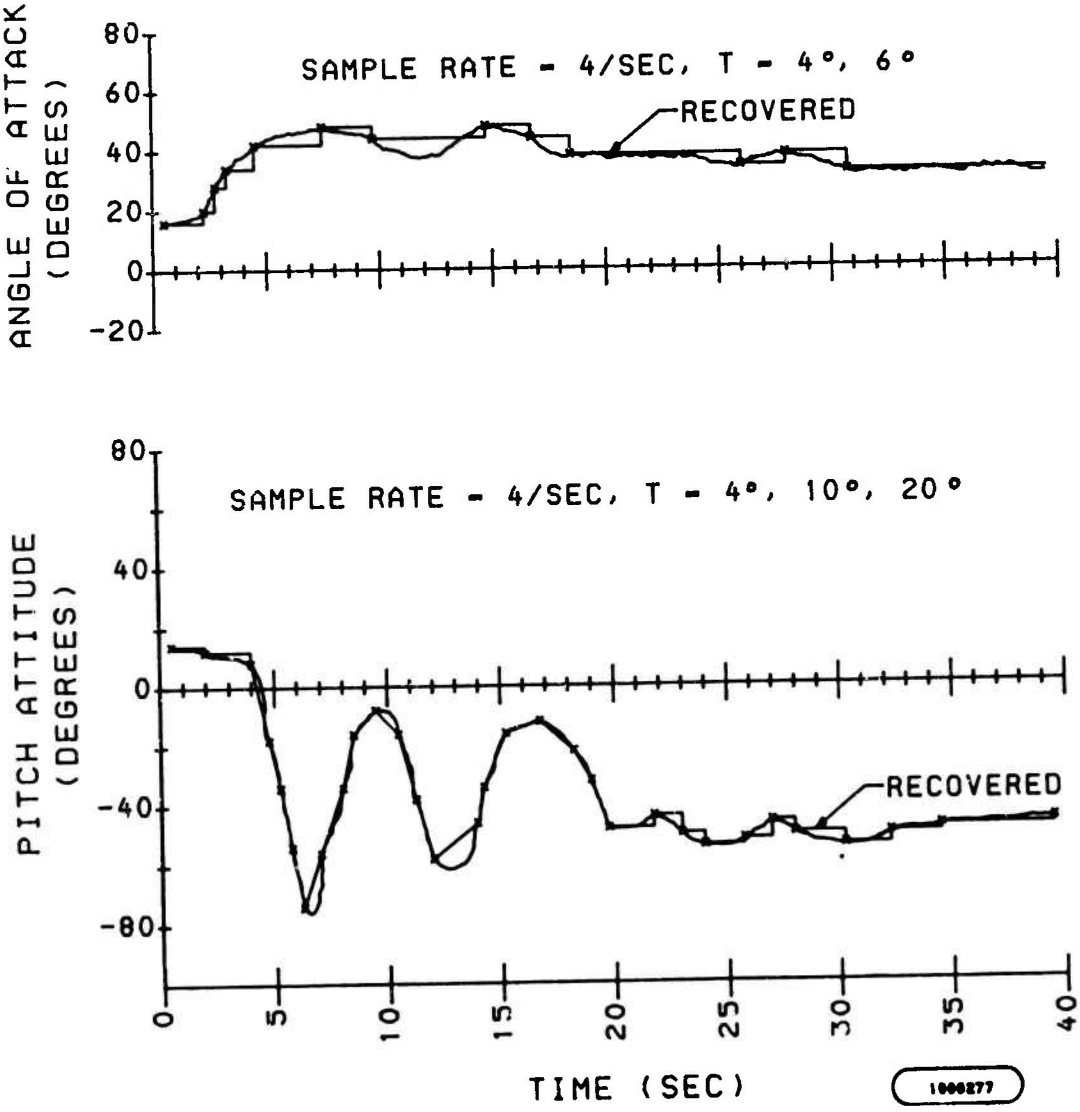


Figure 47. Angle of Attack and Pitch Attitude Versus Time for Turbulent Flight

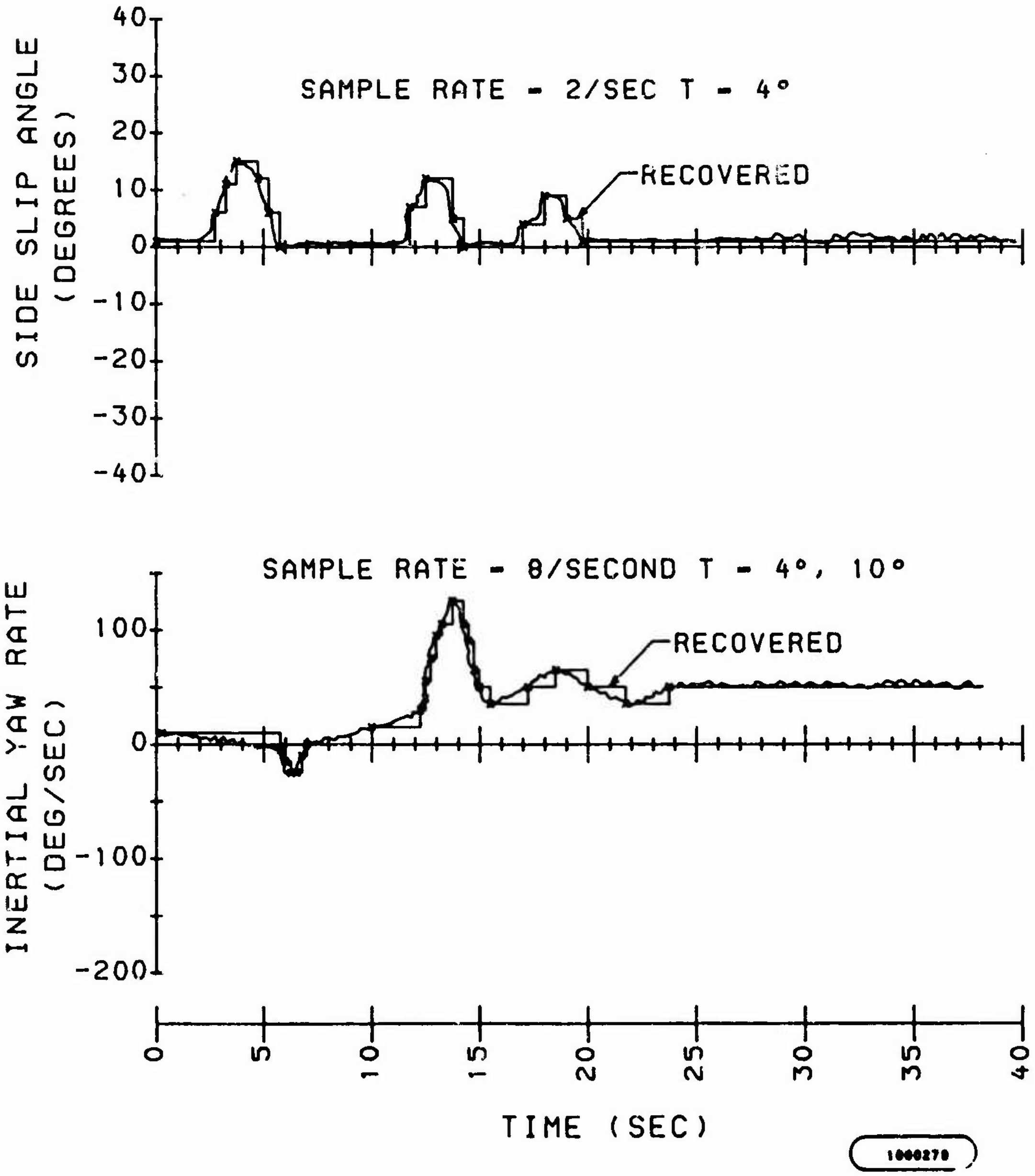


Figure 48. Side Slip Angle and Inertial Yaw Rate Versus Time for Turbulent Flight

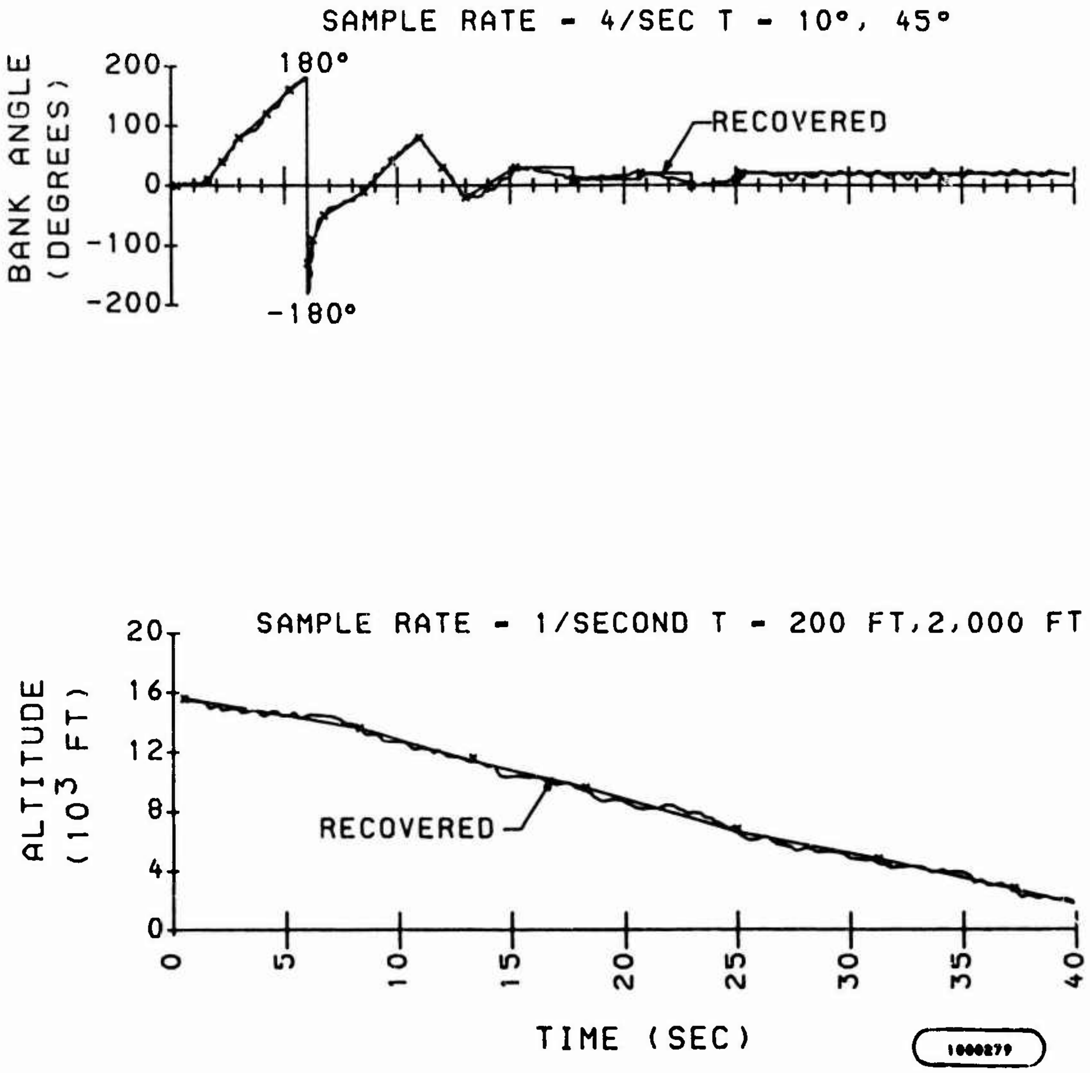


Figure 49. Bank Angle and Altitude Versus Time for Turbulent Flight

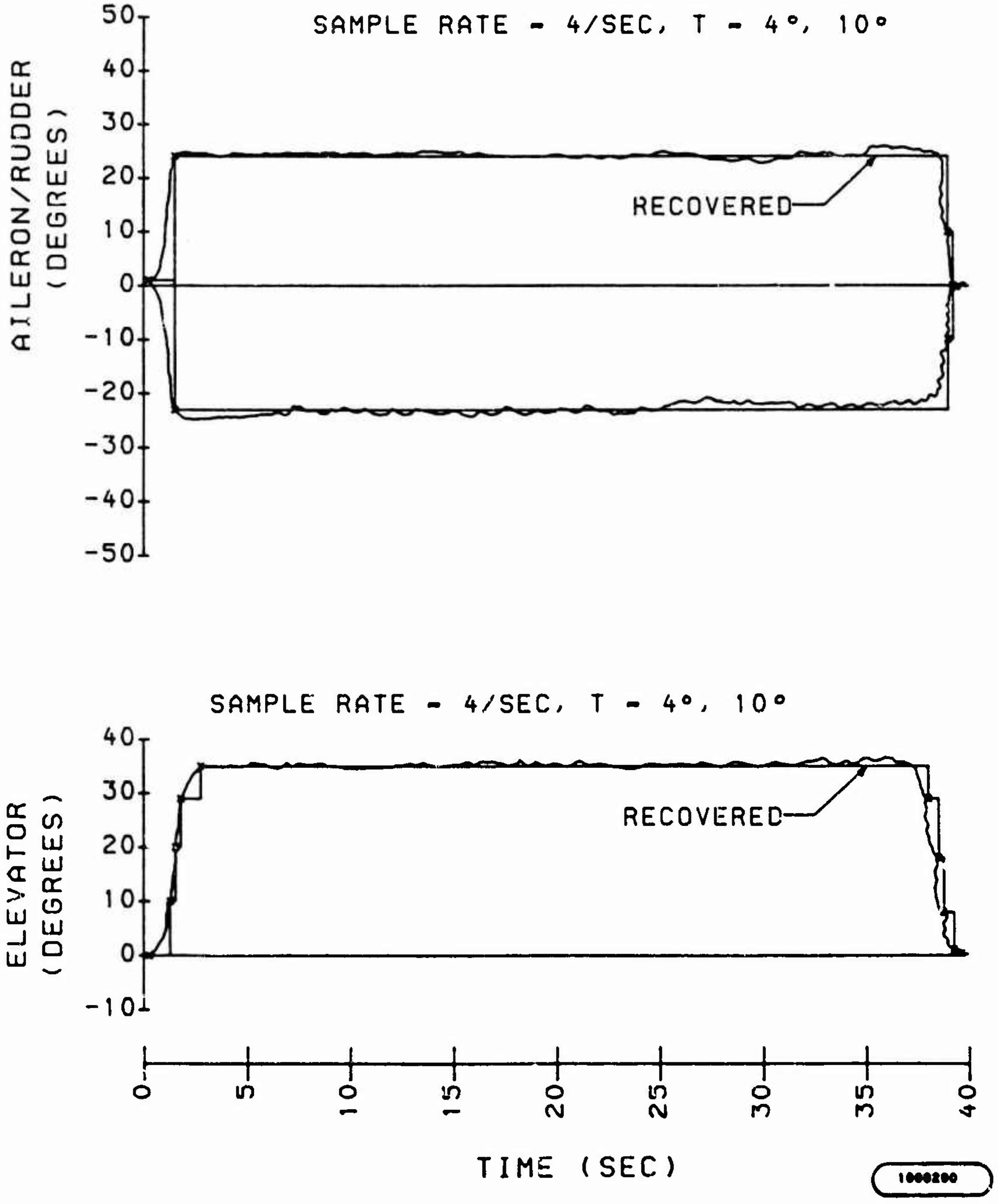


Figure 50. Aileron/Rudder and Elevator Versus Time for Turbulent Flight

Pure Turbulent Mode Configuration I

Number of bits/minute = number of bits/minute for fixed frame at the rate of one frame/minute plus the number of bits/minute in variable frames at turbulent rates

= (451 + 13,667) bpm

= 14,118 bpm

Typical Flight Configuration I

Number of bits/minute = number of bits/minute for fixed frame at the rate of one frame/minute plus the number of bits/minute in variable frames at typical rates

= (451 + 4,048) bpm

= 4,499 bpm

Pure Cruise Mode Configuration I

Number of bits/minute = number of bits/minute for fixed frame at the rate of one frame/minute plus the number of bits/minute in variable frames at pure cruise rates

= (451 + 2083) bpm

= 2,534 bpm

For an 8K x 16-bit CPM (131,072 bits) the following recording times for Configuration I are calculated:

$$\text{Pure turbulent mode time} = \frac{131{,}072 \text{ bits}}{14{,}118 \text{ bpm}}$$

$$= 9.28 \text{ minutes}$$

$$\text{Typical flight time} = \frac{131{,}072 \text{ bits}}{4{,}499 \text{ bpm}}$$

$$= 29.1 \text{ minutes}$$

Pure cruise time = $\frac{131{,}072 \text{ bits}}{2{,}534 \text{ bpm}}$

= 51.7 minutes

These recording times are shown in figure 51.

A typical Configuration II parameter list would be comprised of the parameters listed in table 37 denoted by an asterisk. The recording time/memory relationship is now computed for the configuration II list, assuming a two-engine aircraft. This results in a parameter list of 35 signals.

Pure Turbulent Mode Configuration II

Number of bits/minute = number of bits/minute for fixed frame at the rate of one frame/minute plus the number of bits/minute in variable frames at turbulent rates

= (319 + 10,332) bpm

= 10,651 bpm

Typical Flight Configuration II

Number of bits/minute = number of bits/minute for fixed frame at the rate of one frame/minute plus the number of bits/minute in variable frames at typical rates

= (319 + 3,060) bpm

= 3,379 bpm

Pure Cruise Mode Configuration II

Number of bits/minute = number of bits/minute for fixed frame at the rate of one frame/minute plus the number of bits/minute in variable frames at pure cruise rates

= (319 + 1,575) bpm

= 1,894 bpm

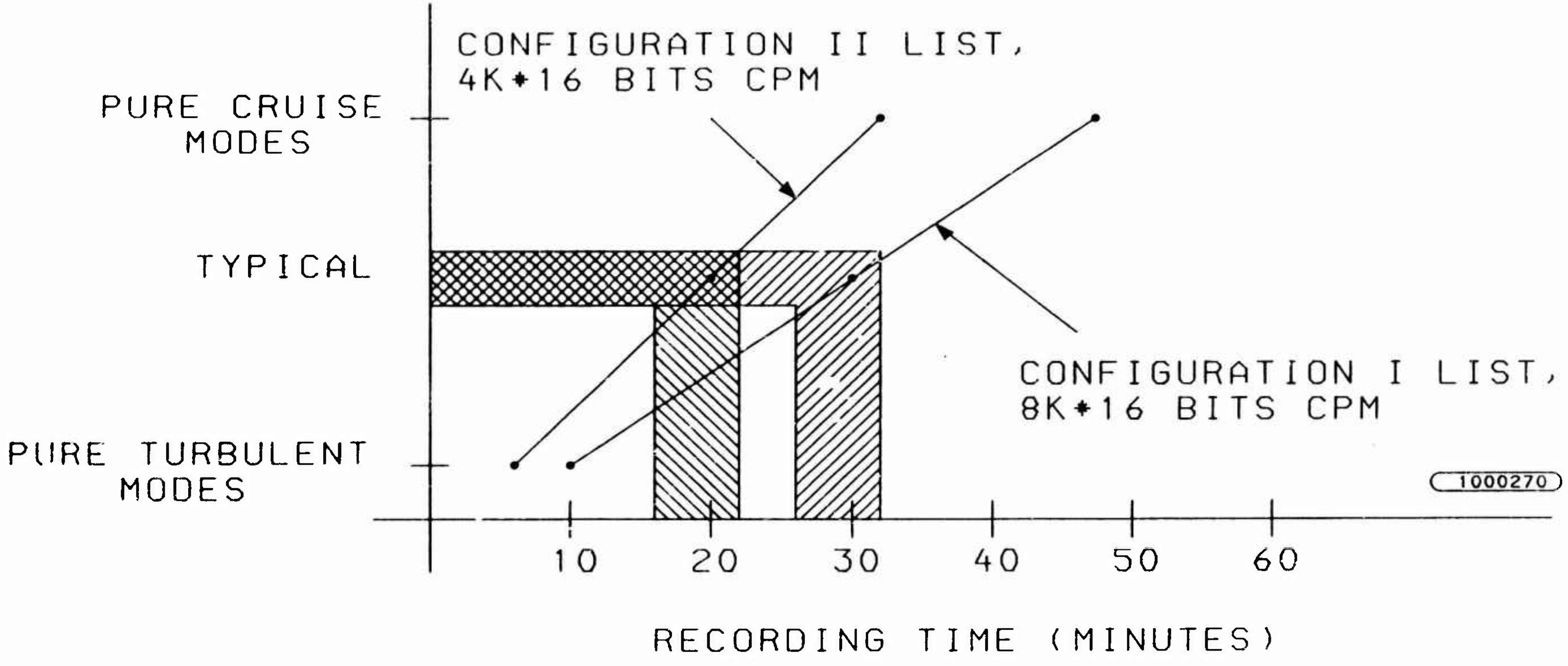


Figure 51. Amount of Recording Time Retained for Configurations I and II Before Memory Wraparound Occurs

For a 4K x 16 bit CPM (65,536 bits) the following recording times for Configuration II are calculated:

$$\text{Pure turbulent mode time} = \frac{65{,}536 \text{ bits}}{10{,}651 \text{ bpm}}$$

$$= 6.15 \text{ minutes}$$

$$\text{Typical flight time} = \frac{65{,}536 \text{ bits}}{3{,}379 \text{ bpm}}$$

$$= 19.4 \text{ minutes}$$

$$\text{Pure cruise mode time} = \frac{65{,}536 \text{ minutes}}{1{,}894 \text{ bpm}}$$

$$= 34.6 \text{ minutes}$$

These recording times are also shown in figure 51. The times in figure 51 represent the amount of flight time which can be retained before memory wraparound occurs.

i. Memory endurance calculations. Table 40 shows the current hours of useage for the A-10, F-15, and F-16 aircraft. These are typical for A/F/T aircraft.

