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Fault Isolation in Environmental Control Systems of Commercial Transports

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1. SCOPE:

This SAE Aerospace Information Report (AIR) outlines concepts for the design and use of fault isolation equipment that have general application. The specific focus is on fault isolation of environmental control systems (ECS) in commercial transports. Presented are general fault isolation purposes, design principles, and demonstration of compliance criteria. These are followed by three design examples to aid in understanding the design principles. Future trends in built-in-test-equipment (BITE) design are discussed, some of which represent concepts already being implemented on new equipment.

1.1 Purpose:

This AIR provides a practical guide for the design and use of fault isolation systems for the ECS in commercial transports.

Airframe manufacturers may use this AIR for guidance in developing practical, efficient, and workable ECS fault isolation equipment. Equipment suppliers may use this AIR for guidance concerning their role with airframe manufacturers in the development and with the operators in the use of effective ECS fault isolation equipment. Operators may use this document to write future ECS fault isolation specifications against which the performance of the delivered system can be measured quantitatively. They may also obtain guidance for making more effective use of existing systems.

2. REFERENCES:

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Douglas Aircraft Company, Flight Development Group, "Finding Faults with FEFI". DC Flight Approach, Second Quarter 1970

Hamilton Standard, "Hamilton Standard Guidelines for Airborne Integrated Data Systems", Report HSPC 70E20, 1970

Hawkins, Capt. F. H. and Vermeulen, H. C., "Aircraft Integrated Data Systems - a Review of Their History and Current Status". Shell Aviation News, No. 401-1971

2.1 Definitions:

AIRCRAFT INTEGRATED DATA SYSTEM (AIDS): A term (adopted by ARINC) in general use for airborne recording systems that include acquisition and signal conditioning.

AUXILIARY POWER UNIT (APU): An on-aircraft unit, usually a gas turbine, that supplies an auxiliary air source for the ECS and auxiliary electrical power generation.

AUTOMATIC TEST EQUIPMENT (ATE): General purpose, usually computerized test equipment that when connected to the unit under test through the necessary interface, automatically performs acceptance testing.

BUILT-IN-TEST (BIT): Tests performed by the system upon itself for the purpose of detecting faults, annunciating fault conditions, isolating faults, and possibly taking corrective action.

BUILT-IN-TEST-EQUIPMENT (BITE): That part of a system, usually sensors, electronics and display, that are used as a tool to supplement maintenance procedures for isolating system faults.

CENTRALIZED FAULT DISPLAY INTERFACE UNIT (CFDIU): A unit (part of the CFDS described by ARINC 604) which interfaces aircraft operational subsystems to the display unit (CFDU).

CENTRALIZED FAULT DISPLAY SYSTEM (CFDS): A system described by ARINC 604 that uses a centralized fault command/display terminal to retrieve and display subsystem produced BITE display data.

CENTRALIZED FAULT DISPLAY UNIT (CFDU): A unit (part of the CFDS described by ARINC 604) which provides the actual display interface for the maintenance crew.

ELECTRICALLY ALTERABLE READ-ONLY MEMORY (EAROM): Nonvolatile computer memory devices whose memory content can only be changed by application of an electrical signal.

ELECTROMAGNETIC INTERFERENCE (EMI): Electromagnetic phenomena which, either directly or indirectly, can contribute to a degradation in performance of an electronic receiver or system.

2.1 (Continued):

ENVIRONMENTAL CONTROL SYSTEM (ECS): That aircraft equipment responsible for maintaining proper cabin ventilation airflow, temperature, and pressure. It usually comprises engine air source control; air conditioning packs and their control; cabin inflow, ventilation, and temperature control; and cabin pressure control. It sometimes includes avionics, cargo, and galley ventilation and temperature control.

FAILURE MODE AND EFFECT ANALYSIS (FMEA): An analysis of a particular design for describing, as a minimum, the most probable ways an equipment can fail and the consequences of such failure.

FAULT ISOLATION: The process and actions, following equipment failure, that are involved in the identification of the unit, assembly, or piece part that has failed.

FAULT ISOLATION ANALYSIS (FIA): A systematic evaluation of failure causes, indications and probabilities to determine the level of Fault Isolability provided for in the system design.

GROUND SUPPORT EQUIPMENT (GSE): As used in this report, it is ground-based equipment not carried on-board the aircraft that is used to inspect, test, or troubleshoot aircraft equipment.

LINE REPLACEABLE UNIT (LRU): A component or assembly of components that by design, is packaged to be removed and replaced as a single item.

MEAN-TIME-BETWEEN-FAILURES (MTBF): A measure of actual hardware reliability, determined by summing operating time on all units and dividing by the number of confirmed failures.

MEAN-TIME-BETWEEN-UNSCHEDULED-REMOVALS (MTBUR): A measure of apparent hardware reliability or actual operational reliability, determined by summing operational flight time on all units and dividing by the number of unscheduled and unplanned unit removals, regardless of cause.

MINIMUM EQUIPMENT LIST (MEL): Refers to the minimum aircraft system hardware that must be operational prior to safe aircraft dispatch. Appropriate procedural limitations may be enacted to account for inoperative equipment to maintain safe, airworthy operation.

ON-BOARD MAINTENANCE SYSTEM (OMS): A system described by ARINC 624 that provides a centralized location on the aircraft for electronically furnishing all the aircraft maintenance information.

RANDOM ACCESS MEMORY (RAM): Volatile computer memory devices whose read/write memory content is only active while electrical power is applied.

READ-ONLY MEMORY (ROM): Nonvolatile computer memory devices whose contents can only be read, not written in normal operation. The memory contents remain intact with or without power applied.

2.1 (Continued):

ROOT-MEAN-SQUARE (RMS): A calculation of the square root of the summation of the squares of individual variables or constants. In this report it is used to determine practical system-level tolerances composed of more than three component tolerances.

3. GENERAL FAULT ISOLATION INFORMATION:

This section first discusses the purpose of ECS fault isolation. The design of an effective fault isolation system is then discussed followed by criteria for demonstrating compliance to fault isolation specification requirements.

3.1 Purpose of ECS Fault Isolation:

The primary purpose of fault isolation is to minimize the total cost of aircraft maintenance by reducing flight delays, out-of-service incidents, and spares requirements.

Commercial jet transports represent a large investment both to the airlines and airframe manufacturers. The airlines have a high investment in direct costs of the aircraft and in costs of flight delays due to the large number of passengers carried per aircraft. The airframe manufacturers (and their subcontractors) have a large investment in guarantees on unscheduled removals of components from the aircraft in service. To ensure safety of flight and to protect these investments, it is important that the flight and ground crews be able to identify an improperly operating aircraft system and that ground crews can isolate and correct the malfunctioning component(s) as quickly as possible with a high level of confidence. To reduce flight crew workload, fast, accurate identification of faults in primary systems is required so that appropriate crew alerts can be provided and backup system(s), either automatic or manual, can be employed with a minimum of flight crew effort. This requirement to minimize crew workload has special importance for two-man crew operations.

A systematic method of fault isolation is required to assure the needed speed and accuracy of fault identification. Historical problems have produced the need for fault isolation methods and equipment on-board the aircraft that operates quickly, accurately, and requires the minimum of maintenance crew training.

3.1.1 Historical Problems: Historical discussion of past fault identification problems is necessary to better recognize the need for accurate, reliable, and readily available fault isolation procedures and equipment.

Historically, the major problem areas aggravating the high cost of aircraft maintenance are:

a. Excessive time to properly isolate system faults
b. Excessive unscheduled removal of line replaceable units (LRUs) which are not faulty
c. Excessive time required to remove many LRUs

3.1.1.1 Excessive times to properly isolate faulty components are caused by several factors in the absence of effective on-board fault isolation equipment:

a. Inexperienced ground crew
b. Ground support equipment (GSE) to aid the ground crew not available
c. GSE not functioning properly
d. Ground crew unfamiliar with GSE operation (takes too long to set up and operate)
e. Maintenance manuals (publication software) not readily accessible
f. Maintenance publications incomplete, unwieldy or out of date

3.1.1.2 Erroneous LRU removal rates among airlines are widely varied with respect to several factors. For example, ECS mechanical LRUs removed for no cause typically run from 15 to 20%; Electrical units incorrectly removed have run at 50% or more; APU controllers on some aircraft apparently removed for no cause have run at about 80%; cabin temperature controllers apparently removed for no cause run from 80 to 90%. The erroneous removal rates of refrigeration units which are physically large is typically low because sufficient troubleshooting time has to be spent to ensure that the unit being pulled is actually faulty. All of these cases involve systems with no on-board fault isolation equipment.

Electronic units such as the cabin temperature or auxiliary power unit (APU) controller are relatively easy to remove. Almost any cabin temperature or APU problem is, therefore, likely to be treated first by replacing the controller. For aircraft without fault isolation systems this easy accessibility contributes to high erroneous removal rates.

3.1.1.3 Excessive time to remove the faulty component involves accessibility and removal ease of each LRU. Historically, these factors have seldom received adequate consideration in the overall system design. Difficulty in reaching and replacing certain LRUs has resulted in delays or, more frequently, unduly long down time. Positive, accurate fault isolation of these hard-to-replace components is required so that time consuming replacements are not made in error. Although they have a secondary impact on fault isolation, the subjects of accessibility and removability will not be discussed in further detail.

3.1.2 Impact of Fault Isolation: Fault isolation has an impact on aircraft dispatchability and maintainability as well as airline spares provisioning.

3.1.2.1 Dispatchability: Dispatchability or dispatch reliability of aircraft is very important for the airlines operating on a regularly scheduled basis. Dispatch delays of any aircraft with a load of passengers can be very expensive if rescheduling of other aircraft is involved.

Good dispatch reliability requires the proper fault isolation of malfunctioning equipment as well as proper design of backup systems that can be readily employed.

3.1.2.2 Maintainability: Maintainability is a subject covering the effectiveness of properly identifying faulty LRUs, readily replacing those units, and of being able to repair or overhaul the faulty units and return them to service. The scope of this report limits itself to properly identifying in order to properly replace faulty LRUs.

3.1.2.3 Spares Provisioning: Costly unnecessary spares requirements at many terminals result from high erroneous removal rates. If units that are not actually faulty are removed often due to "shotgun" (randomly replacing units) fault isolation techniques, costly additional spares must be maintained by the airlines to replace the removed units.

3.1.3 Purpose of Fault Isolation Equipment: The purpose of fault isolation equipment (hardware, electronic software, and publication manuals) is to minimize the historical problems discussed above and, thereby, reduce the total maintenance cost. This is accomplished by reducing delays and costly airplane out-of-service incidents, by providing faster and more accurate means to isolate faulty LRUs to increase mean time between unscheduled removal (MTBUR) performance, and by reducing spares and GSE requirements. A secondary purpose is to properly identify faulty subsystems or LRUs in-flight so that backup subsystems can be employed automatically or by the flight crew. This is a result of LRU fault isolation functions and will only be discussed in general in this report.