Table 40. A-10, F-15, and F-16 Flight Hours/Aircraft/Month

AIRCRAFT	AVERAGE HOURS PER MONTH
A-10	30
F-15	20-25
F-16	20-25

The two prime memory types selected are NMOS EE-PROM and MNOS BORAM. These memories have advertised endurances in the range of 10^5-10^9 erase/write cycles. Assuming worst case (10^5) as the achievable endurance for the CPM, and 30 hours/month/aircraft as the utility rate, the endurance is calculated as follows:

Configuration I

Turbulent Mode (worst case for memory cycling)

$$\text{Endurance} = \frac{10^5 \text{ memory cycles}}{\frac{1800 \text{ flt. min.}}{\text{month}} / \frac{9.28 \text{ flt. min.}}{\text{memory cycle}}}$$

$$= 515.55 \text{ month (or } 42.96 \text{ years)}$$

Configuration II

Turbulent Mode (worst case for memory cycling)

$$\text{Endurance} = \frac{10^5 \text{ memory cycles}}{\frac{1800 \text{ flt. min.}}{\text{month}} / \frac{6.15 \text{ flt. min.}}{\text{memory cycle}}}$$

$$= 341.66 \text{ months (or } 28.47 \text{ years)}$$

Thus, the memory endurance exceeds the life of most A/F/T aircraft even when a worst case calculation is made. Additionally, cycling the CPM in the proposed manner eliminates the need for replacement of the CPM on a periodic basis. This feature offers a significant improvement in the LCC of the CSFDR system when compared to existing recorder systems which use tape or metal foil as the recording medium.

3.3.2.2 CSFDR hardware description - This hardware description is for the following three configurations as described in the section C of the RFP.

- Operational Configuration II - minimum number of flight parameters.
- Alternate Configuration I - maximum number of flight parameters.
- Optional Configuration III - additional bulk memory storage.

The discussion for Configuration II is given in detail, whereas, the paragraph on Configuration I just briefly describes the additional hardware requirements beyond Configuration II. Likewise, the paragraph on Configuration III shows the additions to Configuration I.

a. Hardware description. Operational Configuration II. The CSFDR hardware description that follows is for Operational Configuration II which records the minimum number of flight parameters of highest priority. Also, this write-up will focus on the two-unit configuration comprising a Data Processor Unit and the Crash-Survivable Memory Unit. This two-box approach is selected for discussion based on the results of the installation study. The study analyzed the hardware with respect to system weight, installation cost, volume and various survivability locations in the aircraft. The Data Processor Unit (DPU) is located in the equipment bay area where it has good accessibility to sensor signals and the digital data bus. The Crash-Survivable Memory Unit (CSMU) is mounted in a remote area which has a higher survivability rate.

The CSFDR system block diagram is shown in figure 52. The DPU interfaces with the A/C data bus (e.g., 1553A/B) when available. Data parameters to be recorded that are not on the data bus will be received from their respective sensors. The sensor inputs will be converted to a digital format. After data compression, the information will be transmitted to the remotely located CSMU.

This data is transmitted to and from the CSMU on a high-speed serial channel called the STD I/O Bus. The data words are transmitted at a low duty cycle which prevents internal heating of the thermally-insulated memory within the CSMU. The Data Transfer Module (DTM), which is in the Air Force inventory, is a small non-crash-protected data storage unit. The DTM uses this same STD I/O Bus but at full duty cycle for fast data transfer. If the DPU has a second identical output channel, then a DTM can be used to retrieve data from the CSMU via the DPU. A third identical output channel can be provided to drive a bulk memory as required in Optional Configuration III. The STD I/O Bus is a serial I/O channel which minimizes the cable size and weight between the Data Processor Unit and CSMU. This bus uses the 9614/9615 differential line driver/receiver ICs which are MIL STD parts.

(1) Hardware description of the CSMU. The block diagram for the CSMU is shown in figure 53. The circuitry in the CSMU is divided into two areas. The read/write logic and EE-PROM are protected within the thermal insulation. This circuitry dissipates very little power and will not overheat during normal operation. The I/O logic containing 9614/9615 line drivers and receivers is located outside the insulated region. Also, the power monitor, which is a discrete component design, is located outside the insulated region.

The Crash-Survivable Memory Unit incorporates a high-density electrical and mechanical packaging design. This minimizes the volume which must be thermally insulated. Based on the memory trade study, the EE-PROM has been selected for the non-volatile memory function. A good candidate part is the Hughes HNVM 3008 which is low power and has a 1K x 8-bit organization. Eight of these IC's will give a 4K word x 16-bit nonvolatile memory.

The parallel interface between the read/write logic and EE-PROM contains a large number of interface signals (40-50) depending upon memory size and organization. Therefore, the read/write logic is located inside the thermally insulated region to minimize the number of interconnections passing through the insulation. The serial interface between the STD I/O logic and read/write logic is only about ten wires which will present a minimum thermal path through the insulation.

The read/write logic is a modification of the design used in the DTM. In order to achieve minimum size, the read/ write logic is implemented with a semi-custom CMOS LSI (large scale integrated) module plus two digital IC's. The semi-custom is a 600-gate array device which requires only a single metalization mask to interconnect the circuitry for the read/write logic design.

The power monitor in the CSMU detects a low voltage condition and opens the erase/write line to the EE-PROMs. This prevents loss of data in event of normal power shutdown, momentary power loss or destruction of cable to the unit. The software/hardware power shutdown and startup sequence is discussed under the hardware description for the Data Processor Unit.

(2) Hardware description of the DPU. The block diagram for the Data Processor Unit circuitry is shown in figure 54. The unit exemplifies the concept of modularity. The DPU can be tailored to the various aircraft, such as A-10, F-16, and F-15 by changing four circuit cards in the box. The hardware variations will be discussed in the detailed hardware description that follows.

The A/C data bus monitoring function is performed by the bus receiver and bus I/O logic circuitry. This hardware will change for each particular aircraft depending on the type of A/C data bus (e.g., 1553A/B, the F-15 data bus). The bus receiver provides the transformer coupling to the bus, the signal receiver and digital logic to process the data. The bus I/O logic contains additional monitor circuitry and interface to the internal microprocessor bus. The bus receiver is contained on one card. The bus I/O logic needs one side of a double-sided logic card.

The various functions performed by the Data Processor Unit are controlled by the microprocessor. These functions include:

- Control of A/C data bus monitor
- Receiving and storing data from A/D converter hardware

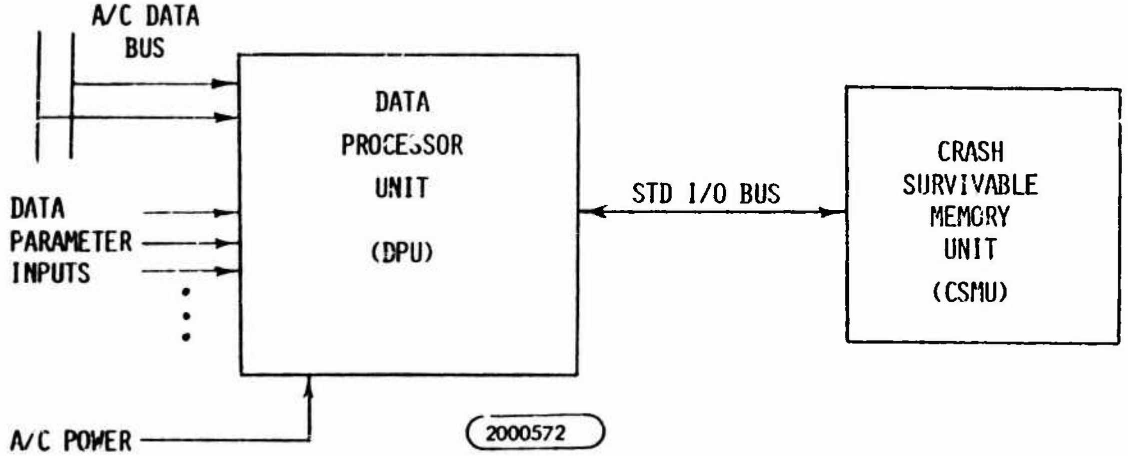


Figure 52. CSFDR System Block Diagram

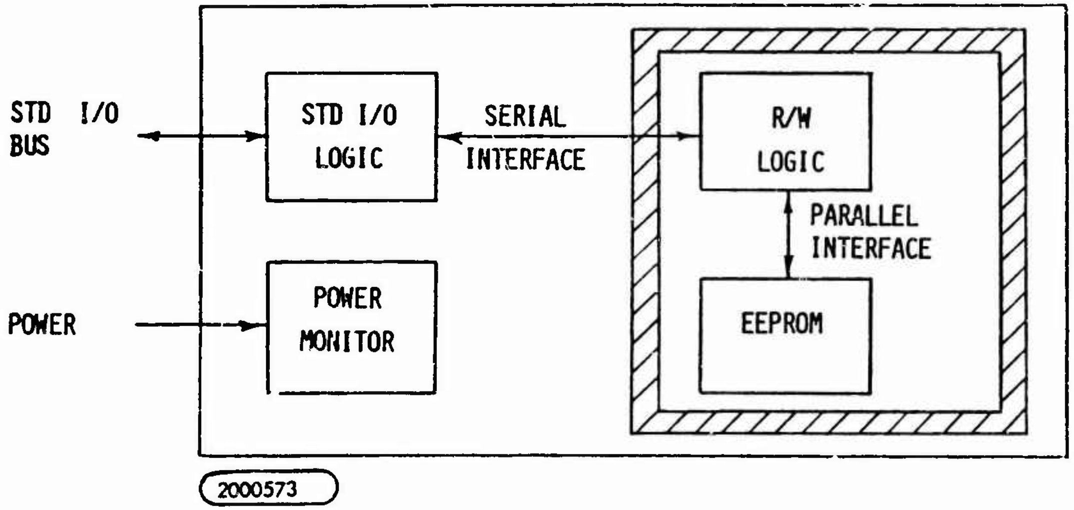


Figure 53. Crash-Survivable Memory Unit Block Diagram

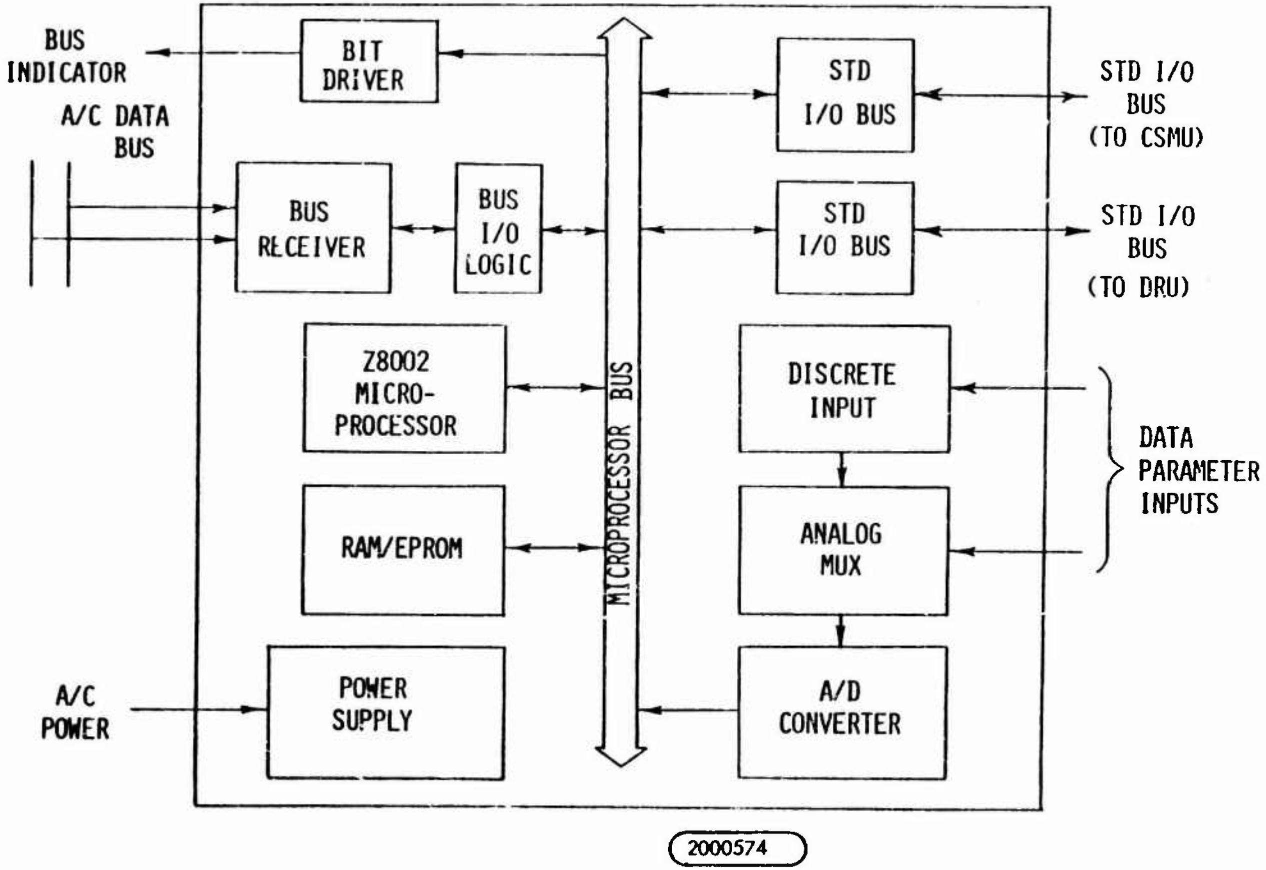


Figure 54. Data Processor Unit Block Diagram

- Execution of data compression algorithms
- Transmission of data to CSMU via STD I/O bus
- Transfer of data from CSMU to external DRU
- BIT

There are several microprocessors available. We have used the following on in-house products: TI9900, 8086, and Z8002. These are all 16-bit machines with good capabilities. We have chosen the Z8002 for this application. This decision is based on the study done for the Data Transfer System which is a similar application. The parameters evaluated for the trade study are: power consumption, estimated cost, time of MIL TEMP availability, time of production parts availability, Microprocessor Development System (MDS) for software development, multiple vendor sources, physical size and instruction execution time. The microprocessor is packaged on a single circuit board using DIP IC's. This board would be identical with the Data Transfer System and each application for CSFDR systems. An alternate approach possibility is to package the microprocessor with flatpaks, where available, to reduce the required packaging area to one side of the board. Then another circuit-function can be added to the other card side. If the additional function is common to each version, the board would still be the same for all configurations. However, the functional modular approach is compromised somewhat at the possibility of reducing card count.

The Air Force STD Group is working toward development of a single-chip microprocessor to implement the MIL-STD-1750A instruction set. The 1750A effort is downstream from this program and not available at this time.

The RAM/EPROM block provides storage for the program which the microprocessor executes and also the temporary scratchpad memory. The RAM/EPROM function is contained on a double-sided card based on the design from the data transfer system. Using 2716 UVPROMS which are organized 2K x 8 will give a maximum EPROM memory capability of 6K x 16. This would allow approximately a 50% growth factor, based on software estimates. Only the number of memory IC's required for each application would be installed.

The RAM function is implemented with a Lear Siegler hybrid. This board would be standard for each application.

The signal converter section is shown in figure 54 as three functional blocks located on two or three separate circuit cards. This partitioning of the converter section permits the standardization of sub-assemblies for various applications. The A/D converter card contains two hybrid microcircuits designed and built by Lear Siegler. One is a successive approximation converter (SAC) which performs all the analog to digital conversions. The other hybrid microcircuit is the quadrature reference generator which monitors the AC reference voltages to provide synchronous demodulation of the AC input signals. Outputs from the quadrature reference generator controls two sample hold amplifiers. As an example, for synchro conversions, the sample and hold amplifiers store the sine and cosine amplitudes. These values are multiplexed to the A/D converter for conversion to digital numbers. This board is general purpose and is used in any application.

The analog MUX function contains the AC input transformers, analog multiplexers and sample/hold amplifiers. This circuitry is tailored for each application. Some may only require component additions/deletions such as for the number of Scott-Tee transformers (synchro inputs). Other aircraft may require modifications to the printed wiring board network.

The discrete input function contains the 28-volt discrete to TTL translators. These translators are packaged in an in-house hybrid microcircuit with four translators per microcircuit. The addition/deletion of components will tailor this circuitry to each application with probably no change in artwork.

The signal converter section is located on two circuit cards for Configuration II (minimum number of flight parameters). Three cards will be assumed for Configuration I (maximum number of flight parameters).

The STD I/O bus driver functions are located on one side of the bus I/O logic card. This function is identical for each application. An additional bus driver can be placed on this card to implement Configuration III. This output would drive the mass storage unit.

The power supply in the Data Processor Unit accepts aircraft power for conversion to logic power, analog power and EE-PROM erase/write power. The only voltage which is heavily loaded is the +5 VDC logic power. A switching mode regulator is used for logic power to minimize power losses, size, and weight. The lightly loaded voltages use monolithic integrated-circuit regulators. The linear regulators provide minimum size and weight for light loads. The voltage regulators are contained on a full-size chassis-mounted circuit card. The input transformer and rectifier diodes are contained on a half-size chassis-mounted circuit card in the case of AC input power.

The type of aircraft input power to the DPU will depend on the particular aircraft involved. A bus with emergency generator or battery backup such as F-16 battery bus may be desirable. This would allow the CSFDR system to continue recording after a main generator failure.

The regulator card also contains the power-down detection circuitry. Upon detection of the beginning of a power transient or complete shutdown, a power-down interrupt (PDI) is sent to the microprocessor. After the PDI is issued the power supply has capacitance to maintain regulation for over 100 milliseconds. During this period the microprocesor will load current address and time into the CSMU's EE-PROM. A master reset (MR) is issued at a specified time after the PDI and also when power comes up. At the end of MR the microprocessor's start-up routine will recall the EE-PROM address and begin loading parameters at this location in the protected memory. This procedure prevents data in the EE-PROM from being overwritten and destroyed on microprocessor start-up after a power transient or shutdown.

A card slot is provided in the Data Processor Unit for the test monitor interface card. This card allows a CRT terminal and test set to be connected to the DPU bus. The interface card contains a test program which the operator can use to test the DPU and CSMU.

Built-in Test (BIT). The Data Processor Unit maintains a modular design with a microprocessor controlling all the functions. This allows the microprocessor to efficiently and comprehensively perform a self-test check on the hardware. The microprocessor can interrogate the CSMU on the two-way STD I/O bus to confirm read/write capability to the EE-PROM.

The analog conversion hardware can be checked by including two reference voltage inputs on the analog MUX board. The BIT subroutine commands the A/D converter to sample and convert these positive and negative references on a periodic basis.

A watchdog timer is used to detect software hangups and other periodic function failures.

A BIT failure signal is provided from the DFU to annunciate the Master Caution/Telelight Panel if a failed condition is detected. Additional failure indicators can be mounted on the DPU to differentiate between DPU and CSMU failures.

DPU chassis description. The DPU chassis is shown in figure 55. The basic chassis construction uses aluminum plates and access covers mechanically assembled using machine screws. The chassis-mounted interface connectors are located on the front plate along with the input transformer (if required) dust cover. The front plate also holds required BIT failure indicators. The power supply regulator card is mounted just above the bottom access cover. The second power supply card which holds the input circuitry is mounted behind the front plate. The sides are machined plates with card guides to hold the plug-in circuit cards. An extra card slot is provided for the test interface card. An adhesively bonded chassis will be utilized for high volume production.

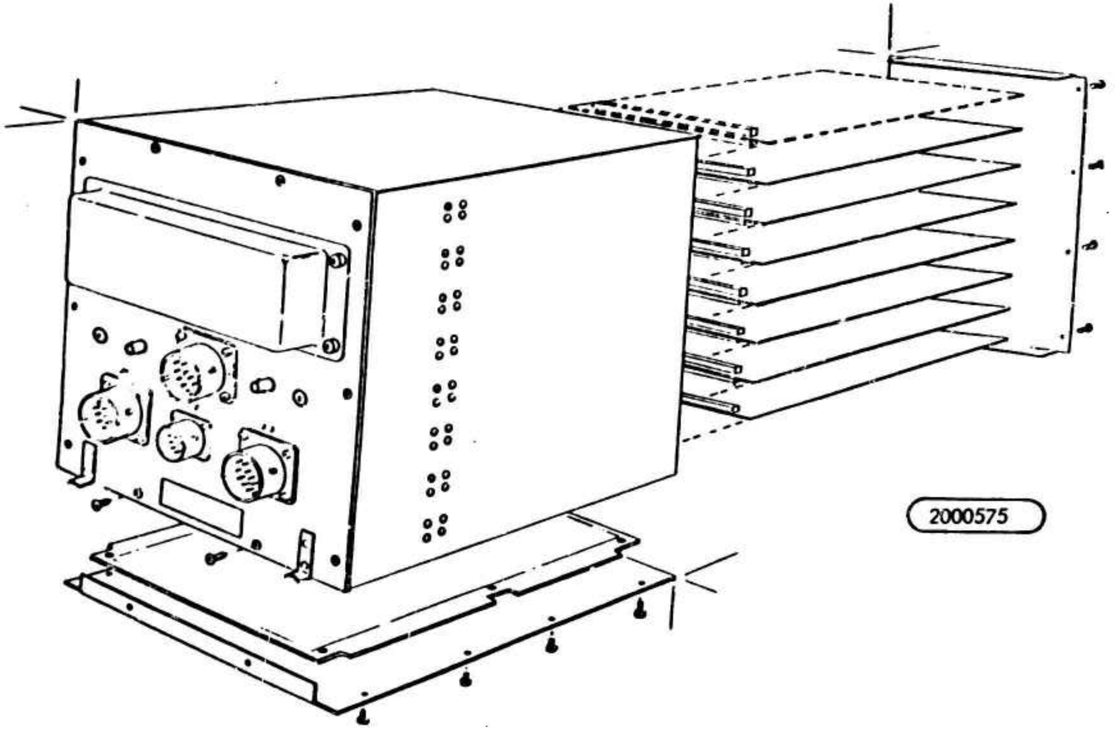
The chassis would be designed to hold seven plug-in boards for Configuration I (maximum number of flight parameters recorded). A smaller chassis to hold six plug-in circuit cards is required for Configuration II (minimum number of flight parameters recorded).

b. Hardware description. Alternate Configuration I. This version of the CSFDR system will record the maximum number of flight parameters for the longest practical time before recycling. The following description gives the modifications to the basic Configuration II hardware in order to record the maximum parameter list of Configuration I. The first change is an increase in size of the Crash-Survivable Memory Unit's (CSMU) nonvolatile memory. The memory comprised of 1K x 8 EE-PROM integrated circuits is increased from 4K words x 16 bits to 8K x 16 bits.

The Data Processor Unit (DPU) has several changes for Configuration I. Another circuit board is needed in the DPU which increases the card count to seven plug-in circuit boards. This card expands the input signal converter section and contains signal conditioning circuitry for the additional flight parameter inputs.

c. Hardware Description. Optional Configuration III. This CSFDR system will record the maximum parameter list as in Configuration I and also features a nonvolatile bulk memory. The mass storage unit (MSU) will contain 256-K words x 16 bits of EE-PROM. An additional standard I/O bus in the Data Processor Unit will provide the interface between the MSU and DPU. The software program will be modified in the DPU to control the I/O channel to the mass storage unit.

The MSU will be composed of groups of EE-PROM packages. Each memory block will be interfaced by two CMOS semi-custom gate arrays. This is an extension of the design approach used for the Crash-Survivable Memory Unit. Where the CSMU is just one block of EE-PROMs driven by a single gate array. Using low power EE-PROMs and CMOS gate arrays provides very low power dissipation for the mass storage unit.



	L (in)	W (in)	H (in)
Configuration I	7.38	5.0	5.75
Configuration II	7.38	5.0	5.35

Figure 55. DPU Chassis

3.3.3 Software/firmware development - The primary purpose of this section is to establish a base for estimating software/firmware development costs and costs for maintaining it in use.

The analytical approach and hardware required for the analytical approach were described in the preceding sections. This section describes the software/firmware development needs of the CSFDR system.

The airborne software program will reside in the EPROM portion of the DPU and will be executed under microprocessor control. A RAM is also required for intermediate calculations and other temporary storage functions. The primary software functions are

- Data Conversion
- Data Processing/Data Compression
- Airborne BIT
- Miscellaneous functions such as Readout Interface, Maintenance Interface, etc.

3.3.3.1 Airborne EPROM requirements

a. Data Conversion Routines. Control of the discrete multiplexer, analog multiplexer and A/D converter is provided by a functionally modular software program. The conversion rates are determined from the sample rates shown in table 37. These rates range from eight samples per second to one-fourth sample per second. For a standard CSFDR system, the following conversion routines are required:

Synchro/Resolver/LVDT to Digital
DC to Digital
AC to Digital (Non-synchro)
Frequency to Digital
Discrete to Digital
Aircraft MUX Bus Interface (1553, and others)

It should be noted that a particular aircraft will not require all of the above conversion routines. However, for a standard CSFDR system which can be applied to old and new aircraft these conversion routines will be required. Additionally, they are required for tri-service standardization.

For the synchro-type inputs, a value of sin θ and cos θ are presented for each sampled parameter. The arc tangent subroutine converts these two inputs into a digital word representing θ in radians or degrees. Also, as described in section 3.3.2, a successive approximation converter is used for analog to digital conversions.

The A/C Data Bus software program handles the job of monitoring the data bus for particular flight data parameters. The program compares terminal address and subaddress of incoming command words to preselected values stored in the software program. When a correct address is identified, the following flight data parameters are stored for processing by the data compression software. Approximately a 985-word software module is needed to interface with the data bus based on a similar program at Lear Siegler, Inc. called the Data Transfer System.

The EPROM required for the data conversion routines, described in the preceding paragraphs, is summarized in table 41. These routines are off-the-shelf routines and therefore the word counts are very accurate. The routines have been developed at Lear Siegler for the Performance Navigation Computer System Program and the Data Transfer System Program.

Table 41. Summary of Required EPROM

DATA CONVERSION ROUTINE	16 BIT WORDS OF EPROM REQUIRED
Synchro/Resolver/LVDT to Digital DC to Digital AC to Digital Frequency to Digital Discrete to Digital	960 words
Aircraft MUX Bus Interface (1553/F-15)	985 words
Arc Tangent Subroutine	150 words
Data Conversion Executive	100 words
Total EPROM for Data Conversion	2,195 words

b. Data Processing/Data Compression. After the input parameters are converted to a digital word, they are placed into a table within the RAM ("scratchpad"). The data compression software then compares the table values to the table of last recorded values which are also held in RAM after they have been transmitted to the CSMU. Current aperture sizes and dynamically coupled parameters are checked to determine whether or not the recently sampled values are redundant. If they are redundant they are not recorded in the CSMU. If they are not redundant, the WRITE CSMU subroutine is called and an output message is formatted in order to write the non-redundant parameters into the CSMU. Only the non-redundant parameters are recorded in the CSMU.

The actual output messages are comprised of labels, time, and data as shown in figure 56. Data word strings varying from one to thirty-two words can be transmitted to the CSMU within a single data burst.

Optionally, it may be desirable to know actual peak values and total time above certain limits for selected parameters. Parameters which could use this format include accelerations (especially vertical), angular rates (especially roll), and engine RPMs. In this format, if specified limits are exceeded, successive values are checked, and peak values, together with the time interval in which the parameter remained above this limit, are transmitted to the CSMU. This format is shown in figure 57.

In addition to the variable frame formats, a fixed frame of data is recommended in order to maintain signal integrity. Formats for the fixed frame are shown in figure 58. Parameters which are common to Configuration I and II maintain identical labels in both configurations.

Actual writing of data into the CSMU is also under EPROM program control. This includes erasing of old data, writing of new data, and verification of write operation. However, actual writing of data into the CSMU must be done efficiently in order to (1) increase the actual reliability of the system, and (2) maximize the useful life of the CPM. Therefore, an inhibit on writing into the CSMU is provided as a function of certain parameters. The parameters used to provide inhibit are squat switch position/engine RPM(s). If these parameters indicate that the aircraft has landed, recording is stopped after a suitable time delay.

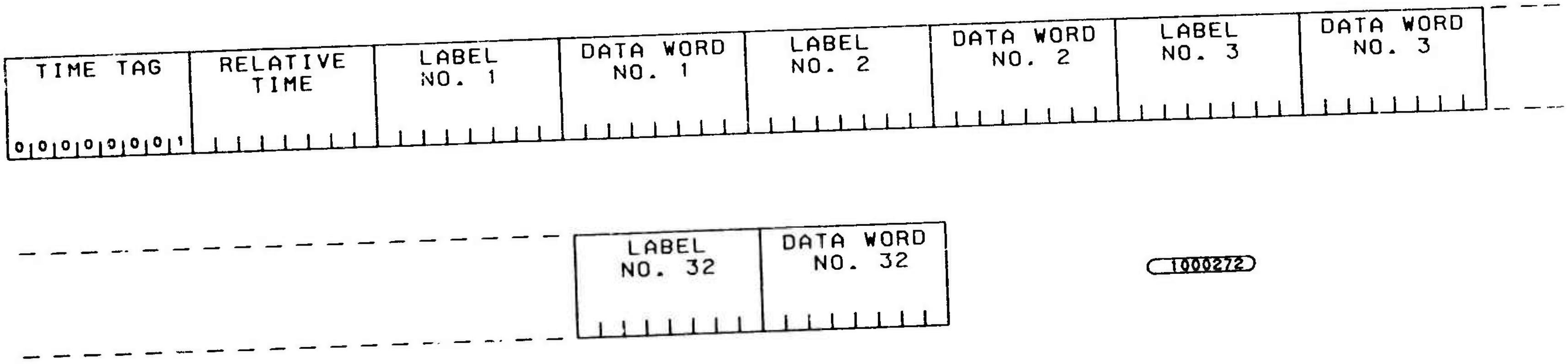


Figure 56. Typical Message Formats for Variable Frames

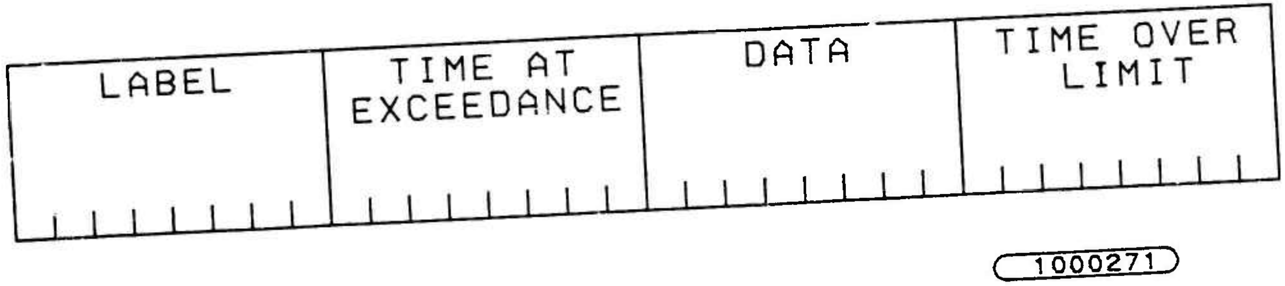


Figure 57. Peak Value Formats

PARAMETER(S)	LABEL(S)
Synchronization	N/A
Time (minutes)	0 0 0 0 0 0 1 0
CAS	0 0 0 0 0 0 1 1
Fuel flow(s)	0 0 0 0 0 1 0 0 - 0 0 0 0 0 1 0 1
Altitude	0 0 0 0 0 1 1 0
Engine RPM(s)	0 0 0 0 0 1 1 1 - 0 0 0 0 1 0 0 0
Roll	0 0 0 0 1 0 0 1
Pitch	0 0 0 0 1 0 1 0
Roll rate	0 0 0 0 1 0 1 1
Pitch rate	0 0 0 0 1 1 0 0
Yaw rate	0 0 0 0 1 1 0 1
PLA(s)	0 0 0 0 1 1 1 0 - 0 0 0 0 1 1 1 1
EGT(s)	0 0 0 1 0 0 0 0 0 0 0 1 0 0 0 1
Vertical acc.	0 0 0 1 0 0 1 0
Lateral acc.	0 0 0 1 0 0 1 1
Longitudinal acc.	0 0 0 1 0 1 0 0
Control surfaces	0 0 0 1 0 1 0 1 - 0 0 1 0 0 1 0 1
Fuel (total + ind.)	0 0 1 0 0 1 1 0 - 0 0 1 0 1 0 0 0
Stick	0 0 1 0 1 0 0 1 0 0 1 0 1 0 1 0
AOA	0 0 1 0 1 0 1 1
Hdg.	0 0 1 0 1 1 0 0
Hyd. pressure(s)	0 0 1 0 1 1 0 1 - 0 0 1 0 1 1 1 0
Oil pressure(s)	0 0 1 0 1 1 1 1 0 0 1 1 0 0 0 0
Rudder pedal(s)	0 0 1 1 0 0 0 1 - 0 0 1 1 0 0 1 0
Mach number	0 0 1 1 0 0 1 1
Afterburner(s)	0 0 1 1 0 1 0 0 0 0 1 1 0 1 0 1
Sideslip	0 0 1 1 0 1 1 0
Gen./Alt./Inv.	0 0 1 1 0 1 1 1 - 0 0 1 1 1 0 0 1
FTIT	0 0 1 1 1 0 1 0 - 0 0 1 1 1 0 1 1
Velocities	0 0 1 1 1 1 0 0 0 0 1 1 1 1 1 0
OAT/IAT	0 0 1 1 1 1 1 1 0 1 0 0 0 0 0 0
Cabin pressure	0 1 0 0 0 0 0 1 0 1 0 0 0 0 1 0
Wing sweep angle	0 1 0 0 0 0 1 1
Cabin temperature	0 1 0 0 0 1 0 0
Discretes	0 1 0 0 0 1 0 1
Growth options	0 1 0 0 0 1 1 0 - 1 1 1 1 1 1 1 0
Reserved Special label	1 1 1 1 1 1 1 1

Figure 58. Fixed Frame Format

Non-catastrophic incident data can be handled in either of three ways:

- Store the information in a DTM located in the cockpit.
- Store the information temporarily in the scratchpad memory of the DPU, then dump this information into the CSMU automatically after landing.
- Inhibit rewrite of a block of CPM memory after an incident so that if wraparound were to occur, this portion of the CPM would be skipped over and, therefore, preserved.

Although these methods are left as options, the first method is the preferred method. This method simply involves removing the DTM after the flight and "plugging" it into a readout station. The ground-based software will then reconstruct the parameters immediately preceding and during the non-catastrophic incident.

The data processing/data compression software approach provides flexibility needed for the CSFDR system. For example, as the aircraft ages, it may become desirable to reprioritize the parameter list and perhaps add certain parameters. Since the approach taken is under software control, a modified airborne program can be generated in a very short period of time. Additionally, the modified program can be generated by the USAF alone or by a USAF/LSI team.

The data processing/data compression software also performs the basic bookkeeping functions of the CSFDR system. These include computing elapsed time, and CSMU address tracking.

Elapsed time is kept by the internal software clock which automatically resets to zero at power turn-on. During temporary power loss the present elapsed time in minutes is stored in the CSMU. When power is recovered, the elapsed time in minutes is read from the CSMU in addition to the last address written into. The seconds portion of the elapsed time is reset to zero.

Table 42 shows the EPROM required for the data processing/data compression routines.

Table 42. EPROM for Data Processing/Data Compression

DATA PROCESSING/DATA COMPRESSION ROUTINE	16-BIT WORDS OF EPROM REQUIRED
Data Compression	365
Write CSMU	60
Bookkeeping	70
DP/DC Executive	50
Total EPROM for DP/DC	545 words

c. Airborne BIT Software. The BIT software is critical in reducing the LCC since it directly reduces the maintenance actions required to verify operation on a periodic basis. The microprocessor within the DPU efficiently and comprehensively performs the self-test checks on the hardware elements of the total CSFDR system. Analog, discrete, and MUX bus test signals are generated as reference voltages and the BIT subroutine commands the interface electronics to sample and convert these positive and negative references on a periodic basis. Moreover, the microprocesser interrogates the CSMU on a two-way standard I/O bus to confirm read/write capability of the CPM. EPROM values are also periodically summed and compared to stored values. In turn, these values are checked in segments of RAM to assure RAM read/write capability. A watchdog timer also is used to detect software hangups and other periodic function failures.

A test program which utilizes all of the microprocessor instructions is also recommended.

Finally, unrealistic changes of sensor inputs and sensor limits may be flagged within the BIT software.

Depending upon the particular type of aircraft in which the CSFDR system is installed, a BIT failure signal is provided from the DPU to annunciate the Master Caution/Telelight Panel whenever a failed condition is detected.

In summary, the following BIT checks are made.

(1) Analog, discrete, MUX input compared to references.

(2) CSMU read after write verify including standard I/O bus operation.

(3) EPROM values summed and compared to references.

(4) RAM address operative and verified sequentially in wraparound procedure.

(5) Watchdog timer used to detect periodic function failures and software hangups.

(6) Test program to exercise microprocessor instruction set.

(7) Sensor inputs checked for validity.

The EPROM required to perform the BIT Function is approximately 200 words. The BIT software is extremely similar to existing BIT programs used at LSI for many production digital computer models, and therefore provides an accurate estimate of words required.

d. Miscellaneous software functions. Additional software functions are required for (1) Portable Data Retrieval Unit interface and (2) Maintenance Equipment interface.

The retrieval software subroutine is initialized when the cable is connected to the DPU and the start push button is depressed. This generates a load discrete signal which halts the normal program and begins execution of the retrieval subroutine. The retrieval subroutine sequentially "dumps" the CSMU contents onto the DTM and during the "dump" process the microprocessor illuminates the busy indicator lamp on the DRU. A BIT procedure is used to read each word back from the DPU and compare it with the word just loaded to check the integrity of the DRU. When the data transfer operation is complete, the busy indicator lamp is turned off. The EPROM required to perform the DRU interface is conservatively estimated at 50 words.

The memory required for the Self-test Program (STP) used by the GSE is contained on the Test Set Interface Board. This board also contains the RAM scratchpad used by the DPU microprocessor while executing the STP. Although this program is not resident in the DPU (an airborne unit), it does impact the LCC of the overall CSFDR system. The STP program is estimated to be 6000 words, based upon similar programs at Lear Siegler, Inc.

e. EPROM Totals. The EPROM totals required for Configurations I and II are summarized below in table 43. The preceding discussion applied to Configuration I, and, therefore, a slight reduction is seen in the airborne program for Configuration II. The PROM required for the STP used by the GSE is also shown below. The additional EPROM required to process the parameters for expanded recording (Section 3.2.4) is estimated at 260 words above that required for Configuration I.

Table 43. Program Memory Totals

Airborne EPROM Requirement	Words For Configuration I	Words For Configuration II
Data Conversion	2,195 words x 16 bits	2,135 words x 16 bits
Data Processing/Data Compression	545 words x 16 bits	495 words x 16 bits
BIT	200 words x 16 bits	170 words x 16 bits
Misc. Software	50 words x 16 bits	50 words x 16 bits
Master Executive	150 words x 16 bits	150 words x 16 bits
Total EPROM	3,140 words x 16 bits	3,000 words x 16 bits
STP	6,000 words x 16 bits	

Since the DPU board which contains the airborne software program can accommodate 6,000 words x 16 bits, adequate growth capability for both Configurations I and II is provided.

3.3.3.2 <u>Airborne RAM requirements</u> - The RAM of the CSFDR system is used for temporary storage of dynamic data and as a CSMU memory buffer. It performs the following functions:

(1) Stores old and new tables of parameter values.

(2) Stores time for fixed and variable frames.

(3) Stores current aperture sizes for each parameter and the parameter status.

(4) Stores "peaks and valleys" of selected parameters.

(5) Stores "non-catastrophic incident" data.

(6) Stores address of certain data.

(7) Stores intermediate results of calculations required in Data Conversion, Data Processing/Data Compression, BIT, and other miscellaneous functions.

The RAM required to perform these functions is 1711 words x 16 bits and 1515 words x 16 bits for Configurations I and II, respectively. Therefore, to provide growth capability, a 2K x 16 bit RAM is recommended for the production versions of the CSFDR system.

3.3.3.3 Airborne microprocessor throughput - Before selecting the microprocessor for the CSFDR system, a throughput approximation was made. This is required in order to avoid the processor saturation problem which could arise if a very slow microprocessor were selected. As is the case with data compression ratios, actual microprocessor throughput is not a constant. Actual throughput is a function of time, types of sensors used, and mode of CSFDR system operation.

The microprocessor operations required for the CSFDR system are relatively simple when compared to the operation required by a more complex avionics problem such as navigation or weapon delivery. The CSFDR system operations are comprised primarily of addition/subtractions, read/write strings, logicals, and multiplications. Very few divides are required.

In order to execute the airborne program described in section 3.3.3.1, throughputs of 23,286 OPS and 18,246 OPS are required for Configurations I and II, respectively.

Because the CSFDR system instructions are relatively simple, the avionics standard instruction mix of 80 adds/20 multiplies can be conservatively used to determine the throughput capability of the selected microprocessor. The additions are further divided into 40 memory-to-register adds and 40 register-to-register adds.

$$\begin{array}{rclcl}
\text{40 mem-reg adds} & = & 40\ (8 \times 0.25\ \mu\text{sec}) & = & 80\ \mu\text{sec} \\
\text{40 reg-reg adds} & = & 40\ (4 \times 0.25\ \mu\text{sec}) & = & 40\ \mu\text{sec} \\
\text{20 mult.} & = & 20\ (72 \times 0.25\ \mu\text{sec}) & = & 360\ \mu\text{sec} \\
\cline{2-5}
 & & \text{100 operations} & = & 480\ \mu\text{sec}
\end{array}$$

$$\begin{aligned}
\text{OPS} &= \left(\frac{100\ \text{operations}}{480\ \mu\text{sec}}\right)\left(\frac{10^6\ \mu\text{sec}}{\text{sec}}\right) \\
&= 208{,}333\quad \text{operations/sec}
\end{aligned}$$

This rating of 208,333 OPS for the selected microprocessor compares favorably with the 23,286 OPS and 18,246 OPS required for CSFDR system normal operation. Even with a 100% growth requirement in throughput, the selected microprocessor is operating far below its saturation level.

3.3.3.4 Ground-based software

a. Software language selection. Although there are three excellent candidates for the readout facility, section 3.2.6 states that the Norton AFB data processing facility be considered as the primary ground-based facility for the CSFDR system support. This data processing facility now utilizes an IBM 360/155 mainframe in conjunction with OS/VS1. Preferred software languages in order of preference for this facility are:

- Fortran IV
- COBAL

Both of these languages are listed in DOD 5000.31 as acceptable standard languages for ground-based facilities. However, Fortran IV is considered to be more acceptable for this application. Therefore, it is recommended that all of the software described in the following paragraphs of this section be written in Fortran IV.

b. Software Layout. The ground-based software will provide plots of parameters vs. time, groups of appropriately coupled parameters vs. time, dynamic reconstruction of accident/mishap for CRT display, parameter synthesis, cross correlation, analysis, and general documentation for a host of applications important to the USAF. A layout of the software required is shown in figure 59 as it would be installed at NAFB.

The time and date of the accident (when known), aircraft type and tail number, local environmental factors at the accident time (when known), and program options desired are manually input to the support software system. Additional input data comes from the CSFDR systems' survivable memory. The inputs are then processed in order to convert the relative time recordings to real time (the data is uncompressed). This step is then followed by a credibility analysis of the uncompressed data in a manner similar to that currently used by the NTSB. Range and range rate limits, correlation with input data, and correlation of multiple source data is made. The next step consists of converting the raw data to engineering/scientific units and storing this converted data on a disk/tape file. This file then becomes the data base for the outputs to be used in the accident investigation. The outputs are briefly described in the following paragraphs.

(1) Individual parameter plots vs. time. Any individual parameter plot may be requested by the accident investigation team. These single parameter plots would have the appearance of the recovered plots shown in figures 47 through 50.