3.2 Fault Isolation System Design:

A "fault isolation system" may be defined as the total process necessary to identify faulty LRUs. The finished product includes all the hardware and software necessary to meet this objective.

This process is applied to a functional system of the aircraft. All interrelated components are a part of the functional system and must be considered. For example, a cabin pressurization system is a single system from the circuit breaker(s) to the outflow valve. It includes all flight deck indicators that provide status information and ground shift or mode change hardware, i.e., relays, switches, mechanical levers/cables, along with the primary LRUs - controllers, valves, motors, and control panels.

The principle of fault isolation design is that for every failure mode of a particular LRU there is an abnormal characteristic which can be detected, indicated, and isolated from other failures. Certain failure modes may be passive by not exhibiting functional degradation at certain conditions, but all are detectable by some means at some conditions. Measurable fault isolation goals must be specified at the beginning of the design process. The design process includes understanding the design principles, then performing the necessary tradeoffs and analysis. Practical tolerance limits must be set considering the hardware requirements and the interfaces to other systems.

3.2.1 Fault Isolation Design Principles: The ultimate purpose of fault isolation systems may be achieved by cooperative effort between the airline operators, airframe manufacturers and the LRU suppliers. Practical design requirements and objectives must be initially determined that include certain principles to be followed during the conception and the implementation of the ECS and fault isolation system design. Among these are:

a. Measurable goals should be established before the beginning of design. They are valuable first, to verify the validity of the maintenance requirements, and second, to demonstrate the benefits that result from meeting those requirements.

   Three goals utilized in a recent design were:

   (1) The fault isolation system and LRU remove/replace design must enable identification and replacement of aircraft dispatch critical components during the minimum turn-around time at the gate, 35 min or less. This must be accomplished to prevent a subsequent aircraft dispatch delay time of greater than 15 min.

   (2) The fault isolation system must allow identification of the faulty component in 10 min with 95% accuracy, using little or no GSE for test.

   (3) Another measurable goal that has been utilized is to minimize the BITE hardware added by planning to use only the sensors required for system control or crew indication. Adding unnecessary sensing only for BIT reduces the overall system reliability. In this example, no sensing is added to achieve a goal of fault isolation to one LRU with 90% accuracy, isolation to either of two LRUs with 95% accuracy, or isolation to any of three LRUs with 100% accuracy.

b. Consideration of fault isolation must be given importance throughout all stages of the design of ECSs from the conceptual to the final design and testing phases. In particular, fault analysis techniques must be considered during preliminary design so that:

   (1) Predominant failures are to a fail-safe operation mode.
   (2) Means for detection and isolation of all predominant failure modes are provided.

   These analyses must consider both steady-state operational tolerances and normal/abnormal system dynamic responses (including electrical system transients) to prevent nuisance fault messages.

3.2.1 (Continued):

c. Means must be provided throughout the functional system design and service introduction whereby it can be examined as a complete whole, including its maintenance and operating environment in scheduled service. In some cases this may mean a fault isolation and maintainability demonstration for compliance with specified goals be performed prior to introduction into service, followed by in-service analysis of equipment, procedures, and maintenance crew performance.

d. As much as possible, the system should provide fault isolation without engine operation and with minimum APU operation. This implies electrical checkout only or utilizing memory recording of electrical, mechanical, and pneumatic faults that occur in flight.

e. Throughout the design the airframe manufacturer and the equipment suppliers must weigh the economic benefits and penalties of their particular system against the overall purpose of a fault isolation system.

3.2.2 Total System Tradeoff Analysis: One of the first steps when designing an ECS with effective fault isolation is properly defining the system requirements (overly severe requirements result in overly complex systems with poor effectiveness). This can be done by determining:

a. The primary operational requirements of the ECS (cooling criteria, heating criteria, flow and pressure criteria, etc.)

b. The design boundaries (operating envelope and acceptable operational tolerances)

c. The secondary system requirements, i.e.,

(1) System and LRU MTBUR and MTBF guarantees

$$\text{Fault isolation accuracy \%} = \frac{\text{MTBUR}}{\text{MTBF}} \times 100 \qquad \text{(Eq. 1)}$$

(2) Likelihood and acceptability of:

(a) Flight squawks which the ground crew is unable to duplicate
(b) Intermittent type faults (unannunciated intermittent faults are generally not acceptable and must be minimized)

(3) Time limitations for fault isolation, turn-around time guarantees (this includes time to fault isolate, remove, and replace LRUs)

3.2.2 (Continued):

(4) AIDS provisions, central fault display system (CFDS) provisions, on-board maintenance system (OMS) provisions, or other system status indication requirements

NOTE: AIDS is a term adopted by Aeronautical Radio, Inc. (ARINC) in general use for airborne recording systems that include acquisition and signal conditioning. CFDS and OMS are terms (adopted by ARINC) that refer to centralized computer retrieval and display of maintenance data and BIT results from the aircraft subsystems.

(5) Special installation environmental conditions that affect the fault isolation design (location, access, temperature)

(6) Maintenance training level or skills in scheduled service (in general the design must be adequate for the least qualified maintenance personnel)

3.2.2.1 Available Concepts: Methods of fault isolation include:

a. Manual BIT (commonly called self-test) - is usually one or a combination of switches, magnetic latching indicators, lights and meters used by ground crews in performing tests on the system to identify which LRU has failed. One of the advantages of using manual self-test is that those minor faults are ignored which have insignificant effect on system operating performance. This is based on the philosophy that the only time BITE is used is when the pilot has written a squawk and maintenance personnel are attempting to determine what LRU to replace to correct the squawk. It may also be used to test the system after maintenance has been performed to verify corrective action. This technique is generally used with relatively simple systems.

b. Automatic BIT - there are basically three methods of implementation:

(1) Fully Automatic: A test is performed continuously or periodically (i.e., once a second) when the aircraft system is operating with no personnel involvement required. The test is usually a go/no-go type test and may test one or more circuits or functions. In many cases a "model" or "window" technique is used to determine "go" or "no-go". "Go" or "no-go" conditions are displayed at a central point on the aircraft. This may be on the system electronic controller face and/or at a centralized maintenance panel which communicates with the system controller(s) or with the system components directly. This approach normally includes "memory" of status information that is retained when electrical power is removed from the system. The most elaborate form of these systems use microprocessor-digital controllers and data bus communication (per requirements such as ARINC 429) both for receipt of data from the aircraft and for communication with a CFDS or OMS.

3.2.2.1 (Continued):

(2) Manual Interrogation: Similar to fully automatic except that failure indications are stored in a "memory" type circuit and are not displayed until requested by maintenance crews. When self-test is manually initiated the memory circuit is interrogated and the failed LRU is identified. This method of BITE display does not exhibit nuisance indications of failure unless manual initiation is accomplished.

(3) Automatic Test Manually Initiated: Requires manual start by maintenance personnel of automatic test (usually pushing a button). Tests will be done automatically that may cause actual system functions to be exercised to check operation. A "go" or "no-go" status indication will give results of the test and what LRU is at fault if "no-go". This test can also be used for verification of proper connection and operation of replacement LRUs and for flight readiness testing.

Many systems and/or LRUs use a combination of automatic BITE noted.

c. Tests Using GSE - GSE should be considered as a last resort for troubleshooting. For GSE to be effective it must be available at every airport where flight squawks may have to be corrected. This becomes costly. For example, an airline fleet may travel into 60 airports where maintenance can occur. All 60 airports must stock that particular piece of GSE. In addition to the cost of purchasing 60 units of GSE, the cost for transportation and periodic calibration or certification would have to be considered, plus cost of replacement parts, stocking, and training of maintenance personnel in the use of particular GSE units.

Some forms of GSE are practical for checking those mechanical or pneumatic units (heat exchangers, air cycle machines, pneumatic valves) that are not cost-effectively checked by BITE. These include special equipment to test the system performance while it is operating under controlled conditions on the ground. These tests are most practically performed during regularly scheduled aircraft maintenance checks.

When GSE is used, it should be:

(1) Very reliable

(2) Simple to operate, not requiring special training

(3) Built with instructions in placard form on the unit, written in a language the average technician or mechanic can understand

(4) Thoroughly tested in its working environment to assure that it will do the intended job in airline turnaround and through-flight environment

3.2.2.1 (Continued):

(5) Cost-effective - A well designed GSE unit can be used in many different fault isolation roles and many different systems. One of the most common and effective (although usually not considered GSE) is the electricians' portable multimeter that measures voltage, current, and resistance in a variety of ranges.

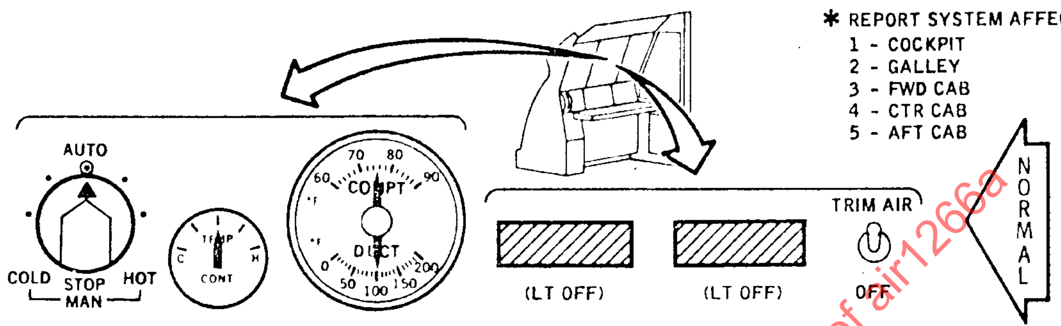
(6) Compact and portable, not requiring electrical or pneumatic power. If electrical power is required on the airplane, it should obtain the power from either batteries built into the GSE or use standard aircraft power.

d. Publication Methods - On some simple or highly reliable systems, BITE cannot be justified. One method of providing fault isolation on such systems is by utilizing a software logic program in a maintenance manual publication. To be effective, the software program design should be managed by the aircraft manufacturer who has the greatest interface with the LRU suppliers and the airlines, and can best integrate all inputs.

There are many software logic publication concepts available. Various aircraft manufacturers have developed individual programs that are similar. Usually there are two manuals involved (see Example, Figures 1, 2 and 3). One manual is used by the flight crew (Figure 1) and one manual is used by maintenance personnel (Figures 2 and 3) for through or turnaround maintenance. The manual for the flight crew shows normal system indications and tolerances. It also shows various abnormal indications and each abnormal indication is given a code number.