(2) Group parameter plots vs. time. Groups of parameters may also be desired by the accident investigation team. These multiple parameter plots would appear as shown in figure 60.

(3) Table of parameters vs. time. A table of parameters vs. time may also be requested as a program option. Any given parameter or group may be requested as desired by the accident investigation team. All parameters will be listed in engineering/scientific units in the time sequence in which they occurred. Additionally, any given block of time may be isolated and requested. This permits the accident investigation team to focus upon a particular segment of the flight. The format is shown in table 44.

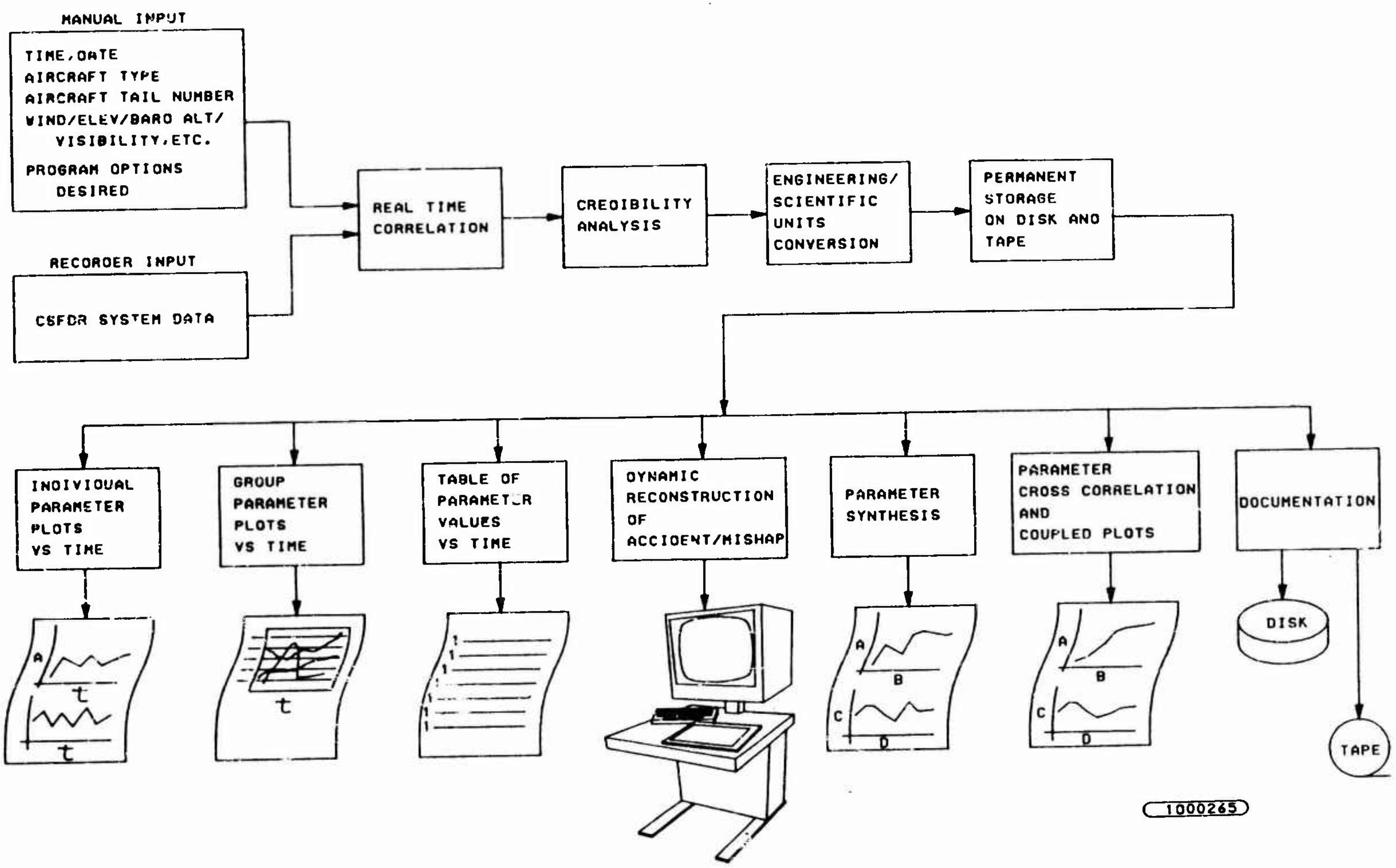


Figure 59. Ground-based Software Layout

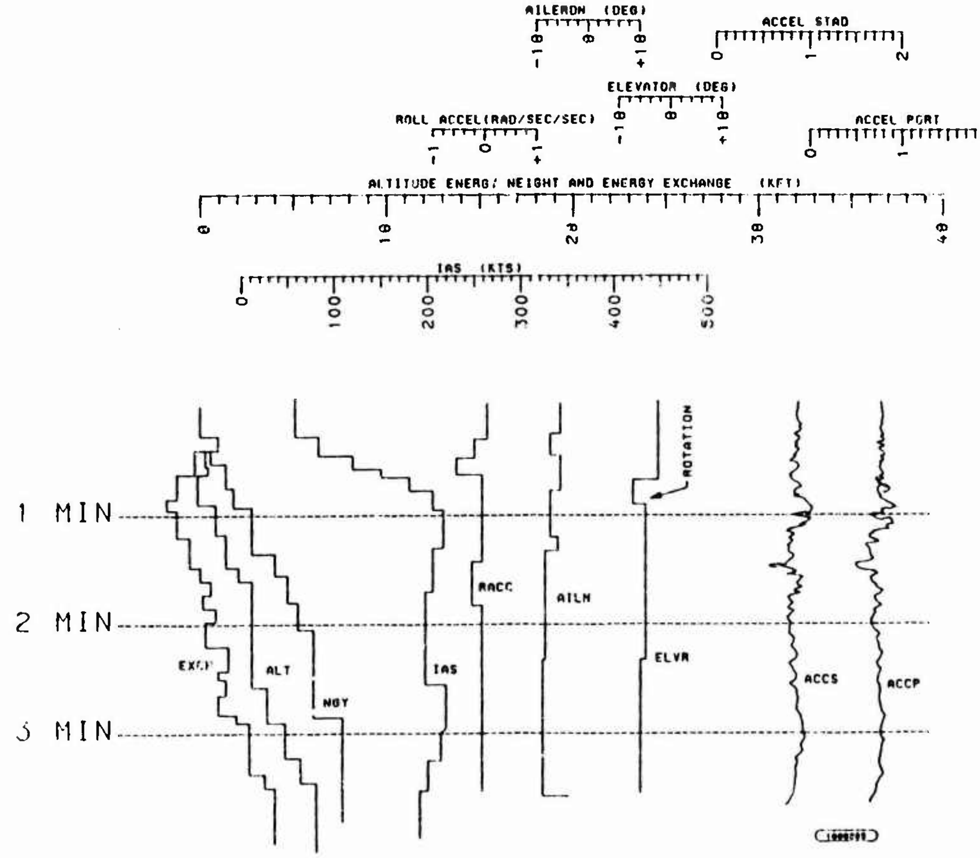


Figure 60. Multiple Parameter Plots

(4) Dynamic reconstruction of accident/mishap. The manual inputs and recorder inputs provide all of the data required to dynamically reconstruct the accident/mishap. A program option to display the actual aircraft motion as a function of time along with a digital display of pertinent parameters is, therefore, recommended. The parameters displayed digitally can be selected as desired. Figure 61 shows an example of this option. The dynamic reconstruction may be stopped (frozen) at any given point in time, or reversed, in order to provide the accident investigator with a "snapshot" capability. Additionally, suspect parameters or known failures, may appear as blinking elements on the CRT.

Table 44. Parameters Vs. Time

RELATIVE TIME	AILERON (DEG)	ROLL (DEG)	RUDDER (DEG)	AIRSPEED (KNOTS)	ETC
9.31	22	6	4	225	
9.32	21	6	4	225	
9.33	20	5	4	224	

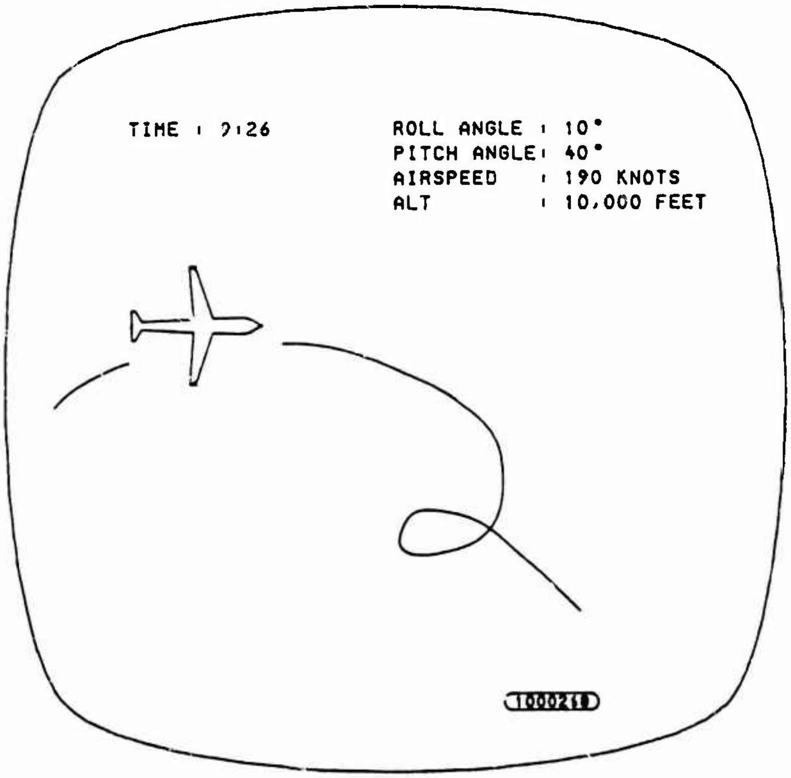


Figure 61. Dynamic Reconstruction of Accident/Mishap

(5) Parameter synthesis. Many parameters can be derived from related parameters and therefore used in additional ground support software subroutines. Heading, roll and pitch can be used to compute roll, yaw, and pitch rates. Vertical velocity can be used to compute altitude or instantaneous normal acceleration. Certain control surface positions can be computed from pilot inputs and aerodynamic data.

(6) Parameter cross-correlation and coupled plots. This subroutine is intended to be used as an investigative technique. Control inputs may be correlated with airframe responses. For example, power lever angle changes can be correlated with longitudinal acceleration. Stick input can be correlated with pitch and roll responses. Rudder pedal can be correlated with yaw angle rate. This subroutine may also be programmed in a flight simulator for comparative analysis purposes. In cases where pilot error is the probable cause of the accident/mishap, additional pilots can be presented with the same situation, in the simulator, to determine their response. Such procedures may ultimately result in technical order changes or changes in basic operating procedures.

(7) Documentation. In addition to the basic data which will be permanently stored on the disk or tape file, documentation data which results from any of the previous subroutines may also be permanently stored via program request. This information may be recalled at a later point in time and incorporated into the accident/mishap report as desired. Additionally, as a library is accumulated, this data can be made available for fleetwide studies throughout the USAF.

c. Ground support program size. The ground support software programs are estimated at 41,200 words x 16 bits. These programs will be written in Fortran IV and the cost per word to develop these programs is considerably less than the cost per word to develop the airborne program.

3.4 Alternate configuration life cycle cost (LCC) estimates

(Detailed inputs for this section are in appendices G and H.)

Life cycle cost estimates have been derived for three different configurations of the Crash-Survivable Flight Data Recorder. Each LCC estimate is an accumulation in FY '80 dollars of development cost, acquisition cost, and support cost for a 20-year operation period.

a. LCC model. The LCC analysis was performed by using the TI-59 handheld calculator LCC model developed by the ASD/AFALD LCC/DTC Advisory Group. The model, which is an adaptation of the USAF Logistic Support Cost (LSC) model, is included in appendix G.

LSI has considerable experience using the TI-59 model. This LCC model has been used by LSI for deriving life cycle costs for other USAF programs. These programs include the Low-cost Inertial Guidance System (LCIGS) Program, the AWACS AHRS Replacement Study, and, presently, the Fuel Savings Advisory System (FSAS) Program, which is in its proposal phase.

The cost equations of the USAF LSC model which are related to the spares and support cost equations of the TI-59 model have also been used in the Support Cost Guarantee (SCG) Program for LSI's F-4E Aircraft Digital Modular Avionics System (AN/ARN-101).

LSI feels this TI-59 LCC model is appropriate for the CSFDR system study. The CSFDR system design is similar at the shop-replaceable-unit (SRU) level to cards that have been designed as part of systems for other programs. This has permitted the use of this detailed model rather than parameter cost estimating relationships. Since SRU configurations can be approximated very well, the related production costs can be determined. The mean time between failures (MTBFs) can be estimated using both the modified existing parts lists and the thermal data analysis of the CSFDR system (see 3.2.8). Many of the other parameters which are inputs to the TI-59 model can also be estimated with reasonable accuracy because of the rather detailed design definition that existed during this study phase of the program. Many of the support input parameters can be adequately estimated based on the similarity of the maintenance concept (see 3.2.8) and the related support equipment, operation and maintenance manuals, etc., to the other programs which have similarity in circuit design.

b. Deployment scenario/usage assumptions. The following deployment and usage assumptions were used in the LCC analysis for each configuration.

- 3,150 aircraft installs: 730 A-10s, 1030 F-15s, 1390 F-16s.

- 25 operating hours per month usage per aircraft.
- Peak operating hours per month equals one-tenth of annual operating hours.
- 68 total base maintenance shops for A-10s, F-15s, and F-16s.
- 20-year projected inventory usage period.

c. Input parameter data. The definition of the TI-59 LCC input parameters is given in appendix G. The parameter values used for the CSFDR system configurations are included in appendix H. Each input sheet represents a particular CSFDR system configuration; each column on a sheet specifies the input for an LCC run for an individual line-replaceable unit (LRU) or shop-replaceable unit (SRU).

The source for data inputs are as follows:

- System development and investment costs are throughputted by the LCC model. The estimation of these values is discussed below.
- "Program data" inputs are derived from the deployment scenario/usage assumptions discussed above.
- "Item Data" inputs are derived from the Production Unit Cost curve determinations and the reliability and maintainability discussions in 3.2.8.
- The "standard parameter values" used for each LCC run for each CSFDR system configuration are listed in appendix G, which has been revised to reflect FY '80 standard parameter values as provided to LSI on another USAF program in November of 1980.

d. LCC model outputs. LCC estimates were calculated by accumulating costs from the individual TI-59 LCC model runs and aggregating them under appropriate cost categories. LCC elements identified in the "Life Cycle Cost Analysis Worksheet", of appendix G are used in this cost analysis effort. They are expanded where necessary for completeness. Summaries of the LCC estimates for various CSFDR system configurations are provided in the following paragraphs (3.4.1, 3.4.2, and 3.4.3). A description of the costs accumulated under each cost element or category is given in the following paragraphs.

Development cost includes the cost estimates for an Advanced Development phase and a Full-Scale Development phase.

Advanced development (ADV) phase costs are based on the assumption that one breadboard system will be designed, built, integrated and debugged, and that the CSMU will be tested on a limited basis for crash-survivability.

Full Scale Development (FSD) phase costs include the design and build of six prototypes; reliability and qualification testing; the installation of prototypes on A-10, F-15, and F-16 aircraft; flight test support; documentation; and blue line installation drawings for each aircraft configuration. FSD costs exclude logistics development costs. These costs will be included in the Support Investment Costs.

Investment Costs include the estimates for System Investment Cost and Support Investment Cost:

System Investment cost is the acquisition cost of 3150 CSFDR systems. The cost is determined from production unit cost curves which take into account learning curves for labor in the assembly and test of the CSFDR system, and the sensitivity of material cost to purchasing volume. The unit cost curves reflect a 92.5 percent learning or cost reduction rate. This rate is consistent with LSI's experience in labor learning curves and material cost reduction curves.

Support Investment costs include estimates for base and depot support equipment, manuals, and training; installation of 3150 CSFDR systems (730 on A-10 aircraft, 1030 on F-15 aircraft, and 1390 on F-16 aircraft); initial CSFDR system base and depot spare LRUs and SRUs; the initial lay-in of consumable pieceparts at the DPU, CSMU, and MSU depot(s); and initial spares for the support equipment at the base and depot repair facilities.

- Base and depot spare LRUs and SRUs are derived by cost equations in the TI-59 LCC model. Other support investment cost estimates are derived separately from the model using past experience on other programs and cost estimating relationships (CERs).
- Support equipment costs for maintenance support equipment (refer to 3.2.8 for equipment definition) and read-out support equipment (refer to 3.2.6 for equipment definition) have been derived by relating to similar existing or proposed support equipment. The maintenance support equipment costs include a DPU tester at each of 68 base shops, a DPU tester and board extenders at the DPU depot, an automatic digital and an automatic analog tester with appro-

priate interface test adapters (ITAs) for testing DPU cards at the DPU depot, and special test equipment for testing and troubleshooting CSMUs and/or MSUs at the depot(s). The read-out support equipment cost includes a data retrieval unit at each of 68 bases, a MSU data retrival unit at each of the 68 bases, and a data processor retrieval unit at the depot.

- Manual costs include estimates for an intermediate maintenance manual and illustrated parts breakdown for the DPU, overhaul manuals with illustrated parts lists for the CSMU and for the MSU, and operation and maintenance manuals with illustrated parts lists for the support equipment.

- Training costs reflect the cost for maintenance training classes to instruct flight line and shop personnel on the test and fault isolation of the CSFDR system LRUs and SRUs, using appropriate support equipment, and for training on the maintenance of the support equipment.

- Provisioning data costs cover the documentation of recommended quantities of spares for the CSFDR systems.

- Installation costs were calculated for individual aircraft types (A-10, F-15, and F-16). The kit cost and installation time varies for the various aircraft types and for the various CSFDR system configurations. Assuming the installations would be performed at Programmed Depot Maintenance (PDM), the following estimates were used:

Config.	Acft.	Kit Cost/Acft.	Install Time/Acft.
I	A-10	$6290	220
	F-15	$5586	190
	F-16	$5342	210
II	A-10	$6035	200
	F-15	$5332	170
	F-16	$5088	195
III	A-10	$8439	240
	F-15	$7735	205
	F-16	$7313	230

Operation and support costs were derived by cost equations in the TI-59 LCC model. Parameter inputs to these equations are indicated in the input worksheets in appendix H. Costs for data read-out from the MSUs in Configuration III were calculated using the assumption that data will be read-out semi-monthly. Data reduction costs for this data have not been included. Since the frequency of data readout from the CSMU is dependent upon mishap frequency, the associated cost has not been calculated. A scheduled maintenance cost for the EE-PROM memory in the CSMU need not be included since the number of write cycles during a 20-year usage period for a given CSMU is significantly smaller than the projected number of cycles at which replacement is required.

The support equipment maintenance cost is not calculated by the TI-59 LCC model. Therefore, it was throughputted. It was determined by using a percentage of the support equipment acquisition cost. The percentage used was 20 percent. This value is considered as conservatively high, based on LSI's previous experience and anticipated support equipment loading factors.

3.4.1 Alternate Configuration I - This configuration is designed to record the maximum number of flight parameters for the longest practical time before recycling. The following summary accumulates costs for development, CSFDR system investment, support investment, and logistics and maintenance support for 20 years.

Development Cost	$ 2,382,800
Investment	84,010,900
Total Operation and Support (20 years)	3,632,700
Total LCC (3,150 CSFDR systems)	$90,026,400
LCC per CSFDR System	$ 28,580

3.4.2 Operational Configuration II - This configuration is designed to record only the highest priority flight data. This configuration is optimized for the lowest practical development, investment, operation and logistics support costs. These costs are derived for the ground support equipment (maintenance and read-out equipment) as well as for the flight hardware. These costs are summarized below.

Development Cost	$ 2,159,600
Investment	72,349,400
Total Operation and Support (20 years)	3,413,400
Total LCC (3,150 CSFDR systems)	$77,922,400
LCC per CSFDR system	$ 24,740

3.4.3 Optional Configuration III - This configuration is similar to Configuration I, except added capability to provide non-crash-survivable memory has been included. The cost summary below accumulates the total development, investment, and 20-year support costs both for the CSFDR system with the additional memory capability provided by the MSU and for the associated ground support equipment. The ground support equipment includes read-out and maintenance equipment for the additional memory. The first set of costs is based on the assumption that four-fifths of each type of aircraft will have Configuration I installed, and one-fifth will have Configuration III installed.

Development Cost	$ 2,899,200
Investment	98,572,600
Total Operation and Support (20 years)	6,558,700
Total LCC (3,150 CSFDR systems)	$108,030,500
Average LCC per system	$ 34,300

If it is assumed that all 3,150 aircraft have Configuration III installed, the following cost summary is derived:

Development Cost	$ 2,899,200
Investment	127,745,700
Total Operation and Support (20 years)	16,793,100
Total LCC (3,150 CSFDR systems)	$147,438,000
LCC per system (CSFDR system + MSU)	$ 46,800

3.5 Cost/benefit analysis summary

The cost/benefit analysis is the portion of the study effort which determines the true value of the overall CSFDR system. Although many of the benefits to be derived from the use of the CSFDR system are tangible and have dollar values directly associated with them, there are also some very important intangible values which must be included in a thorough cost/benefit analysis, especially where safety is involved.

The cost/benefit analysis is extremely important for two reasons:

a. It provides the basis for the recommendation to continue or to stop work in the CSFDR system area.

b. Since the recommendation is to continue, the analysis can become a valuable document used to eliminate waiver requests (or the equivalent thereof) which have historically been used to prevent the incorporation of CSFDR systems into A/F/T aircraft.

3.5.1 Analysis of tangible benefits - The purpose of this section is to determine the tangible dollar savings that would be achieved by incorporating the CSFDR system into A/F/T aircraft. The A-10, F-15, and F-16 aircraft are used as examples for the model developed. However, since these aircraft are already in production and have already experienced some accidents, the full benefits to be derived from CSFDR systems will not be experienced by these programs. The results are adjusted accordingly to reflect the fact that these programs are already downstream in their life cycles; however, the conclusions of the analysis are unaffected.