When a system abnormality (commonly referred to as a flight squawk) occurs the flight crew member enters a code number in the airplane logbook instead of some abbreviated description, such as, "Flight Compartment Temp Control Inop in Auto." The appropriate fault code is selected from the flight crew manual. The fault code number represents a complete and accurate description of what actually was observed. For example, fault code 21-60-E-1 describes the following condition: cockpit temperature control inoperative in auto, OK in manual; all circuit breakers OK; valve position indicator, hot; duct temperature, high; compartment temperature, high; all abnormal lights, off; trim air switch, on. The flight crew would then radio the code number to the next maintenance station where the maintenance man has a similar book, but which contains additional information. For a given code number it will indicate what BITE to actuate or if BITE is not installed, what checks to be done rapidly to isolate to a given LRU. The checks are usually given in detail with pictures showing location and necessary part numbers. From an airline standpoint, the software logic publication is the nucleus for all system fault isolation because of the following advantages:

AIR CONDITIONING TEMPERATURE CONTROL



* REPORT SYSTEM AFFECTED
1 - COCKPIT
2 - GALLEY
3 - FWD CAB
4 - CTR CAB
5 - AFT CAB

TEMP SELECTOR	VALVE POS IND	COMPT/DUCT TEMP GAGE		DUCT-AVIONIC COMPT OVERHEAT LT	AIR COND TRIM AIR PRESS HI LT	TRIM AIR SW	FAULT CODE REPORT SYS AFFECTED
AUTO OR MANUAL					AIR COND TRIM AIR PRESS HI		21-60 U *
AUTO OR MANUAL	NO CHANGE					TO OFF	21-60 V *
AUTO	HOT	HIGH	HIGH				21-60 (E) *
AUTO	COLD	LOW	LOW				21-60 F *
AUTO	HOT	HIGH	HIGH	DUCT-AVIONIC COMPT OVERHEAT			21-60 G *
AUTO OR MANUAL	HOT	LOW	LOW				21-60 H *
MANUAL	COLD	LOW	LOW				21-60 J *
MANUAL	HOT	HIGH	HIGH				21-60 K *
MANUAL	HOT	HIGH	HIGH	DUCT-AVIONIC COMPT OVERHEAT			21-60 L *
AUTO OR MANUAL	HOT						21-60 M *
AUTO OR MANUAL	COLD						21-60 N *
AUTO OR MANUAL	COLD	HIGH	HIGH				21-60 P *
AUTO OR MANUAL		HIGH					21-60 Q *
AUTO OR MANUAL		LOW					21-60 R *
AUTO OR MANUAL			HIGH				21-60 S *
AUTO OR MANUAL			LOW				21-60 T *
REPORT ANY FAULT SYMPTOM OR PATTERN NOT SHOWN ABOVE							21-60 XX *

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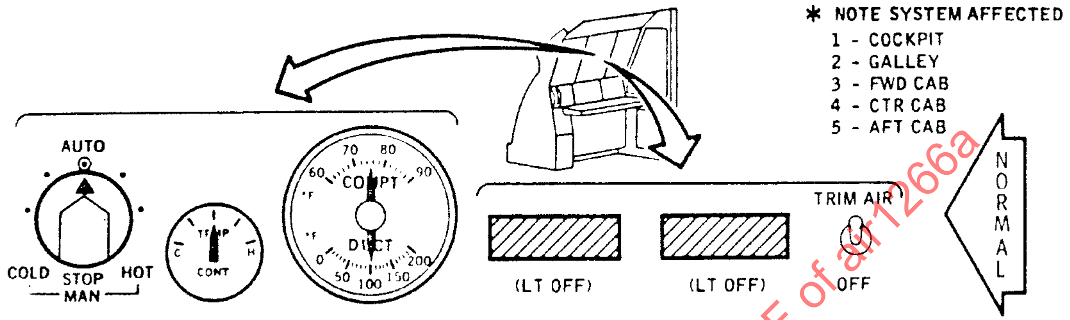
FIGURE 1 - Flight Fault Isolation
Air Conditioning Temperature Control

Turn Around Fault Isolation
(AIR CONDITIONING) TEMPERATURE CONTROL



TEMP SELECTOR	VALVE POS IND	COMPT/DUCT TEMP GAGE		DUCT-AVIONIC COMPT OVERHEAT LT	AIR COND TRIM AIR PRESS HI LT	TRIM AIR SW	FAULT CODE NOTE SYS AFFECTED
AUTO OR MANUAL					AIR COND TRIM AIR PRESS HI		21-60 U *
AUTO OR MANUAL	NO CHANGE					TO OFF ↓	21-60 V *
AUTO	HOT	HIGH	HIGH				21-60 (E)*
AUTO	COLD	LOW	LOW				21-60 F *
AUTO	HOT	HIGH	HIGH	DUCT AVIONIC COMPT OVERHEAT			21-60 G *
AUTO OR MANUAL	HOT	LOW	LOW				21-60 H *
MANUAL	COLD	LOW	LOW				21-60 J *
MANUAL	HOT	HIGH	HIGH				21-60 K *
MANUAL	HOT	HIGH	HIGH	DUCT AVIONIC COMPT OVERHEAT			21-60 L *
AUTO OR MANUAL	HOT						21-60 M *
AUTO OR MANUAL	COLD						21-60 N *
AUTO OR MANUAL	COLD	HIGH	HIGH				21-60 P *
AUTO OR MANUAL		HIGH					21-60 Q *
AUTO OR MANUAL		LOW					21-60 R *
AUTO OR MANUAL			HIGH				21-60 S *
AUTO OR MANUAL			LOW				21-60 T *
REPORT ANY FAULT SYMPTOM OR PATTERN NOT SHOWN ABOVE							21-60 XX*

FIGURE 2 - Turnaround Fault Isolation
Air Conditioning Temperature Control

TURN AROUND FAULT ISOLATION
(AIR CONDITIONING) TEMPERATURE CONTROL

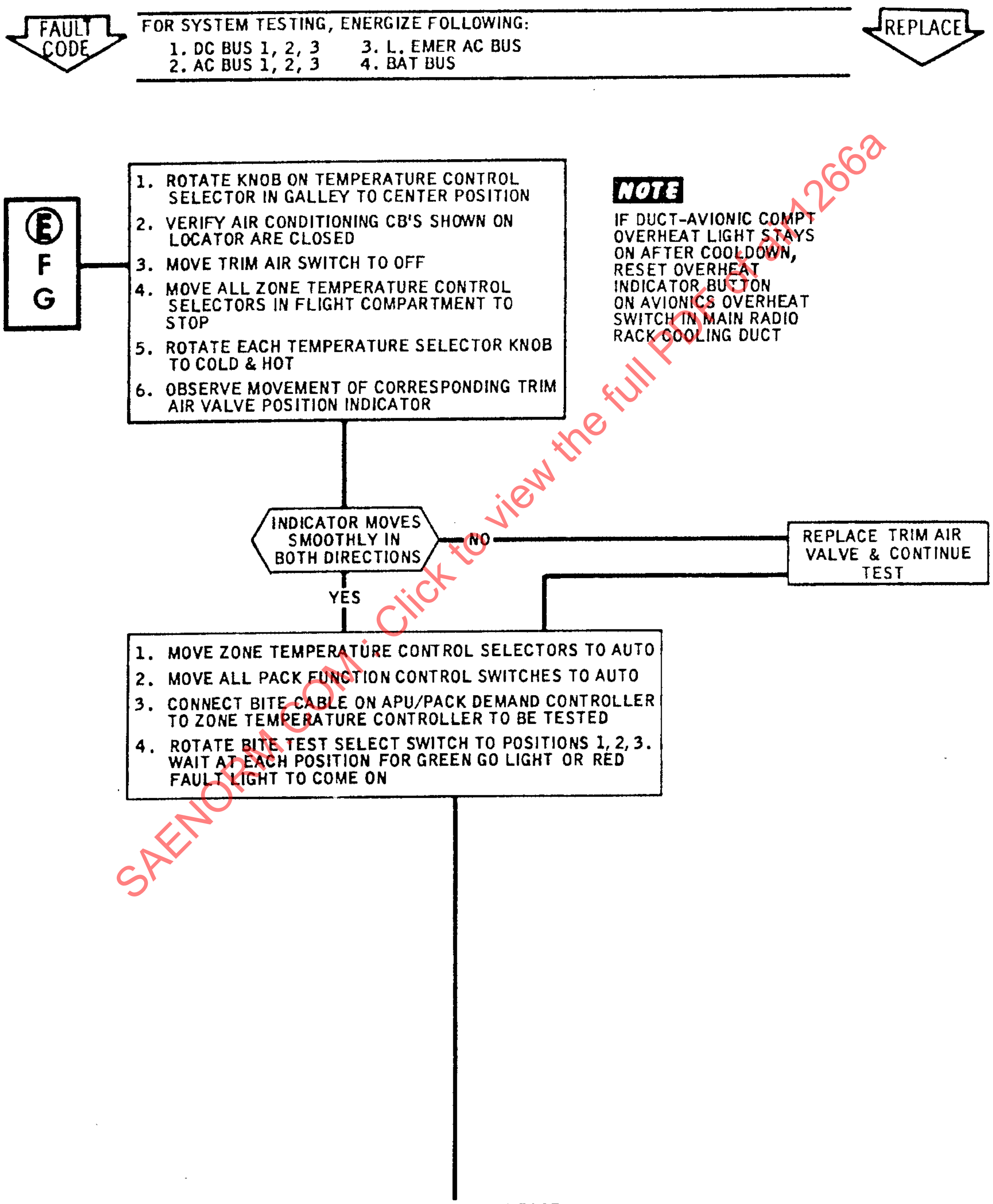


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FIGURE 3 - TAFI Fault Tree
Air Conditioning Temperature Control

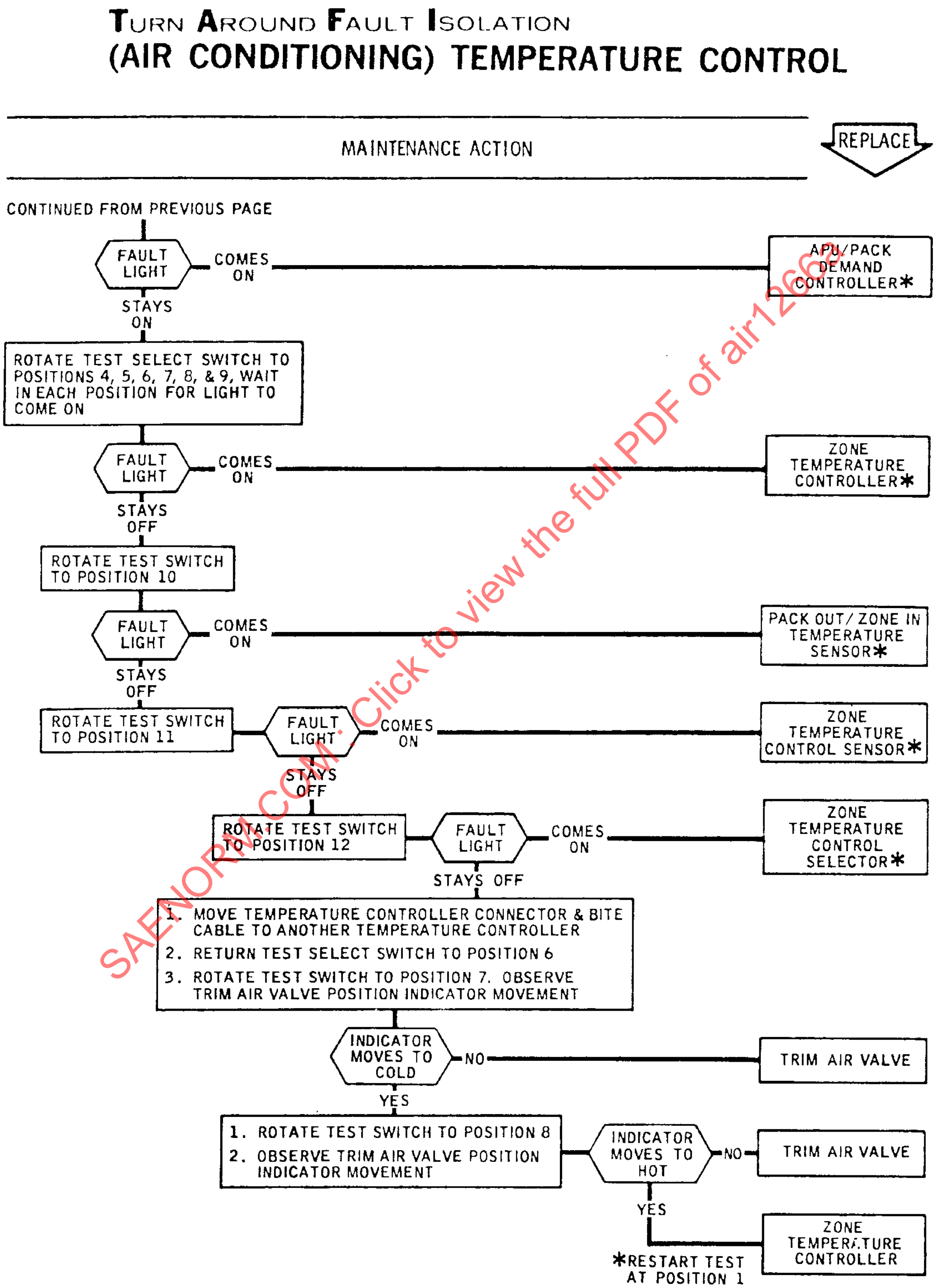


FIGURE 3 (Continued)

3.2.2.1 (Continued):

(1) Eliminates vague flight squawks written by flight crew.

(2) Provides an efficient way of transferring information of flight squawks to maintenance personnel before aircraft arrival thereby giving maintenance personnel adequate time to obtain replacement parts and review fault isolation procedures.

(3) Provides maintenance personnel with one manual for the entire airplane for fault isolation, including necessary information on how, when, and where to use BITE.

(4) Provides a convenient, economical, centralized method for updating, improving, and correcting flight squawk reporting and maintenance fault isolation procedures.

3.2.2.2 Detailed Design Tradeoffs: Detail tradeoff studies on candidate systems must be performed by using many pertinent criteria. Illustrations demonstrating the use of many of these tradeoff criteria in the actual design phase is presented in subsequent sections. The minimum tradeoff criteria include:

a. Fault isolation effectiveness - requires preliminary fault isolation analysis (FIA) - see 3.2.3.

b. System LRU count and cost optimization from provisioning standpoint

c. System reliability (MTBF)

d. System MTBUR (requires preliminary FIA)

e. System or LRU simplicity

f. Dispatch inoperative or Minimum Equipment List (MEL) limitations

g. Costs: Manufacturer's design and development, hardware, and airline operation

h. Development risk

i. Development time

j. Customer acceptance

k. Cockpit and installation space allocation and cockpit operating and display philosophy

l. Installed weight

m. Crew workload (requires preliminary FIA)

3.2.2.2 (Continued):

n. Commonality to existing systems (influences provisioning and training)

o. Operation and maintainability training requirements (includes consideration of maintenance crew skill level)

p. Component and system tolerance prediction and cost-effective control

q. Provisions in service (spares requirements)

NOTE: Operational requirements not included in above. It is assumed all candidate systems meet operational requirements although, in some cases, operational complexity may be influenced by reliability and fault isolation capability requirements and, thereby, become a tradeoff criteria.

3.2.3 System Fault Isolation Analysis (FIA) and Final Design: Using a preliminary system design, a system FIA should be performed to determine when and where BITE or some method of fault isolation should be utilized.

One method of analyzing a system for fault isolation is:

a. List all LRUs that are in the system; this includes switches, circuit breakers, relays, etc.

b. Perform a failure mode and effect analysis (FMEA) for each LRU and show the effect of each failure mode on the system.

c. For each LRU list the primary system failure modes that will occur in airline service. System failure modes should be output functions from the LRU FMEA and not detail part failures inside the LRU.

d. For each major interfacing system, consider each malfunction which could cause the system being analyzed to exhibit an apparent fault indication (as observed by the flight crew).

e. For each LRU failure mode list the percent that failure mode is of the total system failures.

f. For each LRU failure mode list the primary apparent indications (as observed by the flight crew). If any LRU failure mode always exhibits a particular indication (and different from any other LRU), a software logic maintenance manual program keying the indications to that particular LRU may suffice. If many LRU failure modes exhibit the same indication, a logic process method of fault isolation should be considered in the design.

g. When the fault isolation analysis is initially completed, weaknesses in system design will be apparent and changes in system or fault isolation implementation (BITE, etc.) will be required. Repeat Steps 1 through 5 when design or fault isolation implementation is changed.

3.2.4 Design Limits Versus Acceptable Operating Limits: Before the total system design is frozen, a tolerance study should be conducted. The study should start at the component level and end at the operating system level. The purpose of the study is to allow analysis of normal tolerance buildups that occur due to manufacturing limitations, operational limits, and acceptable in-service deterioration limits. Design limits are kept as small as possible and are established to produce a functional product within manufacturing tolerances. Larger acceptable operating limits are established for the system outside of which the BIT checks should occur. The analysis yields design data to prevent nuisance fault information being presented to flight crews or ground maintenance personnel due to BIT checks being within acceptable in-service deteriorization limits.

Electrical/electronic components usually do not exhibit an in-service degradation characteristic while pneumatic, mechanical, and electromechanical components usually do have an operation in-service degradation tolerance. These tolerances are used as the Go/No-Go limits for an "on-condition" maintenance program such as inspect, test and correct as necessary (ITCAN) or test and repair as necessary (TARAN).

Using a total system schematic as a guide, tolerances should be determined for functional inputs and outputs of each component. A realistic system tolerance should be stated for each cockpit indicated function and mode. Operational tolerances should be greater than those for any system acceptance test, which in turn should be greater than the individual component receiving acceptance test tolerances.

System tolerances should be derived by using either of the two following methods as guidelines:

a. If the system has three or less variables, use the absolute sums of the individual positive and negative worst-case tolerance variables controlling the checkpoint.

b. If more than three variables contribute to the checkpoint, a root mean square (RMS) method should be used. When a RMS method is used, it is necessary to monitor actual results, and either expand tolerances or make design changes to meet operational and contractual requirements.

If a primary failure mode of a component is an output function drift, the tolerance study has to be accomplished so that BIT thresholds can be determined.

Analyzing and documenting operational in-service limits is important since these boundaries dictate to flight crews when a system will be "squawked". A squawk results in a component being replaced in the aircraft system. If the acceptable tolerances are adequate and the fault isolation procedure is accurate, the part that is removed and checked in the shop will be a confirmed failure within the specified probability and not a "retest-ok".

3.2.5 Concept Integration (Interfaces): On some designs major interfacing subsystems within the ECS have to be accounted for in the fault isolation design. For example, if failures (either gross or gain tolerance shift) of pneumatic or air conditioning pack systems could cause the pressurization system to appear faulty, it must be considered in the fault isolation design of the pressurization system. This is especially true if the pack or pneumatic failure is not readily apparent in the cockpit.

Also, as part of the ECS component or system design process, information must be known concerning other systems or components providing inputs to or receiving outputs from the ECS. ECS inputs and outputs are usually electrical, pneumatic, or mechanical in nature. Different equipment configurations and various steady state and dynamic performance of inputs and outputs must be considered for the interfaces of each LRU to the ECS and other subsystems, as well as for the integration of the ECS with the aircraft so that accurate fault isolation criteria can be determined.

3.2.6 Hardware Considerations: Fault isolation or troubleshooting on commercial aircraft is usually the result of a "pilot squawk". The pilot usually squawks functional systems, not components or subsystems. A squawk results in a hardware LRU being removed. The designer must become aware of the variety of organizational structures, jurisdictions, and maintenance skills within different airline maintenance operations. The hardware design and fault isolation procedures must minimize any adverse effects that these factors may have on the complete process of properly identifying and replacing LRUs.

The hardware design must include consideration of fault isolating by LRU reliability, LRU remove and replace time, fault data presentation, and instruction placards.

a. Isolating by LRU Reliability: LRU reliability is an important consideration in fault isolation design. In fact, reliability can be used to fault isolate systems with few LRUs. For example, in a system with two LRUs, it is possible that the LRUs would have approximately the same MTBF. This means if fault isolation provisions (i.e., BITE) were not included in the design, 50% of the initial corrective action would be correct if maintenance personnel "shot gunned" the system by arbitrarily removing one of the two components, or removing the one that is more readily accessible. If the system was initially designed with two LRUs and one had an MTBF of 100 000 h and the other LRU had an MTBF of 5000 h, it may be desirable to put BITE on the more complicated lower reliability part isolating the less complicated part by exclusion. Adding BITE to the simpler, high reliability (100 000 h MTBF) LRU may undesirably lower the effective operational reliability of that LRU and produce nuisance LRU fault indications caused by failure modes of the BITE. It would also be possible to use no BITE at all and reliability experience would dictate replacing the LRU with 5000 h MTBF and, thereby, "shot gun" with a 95% effectiveness.

3.2.6 (Continued):

b. Time to Remove and Replace - The time to remove and replace LRUs can affect a system's fault isolation effectiveness. An LRU that is readily accessible and easy to remove and replace, such as the system controllers, historically have a high unnecessary removal rate.