3.5.1.1 Calculation of Class-A aircraft mishaps - The following method was used to calculate the expected aircraft mishaps for the A-10, F-15, and F-16 during their life cycle. The answer was then run by safety personnel and found to correspond very well to experienced results for A/F/T aircraft.

The actual calculations of aircraft losses is complicated by the fact that the fleet size is progressively reduced following each accident and therefore, the total flight hours for a given aircraft is a variable. Additionally, most aircraft do not realize their total design life before they are "moth-balled" or cannibalized for spare parts. Therefore, the total design life of 8,000 hours for the aforementioned aircraft cannot be assumed for the surviving aircraft which are retired.

The method for calculating aircraft losses is based upon probabilistic considerations. The probability of a given aircraft to survive its' life cycle without a Class-A mishap is given by

$$P_S = e^{-\lambda T}$$

where

P_S = probability that a given aircraft will survive its life cycle without experiencing a Class-A mishap

λ = Class-A accident rate for the aircraft type (A-10, F-15, etc.)

T = average accumulative flight hours on surviving aircraft.

The probability that a given aircraft will experience a Class-A mishap is given by

$$P_M = 1 - e^{-\lambda T}$$

where

P_M = probability that a given aircraft will experience a Class-A mishap.

If $\bar{n}$ is the total number of Class-A mishaps, they are distributed according to the following equation (assuming a binomial distribution):

$$P_{\bar{n}} = \sum_{i=0}^{n} \binom{n}{i} (1 - e^{-\lambda T}) e^{-\lambda T}$$

where

$\bar{n}$ = total number of Class-A mishaps

n = total number of aircraft type produced.

The number of Class-A mishaps is then

$$\bar{n} = n(1 - e^{-\lambda T})$$

Table 45 shows the data used to compute the specific number of aircraft Class-A mishaps for the A-10, F-15, and F-16, respectively.

Table 45. Aircraft Specific Data

AIRCRAFT TYPE	CLASS A ACCIDENT RATE (λ)	AVERAGE FLT. HRS. PER MONTH PER A/C	AVERAGE ACCUMULATIVE FLT. HOURS ON SURVIVING AIRCRAFT (T)	AIRCRAFT PRODUCED (n)	AVERAGE $ PER CLASS A MISHAP
A-10	5.81×10^{-5}	30	7,200	730	5.5 M
F-15	6.00×10^{-5}	25	6,000	1,030	11.7 M
F-16	7.00×10^{-5}	25	6,000	1,390	12.63 M

Using the preceding equation for $\bar{n}$, the following Class-A mishap totals are computed.

A-10 Class-A mishaps in life cycle = 250
F-15 Class-A mishaps in life cycle = 311
F-16 Class-A mishaps in life cycle = 476

However, because these aircraft programs are already within their life cycles, the Class-A mishaps to date must be subtracted from the totals. Thus, we have

A-10 Class-A mishaps remaining in
life cycle = 250 - 19 = 231

F-15 Class-A mishaps remaining in
life cycle = 311 - 25 = 286

F-16 Class-A mishaps remaining in
life cycle = 476 - 7 = 469

3.5.1.2 <u>Minor mishaps</u> - Although the CSFDR system would occasionally be useful in regard to minor mishaps, a benefit for class B, C, and D mishaps will not be included in the cost/benefit analysis. This is in accordance with the general policy of keeping the analysis conservative. Moreover, the benefit provided by the CSFDR system in the minor mishap cases is relatively small when compared to the benefit provided by the CSFDR system for Class-A mishaps.

3.5.1.3 <u>Recovery costs</u> - Typical recovery costs for water-submerged and non-submerged aircraft are approximated at $500,000 per Class-A mishap and $100,000 per Class-A mishap, respectively.

3.5.1.4 Recovery ratios - Based upon the study of 221 A/F/T Class-A mishaps it is estimated that 5% of these mishaps will result in a water-submerged aircraft and that 95% will occur over land.

3.5.1.5 Calculation for expected loss of life - Loss-of-life ratios are calculated for the cost/benefit model based upon actual data. Table 2-1, page 2-9 of AFR127-4 lists fatality costs as \$260,000 per rated officer and \$118,000 per nonrated officer. Using actual data, then, for the A-10, we have

$$\begin{aligned}\begin{matrix}\text{Fatality cost}\\ \text{per A-10}\\ \text{Class-A mishap}\end{matrix} &= \frac{\text{8 rated officers x \$260,000}}{\text{19 Class-A mishaps}}\\ &+ \frac{\text{1 nonrated officer x \$118,000}}{\text{19 Class-A mishaps}}\\ &= \text{\$115,684/Class-A mishap}\end{aligned}$$

Similarly for the F-15 and F-16 we have

$$\begin{aligned}\begin{matrix}\text{Fatality cost}\\ \text{per F-15}\\ \text{Class-A mishap}\end{matrix} &= \frac{\text{7(\$260,000) + 1x \$118,000}}{\text{25 Class-A mishaps}}\\ &= \text{\$77,520/Class-A mishap}\end{aligned}$$

$$\begin{matrix}\text{Fatality cost}\\ \text{per F-16}\\ \text{Class-A mishap}\end{matrix} = 0$$

Note that the loss-of-life calculations are conservative in that they do not include hospitalization if loss of life is not immediate and they do not include survivor's insurance. Moreover, the F-16 loss-of-life is assumed to continue at its current rate of 0.

3.5.1.6 Probable cause ratios - Based upon NAFB experience, since 1976, for A/F/T Class-A mishaps, the cause ratios are

1.	Operations, design induced	-	34.3%
2.	Operations, misjudgement	-	17.2%
3.	Logistics (part and failure mode known)	-	13.1%
4.	Logistics (part only, failure mode unknown)	-	26.2%
5.	Undetermined	-	9.2%

3.5.1.7 Tangible cost/benefit calculations - The cost/benefit formula for tangible savings due to a CSFDR system is

$$\text{Tangible dollar value of benefits} = \cancelto{0}{\text{minor mishaps cost savings}} + \text{total over-water accident cost savings} + \text{total over-land accident cost savings}$$

Using the data previously computed and/or determined from the actual mishap listing survey, the tangible dollar value of benefits for the CSFDR system as applied to the A-10, F-15, and F-16 aircraft becomes

$$\begin{aligned}
\text{Tangible dollar value of benefits} = E \cdot \Big\{ & 11 \text{ A-10 mishaps over water} \cdot \left[\$5{,}500{,}000 \text{ aircraft damage} + \$115{,}684 \text{ loss of life} + \$500{,}000 \text{ recovery cost}\right] \\
& + 220 \text{ A-10 mishaps over land} \cdot \left[\$5{,}500{,}000 \text{ aircraft damage} + \$115{,}684 \text{ loss of life} + \$100{,}000 \text{ recovery cost}\right] \\
& + 14 \text{ F-15 mishaps over water} \cdot \left[\$11{,}700{,}000 \text{ aircraft damage} + \$77{,}520 \text{ loss of life} + \$500{,}000 \text{ recovery cost}\right] \\
& + 272 \text{ F-15 mishaps over land} \cdot \left[\$11{,}700{,}000 \text{ aircraft damage} + \$77{,}520 \text{ loss of life} + \$100{,}000 \text{ recovery cost}\right] \\
& + 23 \text{ F-16 mishaps over water} \cdot \left[\$12{,}630{,}000 \text{ aircraft damage} + 0 \text{ loss of life} + \$500{,}000 \text{ recovery cost}\right] \\
& + 446 \text{ F-16 mishaps over land} \cdot \left[\$12{,}630{,}000 \text{ aircraft damage} + 0 \text{ loss of life} + \$100{,}000 \text{ recovery cost}\right] \Big\} \\
= {} & \{10.7 \times 10^9\}E
\end{aligned}$$

where E is the effectiveness of the CSFDR system in preventing Class-A mishaps taken over all mishap types. Although E is a somewhat subjective factor, a range of E can be hypothesized as shown in table 46.

Table 46. Calculation of Composite E

PROBABLE CAUSE TYPE	PERCENT CONTRIBUTION	CONFIG-URATION	CSFDR SYSTEM EFFECTIVENESS RANGE PER PROBABLE CAUSE TYPE %			OVERALL EFFECTIVENESS PER PROBABLE CAUSE TYPE		
			(1)	(2)	(3)	(1)	(2)	(3)
1. Operations, design induced	34.3%	I	12.5	25	50	4.28	8.57	17.2
		II	11.0	22	44	3.77	7.55	15.1
2. Operations, misjudgement	17.2%	I	0	0	0	0	0	0
		II	0	0	0	0	0	0
3 Logistics (part and failure mode known)	13.1%	I	0	0	0	0	0	0
		II	0	0	0	0	0	0
4. Logistics (part only-failure mode unknown)	26.2%	I	12.5	25	50	3.28	6.55	13.1
		II	11.0	22	44	2.88	5.76	11.53
5. Undetermined	9.2%	I	12.5	25	50	1.15	2.3	4.6
		II	10.0	20	40	0.92	1.84	3.68
			Conf. I →			8.71	17.4	34.9
			Conf. II →			7.6	15.2	30.3

(1) - Minimum
(2) - Expected
(3) - Optimistic

Note that the analysis must account for corresponding values of E for Configurations I and II. Because Configuration I records more parameters and for a longer time period than Configuration II, the effectiveness of Configuration II is somewhat lower than that of Configuration I. Table 46 shows corresponding values of effectiveness for each probable cause type. These values for E are also based upon the definitions of Configurations I and II as defined in this study.

The tangible dollar value of benefits is tabulated in table 47 for various values of E.

Table 47. Tangible Savings Achieved by Incorporating CSFDR System into A-10, F-15, and F-16 Aircraft

TOTAL TANGIBLE SAVINGS ($)		COMPOSITE VALUE OF E (%)		COMMENTS
Conf. I	Conf. II	Conf. I	Conf. II	
0.931×10^9	0.813×10^9	8.7	7.6	Minimum benefits
1.86 x	1.63 x	17.4	15.2	Expected benefits
2.79 x	2.43 x	26.1	22.7	
3.74 x	3.24 x	34.9	30.3	Optimistic benefits
4.67 x	4.06 x	43.6	37.9	
5.60 x	4.87 x	52.3	45.5	
6.53 x	5.67 x	61.0	53.0	
7.47 x	6.49 x	69.8	60.6	
8.40 x	7.30 x	78.5	68.2	
9.33 x	8.10 x	87.2	75.7	
10.26 x	8.91 x	95.9	83.3	

Table 46. Calculation of Composite E

PROBABLE CAUSE TYPE	PERCENT CONTRIBUTION	CONFIG-URATION	CSFDR SYSTEM EFFECTIVENESS RANGE PER PROBABLE CAUSE TYPE %			OVERALL EFFECTIVENESS PER PROBABLE CAUSE TYPE		
			(1)	(2)	(3)	(1)	(2)	(3)
1. Operations, design induced	34.3%	I	12.5	25	50	4.28	8.57	17.2
		II	11.0	22	44	3.77	7.55	15.1
2. Operations, misjudgement	17.2%	I	0	0	0	0	0	0
		II	0	0	0	0	0	0
3. Logistics (part and failure mode known)	13.1%	I	0	0	0	0	0	0
		II	0	0	0	0	0	0
4. Logistics (part only-failure mode unknown)	26.2%	I	12.5	25	50	3.28	6.55	13.1
		II	11.0	22	44	2.88	5.76	11.53
5. Undetermined	9.2%	I	12.5	25	50	1.15	2.3	4.6
		II	10.0	20	40	0.92	1.84	3.68
					Conf. I →	8.71	17.4	34.9
					Conf. II →	7.6	15.2	30.3

(1) - Minimum
(2) - Expected
(3) - Optimistic

3.5.1.8 Tangible cost/benefit results - The results of the cost/benefit model show a dramatic savings of tangible dollars. With 7.6% and 8.7% recovery rates (composite E) a savings of approximately \$813,000,000 and \$931,000,000 will be realized by Configurations II and I, respectively, for the life cycle of the aircraft under consideration. At expected recovery rates of 15.2% and 17.4%, respectively, savings of approximately \$1,630,000,000 and \$1,860,000,000 could be realized.

At the optimistic recovery rates, savings of approximately \$3,240,000,000 and \$3,740,000,000 could be realized.

Using the expected recovery rates, the benefit/cost ratios for Configurations I and II become

$$\text{RATIO}_{\text{I}} = \frac{1{,}860{,}000{,}000 - 3{,}632{,}700}{86{,}393{,}700} = 21.5$$

$$\text{RATIO}_{\text{II}} = \frac{1{,}630{,}000{,}000 - 3{,}413{,}400}{74{,}509{,}000} = 21.8$$

where 3,632,700 and 3,413,400 are the negative logistic cost savings and 86,393,700 and 74,509,000 are the initial logistics costs.

Note that the Configurations I and II provide a better than 20/1 payback.

The cost/benefit analysis for Configuration III is performed by assuming the same tangible dollars saved, as a result of reduced mishaps, as was the case for Configuration I, and by analyzing the expanded recording functions incrementally. The analysis is simplified by assuming that the same expanded recording functions will be accomplished with Configuration III as are currently accomplished with ASIP recorders. The savings in life cycle costs of not having to procure and support the existing type of electromechanical recorders now used for ASIP recording functions appears as a benefit in the benefit/cost ratio. Therefore, for Configuration III

$$\text{RATIO}_{\text{III}} \cong \frac{1{,}860{,}000{,}000 - 6{,}558{,}700 + 13{,}745{,}300}{101{,}471{,}800 - 13{,}071{,}900} = 21.1$$

where 13,071,900 is the benefit derived by not procuring separate recorders for the ASIP recording functions. For the A-10, F-15, and F-16 retrofit applications, a replacement analysis of the existing recorders provides a slightly lower ratio of approximately

$$\text{RATIO}_{\text{III}} \cong \frac{1{,}860{,}000{,}000 - 6{,}558{,}700 + 13{,}745{,}300}{101{,}471{,}800} \cong 18.4.$$

3.5.2 Discussion of intangible benefits - Intangible benefits derived through useage of the CSFDR system are those which are known to have a definite value that cannot reasonably be converted to actual dollars. Intangible benefits projected for the CSFDR system include the following:

- Improved strike capability due to a reduction in fleet down time following a mishap or spate of mishaps.
- Improved crew morale by quick determination of mishap cause and eliminating a spate of accidents due to similar causes.
- Improved data concerning airborne "incidents", which do not result in accidents, but provide valuable data concerning subsystem performance and aircraft performance.
- Elimination of the element of doubt in determining the true cause where nonsurvivable-operations type mishaps occur.

These areas are discussed in more detail in the following paragraphs.

3.5.2.1 Reduction in fleet down time - Historically mishaps and a spate of mishaps can result in grounding of the aircraft fleet until the basic cause is determined and the deficiency corrected. By having a CSFDR system on board, the investigative and analys [illegible] ime will be shortened. Therefore, the CSFDR system will not only reduce the incidence of similar mishaps, it will also reduce the time in which the fleet is grounded.

The dollar value associated with a reduction in fleet down time is variable and intangible. Fleet readiness is of the utmost importance in times of national emergency and it is not possible to predict when and how frequently national emergencies will occur.

Loss of training time and reduction in morale (discussed in the next section) also occur during prolonged periods of fleet grounding. Loss of confidence in the aircraft itself can often result. The dollar value associated with these losses simply cannot be measured.

3.5.2.2 Improved crew morale - Quick and accurate determination of the mishap cause eliminates the possibility of a spate of mishaps due to identical or similar causes. There are several such cases in military aviation history, where an outburst of mishaps due to identical causes has occured. In one case 42 mishaps occured before the real cause was identified. In another case 10 mishaps occured within a span of one month. During such short periods of high accident rates, crew confidence and morale deteriorates significantly. The deterioration of confidence and morale has an immeasureable effect on crew performance and can probably be linked to crew turnover rate. It cannot be measured in real dollars, however. The important point, is that an onboard CSFDR system will eliminate the possibility of a spate of mishaps due to similar causes and, therefore, improve crew morale.

3.5.2.3 Improved incident data - There are many non-catastrophic airborne incidents which either (1) fail to get reported or (2) are reported inaccurately due to heavy pilot workload or other reasons. Such incidents may occur near the operating envelope of the aircraft and it becomes difficult to determine if the actual cause was due to exceeding operational limits, subsystem failure, or incorrect limit specifications.

Data concerning such incidents are valuable.

3.5.2.4 More accurate determination of true cause for non-survivable-operations mishaps - Mishap data for A/F/T aircraft is accumulated through analysis of wreckage, eyewitness accounts, site scars, and any other available source. Mishap Investigation Boards (MIBs) use the "preponderance of evidence" method is assessing cause factors where there are no survivors. Operator error findings may result from the weight of evidence in the absence of contradictory information. The CSFDR system will significantly change the "preponderance of evidence" method and permit a more accurate determination of true cause for the non-survivable-operations related mishaps.

3.5.3 Discussion of benefit-to-cost ratios - On the surface, the calculated benefit-to-cost ratios appear to be unusually high. Typically, a benefit-to-cost ratio of 3:1 or 4:1 would totally justify a go-ahead decision for the type of program being considered. The calculated ratios for the CSFDR system program are in the range of 20:1. However, this unusually high ratio is totally justified, and is realistic for the program considered for the following reasons:

a. The A-10, F-15, and F-16 represent an expensive group of aircraft. If a similar cost/benefit analysis were conducted for the A-7, F-4, and F-5, the benefit-to-cost ratio would be reduced by approximately a factor of 3.

b. Standardizing the CSFDR system for a group of aircraft, such as the A-10, F-15, and F-16, reduces the life cycle cost per aircraft. This reduction is then reflected in an increase in the benefit-to-cost ratio.

c. The accident rates for the three aircraft considered are slightly higher than historic fleet averages for A/F/T aircraft. However, the accident rates assumed are felt to be realistic.

4. CONCLUSIONS

The primary conclusions derived from the CSFDR system study are as follows:

a. The current state of the art in electronics technology permits Configuration II, with a minimum level of input parameters (typically 35), and an average real-time storage of 19 minutes, to be designed and produced at a size and weight applicable to A/F/T aircraft. The size and weight are significantly less than contemporary electromechanical recorders.

b. Also, Configuration I, with a higher level of input parameters (typically 56), and an average real-time storage of 29 minutes, can be designed and produced at a size and weight applicable to A/F/T aircraft. The size and weight of this configuration are also significantly less than contemporary electromechanical recorders. Moreover, the addition of solid-state mass storage units permits this configuration to be used for expanded airborne recording functions. The resulting recorder system, Configuration III, is a single standardized family of modules which can be used for any set of airborne recording functions.

c. High performance aircraft, such as A/F/Ts, have complex flight control systems and aerodynamic behavior. Consequently, the use of a very small parameter list (such as 8-10 parameters) will not provide sufficient accident investigation capability for these aircraft.

d. Separation of the survivable memory pack from the conversion/ processing functions enhances survivability, reduces the total weight of the installation, and increases the number of potential installation locations for the survivable function.

e. Use of multiple, non-hardened memories located in the aircraft extremities will not provide the required survivability ratios for A/F/T applications. However, the extremities of A/F/T aircraft, such as the wing tips and tail sections, exhibit the best mechanical and thermal survivability characteristics and these areas are recommended for the hardened module.

f. The TSO-C51A was not conceived with A/F/T applications in mind. Therefore, it is recommended that the A/F/T crash-survivability specification developed in this study be used instead of TSO-C51A.

g. A tri-service standard crash-survivable flight data recorder is feasible if two parameters are not included in the design:

- audio
- recording through impact

The ejectability requirement (and floatation) is required for Navy applications and is compatible with the two-box approach recommended.

h. Application to future A/F/T aircraft will be simplified because the standard CSFDR system can be planned into the design from the beginning, thereby eliminating some of the costs and technical problems which are directly related to the retrofit operation. The standard CSFDR software can be reprogrammed for this application. Configuration III is the recommended configuration for future A/F/T aircraft.

i. Large-scale standardization to cargo/passenger/bomber aircraft is feasible, but requires a modified survivable memory due to the longer time history of parameters and the different crash-survivability test required. All other units of the standard CSFDR system are directly applicable to these aircraft.

j. Expanded recording functions, such as ASIP, TEH, and FC system monitoring have only a minimal effect on the conversion and processing functions of Configuration I. These expanded recording functions are easily achieved by adding mass storage units to the basic system.

k. Encryption techniques, which result in only one-half of a board of processor "real estate", can be used to provide all the security protection features requried for operation at or near enemy territory.

l. A readout station having a four-level readout capability can easily be provided to Norton Air Force Base for mishap investigations. This station would utilize a solid-state data processor retrieval unit made directly compatible with the existing Norton AFB EDP facility. Alternate readout facilities are also possible at minimum risk to the USAF.

m. The memory technologies most suitable for incorporation into the Crash-Survivable Memory Unit (CSMU) are the EE-PROM and MNOS types.

n. A data compression technique which uses floating apertures and a zero-order polynomial predictor, which is adaptive to flight conditions, can be used to reduce the crash-survivable memory required. This, in turn, reduces the overall cost of the CSFDR system.

o. The reprogrammability feature of the Data Processor Unit permits a common design to be used for various aircraft. The A-10, F-15, and F-16 were studied for specific applications. Enough commonality exists such that a single CSFDR system concept can be implemented for these aircraft. In addition, the standard CSFDR system can be reprogrammed for many other applications.

p. The estimated size and weight of Configuration II are 232 cubic inches and 10 pounds. For Configuration I, a size of 254 cubic inches and weight of 11.2 pounds are projected. For Configuration III, a size of 362 cubic inches and weight of 17.2 pounds are projected.

q. For a three-aircraft program (A-10, F-15, and F-16), LCCs of $28,580, $24,740, and $34,300 are computed on a per aircraft basis for Configurations I, II, and III. These calculations include the mass storage unit required for Configuration III and assume that one-fifth of the aircraft have the mass storage units installed. If all of the aircraft have the mass storage units installed, the LCC per aircraft is computed as $46,800.

r. All configurations studied have positive cost/benefit ratios for the three-aircraft program.