High-confidence BITE is required to prevent unnecessary controller removals. An LRU that is difficult or time consuming to remove and replace will usually not be removed to correct a flight squawk unless:

(1) The other easier-to-replace LRUs have been replaced at least once
(2) The system contains a method of fault isolation (BITE, etc.) that has a high confidence level so that when a particular LRU is indicated faulty, it definitely is faulty. BITE, therefore, may prove cost-effective for some LRUs simply because they are very time-consuming to remove and replace. The airframe manufacturer and the system designer must carefully consider the accessibility of lower reliability LRUs. The optimum benefits are achieved when low reliability LRUs are cost-effectively checked by BITE and the LRUs are readily accessible for replacement.

c. Presentation: The indication that a fault exists in a particular LRU can be displayed many ways. The presentation should be used that is most positive and provides the highest confidence level. Where BITE is involved, the hardware for presentation of status information to flight crews and fault information to ground crews must carefully consider the human factors involved. Some display hardware examples are indicated below:

(1) On LRU (Usually Electronic Controller):

(a) Lamps - One for GO, one NO GO for each LRU
(b) Light Emitting Diodes (LED) - One for GO, one NO GO for each LRU
(c) Magnetic Latching Indicators - Drive signals must be properly filtered to prevent nuisance latching
(d) Alphanumeric Display - Provides greatest amount of information (only practical with digital microprocessor unit)

(2) In Flight Deck or at Central Maintenance Panel:

(a) Lamps - Primarily for flight deck status display
(b) Cathode Ray Tube (CRT) Display - Complete, formatted displays for both system status and LRU fault identification - requires data interface, either centralized or in the LRU (usually system controller)

Effective fault isolation designs must eliminate problems of erroneous fault displays or lack of display when system faults are observed. These problems must be resolved early in the LRU and system design phase and proper design confirmed during system test, flight test, and early aircraft operational stages.

3.2.6 (Continued):

d. LRU Placards - Clear and concise placards should be located on the LRU to explain what to do when a fault indication is shown, or to provide instructions for performing manual BITE checks (Reference Example, Figure 4). The human factors elements must be carefully considered in the wording of the instructions.

3.2.7 Other Considerations: Other functional aspects of BITE must be considered. These include system readiness testing, system performance monitoring, automatic corrective action during system failure modes, central maintenance signalling and recording, recording of sub-LRU fault data, minimizing dedicated BITE sensing, and system and component trend monitoring.

3.2.7.1 System Readiness Testing: This test provides the flight crew with a direct readout automatically or upon interrogation, of subsystem malfunctions which affect the takeoff decision. This test is done in parallel with the active system performance monitoring described. Additional data necessary to make dispatch decisions on subsystem degraded mode capability using the minimum equipment list (MEL) can also be provided by this test.

The system should automatically, upon command, quickly exercise the system components (valves, fans, etc.) and determine proper operation on the ground, before flight conditions are encountered where passive faults become evident. This includes exercising all normal system functions and protective devices in a non-harmful manner. Design of protective devices so they are testable in-situ must be considered.

3.2.7.2 System Performance Monitoring: This test provides numerical and graphical readout on a display screen of the performance of selected subsystems such as the bleed air subsystem, air-conditioning packs, avionic cooling, wing anti-ice, etc. In-tolerance performance can be indicated on the display in green color while marginal or out of tolerance parameters can be indicated in amber or red.

More sophisticated graphics can be utilized to enable the crew to readily observe system operation. Display "pages" can appear on the monitor screen automatically when faults occur in a subsystem. The display systems should intimately tie in with the system controller electronics for more comprehensive display while reducing the dedicated sensing required for display purposes only. Control sensors can be used for display purposes if they are properly fault isolated and if automatic system corrective action provides fail-operational fail-safe performance.

3.2.7.3 Automatic Corrective Action: Consideration must be given to automatic corrective action in prescribed manners when certain hard faults are detected and isolated. During continuous BIT monitoring in flight or on the ground, if faults are detected and isolated at least to the operational function level, backup control functions can be appropriately employed. Operation in a degraded mode can also be employed for certain failure modes that do not affect flight safety or significantly affect passenger or crew comfort.

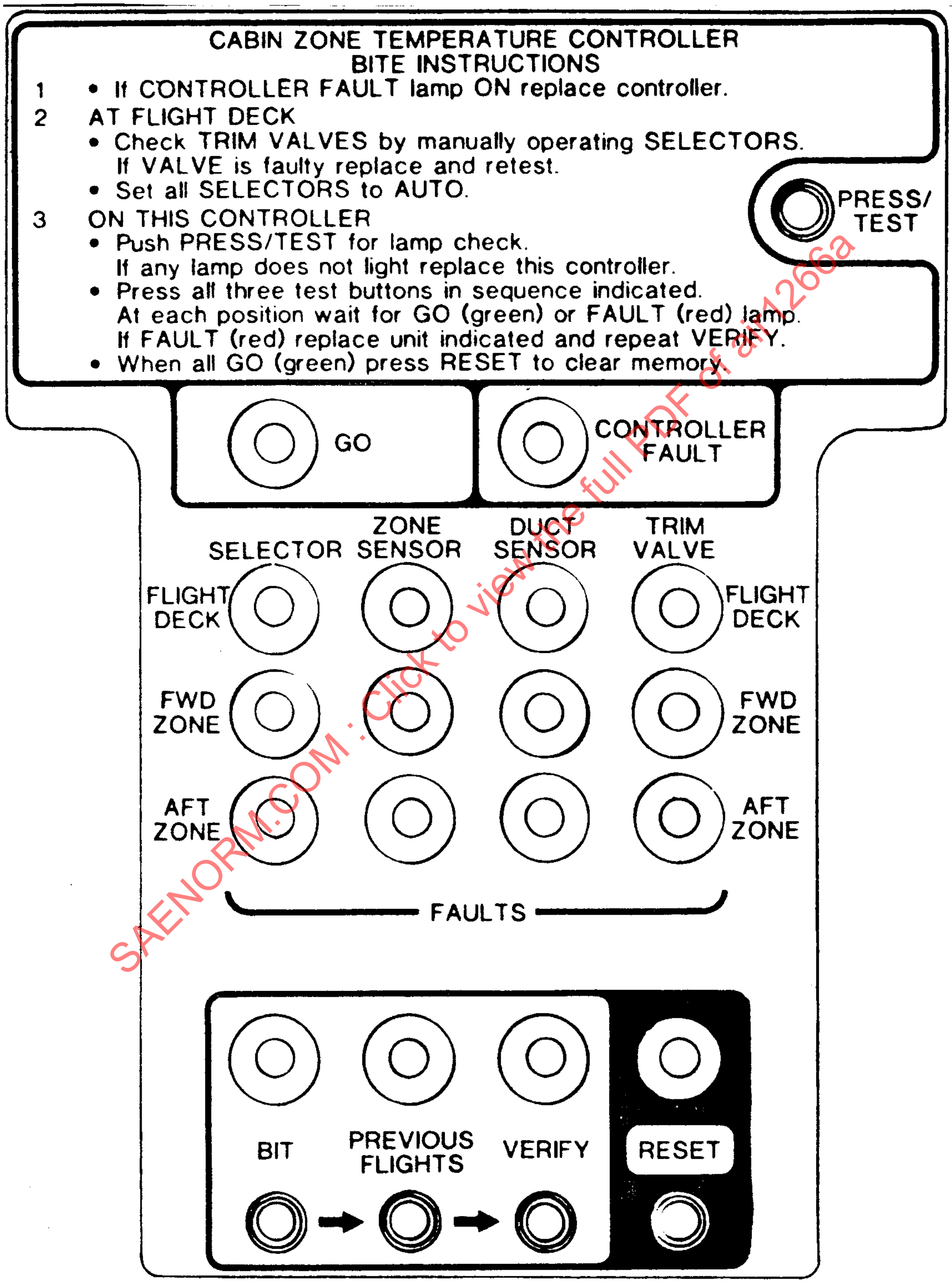


FIGURE 4 - Temperature Controller
BITE Instructions

3.2.7.3 (Continued):

Tradeoff analysis and decisions must be made to determine the extent required of automatic backup functions, manual crew operated backup functions, or no backup function for each system failure mode. Flight safety and flight crew workload must be considered in the tradeoffs.

3.2.7.4 Central Maintenance Computer Systems: Central maintenance systems that command and readout fault isolation data from the aircraft subsystems at a central computer location reduce maintenance crew access times and provide a consistent user interface for all subsystems. Two basic forms of this concept are the CFDS and the OMS. These concepts are described in detail in ARINC 604 (CFDS) and ARINC 624 (OMS). An example system employing CFDS is discussed in 4.3.

3.2.7.5 Recording of Sub-LRU Fault Data: LRU faults are determined by recognizing and analyzing the various failure modes of the LRU. This sub-LRU data are, therefore, available and can be stored within the controller memory. It can then accompany the controller LRU from the aircraft to the shop to aid in shop diagnosis and repair of the part. The controller can additionally perform more self-diagnosis to the sub-LRU module level when connected to simple automatic test equipment (ATE) in the shop.

3.2.7.6 Minimizing Dedicated BITE Sensing: Interactive data from other aircraft systems and flight instrumentation (air data computers, automatic flight control systems, engine controls, etc.) can be used by the ECS to aid in more comprehensive fault isolation while minimizing the need for BITE dedicated sensing. These data are generally available on data busses. Tradeoff analysis must be performed to determine whether it is effective to use these data. That tradeoff must consider the real need for the data, are these data presently available to the controllers or must a data bus input be added, or should a dedicated sensor be used. Impacts of reliability and added wiring weight and cost must also be considered.

3.2.7.7 System/Component Performance Degradation Trend Monitoring: This test is a periodic automatic and/or manual recording of selected performance parameters for ground analysis or out-of-tolerance limit performance inspection. These tests provide the capability to reduce the number of in-flight failures and/or increase the time between scheduled replacement of system components. These tests are to be implemented only where the best available, state-of-the-art design for failure prediction has been successfully demonstrated and the impact on safety, schedule completion and cost savings is of sufficient significance.

This testing is normally performed only during controlled ground checkout tests. Using the system sensors plus specially added test sensors, impending failure is predicted (heat exchanger blockage or leaks, air cycle machine performance degradation due to nozzle erosion, valves slow or sticking, etc.).

3.3 Demonstration of Specification Compliance:

Before final approval and delivery of a system, a prototype verification and detail qualification test is performed to determine that the system including BITE will perform the function for which it was designed. After qualification test a flight test is performed to verify that the system will perform as intended in the "real world" (flight). Final verification is realized during the initial airline service period. Flight test and in-service flight squawks and the corresponding corrective action must be correlated to assure that the fault isolation is functioning properly.

3.3.1 Prototype Verification: Early in the program and to the greatest extent possible, validate the fault isolation and system tolerance analyses with prototype assemblies on a complete simulated system or on an aircraft if possible. This validation should include simulating the failures that have been analyzed, then verifying the system effect and the successful operation of the chosen fault isolation scheme within the specified criteria.

3.3.2 Qualification Testing: It is mandatory that when qualification testing is accomplished that the system component fault isolation procedures and installed BITE be verified. Qualification tests on components and systems should include duplicating failures as noted in the FIA, verifying and documenting that the fault isolation procedures and any installed BITE is functioning as intended. Where BITE is utilized, the qualification test and the flight test should also check:

a. That the BITE does not produce false failure indications during testing, duplicating all modes at maximum and minimum acceptable in service operational tolerances.

b. That BITE does not produce false indications when subject to electromagnetic interference (EMI) and electrical power transients that will normally occur.

c. That the BITE does not produce false indications when interfacing systems produce faults, or when interfacing systems are operating at acceptable maximum or minimum limits.

3.3.3 Initial Airline Service Period: The intent of all parties during this initial period is to identify and to correct, as rapidly as possible, any problems associated with fault isolation hardware, software and/or corrective action procedures. Specification requirements and/or design goals of acceptable MTBUR/MTBF ratios and time-related dispatchability are also verified.

During initial service the working unit of measure for identifying problems should be MTBUR. This rate provides the best single indicator of the performance of an LRU, both in use and in ease of maintenance and fault isolation.

3.3.3 (Continued):

If the MTBUR of an LRU becomes unacceptable, the complete files of the operator should become available to the airframe manufacturer and, in turn, to the LRU supplier containing all relevant detail data to help determine if the problem is LRU reliability and/or fault isolation effectiveness. The operator and the airframe manufacturer, assisted by the LRU supplier, can then cooperate to determine the best courses of action to improve the overall MTBUR reliability. If the problem is LRU reliability or defective BITE (if applicable) design, the LRU supplier must be responsible for the corrective action. If the problem is fault isolation effectiveness due to no BITE or improper use of BITE, all must cooperate to solve the problem. The airframe manufacturer must be responsible for any effect that a design change may have on aircraft operation and certification.

Procedures and plans should be established, prior to initial service, whereby selected airframe manufacturer and LRU supplier representatives can be available at the operator's maintenance facilities. There is no substitute for qualified personnel actually witnessing the total in service environment in which the fault isolation systems operate.

Procedures should be established, prior to initial service, whereby selected airframe manufacturer representatives may be permitted to observe in the flight compartment the actual performance of systems and the operation of flight crews in scheduled service.

Flight squawks and respective corrective action must be monitored to determine:

a. That squawks noted are really malfunctions, and not the result of lack of knowledge of acceptable parameters or idiosyncrasies peculiar to the system or flight crew involved. To reduce this common problem, adequate airline personnel training must take place taught by both the airframe manufacturer and the system/LRU supplier instructors.

b. That the troubleshooting accomplished to isolate an LRU actually utilizes the BITE or procedural software logic provided and that the results are correct. A follow-up record should be maintained by the airline personnel that indicates the extent of utilization of the established fault isolation procedures and BITE (where applicable).

c. Whether initial airline service squawks are due to system fault isolation design or tolerance problems or are anticipated, isolated failures.

The LRU supplier and the airframe manufacturer should be made aware of all LRU failures occurring in airline service. Failure analysis reports should be forwarded by the LRU supplier to the airframe manufacturer identifying the reason for failure and delineating the action taken to eliminate or reduce the probability of reoccurrence. The airframe manufacturer should be provided with regular updates on LRU failure information. He, in turn, should identify whether any of the faults may be due to aircraft system interfaces.

4. FAULT ISOLATION HARDWARE DESIGN EXAMPLES:

This section, in general, summarizes the preceding discussions with the presentation of example ECS fault isolation methods that are presently in airline service. Three examples are presented:

a. Manual BITE
b. Automatic BITE
c. Automatic BITE using a CFDS

By moving through these examples, actual implementation of the principles presented in Section 3 are discussed. These examples do not necessarily represent recommendations, but can be used to help formulate a cost-effective design for a specific application.

The first example, Manual BITE, is for an all analog control system with limited automatic BIT capability. It is presented to illustrate all the BITE design principles necessary for this type of simpler BITE hardware design. The second example, Automatic BITE, uses similar design principles but illustrates the added functionality offered by digital microprocessor based BITE design. The third example uses a similar digital microprocessor design more fully by interfacing with a CFDS.

4.1 Manual BITE Example:

The example environmental control subsystem to be discussed is a cabin zone and refrigeration pack temperature control subsystem. Figure 5 depicts the cabin temperature control subsystem components which are all checked by the BITE in this fault isolation example. Those components include the individual pack controllers (3), the zone temperature controllers (5), the ECS/APU interface controller which contains the BITE, zone trim valves (5), pack ram air door actuators and turbine bypass valves (3), temperature sensors (18), and temperature selectors (6).

4.1.1 Subsystem Operation Description: To understand how the fault isolation functions in this subsystem, a discussion of the basic operation of the subsystem and the components in the subsystem is first presented below.

a. System Operation: The air-conditioning system is supplied by bleed air from either the engines, an on-board APU, or from ground carts. Three air-conditioning packs supply air to five temperature controlled zones. Each zone temperature is individually controlled. The three pack discharge temperatures and the APU speed are programmed as a function of zone demand.

(1) Automatic Temperature Control: Inputs from temperature selectors on the flight deck panel (labeled COCKPIT, GALLEY, FWD CAB, CTR CAB, AND AFT CAB in Figure 6) and from sensors in each zone and zone supply duct are connected to zone temperature controllers. The zone controllers operate electric motor driven trim valves and provide demand signals for the pack controls and APU controls.