5. RECOMMENDATIONS

Based upon the results of the USAF CSFDR system study contract, the following recommendations are made:

a. Work on the standard CSFDR system should continue.

(1) A follow-on program should be established for a prototype feasibility flight test for Configurations II and III.

(2) Prototype CSMUs which meet the A/F/T crash-survivability specification as outlined herein should be constructed and tested.

b. The results of this study should be made available to cognizant personnel within the USAF so that the need for the standard CSFDR system is fully realized in establishing the funding for the follow-on phase.

c. For the retrofit applications such as A-10, F-15, and F-16, Configuration II should be developed and produced.

d. For future aircraft, Configuration III should be developed and produced, thereby eliminating the proliferation of recorders which perform similar functions.

APPENDIX A

References

[1]USAF Manual, 127-1, "Aircraft Accident Prevention and Investigation". Effective date 14 July 1976.

[2]USAF Regulation, 127-4, "Investigating and Reporting U.S. Air Force Mishaps". Effective date 18 Jan. 1980.

[3]USAF "SON for FDR for Attack/Fighter/Trainer Aircraft", from AFISC dated 27 August 1979, signed by General Garry A. Willard, Jr.

[4]U.S. Air Force, "Air Force Policy on Flight Data Recorders and Crash Position Indicators", Chief of Staff Policy Letter dated 16 June 1973, signed by General John D. Ryan.

[5]U.S. Navy, "Crash Position Indicator/Flight Data Recorder Systems for Naval Aircraft". Chief of Naval Operations Message CNO 1416102, April 1972.

[6]Letter from Philip J. Greeley, Col USAF, Dated 7 October 1980, to Lear Siegler, Inc.

[7]Raymond J. Roark and Warren C. Young: "Formulas for Stress and Strain", Fifth Edition, McGraw Hill, 1975, pp. 572-3.

[8]J. R. Welker and C.M. Sliepcevich, "Heat Transfer by Direct Flame Contact - Fire Test - Phase I", final report prepared for the National Academy of Sciences, July 1971.

[9]L.H. Russell and J.A. Canfield, "Experimental Measurement of Heat Transfer to a Cylinder Immersed in a Large Aviation Fuel Fire", Journal of Heat Transfer, Transactions of the ASME, August 1973, p. 399.

[10]Thomas Rust, Jr. and Paul N. Boris, "Fire Test Criteria For Recorders", NAFEC, Atlantic City, N.J. Final report prepared for the FAA (Report No. FAA-DS-70-16), July 1970, pp. 2, 34.

[11]Kjell O. Jeppson and Christer M. Svensson, "Retention Testing of MNOS LSI Memories", IEEE Journal of Solid State Circuits, Vol. SC-14, No. 4, August 1979, p.723-9.

[12] LSI brochure entitled "Shirt Pocket Precision: The LSI Data Transfer System", LSI Publication No. ID-028-0280.

[13] ARINC Characteristic No. 542, "Airborne Oscillographic Flight Data Recorder", Aeronautical Radio, Inc.

[14] U.S. Federal Aviation Regulation, Part 37.150, "Aircraft Flight Recorder", TSO-C51 a.

[15] ARINC Characteristic No. 541, "Airborne Magnetic Flight Data Recorder", Aeronautical Radio, Inc.

[16] ARINC Characteristic No. 537-7, "Mark II Aircraft Integrated Data System", Aeronautical Radio, Inc.

[17] Trageser, James H., "Non-Volatile Memory System for Severe Environment Flight Recorders", Technology, Inc., Dayton, Ohio, May 18, 1978.

[18] Hnatek, Eugene R., "An Overview of Advanced LSI Technology", Monolithic Memories, Inc., Sunnyvale, California, 1977.

[19] Belt, Ronald A., "Advanced Memories for Military Systems", NAECON Record, 1976.

[20] Johnson, W.S., "16-K EE-PROM Relies on Tunneling for Byte-Erasable Program Storage", Electronics, February 28, 1980.

[21] Shelton, E.K., "Low-Power EE-PROM Can Be Reprogrammed Fast", Electronics, July 31, 1980.

[22] Lloyd N. Baetz, "Study and Design of Flight Data Recording Systems for Military Aircraft", Master's Thesis, NPS Monterey, California, June 1976.

[23] Department of the Army, "Accident Information Retrieval System (AIRS)", Final Report, AVRADCOM, August 1977.

[24] Department of the Air Force, "Development and Evaluation of L/ESS Data Compression Techniques", Final Report, University of Dayton Research Institute, Dayton, Ohio.

APPENDIX B

Abbreviations/Acronyms

ACS	Armament Control Set
ADV	Advanced Development
AFISC	Air Force Inspection and Safety Center
AHMR	Aircraft Health Monitoring Recorder
AHRS, HARS, AHARS	Attitude and Heading Reference System
AIRS	Accident Information Retrieval System
AOA	Angle Of Attack
APU	Auxiliary Power Unit
ASIP	Aircraft Structural Integrity Program
ATE	Automatic Test Equipment
A/F/T	Attack/Fighter/Trainer
BIT	Built In Test
BORAM	Block Oriented Random Access Memory
BUC	Back-Up Control
CADC, ADC	Central Air Data Computer
CAS	Control Augmentation System
CAVT	Cavitation
CC	Central Computer
CCD	Charge-Coupled Devices
CDP	Compressor Discharge Pressure
CER	Cost Estimating Relationship
CIVV	Compressor Inlet Variable Vanes
CMOS	Complementary Metal Oxide Semiconductor
CPM	Crash Protected Memory
CSFDR	Crash-Survivable Flight Data Recording
CSMU	Crash Survivable Memory Unit
DDC	Direct Data Compressor
DES	Data Encryption Standard
DFDR	Digital Flight Data Recorder
DME	Distance Measuring Equipment
DPRU	Data Processor Retrieval Unit
DPU	Data Processing Unit
DP/DC	Data Processing/Data Compression
DRU	Data Retrieval Unit
DTM	Data Transfer Modules
DTS	Data Transfer System
EAROM	Electrically Alterable Read Only Memory
ECA	Electronic Component Assembly
ECL	Emitter-Coupled Logic
EDP	Electronic Data Processing
EDS	Engine Diagnostic System
EEC	Electronic Engine Control

EE-PROM	Electrically Erasable-Programmable Read only Memory
EGT	Exhaust Gas Temperature
EHR	Engine Health Recorder
EPR	Engine Pressure Ratio
EPROM	Electrically Programmable Read Only Memory
EPU	Emergency Power Unit
ETTR	Engine Time/Temperature Recorder
FC	Flight Control
FCC	Fire Control Computer
FCS	Flight Control System
FDA	Flight Director Adapter
FDAU	Flight Data Acquisition Unit
FIR	Flight Incident Recorder
FIR/UL	Flight Incident Recorder/Universal Locator
FLCC or FCC	Flight Control Computer
FSD	Full Scale Development
FTIT	Fan Turbine Inlet Temperature
GSE	Ground Support Equipment
HSIS	Horizontal Situation Indicator Set
HUD	Head Up Display
IAW	In Accordance With
ICD	Interface Control Document
IECMS	Integrated Engine Condition Monitoring System
IMU	Inertial Measurement Unit
INS	Inertial Nav System
INU	Inertial Nav Unit
ITA	Interface Test Adapter
ITT	Interstage Turbine Temperature
I^2L	Integrated Injection Logic
I^3L	Isoplanar Integrated Injection Logic
JFS	Jet Fuel Starter
LCC	Life Cycle Cost
LCG	Lead Computing Gyro
LEF	Leading Edge Flap
LRU	Line Replaceable Unit
MBC	Master Bus Controller
MDRM	Maintenance Data Recorder Magazine
MDS	Microprocessor Development System
MER	Multiple Ejector RACK
MNOS	Metal Nitride Oxide Semiconductor
MR	Master Reset
MSU	Mass Storage Units
MTBF	Mean Time Between Failures
NBS	National Bureau of Standards

NMOS	N-Channel Metal Oxide Semiconductor
NPS	Naval Postgraduate School
NPS-1	Naval Postgraduate School (List 1)
NPS-2	Naval Postgraduate School (List 2)
NTSB	National Transportation Safety Board
OAT	Outside Air Temperature
OPS	Operations Per Second
PDI	Power-Down Interrupt
PDM	Programmed Depot Maintenance
PIU	Playback Interface Unit
PMOS	P-Channel MOS
PROM	Programmable Read Only Memory
PSI	Pounds per Square Inch
PSIG	Pounds per Square Inch Gauge
RAM	Random Access Memory
RCVV	Rear Compressor Variable Vanes
SAS	Stability Augmentation System
SMS	Stores Management System
SON	Statement of Need
SOS	Silicon On Sapphire
SRU	Shop Replaceable Unit
STP	Self Test Program
TEH	Turbine Engine Health
TEMS	Turbine Engine Monitoring System
TTL	Transistor Transistor Logic
UART	Universal Asynchronous Receiver Transmitter
UFC	Unified Fuel Control
UGTU	Universal Ground Terminal Unit
ULAIDS	Universal Locator Airborne Integrated Data System
VMOS	V-Groove MOS
VTR	Video Tape Recorder

APPENDIX C

Applicable Documents to Installation Investigation

The following is a list of federal and military specifications, military standards, and technical orders that are adhered to during system design, fabrication and installation.

SPECIFICATIONS

Federal

QQ-W-343	Wire, Electrical (uninsulated)
QQ-S-571	Solder, Tin Alloy, Lead-tin Alloy, and Lead Alloy
QQ-P-575	Braid, Wire (Copper, Tin Coated Tubular)

Military

MIL-C-17	Cables, Radio Frequency, Flexible and Semi-rigid
MIL-C-572	Cords, Yarns, and Monofilaments - Organic Synthetic Fiber
DOD-D-1000	Drawings, Engineering and Data
MIL-C-5015	Connectors, Electrical, Circular Threaded, AN Type, General Specification for
MIL-W-5088	Wiring, Aircraft, Installation of
MIL-E-6051	Electromagnetic Compatibility Requirements, Systems
MIL-E-7016	Electrical Load and Power Source Capacity, Aircraft, Analysis of
MIL-T-7928	Terminal, Lug and Splice, Crimp Style, Copper
MIL-S-8516	Sealing Compound, Polysulfide Rubber Base, Electric Connectors and Electric Systems, Chemically Cured
MIL-I-15126	Insulation Tape, Electrical Pressure Sensitive
MIL-W-22759	Wire, Electric, Fluoropolymer-insulated Copper or Copper Alloy

MIL-I-23053	Insulation, Sleeving, Electrical, Heat Shrinkable, General Specification for
MIL-W-25038	Wire, Electrical, High Temperature and Fire Resistant, Aircraft
MIL-S-23586	Silicone Rubber Compound, Room Temperature Vulcanizing
MIL-I-23594	Insulation Tape, Electrical High Temperature, Polytetrafluroethelene, Pressure Sensitive
MIL-C-26482	Connector, Electrical, Bayonet Coupling, Crimp Type Contact Corrosion Proof
MIL-C-27500	Cable, Electrical Shielded and Unshielded, Aerospace
MIL-C-27599	Connector, Electrical, Miniature, Quick Disconnect (for Weapons Systems) Established Reliability
MIL-C-38999	Connectors, General Purpose, Electrical, Miniature, Circular, Environment Resisting
MIL-C-39012	Connectors, Coaxial, Radio Frequency
MIL-T-43435	Tape, Lacing and Tying
MIL-I-46852 (SM2173)	Insulation Tape, Electrical, Self Adhering, Unsupported, Silicone Rubber
MIL-W-81381	Wire, Electric, Polyimide - Insulated, Copper or Copper Alloy
MIL-M-81531	Marking of Electrical Insulating Materials
MIL-S-81824	Splice, Electric, Permanent Crimp Style, Copper, Insulated, Environment Resistant, Class I
MIL-C-83723/I	Connectors, Electrical, (Circular, Environment Resisting) Bayonet Coupling, Solder Contact, Series I

STANDARDS

Military

MIL-STD-1353	Electrical Connectors and Associated Hardware, Selection and Use of
MIL-STD-129	Marking for Shipment and Storage
MIL-STD-202	Test Methods for Electronic and Electrical Component Parts
MIL-STD-454	Standard General Requirements for Electronic Equipment
MIL-STD-461	Electromagnetic Interference Characteristics, Requirements for Equipment
MIL-STD-794	Parts and Equipment, Procedures for Packaging and Packing of
DOD-STD-100	Engineering Drawing Practices
MIL-STD-704	Electric Power Aircraft Characteristics and Utilization of

National Aerospace Standard

NAS1745	Splice, Conductor, Hot Air Shrinkable, Insulated
NAS1746	Splice, Conductor, Heat Shrinkable, Insulated

Technical Orders

1-1A-14	Installation Practices, Aircraft Electric and Electronic Wiring

APPENDIX D

Review of Mishap Data

The following data and conclusions were assembled after reviewing A-10 and F-16 Class-A accident reports on file at Norton A.F.B. In addition, the computer printout of some 500 Class-A and -B, Part I accident reports were reviewed.

A-10/F-16 DAMAGE FROM CLASS-A MISHAPS

A summary of the aircraft damage which has resulted from A-10 and F-16, Class-A mishaps is shown in tables D-1 and D-2, respectively. The definitions are repeated here for the reader's convenience.

Mechanical Break-Up Damage

1. Total - Many small pieces, not recognizable.

2. Major - Many medium sized pieces, some recognizable.

3. Significant - Some large pieces, many recognizable.

4. Minor - Relatively intact.

\- Unknown - Wreckage not recovered.

Fire Damage

1. Total - Major puddling.

2. Major - Burnthrough, some puddling.

3. Minor - Paint burn, sooting.

4. None - No post-crash fire.

\- Unknown - Wreckage not recovered.

Table D-1. A-10 Survivability Data From Class-A Mishaps (10 accidents)

AIRCRAFT SECTION	AIRCRAFT DAMAGE ***																							
	MECHANICAL BREAK-UP										M.A.	FIRE										F.A.	C.A.	RANKING
					**											**								
TAIL					*					**						*					**			
VERTICAL	3	2	1	-	4	2	3	-	2	-	2.43	-	3	-	-	4	-	2	-	3	4	3.20	2.82	5
CONE	-	-	1	-	4	2	-	-	3	-	2.50	-	-	-	-	4	-	2	-	3	4	3.25	2.87	4
EJ. SEAT	2	3	2	3	4	2	3	4	3	3	2.90	-	4	-	-	4	2	-	3	-	4	3.40	3.15	1
CANOPY RAIL	2	3	2	3	4	2	-	4	3	3	2.89	-	4	-	-	4	2	-	3	-	4	3.40	3.145	2
WING TIPS																								
LEFT	2	3	2	-	4	2	3	2	4	4	2.89	-	3	-	-	4	-	-	-	3	4	3.50	3.195	3
RIGHT	3	3	2	-	1	2	3	1	3	4	2.44	-	3	-	-	4	-	-	-	2	4	3.25	2.845	
COCKPIT	2	2	1	-	4	2	2	2	-	4	2.37	-	-	-	-	4	-	-	3	-	4	3.67	3.02	Insuf. Data
AVIONICS BAY	-	1	1	-	4	-	-	2	-	-	2.00	-	-	-	-	4	-	-	3	-	4	3.67	2.83	Insuf. Data

Impact Velocity Range 0 - 326 KIAS, 550 fps
Impact Angle Range 0° to 70° (nose down)

*	No Impact
**	No Fire
***	Each of the ten columns represents one accident.
M.A.	(Mechanical Average)
F.A.	(Fire Average)
C.A.	(Composite Mechanical and Fire Average)

Table D-2. F-16 Survivability Data From Class-A Mishaps (5 accidents)

AIRCRAFT SECTION	AIRCRAFT DAMAGE *					
	MECHANICAL BREAK-UP	M.A.	FIRE	F.A.	C.A.	RANKING
TAIL						
VERTICAL	4 4 4 4 4	4.0	4 4 4 3 4	3.8	3.9	2
CONE	4 4 3 3 4	3.6	4 4 4 3 4	3.8	3.7	3
EJ. SEAT	4 4 4 4 4	4.0	4 4 4 4 4	4.0	4.0	1
CANOPY RAIL	3 1 2 2 2	2.0	3 4 3 2	3.0	2.5	5/6
WING TIPS						
LEFT	4 4 4 3 3	3.6	4 4 4 3 3	3.6	3.6	4
RIGHT	4 4 4 3 4	3.8	4 4 4 3 3	3.6	3.7	
COCKPIT	3 1 2 2 2	2.0	3 3 3 2 3	2.8	2.4	7
AVIONICS BAY	3 1 2 2 2	2.0	3 4 3 2 3	3.0	2.5	5/6

Impact Velocity Range 0 - 250 KIAS, 500 fps

Impact Angle Range 0° to 25° Nose Down

* Each of the five columns represents one accident.

M.A. (Mechanical Average)

F.A. (Fire Average)

C.A. (Composite Mechanical and Fire Average)

CONCLUSIONS FROM F-16 DATA

1. The ejection seat is an excellent location for a semi-protected fly-away memory pack, however, use of this location for the CSFDR system memory module violates the RFP ground rules for Configurations I and III.

2. The vertical tail section is an excellent location and is a recommended location for the CSMU.

3. The tail cone and wing tips are also excellent locations for the CSMU and are considered as good alternatives to the vertical tail section.

4. The canopy rail, cockpit, and avionics bay are unacceptable locations for the CSMU.

5. The avionics bay is acceptable as a location for the non-survivable data compression/data processing functions.

CONCLUSIONS FROM A-10 DATA

1. No section of the A-10 aircraft is immune from significant mechanical or fire damage.

2. Both the ejection seat and canopy rail are good locations for a semi-protected fly-away memory pack in terms of survivability. However, this location is discouraged for two reasons:

   a. Violates ground rules for Configurations I and III.

   b. The ejection ratio for the A-10 is far too low to permit this location to be used for semi-survivable modules while still satisfying 90% survivability.

3. The wing tips are a good location for the CSMU.

4. The vertical tail and tail cone sections are reasonable alternatives to the wing tips.

5. The avionics bay is acceptable as a location for the non-survivable data compression/data processing functions.

COMPOSITE CONCLUSIONS

For the preferred installation locations, tail sections and wing tips, the CSMU must survive impact velocities up to 550 fps for impact angles up to 70° nose down.

SUMMARY OF ACCIDENT DATA FOR 221 A/F/T CLASS-A MISHAPS FROM 1976 TO DATE

The aircraft type, number of accidents, dollar value range of the destroyed aircraft, dollar value average of the destroyed aircraft, and ejection ratio are shown in table D-3. A composite average for all A/F/T aircraft is also included. (The ejection ratio is the number of times the crew members ejected divided by the number of times the aircraft impacted the surface in an out-of-control situation.)

CONCLUSIONS FROM A/F/T MISHAPS (1976 TO DATE)

1. Except for the F-16 aircraft, the ejection ratios are not good enough to consider the ejection seat or canopy as a location for a semi-survivable module under the single CSMU concept. These locations do have value, however, for the multiple memory concept.

The ejection ratio for all A/F/T Class-A mishaps ranges from 41.1% to 100%, with the composite average computed to be about 66.9%. The A-10/F-15/F-16 composite is computed to be 59.3% at this time.

2. The dollar value of Class-A mishaps ranges from 0.167M to 15.4M, with the composite average computed to be 4.8M. The A-10/F-15/F-16 mishaps range from 2.6M to 12.7M, and average out to be 9.3M per Class-A mishap.

5. The test sequence used to simulate a crash for commercial recorders is also valid for A/F/T aircraft. The sequence is:

impact
penetration
static crush
fire
water

In spite of the fact that USAF operates over land more than the USN, the water test is required because a significant number of USAF mishaps resulted in water-submerged aircraft. The humidity test is not critical and could be made a part of the environmental qualification test or part of the crash survivability test.

Table D-3. A/F/T Class-A Mishap Summary

USAF AIRCRAFT TYPE*	NUMBER OF CLASS-A MISHAPS REVIEWED	DOLLAR VALUE RANGE OF DESTRUCTION (M)	AVERAGE DOLLAR VALUE OF DESTRUCTION (M)	CREW EJECTION RATIO (%)
A-7	24	2.6 - 3.69	3.1	75.0
A-10	15	2.6 - 7.4	5.5	41.1
F-4	77	1.6 - 12.1**	3.0	66.2
F-5	6	.69 - 3.9	2.9	66.7
F-15	17	11.3 - 11.9	11.7	69.2
F-16	5	12.6 - 12.7	12.63	80.0
QF-102	1	0.95	0.95	100.0
F-105	15	1.3 - 6.1	3.2	86.7
F-106	10	4.7 - 5.9	5.1	60.0
F-111	22	1.8 - 15.4	11.8	63.6
T-37	5	.167 - .284	.191	60.0
T-38	24	.219 - 1.60	1.02	66.7
COMPOSITE A/F/T	221	.167 - 15.4	4.8	66.9
A-10/F-15/F-16 COMPOSITE	37	2.6 - 12.7	9.3	59.3

* Additional aircraft types reviewed but not shown on this table are: KA-3, F-101, A-4, A-37, F-104, and F-100.

** Contained expensive weapons.

APPENDIX E

Impact Testing

The following short appendix describes the preliminary impact shock testing which was undertaken to verify the mechanical design worthiness of our CPM. The test setup, procedures, and results are briefly described.

PRELIMINARY IMPACT TESTING

Some preliminary Impact Testing has been completed in LSI's Environmental Test Lab. A quick release package drop tester was used to drop a 6" cube, 21 lbm. aluminum block from heights varying from 32" to 9'. The drop weight was instrumented with an Endevco accelerometer to measure the resulting shock pulse and its duration. The aluminum block was fixtured with a guide rail and bracket, so that the block would impact in a flush and repeatable manner.