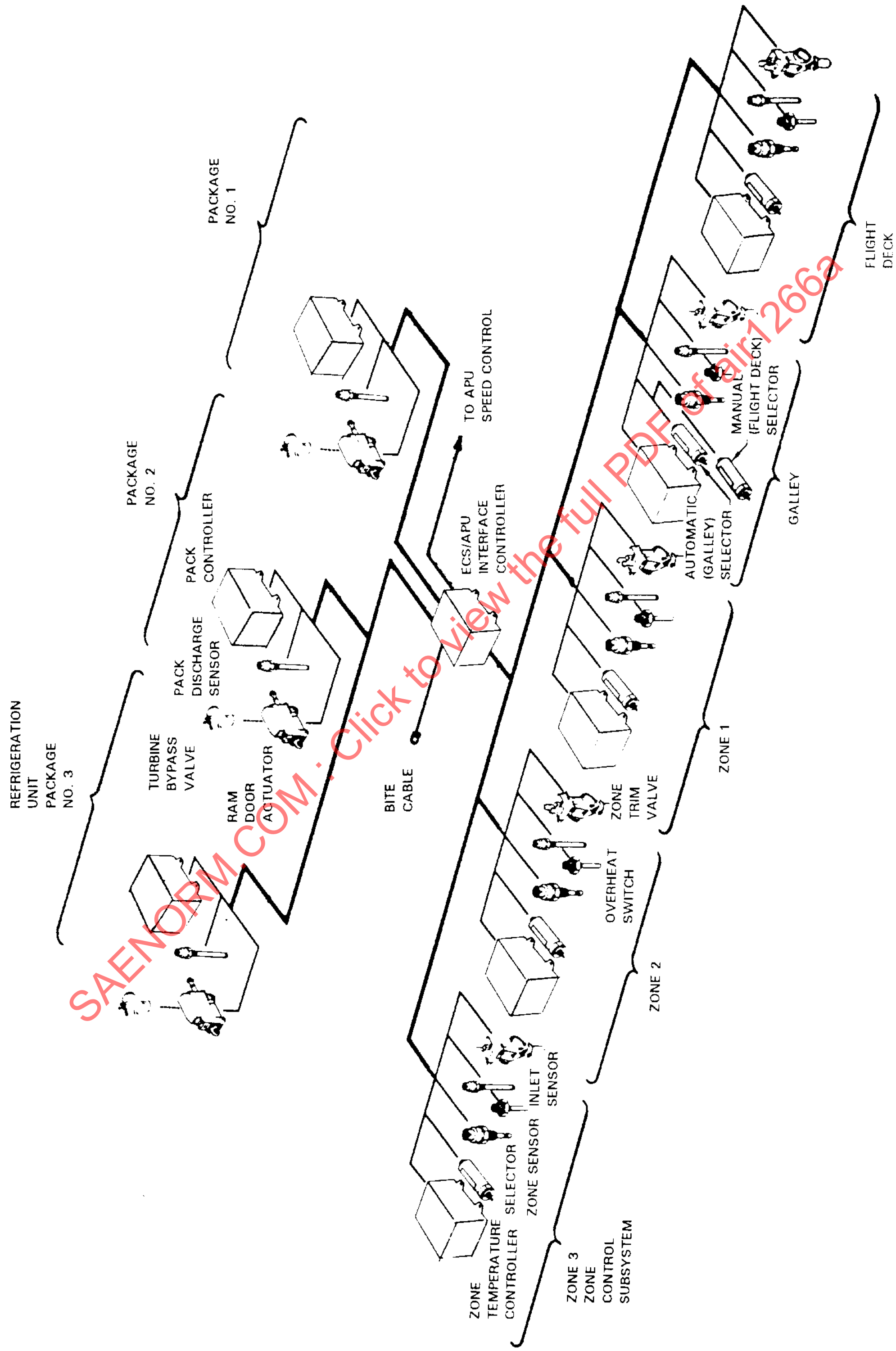


FIGURE 5 - Component Pictorial Tabulation
Cabin Temperature Control Subsystem

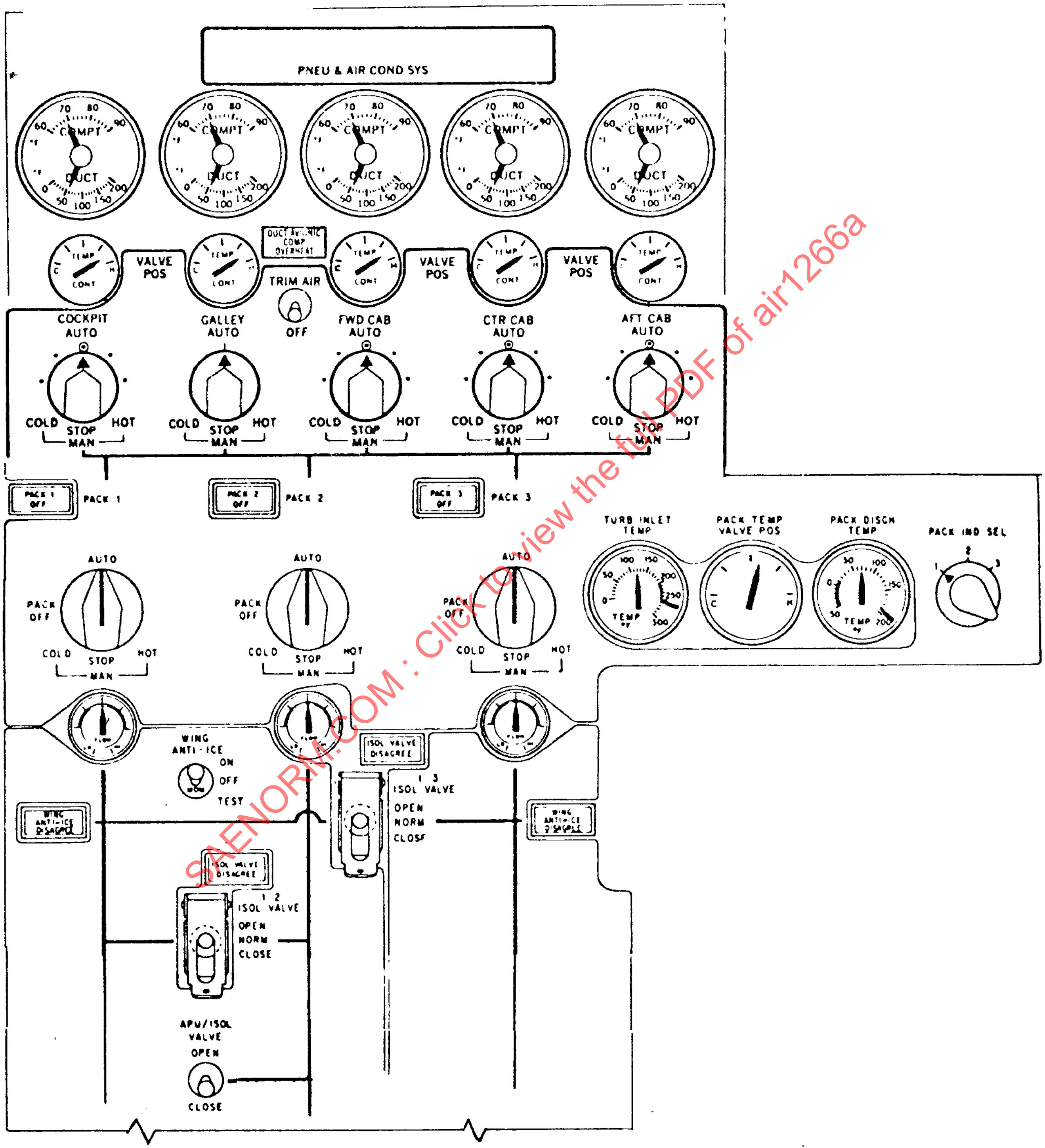


FIGURE 6 - Flight Deck Panel
Zone and Pack Temperature Control

4.1.1 (Continued):

The pack discharge temperatures are individually controlled to the appropriate zone demands by modulating electric motor driven actuators coupled to ram air and turbine bypass valves.

(2) Manual Temperature Control: Manual backups are provided to control zone and pack temperatures.

b. Flight Management of the Zone and Pack Temperature Control System: In order to properly manage the system, a minimum set of instruments and indicators was devised for the flight crew to monitor system performance and evaluate manual operation. Readings from these instruments also form an integral part of the system fault isolation scheme.

(1) Flight Deck Panel Instruments: The flight deck panel (Figure 6) is provided with instruments for the following indications laid out in a logical manner from top down:

Individual zone temperature (COMPT) - Five

Individual zone inlet duct temperature (DUCT) - Five

Individual zone trim valve positions (VALVE POS) - Five

Pack off lights (PACK 1,2,3 OFF) - Three

Pack turbine inlet temperature (TURB INLET TEMP), bypass valve position (PACK TEMP VALVE POSITION), discharge temperature (PACK DISCH TEMP) individually selectable for each of the three packs (PACK IND SEL)

Individual pack flow indicators (FLOW) - Three

Comparison can be made between instrument readings and known limits of acceptable performance under various conditions for fault monitoring.

(2) Out-of-Tolerance Indicators - The following indicators are provided to signal gross out-of-tolerance conditions:

DUCT/AVIONIC COMP. OVERHEAT light - This light illuminates when:

(a) Any one of the five zone inlet overheat thermal switches activates.

(b) A failed trim air duct in the avionics compartment is sensed by a compartment overtemperature switch.

4.1.1 (Continued):

Individual ZONE INLET OVERHEAT indicators (five, located on a separate maintenance panel) - The appropriate indicator lights when a zone inlet overheat switch activates along with the DUCT/AVIONIC COMP. OVERHEAT light. This aids fault isolation of the particular zone inlet that caused the overheat.

Individual PACK OFF lights (three) - The appropriate light illuminates when the pack flow control closes due to pack overheat, loss of supply pressure, or when packs are manually selected OFF.

TRIM PRESSURE HI light (located on Master caution panel) - Illuminates when a pressure switch indicates trim manifold pressure is high due to trim regulator failure.

4.1.2 Fault Isolation Preliminary Design Analysis: A preliminary design analysis was conducted following the guidelines listed in 3.2. As a result of the analysis the requirements were established for the detail design. Fault isolation equipment and techniques became an integral part of the total subsystem design.

Certain hardware design considerations were dictated by the results of the preliminary design analysis:

a. Consideration was given to both active failures (those which display a positive failure indication at the flight deck panel), and to passive failures (those failures which do not display a positive failure indication at the flight deck panel).

b. Application of the fundamental design philosophy required that BITE be utilized and that it be significantly more reliable than the control units being tested. Simplified detection schemes as well as simplified circuitry were utilized as much as possible to achieve high reliability. The BITE was designed to be operated by the ground maintenance crew, on the ground, with pneumatic power off, and only electrical power on. Thus, all electrical components are directly checked but must be checked through software logic procedures.

c. The BITE was designed with the assumption that only single LRU failures occurred and would not isolate multiple LRU failures in all cases (another design simplification for reliability).

d. The BITE was designed to be capable of operation at the extremes of the aircraft temperatures and pressure environment on the ground. This presented special problems when checking some LRUs such as temperature sensors.

4.1.2 (Continued):

e. The design philosophy was to use the BITE only when an active system failure had been indicated by the flight crew.

f. There was no memory storage of information designed for this system which would retain data of intermittent faults (i.e., only occurring in flight). Testing for intermittent operation of the LRUs which are all electrical was not a requirement.

4.1.2.1 Preliminary Design Analysis Findings - Software: Design analysis showed that with adequate instrumentation in the cockpit the use of pattern-of-cockpit-indication methods (a procedural program) provided the most cost-effective method of fault isolation for much of the subsystem. The LRU supplier cooperated with the airframe manufacturer (see 3.2.2.1.d.), and provided the detail design data necessary to produce an adequate software logic procedural program.

4.1.2.2 Preliminary Design Analysis Findings - Hardware: The LRU supplier implemented the procedural programs with on-board GSE (Manual BITE). BITE circuitry was designed with adequate flexibility and located such that several adjacent LRUs could be checked out from a single LRU containing all the BITE circuitry rather than repeating the BITE circuitry in each LRU. These concepts were selected as those most cost-effective of the concepts available to the LRU supplier (see 3.2.2.1).

4.1.3 Design Implementation: The completed fault isolation design utilizes a software logic procedural program where information obtained from the flight crew generates a sequence of ground maintenance crew procedures that rely heavily on the BITE hardware as a fault isolation tool.

4.1.3.1 Maintenance Manual Design Procedure: Implementing the use of maintenance manual procedures for fault isolation requires the installation of sufficient instrumentation on the cockpit instrument panels for the flight crew to be able to detect a failure in an aircraft subsystem, take any necessary corrective action, and note the suspected failure in the flight log. The ground maintenance crew can then utilize the flight log to determine which system was faulty during flight and utilize the flight deck panel instruments and BITE to isolate the failure to the proper LRU.

Certain infrequent types of faults would necessitate the use of special information in the maintenance manual to isolate the fault, such as faults in ducts and heat exchangers or aircraft wiring which are not directly fault isolated by the BITE.

During the detail design phase, tables are devised to present the possible flight-engineer-panel indications of system malfunction and the possible causes of those indications from which fault trees are produced to show the step-by-step procedures to be followed to arrive at the correct problem element. This type of design data is lengthy and only portions are presented as an example. Complete data would be included in the FIA document.

4.1.3.1 (Continued):

Table 1 presents three of the fault indication patterns for the ECS that can be indicated to the flight crew. If a fault does occur, the pattern or a representative code of the pattern is to be noted by the flight crew in a logbook entry. The ground maintenance crew then utilizes that pattern or pattern code in order to follow a logic tree process to lead to the faulty LRU responsible for the fault indications. A sample logic tree that leads to the zone temperature controller as the faulty LRU is presented in Figure 7. The logic tree corresponds to fault pattern No. 6 only in Table 1. The BITE switch position steps are shown in Figure 8 and Table 2.

The following considerations apply to the fault isolation analyses data:

a. Proper electrical power is assumed to be available to the system.

b. MEL dispatch configuration is not analyzed. The failure modes listed in Table 1, column 2 are considered to be the first failure for the aircraft system.