The testing was designed to vary the drop height and impact media in hopes of attaining shock pulses in excess of 1000 G. and 5 msec. duration. In addition, a simulated memory module of similar construction to the CSFDR system Crash Protected Memory (CPM) was mounted to the block, in order to verify its impact shock worthiness. The module was shim mounted along its two short edges to simulate a worst case condition (see sketch).

Approximately 70 drops were completed and the simulated CPM substrate survived without suffering any noticeable damage. The impact media included Dupont Aduprene, G.E. Elastomeric pads, hard rubber pads, ½" plywood, molded lead cone shaped billets, and various combinations of the above. The shock pulse amplitude and duration was measured with an Endevco shock amplifier and digital display. In addition, the shock pulse shapes were captured on a Tektronics oscilloscope. The shock pulses were consistently initial peak sawtooth pulses and the fixturing resulted in attaining somewhat repeatable results.

The resulting shock pulses ranged in magnitude from 150 to 4580 G. peak with time durations ranging from .2 to 13.6 milliseconds. The majority of shock pulses had too short of a time duration, with most falling under 3 milliseconds in length. Some of the more noteworthy impact shock pulses are listed below.

2130 G.	5.3 msec.
2190 G.	3.34 msec.
1900 G.	6.0 msec.
1800 G.	1.5 msec.
200 G.	11.4 msec.
4580 G.	.32 msec.

This testing leaves no doubt that the CPM design will be structurally shock worthy of the CSFDR system impact shock requirements.

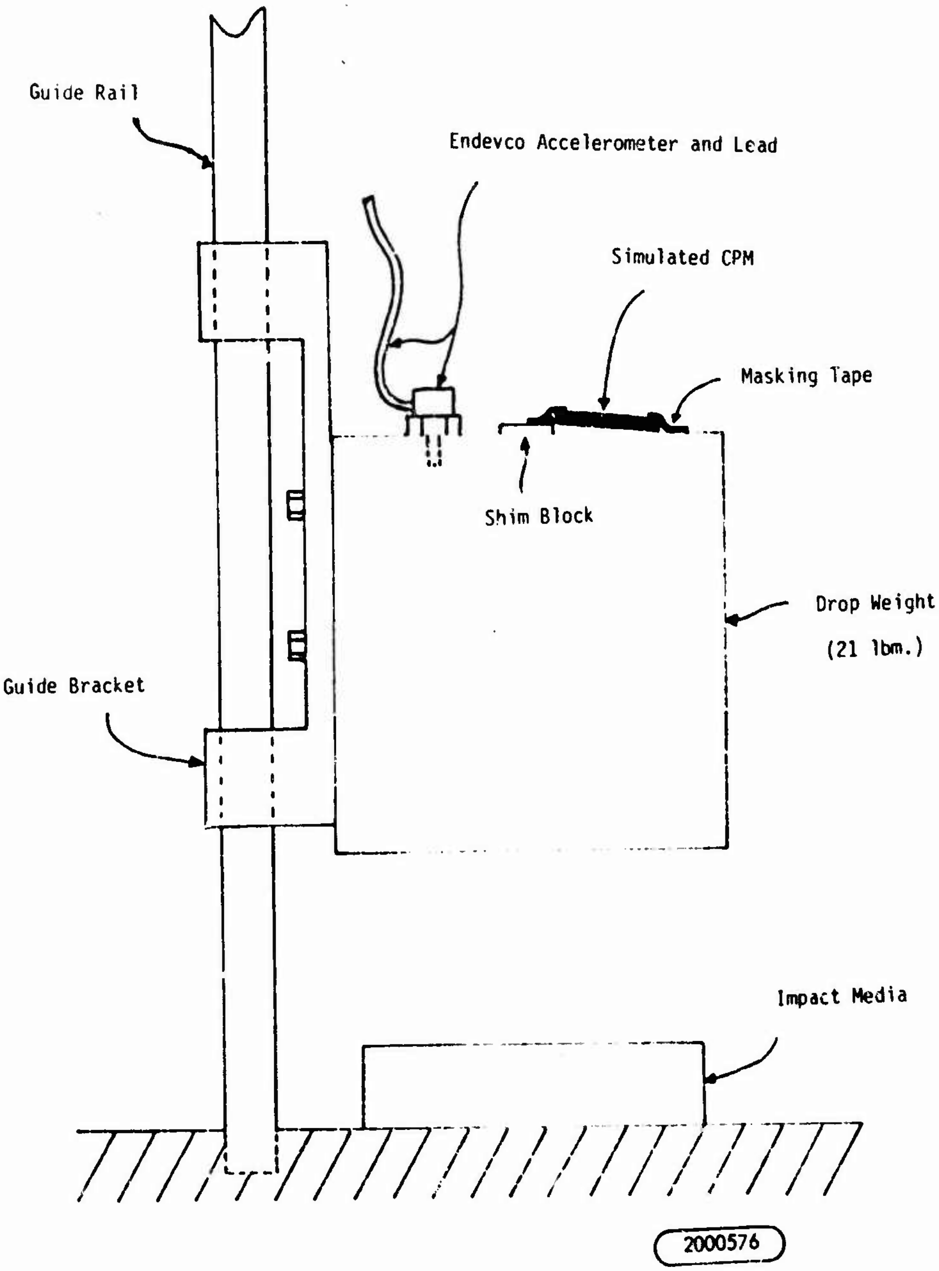


Figure E-1. Sketch of Impact Test Fixtu e

Appendix F

Cross Reference of Military Directives Related to Aircraft Accident Safety Investigation

Applicable Directive

	Air Force ANG USAFR	Navy, USNR, Marine Corps USMCR	Army ARNG USAR	Coast-Guard
Aircraft Accidents	AFR 127-4 AFM 87-18 AFM 93-1 AFR 160-109 AFM 127-1 AFR 127-2 AFR 190-20	OPNAV INST 3750.6	AR 385-40 AR 95-5	Chapter 2B of CG 405
Missing Aircraft	AFR 127-4 AFR 23-19 AFM 55-8 AFM 30-25 AFR 127-2	OPNAV INST 3750.6	AR 385-40 AR 95-5	Chapter 2B of CG-405
Investigating Boards	AFR 11-1 AFR 35-67 AFR 110-14 AFR 127-4 AFR 62-5 AFM 127-2	JAG Manual OPNAV INST 3750.6	AR 385-40 AR 15-6 AR 95-5	CG Supplement to the Manual for Courts-Martial CG-241
Accident Claims	AFM 112-1 AFR 127-4 AFM 127-1	JAG Manual	AR 27-20	COMDTINST 5890.4 series
News Releases	AFR 190-10 AFR 205-1 AFM 30-25 AFR 127-4 AFM 127-1	NAVSO P-1035	AR 340-16 AR 360-5 AR 340-17 AR 360-80	CG-247
Flying Violations	AFR 62-5 AFR 127-4 AFM 127-1 AFR 127-2	OPNAV INST 3760.1	AR 95-12	CG-333

Air Traffic Control & Flight Rules	AFR 55-19 AFR 86 series AFM 60-5	OPNAV INST 3710.7	AR 95-1 AR 95-9 AR 95-37 NGR 95 TM 1/2557-26 29 30	CG-333

NTSB Organizational/Procedural Regulations

CODE	PART NUMBER	TITLE
49 USC 1801		Transportation Safety Act of 1974
	800	Statement of Organization and Functions of the Board and Delegations of Authority
	801	Public Availability of Information
	821	Rules of Practice in Air Safety Enforcement Proceedings
	830	Rules Pertaining to the Notification and Reporting of Aircraft Accidents, Incidents, and Overdue Aircraft, and Preservation of Aircraft Wreckage, Mail, Cargo, and Records
	831	Rules of Practice in Aircraft Accident/Incident Investigations
	835	Testimony of Board Accident Investigators

APPENDIX G

TI-59 LCC Model

TI 59 HANDHELD CALCULATOR
LCC MODEL
USER'S HANDBOOK

LAVERN J. MENKER

MAY 1978

ASD/AFALD LCC/DTC ADVISORY GROUP
STUDIES AND APPLICATIONS DIVISION
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COMPTROLLER
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FOREWORD

There is a need to provide engineers, decisionmakers and analysts with a do-it-yourself, quick reaction capability to make life cycle cost assessments. Currently assessing the life cycle cost implications of design and support alternatives is both time consuming and costly. This document presents a life cycle cost model programmed for a TI 59 handheld calculator. By using this analysis tool, personnel will be able to assess the life cycle cost implications of particular alternatives easily and quickly. This model can be used by anyone equipped with a TI-59 handheld programmable calculator.

I have reviewed and approved this report.

CHARLES W. ADAMS
Director of Cost Analysis
Comptroller

I. INTRODUCTION

The introduction of handheld programmable calculators has provided a tool to make life cycle cost assessments of design and support options a way of life. The key advantage of this tool is that it drastically shortens the feedback loop for information on life cycle cost impacts. Besides providing timely support, another important advantage of this tool is that it allows life cycle cost assessments to be generated by the persons who need them most. Handheld programmable calculators along with this user's guide should greatly improve communications among the different disciplines that are involved in designing, developing, acquiring and supporting lower life cycle cost equipments.

II. DESCRIPTION OF THE MODEL

The model is as complete as most computer life cycle cost models. However, significant memory capacity is saved by concentrating on a single item such as a line replaceable unit. This avoids the aggregation and control coding required in larger system models. Costs are printed or displayed, at the user's option, by cost element and by cost category (development, acquisition, operating and support and total life cycle cost).

To get started, a data set of 33 variables must be assembled. Of these, 4 are descriptive of the program environment, 19 are descriptive of the item or equipment and 8 are standard parameter values that are most appropriate for the item being considered. A simple data collection worksheet has been designed for this purpose (See Appendix 3). This worksheet contains the variable name, dimensions, a column for entering the value, storage location and variable definition.

After the data is collected, no more than five minutes are required to load the program, enter the full data set, and run the program. Life cycle cost can be calculated with the "touch of a button". If a printer is not used, a flag is set to display the estimates. The estimates are displayed in the order that they appear on the Life Cycle Cost Analysis Worksheet (See Appendix 2). By simply pushing the "R/S" key, the next estimate in this sequence will appear on the calculator display. Appendix 6 provides a sample output if the printer is used.

To change the data set, the only action required is to enter the new data in the same storage location as the data being replaced. By overriding the data in this manner the latest value will be used to complete the calculation. This feature can be used to perform sensitivity analyses of various data elements in a timely manner. A complete set of user's instructions is included in Appendix 1.

In addition to cost data, the model provides other data that may be useful to an analyst or decisionmaker. For example, the model computes and displays the quantity of spares required per base, the quantity of spares required at the depot level and the quantity of condemnation spares that are expected over the life of the program. This additional information provides meaningful visibility into the computation results. The model also computes the direct manhours per base per year and the direct manhours required at the depot per year. This information is useful in assessing the impact on manpower requirements. Direct manpower requirements can be converted to manpower equivalents using AFM 26-3 procedures. The model also computes the peak month direct shop manhours. This information can provide some insight into the base shop support equipment requirements. The depot direct manhour requirements can also provide some insight into the depot support equipment requirements. The model does not include these costs:

(1) training equipment and services.

(2) documentation.

(3) facilities.

(4) War Readiness Materiel.

APPENDIX 1

PROGRAM RECORD AND USER INSTRUCTIONS

TITLE LCC TI 59 MODEL PAGE 1 OF 4 **TI Programmable Program Record**

PROGRAMMER MENKER DATE 2/22/78

Partitioning (Op 17) Library Module NOT REQUIRED Printer OPTIONAL Cards (2 SIDES)

PROGRAM DESCRIPTION

The model is used to compare and discriminate among design alternatives where relative life cycle cost differences are the desired figure of merit. The significance of the results, therefore, is not based on the absolute value but on the magnitude of the cost differences between alternatives. The model also provides insights into manpower and support equipment requirements. Base and depot pipeline spare quantities are also computed.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Prepare to read 1st side of card		INV	2nd	Write	
2	Insert 1st side of card					1
3				CLR		
4	Prepare to read 2nd side of card		INV	2nd	Write	
5	Insert 2nd side of card					2
6	If no printer available set Flg 0		2nd	St Flg	0	0
7	Input data values 00 thru 32	DEVC	STO	00		
8	(Data value is entered for each	SYSI	STO	01		
9	variable shown in ENTER column)	SEC	STO	02		
10		M	STO	03		
11		AOH	STO	04		
12		POH	STO	05		
13		PIUP	STO	06		
14		UC	STO	07		
15		W	STO	08		
16		MTBF	STO	09		
17		NRTS	STO	10		
18		RTS	STO	11		

USER DEFINED KEYS	DATA REGISTERS		LABELS (Op 08)
A START	00 DEVC	10 NRTS	
B	01 SYSI	11 RTS	
C	02 SEC	12 COND	
D	03 M	13 PAMH	
E	04 AOH	14 RMH	
A'	05 POH	15 SMI	
B'	06 PIUP	16 SMH	
C'	07 UC	17 BCMH	
D'	08 W	18 BMH	
E'	09 MTBF	19 BMC	

FLAGS 0 1 2 3 4 5 6 7 8 9

TITLE LCC TI 59 MODEL PAGE 2 OF 4

TI Programmable Program Record

PROGRAMMER DATE

Partitioning (Op 17) Library Module Printer Cards

PROGRAM DESCRIPTION

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
19		COND	STO	12		
20		PAMH	STO	13		
21		RMH	STO	14		
22		SMI	STO	15		
23		SMH	STO	16		
24		BCMH	STO	17		
25		BMH	STO	18		
26		BMC	STO	19		
27		BRCT	STO	20		
28		DMH	STO	21		
29		DMC	STO	22		
30		PA	STO	23		
31		PP	STO	24		
32		PCB	STO	25		
33		OST	STO	26		
34		DRCT	STO	27		
35		BLR	STO	28		
36		DLR	STO	29		

USER DEFINED KEYS	DATA REGISTERS		LABELS (Op 08)
A	20 BRCT	30 PSC	
B	21 DMH	31 SA	
C	22 DMC	32 IMC	
D	23 PA	33 RMC	
E	24 PP	34 BSC	
A'	25 PCB	35 BSTK	
B'	26 OST	36 DSC	
C'	27 DRCT	37 DSTK	
D'	28 BLR	38 SIC	
E'	29 DLR	39 TPC	

FLAGS 0 1 2 3 4 5 6 7 8 9

TITLE LCC TI 59 MODEL PAGE 3 OF 4

TI Programmable Program Record

PROGRAMMER ______ DATE ______

Partitioning (Op 17) ______ Library Module ______ Printer ______ Cards ______

PROGRAM DESCRIPTION

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
37		PSC	STO	30		
38		SA	STO	31		
39		IMC	STO	32		
40		RMC	STO	33		
41	If printer is attached begin execution		A			
	Prints out Memory Registers 00-57 showing					
	all inputs and outputs. Memory Registers					
	53-57 should be ignored as outputs since					
	they are internal working files.					
42	If printer is not attached begin execution		A			(00)
	and total development cost					
43	System Investment Cost		R/S			(01)
44	Support Equipment Cost		R/S			(02)
45	Base Spares Cost		R/S			(34)
46	Qty Spares per Base		R/S			(35)
47	Depot Spares Cost		R/S			(36)
48	Qty Depot Spares		R/S			(37)
49	Support Investment Cost		R/S			(38)

USER DEFINED KEYS	DATA REGISTERS		LABELS (Op 08)
A	40 BMHC	50 IMCC	
B	41 BMMH	51 TOC	
C	42 PMSH	52 LCC	
D	43 BMMC	53 WS_1	
E	44 DMHC	54 WS_2	
A'	45 DMMH	55 X Subroutine CE	
B'	46 DMMC	56 Fraction of X	
C'	47 SDTC	57 Integer of X	
D'	48 CSC	58	
E'	49 QCS	59	

FLAGS 0 1 2 3 4 5 6 7 8 9

TITLE LCC TI 59 MODEL PAGE 4 OF 4 TI Programmable

PROGRAMMER DATE **Program Record**

Partitioning (Op 17) Library Module Printer Cards

PROGRAM DESCRIPTION

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
50	Total Procurement Cost		R/S			(39)
51	Base Maintenance Manhour Cost		R/S			(40)
52	Direct Manhours per Base per Year		R/S			(41)
53	Peak Month Direct Shop Manhours		R/S			(42)
54	Base Maintenance Material Cost		R/S			(43)
55	Depot Maintenance Manhour Cost		R/S			(44)
56	Depot Direct Manhours per Year		R/S			(45)
57	Depot Maintenance Material Cost		R/S			(46)
58	Second Destination Transportation Cost		R/S			(47)
59	Condemnation Spares Cost		R/S			(48)
60	Quantity of Condemnation Spare for Life		R/S			(49)
	Cycle					
61	Inventory Management Cost		R/S			(50)
62	Total Ownership Cost		R/S			(51)
63	Life Cycle Cost		R/S			(52)

USER DEFINED KEYS	DATA REGISTERS		LABELS (Op 08)
A	0	0	
B	1	1	
C	2	2	
D	3	3	
E	4	4	
A'	5	5	
B'	6	6	
C'	7	7	
D'	8	8	
E'	9	9	

FLAGS 0 1 2 3 4 5 6 7 8 9

PROGRAM RECORD

```
000  76 LBL
001  11  A
002  43 RCL
003  11  11
004  65  ×
005  43 RCL
006  20  20
007  85  +
008  43 RCL
009  10  10
010  65  ×
011  43 RCL
012  26  26
013  95  =
014  42 STO
015  54  54
016  43 RCL
017  05  05
018  55  ÷
019  43 RCL
020  09  09
021  55  ÷
022  43 RCL
023  03  03
024  95  =
025  42 STO
026  53  53
027  43 RCL
028  53  53
029  65  ×
030  43 RCL
031  54  54
032  95  =
033  42 STO
034  35  35
035  43 RCL
036  35  35
037  34 ΓX
038  65  ×
039  01  1
040  93  .
041  05  5
042  95  =
043  44 SUM
044  35  35
045  43 RCL
046  35  35
047  71 SBR
048  24 CE
049  95  =
050  42 STO
```

```
051  35  35
052  53  (
053  43 RCL
054  17  17
055  85  +
056  43 RCL
057  11  11
058  65  ×
059  43 RCL
060  18  18
061  54  )
062  65  ×
063  43 RCL
064  53  53
065  95  =
066  42 STO
067  42  42
068  43 RCL
069  35  35
070  65  ×
071  43 RCL
072  03  03
073  65  ×
074  43 RCL
075  07  07
076  95  =
077  42 STO
078  34  34
079  43 RCL
080  53  53
081  65  ×
082  43 RCL
083  03  03
084  65  ×
085  43 RCL
086  10  10
087  65  ×
088  43 RCL
089  27  27
090  95  =
091  71 SBR
092  24 CE
093  95  =
094  42 STO
095  37  37
096  43 RCL
097  37  37
098  65  ×
099  43 RCL
100  07  07
```

```
101  95  =
102  42 STO
103  36  36
104  43 RCL
105  04  04
106  55  ÷
107  43 RCL
108  03  03
109  95  =
110  42 STO
111  53  53
112  43 RCL
113  04  04
114  55  ÷
115  43 RCL
116  09  09
117  95  =
118  42 STO
119  54  54
120  53  (
121  53  (
122  43 RCL
123  13  13
124  85  +
125  43 RCL
126  14  14
127  85  +
128  43 RCL
129  17  17
130  85  +
131  43 RCL
132  11  11
133  65  ×
134  43 RCL
135  18  18
136  54  )
137  55  ÷
138  43 RCL
139  09  09
140  95  =
141  42 STO
142  41  41
143  00  0
144  32 X:T
145  00  0
146  43 RCL
147  15  15
148  67  EQ
149  13  C
150  43 RCL
```

PROGRAM RECORD

```
151   16   16
152   55   ÷
153   43  RCL
154   15   15
155   95   =
156   44  SUM
157   41   41
158   76  LBL
159   13   C
160   43  RCL
161   53   53
162   49  PRD
163   41   41
164   43  RCL
165   41   41
166   65   ×
167   43  RCL
168   03   03
169   65   ×
170   43  RCL
171   06   06
172   65   ×
173   43  RCL
174   28   28
175   95   =
176   42  STO
177   40   40
178   43  RCL
179   54   54
180   65   ×
181   43  RCL
182   06   06
183   65   ×
184   43  RCL
185   11   11
186   65   ×
187   43  RCL
188   19   19
189   95   =
190   42  STO
191   43   43
192   43  RCL
193   54   54
194   65   ×
195   43  RCL
196   10   10
197   65   ×
198   43  RCL
199   21   21
200   95   =
```

```
201   42  STO
202   45   45
203   43  RCL
204   45   45
205   65   ×
206   43  RCL
207   06   06
208   65   ×
209   43  RCL
210   29   29
211   95   =
212   42  STO
213   44   44
214   43  RCL
215   06   06
216   49  PRD
217   54   54
218   43  RCL
219   54   54
220   65   ×
221   43  RCL
222   12   12
223   95   =
224   71  SBR
225   24  CE
226   95   =
227   42  STO
228   49   49
229   43  RCL
230   10   10
231   49  PRD
232   54   54
233   43  RCL
234   54   54
235   65   ×
236   43  RCL
237   22   22
238   95   =
239   42  STO
240   46   46
241   43  RCL
242   54   54
243   65   ×
244   02   2
245   93   .
246   07   7
247   65   ×
248   43  RCL
249   30   30
250   65   ×
```

```
251   43  RCL
252   08   08
253   95   =
254   42  STO
255   47   47
256   43  RCL
257   49   49
258   65   ×
259   43  RCL
260   07   07
261   95   =
262   42  STO
263   48   48
264   53   (
265   43  RCL
266   32   32
267   85   +
268   43  RCL
269   06   06
270   65   ×
271   43  RCL
272   33   33
273   54   )
274   65   ×
275   53   (
276   43  RCL
277   23   23
278   85   +
279   43  RCL
280   24   24
281   85   +
282   01   1
283   54   )
284   85   +
285   43  RCL
286   03   03
287   65   ×
288   43  RCL
289   31   31
290   65   ×
291   43  RCL
292   06   06
293   65   ×
294   53   (
295   43  RCL
296   23   23
297   85   +
298   43  RCL
299   25   25
300   85   +
```

PROGRAM RECORD

```
301  01    1
302  54    )
303  95    =
304  42  STO
305  50   50
306  43  RCL
307  02   02
308  85    +
309  43  RCL
310  34   34
311  85    +
312  43  RCL
313  36   36
314  95    =
315  42  STO
316  38   38
317  42  STO
318  39   39
319  42  STO
320  52   52
321  43  RCL
322  01   01
323  44  SUM
324  39   39
325  44  SUM
326  52   52
327  43  RCL
328  40   40
329  85    +
330  43  RCL
331  43   43
332  85    +
333  43  RCL
334  44   44
335  85    +
336  43  RCL
337  46   46
338  85    -
339  43  RCL
340  47   47
341  85    +
342  43  RCL
343  48   48
344  85    +
345  43  RCL
346  50   50
347  95    =
348  44  SUM
349  52   52
350  42  STO
351  51   51
352  43  RCL
353  00   00
354  44  SUM
355  52   52
356  22  INV
357  87  IFF
358  00   00
359  12    B
360  43  RCL
361  00   00
362  91  R/S
363  43  RCL
364  01   01
365  91  R/S
366  43  RCL
367  02   02
368  91  R/S
369  43  RCL
370  34   34
371  91  R/S
372  43  RCL
373  35   35
374  91  R/S
375  43  RCL
376  36   36
377  91  R/S
378  43  RCL
379  37   37
380  91  R/S
381  43  RCL
382  38   38
383  91  R/S
384  43  RCL
385  39   39
386  91  R/S
387  43  RCL
388  40   40
389  91  R/S
390  43  RCL
391  41   41
392  91  R/S
393  43  RCL
394  42   42
395  91  R/S
396  43  RCL
397  43   43
398  91  R/S
399  43  RCL
400  44   44
401  91  R/S
402  43  RCL
403  45   45
404  91  R/S
405  43  RCL
406  46   46
407  91  R/S
408  43  RCL
409  47   47
410  91  R/S
411  43  RCL
412  48   48
413  91  R/S
414  43  RCL
415  49   49
416  91  R/S
417  43  RCL
418  50   50
419  91  R/S
420  43  RCL
421  51   51
422  91  R/S
423  43  RCL
424  52   52
425  91  R/S
426  76  LBL
427  12    B
428  00    0
429  22  INV
430  90  LST
431  91  R/S
432  76  LBL
433  24   CE
434  53    (
435  42  STO
436  55   55
437  22  INV
438  59  INT
439  42  STO
440  56   56
441  43  RCL
442  55   55
443  59  INT
444  42  STO
445  57   57
446  00    0
447  32  X:T
448  00    0
449  43  RCL
450  56   56
451  67   EQ
452  14    D
453  01    1
454  76  LBL
455  14    D
456  85    +
457  43  RCL
458  57   57
459  54    )
460  92  RTN
```

APPENDIX 2

LIFE CYCLE COST ANALYSIS
WORKSHEET

LIFE CYCLE COST ANALYSIS WORKSHEET

DEVELOPMENT

TOTAL DEVELOPMENT COST = 00

PROCUREMENT

SYSTEM INVESTMENT = 01

SUPPORT INVESTMENT

SUPPORT EQUIPMENT = 02

BASE SPARES = 34

QTY PER BASE = 35

DEPOT SPARES = 36

QTY = 37

02 + 34 +36 = 38

TOTAL PROCUREMENT COST = 39

OWNERSHIP

BASE MAINTENANCE MANHOUR = 40

DIRECT MANHOURS PER BASE PER YEAR = 41

PEAK MONTH DIRECT SHOP MANHOURS = 42

BASE MAINTENANCE MATERIAL = 43

DEPOT MAINTENACE MANHOUR = 44

DIRECT MANHOURS PER YEAR = 45

DEPOT MAINTENANCE MATERIAL = 46

SECOND DESTINATION TRANSPORTATION = 47

CONDEMNATION SPARES = 48

QTY FOR LIFE CYCLE = 49

INVENTORY MANAGEMENT = 50

TOTAL OWNERSHIP COST = 40+43+44+46+47+48+50 = 51

LIFE CYCLE COST = 00 + 39 + 51 = 52

NOTES:

APPENDIX 3

DATA COLLECTION WORKSHEET
(INPUT PARAMETERS/VARIABLES)

DATA COLLECTION WORKSHEET
INPUT PARAMETER VARIABLES ITEM ____________

VARIABLE NAME	UNITS	VALUE	STORAGE LOCATION	DEFINITION
DEVC	$		00	Development Cost
SYS I	$		01	System Investment Cost
SEC	$		02	Support Equipment Cost
		PROGRAM DATA		
M	-		03	Number of Operating Bases
AOH	Hours		04	Average Annual Operating Hours
POH	Hours		05	Peak Month Operating Hours
PIUP	Years		06	Projected Inventory Usage Period
		ITEM DATA		
UC	$		07	Unit Cost of Item as a Spare
W	Lbs		08	Weight of Item
MTBF	Hours		09	Mean Time Between Failure
NRTS	Fraction		10	Fraction of Failures Not Reparable At Base
RTS	Fraction		11	Fraction of Failures Reparable at Base
COND	Fraction		12	Fraction of Failures where Item is Condemned
PAMH	Hours		13	Preparation and Access Manhours
RMH	Hours		14	Replacement Manhours
SMI	Hours		15	Scheduled Maintenance Interval
SMH	Hours		16	Scheduled Maintenance Manhours
BCMH	Hours		17	Bench Check Manhours
BMH	Hours		18	Base Maintenance Manhours
BMC	$		19	Base Direct Material Cost per Failure
BRCT	Months	(.2 or .33)	20	Base Repair Cycle Time (Use .2 for Avionics or .33 for all other non-modular equipment).
DMH	Hours		21	Depot Maintenance Manhours
DMC	$		22	Depot Direct Material Cost per Failure
PA	-		23	New Reparable Items ("P" coded)
PP	-		24	New Consumable Items ("P" coded)
PCB	-		25	New Consumable Items ("p" coded) stocked at base level

STANDARD PARAMETER VALUES

PARAMETER	UNITS	VALUE*	STORAGE LOCATION	DEFINITION
OST	Months	0.4	26	Order and Shipping Time
DRCT	Months	1.57	27	Depot Repair Cycle Time
BLR	$	24.21	28	Base Labor Rate per Manhour
DLR	$	38.27	29	Depot Labor Rate per Manhour
PSC	$	0.73	30	Packing & Shipping Cost per Lb.
SA	$	8.39	31	Base Supply Inventory Management Cost per Item per Year
IMC	$	1200.00	32	Initial Inventory Management Cost per Item
RMC	$	150.00	33	Recurring Inventory Management Cost per Item per Year

*These are 1980 average values covering all commodities. The values used should be the most appropriate for the item being considered.

APPENDIX 4

DATA ELEMENT DEFINITIONS

NOTE: (I) = PROGRAM OR ITEM INPUT VARIABLE
(S) = STANDARD VALUE
(C) = COMPUTED VALUE

DATA ELEMENT DEFINITIONS

AOH - Average annual operating hours expected over the program inventory usage period. (I)

BCMH - Average manhours to perform a shop bench check, screening, and fault verification of an item prior to initiating repair action or condemning the item. (I)

BLR - Base Labor Rate including direct labor and indirect labor and material costs. (S)

BMC - Average direct material cost to repair an item at base level including direct material cost of repairing lower level assemblies. (I)

BMH - Average manhours to perform intermediate level (base shop) maintenance on a removed item including fault isolation, repair, and verification. (I)

BMHC - The cost of base maintenance manhours (direct and indirect) over the life cycle. (C)

BMMC - Cost of material to repair failed units at the base. (C)

BMMH - Direct labor manhours per year to accomplish depot-level repairs. (C)

BRCT - Average Base Repair Cycle Time in months. The elapsed time for an item repaired at the base from removal of the failed item until it is returned to base serviceable stock (less time awaiting parts). For items of a "black box" variety (e.g., avionics LRUs), the repair of which normally consists of removal and replacement of "plug-in" components (SRUs), BRCT = 0.20 months (6 days). For other, nonmodular FLUs, BRCT = 0.33 months (10 days). (I)

BSC - The cost to provide base repair pipeline spares for all bases. (C)

BSTK - The number of spares required for each base to fill the base repair pipeline including a safety stock to protect against random fluctuations in demand. (C)

COND - Fraction of failed items expected to result in condemnation. NOTE: RTS + NRTS + COND = 1 only if all condemnations occur at base level. (I)

CSC - The cost of spares required over the life cycle to replace condemned items. (C)

DEVC - All nonrecurring and recurring engineering, tooling, manufacturing (e.g., breadboards, prototypes, flight vehicles, DT&E items, IOT&E items and spares to support RDT&E efforts), purchased equipment, quality control, allowance for changes, General and Administrative, and Profit associated with RDT&E funded efforts over the life cycle for the appropriate Work Breakdown Structure (WBS) elements. (I)

DLR - Depot Labor Rate including direct labor and indirect labor and material costs. (S)

DMC - Average direct material cost to repair an item at depot level including direct material cost of repairing lower level assemblies. (I)

DMH - Average manhours to perform depot-level maintenance on a removed item including fault isolation, repair, and verification. (I)

DMHC - The cost to accomplish depot-level maintenance of failed items over the program inventory usage period. (C)

DMMC - The cost of material to repair failed items at the depot level. (C)

DMMH - The direct labor manhours per year to accomplish depot-level repairs. (C)

DRCT - Average depot repair cycle time in months. The elapsed time for a NRTS item from removal of the failed item until it is made available to depot serviceable stock. (S)

DSC - The cost to provide depot repair pipeline spares. (C)

DSTK - The number of spares required to fill the depot repair pipeline. (C)

IMC - Initial management cost to introduce a new line item of supply (assembly or piece part) into the Government inventory. (S)

IMMC - The cost to enter new line items of supply into the Government inventory and to manage these over the life of the equipment, and the cost of base level supply management of these new items. (C)

LCC - The total cost to the Government for an item over its full life, including the cost of development, procurement and ownership. (C) .

M - Number of intermediate repair locations (operating bases). (I)

MTBF - Mean Time Between Failures in operating hours of the item in the operational environment. This model assumes that all failed items are removed for repair. (I)

NRTS - Fraction of removed items expected to be returned to the depot for repair. (I)

OST - Average Order and Shipping Time in months. The elapsed time between the initiation of a request for a serviceable item and its receipt by the requesting activity. (S)

PA - Number of new "P" coded reparable assemblies within the item. (I)

PAMH - Average manhours expended on the installed equipment for preparation and assessment to the item; for example, jacking, unbuttoning, removal of other units and hook up of support equipment. (I)

PCB - Number of new "P" coded consumable items within this item that will be stocked at base level. (I)

PIUP - Program Inventory Usage Period. Operational service life in years. (I)

PMSH - Direct intermediate level (base shop) manhours for the peak month. (C)

POH - Expected operating hours for one month during the peak usage period. (I)

PP - Number of new "P" coded consumable items within this item. (I)

PSC - Average Packing and Shipping Cost. (S)

QCS - Quantity of spares required over the life cycle to replace condemned items. (C)

RMH - Average manhours to fault isolate, remove, and replace the item on the installed equipment and verify restoration of the equipment to operational status. (I)

RMC - Recurring management cost to maintain a line item of supply (assembly or piece part) in the wholesale inventory system. (S)

RTS - Fraction of failed items expected to be repaired at base level. (I)

SA - Annual base supply line item inventory management cost. (S)

SDTC - The cost of roundtrip transportation of items sent to the depot for repair. (C)

SEC - The cost of equipment, vehicles and tools required to maintain and care for the item or portions of the item while not directly engaged in the performance of its mission including all effort associated with design development and production of the support equipment. (I)

SIC - The cost of support equipment, base spares and depot spares. (C)

SMH - Average manhours to perform a scheduled, periodic, or phased inspection on the item. (I)

SMI - Operating hour intervals between scheduled, periodic, or phased inspections on the item. (I)

SYSI - The cost of acquiring the production funded items including engineering, tooling, manufacturing, subcontract, purchased parts and equipment, quality control, General and Administrative (G&A) and Profit. (I)

t - Pipeline time in months computed by the following equation: (C)

$$t = (RTS)(BRCT) + (NRTS)(OST)$$

TOC - The total cost of ownership including, base maintenance manhour and material costs, depot maintenance manhour and material cost, second destination transportation costs, condemnation spares costs and inventory management costs. (C)

TPC - The total cost of system investment and support investment. (C)

UC - Expected unit cost of the item at the time of initial spares provisioning. (I)

W - Item unit weight in pounds. (I)

APPENDIX 5

LCC MODEL
EQUATIONS

1. BASE SPARES (BSTK)

$$BSTK = \left[\frac{POH}{(M)(MTBF)}\right] t + 1.5\sqrt{\left[\frac{POH}{(M)(MTBF)}\right] t}$$

where t = Pipeline time in months
t = (RTS)(BRCT) + (NRTS)(OST)

This equation computes the number of spares required for <u>each</u> base to fill the base repair pipeline including a safety stock to protect against random fluctuations in demand. The computation considers the mean demand rate per base and a coefficient which represents a 95 percent probability of satisfying a demand where the distribution of probabilities of a demand, given a mean demand, is Poisson.

NOTE: The program integerizes the fractional spares quantity to the next higher integer value.

2. BASE SPARES COST (BSC)

$$BSC = (M)(BSTK)(UC)$$

This equation computes the cost to provide base repair pipeline spares for all bases.

3. DEPOT SPARES (DSTK)

$$DSTK = \frac{(POH)(NRTS)(DRCT)}{MTBF}$$

This equation computes the number of spares required to fill the depot repair pipeline.

NOTE: The program integerizes the fractional spares quantity.

4. DEPOT SPARES COST (DSC)

$$DSC = (DSTK)(UC)$$

This equation computes the cost to provide depot repair pipeline spares.

5. BASE MAINTENANCE MANHOURS (BMMH)

$$BMMH = \frac{(AOH)}{(M)(MTBF)}\left[PAMH + RMH + BCMH + (RTS)(BMH)\right] + \frac{(AOH)(SMH)}{(M)(SMI)}$$

The first term computes the direct base maintenance manhours per base per year including preparation and access time, removal and replacement time, bench check time and the repair time for those items repaired in the base intermediate shop.

The second term computes the labor manhours to perform scheduled maintenance per base per year. This information can provide insight into base manpower requirements.

6. BASE MAINTENANCE MANHOUR COST (BMHC)

$$\text{BMHC} = (\text{BMMH})(\text{M})(\text{PIUP})(\text{BLR})$$

This equation computes the cost of base maintenance manhours over the life cycle.

7. PEAK DIRECT BASE MAINTENANCE SHOP MANHOURS (PMSH)

$$\text{PMSH} = \frac{(\text{POH})}{(\text{M})(\text{MTBF})}\left[(\text{BCMH}) + (\text{RTS})(\text{BMH})\right]$$

This equation computes the direct intermediate shop manhours for the peak month. This information can provide insight into support equipment utilization.

8. BASE MAINTENANCE MATERIAL COST (BMMC)

$$\text{BMMC} = \frac{(\text{AOH})(\text{PIUP})(\text{RTS})(\text{BMC})}{(\text{MTBF})}$$

This equation computes the cost of material to repair failed items at the base.

9. DEPOT MAINTENANCE MANHOURS (DMMH)

$$\text{DMMH} = \frac{(\text{AOH})(\text{NRTS})(\text{DMH})}{(\text{MTBF})}$$

This equation computes the direct labor manhours per year to accomplish depot-level repairs. This information can provide insight into depot manpower and depot support equipment requirements.

10. DEPOT MAINTENANCE MANHOUR COST (DMHC)

$$\text{DMHC} = (\text{DMMH})(\text{PIUP})(\text{DLR})$$

This equation computes the cost to accomplish depot-level maintenance of failed items over the life cycle.

11. DEPOT MAINTENANCE MATERIAL COST (DMMC)

$$DMMC = \frac{(AOH)(PIUP)(NRTS)(DMC)}{MTBF}$$

This equation computes the cost of material to repair failed items at the depot level.

12. SECOND DESTINATION TRANSPORTATION COST (SDTC)

$$SDTC = \frac{(AOH)(PIUP)}{MTBF} \left[2\ (NRTS) \right] (PSC)(1.35)(W)$$

This equation computes the cost of roundtrip transportation of items sent to the depot for repair. The 1.35 factor is the ratio of packed to unpacked weight.

13. CONDEMNATION SPARES (QCS)

$$QCS = \frac{(AOH)(PIUP)(COND)}{MTBF}$$

This equation computes the quantity of spares required over the life cycle to replace condemned items.

NOTE: The program integerizes the fractional spares quantity.

14. CONDEMNATION SPARES COST (CSC)

$$CSC = (QCS)(UC)$$

This equation computes the cost of spares required over the life cycle to replace condemned items.

15. INVENTORY MANAGEMENT COST (IMCC)

$$IMCC = \left[IMC + (PIUP)(RMC) \right] (PA + PP + 1) + (M)(SA)(PIUP)(PA + PCB + 1)$$

The first term computes the cost to enter new line items of supply into the Government inventory and to manage them over the life of the equipment.

The second term computes the cost of base level supply management of these items.

APPENDIX 6

SAMPLE OUTPUT

```
 10000.           00
100000.           01
  1000.           02
    10.           03
 10000.           04
  1000.           05
    10.           06
   100.           07
    10.           08
   500.           09
     0.8          10
     0.2          11
     0.1          12
     0.5          13
     1.           14
   250.           15
    10.           16
     0.1          17
     1.           18
    20.           19
     0.3          20
    10.           21
    40.           22
     1.           23
    10.           24
     0.           25
     0.5          26
     2.           27
    15.           28
    25.           29
     1.           30
    50.           31
    50.           32
   100.           33
  1000.           34
     1.           35
   400.           36
     4.           37
  2400.           38
102400.           39
 65400.           40
    43.6          41
     0.06         42
   800.           43
 40000.           44
   160.           45
  6400.           46
  4320.           47
  2000.           48
    20.           49
 22600.           50
141520.           51
253920.           52
  1000.           53
   160.           54
    20.           55
     0.           56
    20.           57
```

APPENDIX H

CSFDR SYSTEM LCC

Input Parameters

Table H-1

Input Parameters for Configuration I

VARIABLE NAME	STOR. LOC.	DPU LRU	DPU SRU(AVG.)	CSMU
DEVC	00	2,382,800		
SYS I	01	84,010,900	(All DEVC,SYSI,SEC costs inputted under DPU LRU)	
SEC	02			
M	03	68	68	68
AOH	04	945,000	945,000	945,000
POH	05	94,500	94,500	94,500
PIUP	06	20	20	20
UC*	07			
W	08	8.4	0.5	2.8
MTBF	09	5,260	48,648	63,580
NRTS	10	.05	1.0	1.0
RTS	11	.95	0	0
COND	12	0	0	0
PAMH	13	0	0	0
RMH	14	1.0	0	1.0
SMI	15	0	0	0
SMH	16	0	0	0
BCMH	17	1.0	0	1.0
BMH	18	2	0	0
BMC	19	0	0	0
BRCT	20	.2	.2	.2
DMH	21	5	11	11
DMC	22	0	150	200
PA	23	9	9	2
PP	24	0	18	5
PCB	25	0	0	0

*Company Proprietary

Table H-2

Input Parameters for Configuration II

VARIABLE NAME	STOR. LOC.	DPU LRU	DPU SRU(AVG.)	CSMU
DEVC	00	2,159,600		
SYS I	01	72,349,400	(All DEVC,SYSI,SEC costs inputted under DPU LRU)	
SEC	02			
M	03	68	68	68
AOH	04	945,000	945,000	945,000
POH	05	94,500	94,500	94,500
PIUP	06	20	20	20
UC*	07			
W	08	7.6	0.5	2.4
MTBF	09	5,580	45,714	89,000
NRTS	10	.05	1.0	1.0
RTS	11	.95	0	0
COND	12	0	0	0
PAMH	13	0	0	0
RMH	14	1.0	0	0
SMI	15	0	0	0
SMH	16	0	0	0
BCMH	17	1.0	0	0
BMH	18	2.0	0	0
BMC	19	0	0	0
BRCT	20	.2	.2	.2
DMH	21	5.0	11.0	11.0
DMC	22	0	150	200
PA	23	8	8	2
PP	24	0	18	5
PCB	25	0	0	0

*Company Proprietary

Table H-3

Input Parameters for Configuration III

VARIABLE NAME	STOR. LOC.	DPU LRU	DPU SRU(AVG.)	CSMU	MSU
DEVC	00	(All DEVC,SYSI,SEC costs inputted under MSU)			2,899,200
SYS I	01				98,572,600[1]
SEC	02				
M	03	68	68	68	68
AOH	04	945,000	945,000	945,000	189,000[2]
POH	05	94,500	94,500	94,500	18,900[3]
PIUP	06	20	20	20	20
UC*	07				
W	08	8.4	0.5	2.8	5.0
MTBF	09	5,260	48,648	63,580	3,400
NRTS	10	.05	1.0	1.0	1.0
RTS	11	.95	0	0	0
COND	12	0	0	0	0
PAMH	13	0	0	0	0
RMH	14	1.0	0	1.0	1.0
SMI	15	0	0	0	12.5
SMH	16	0	0	0	.25
BCMH	17	1.0	0	1.0	0
BMH	18	2	0	0	0
BMC	19	0	0	0	0
BRCT	20	.2	.2	.2	0
DMH	21	5	11	11	.2
DMC	22	0	150	200	11
PA	23	9	9	2	200
PP	24	0	18	5	2
PCB	25	0	0	0	5
					0

*Company Proprietary

[1] 127,745,700 if all aircraft have Configuration III.

[2] 945,000 if all aircraft have Configuration III.

[3] 94,500 if all aircraft have Configuration III.