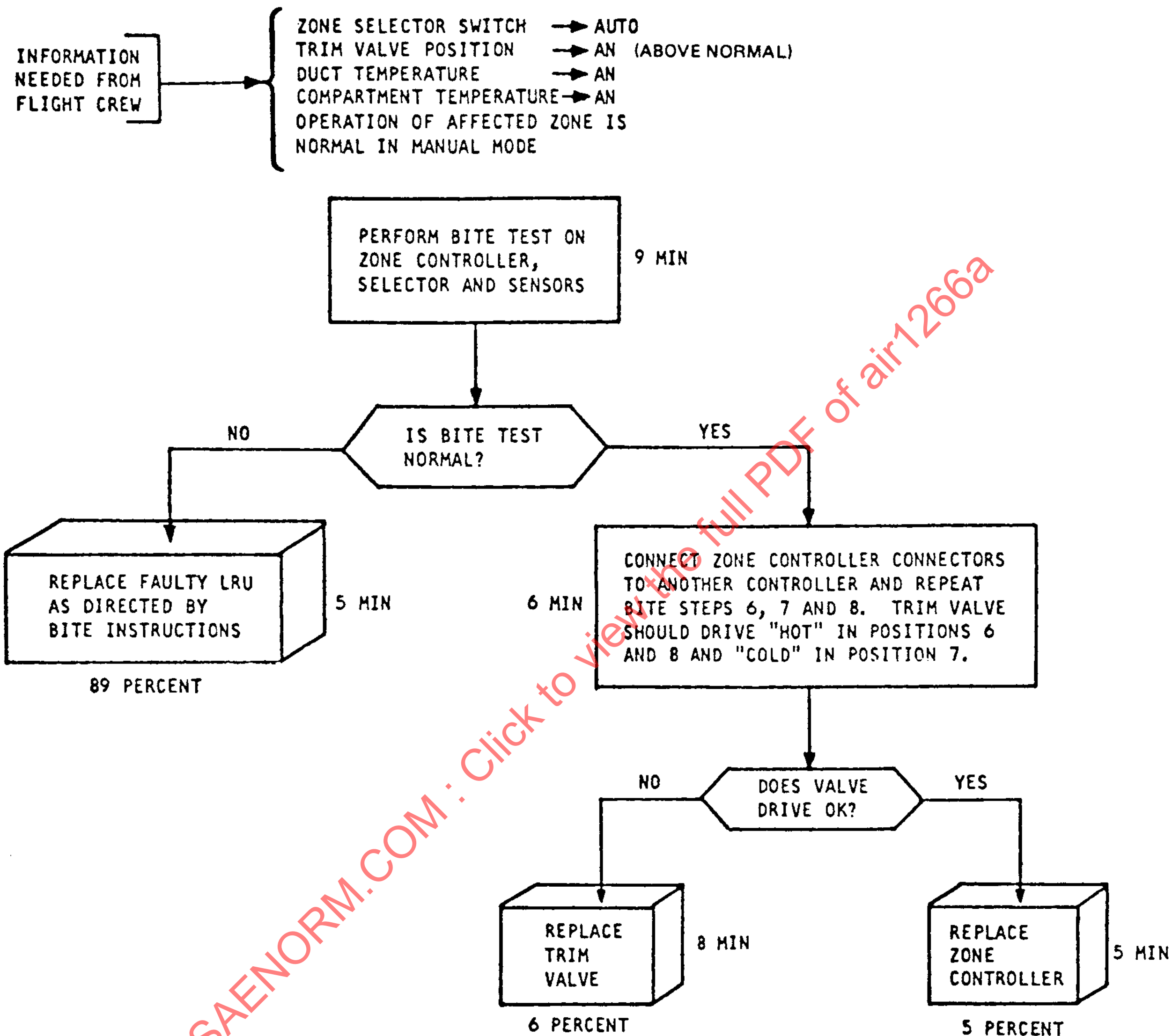
c. The time required to isolate a given fault is determined by adding the task times shown on the fault trees. Compartment access time is not included in the time estimates.

From data such as this, flight crew and maintenance crew manuals are devised that are extremely efficient as aids for rapid, accurate, and thorough fault isolation to the LRU level (see 4.1.3.3).

4.1.3.2 Hardware Design: All the system controllers are designed with analog circuitry. The BITE for the zone and pack temperature control system is located in the APU/pack demand controller unit. This unit is mounted centrally between all five zone temperature controllers and the three pack temperature controllers on the aircraft. This location allows a test cable from the BITE to be connected to any one of the zone or pack temperature controllers, each of which is the focal point for all the LRUs in that particular system (see Figure 8).

Necessary BITE operating instructions are printed on the face of the unit containing the BITE. The instructions are written in a step-by-step fashion to guarantee that all operating conditions are proper before manually interrogating the system components.

A multiposition BITE switch is located on the unit. The switch is positioned sequentially, stopping if an LRU fault is indicated. Sequential operation of the BITE simplifies the BITE design by allowing previously checked properly operating components or component elements to be utilized in checking subsequent component or component elements. The BITE functions are described in Table 2.



NOTES:
1. PERCENT BESIDE BLOCKS IS PROBABILITY OF FAILURE FOR THIS SET OF INDICATIONS.
2. TIME BESIDE BLOCKS IS ESTIMATED FAULT ISOLATION TASK TIME.

FIGURE 7 - Fault Tree No. 6
Zone and Pack Temperature Control

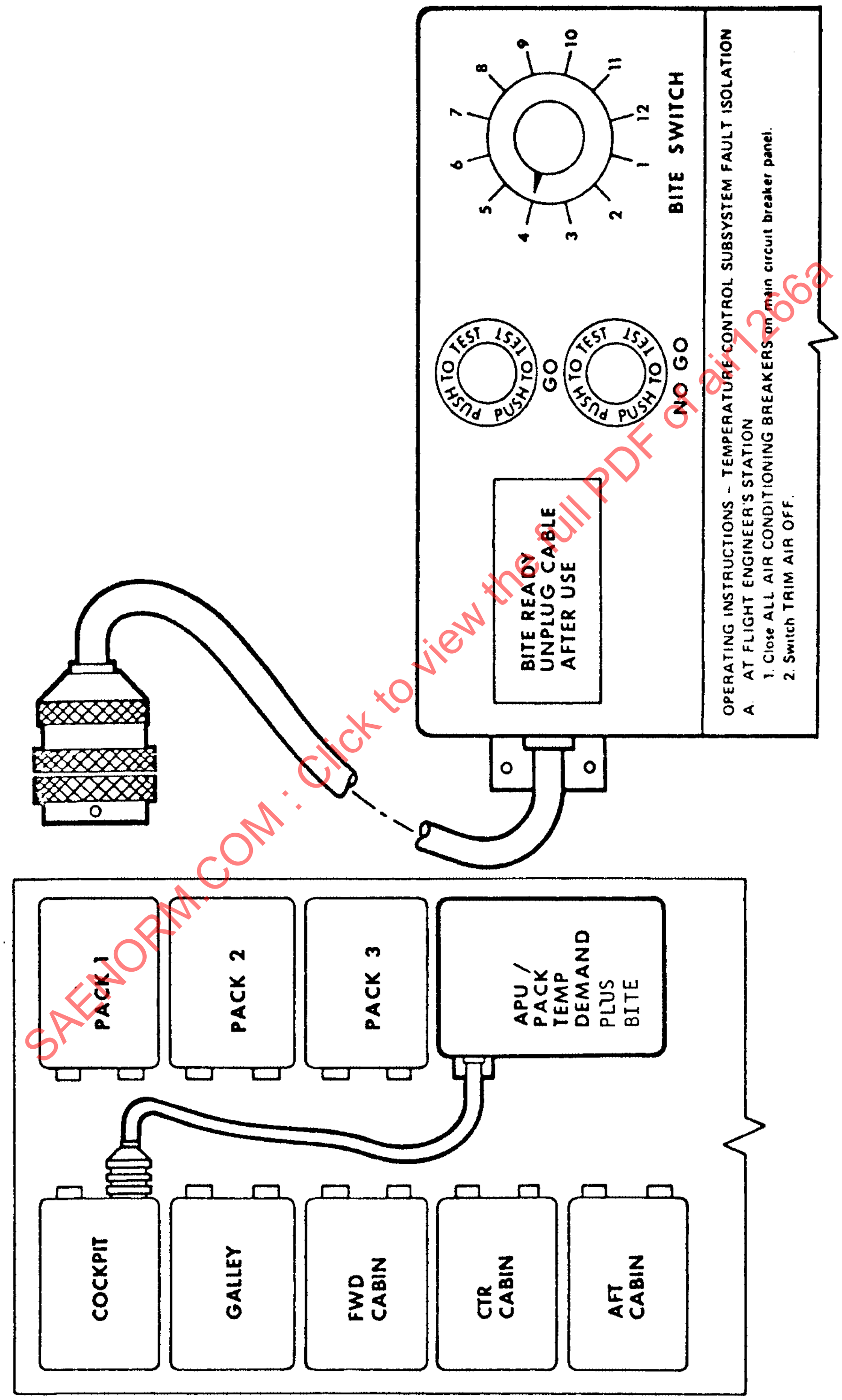


FIGURE 8 - Temperature Controllers and BITE Box Installation

TABLE 1 - Fault Indication Patterns

[Tree No.] Pattern No.	Indications	Faulty LRU(s)	Probability of Occurrence: Mode Failure % of System	Probability of Occurrence: Mode Failure % of Pattern	Pattern No. of System Failure
5	Trim Air Press HI-Light - blinks or cycles "ON." Trim air ducting may be noisy and/trim valves may cycle excessively.	1. Unstable trim Press. Regulator operation.	3.6	100	3.6
6	Zone Sel. Switch - Auto Trim Valve Pos. - AN (Above Normal) Duct Temp - AN Comp Temp - AN System operation for affected zone normal in MANUAL mode.	1. Zone Controller - 5 failure modes	5.9	37	15.8
		2. Zone inlet temp sensor fails OPEN.	2.7	17	
		3. Zone temp sensor fails OPEN.	5.4	34	
		4. Zone temp selector pot fails open on one end or the wiper. Also applies to Galley Temp Selector (on Galley Panel).	1.0	6	
		4A Zone Temp Selector segment switch failure. Excluded from tree because of low probability.	0.04	0.24	
		5. Trim Air Valve - CLOSED (COLD) Limit Switch fails OPEN.	0.8	5	
7	Zone Sel Switch - AUTO Trim Valve Pos - BN (Below Normal) Duct Temp - BN Comp Temp - BN System operation for affected zone normal in MANUAL mode.	1. Zone Controller - 5 failure modes.	7.1	70	10.1
		2. Zone inlet temp sensor fails shorted.	0.3	3	
		3. Zone temp sensor fails shorted.	0.3	3	
		4. Zone temp selector pot fails open on one end or the wiper. Also applies to Galley Temp Selector (on Galley Panel)	1.0	10	
		4A Zone Temp Selector segment switch failure (excluded from tree because of low probability).	0.05	0.5	
		5. Trim Air Valve - OPEN (HOT) Limit Switch fails open.	1.3	13	

TABLE 2 - BITE Functions
Air Conditioning Temperature Control

BITE Switch Position	Pack Subsystem Indicates Fault In	Pack Subsystem Test Method	Zone Subsystem Indicates Fault In	Zone Subsystem Test Method
1	APU/pack demand controller	Inject signal into discriminator and check sum of outputs of pack scaling amplifiers	APU/pack demand controller	Same as pack
2	APU/pack demand controller	Inject signal into discriminator and check APU speed demand signal for maximum cooling	APU/pack demand controller	Same as pack
3	APU/pack demand controller	Inject signal into discriminator and check APU speed demand signal for maximum heating	APU/pack demand controller	Same as pack
4	Pack controller	Check bridge power supply output	Zone controller	Check bridge power supply output
5	Pack controller	Inject signal into main channel amplifier and check amplifier output	Zone controller	Inject signal into duct amplifier and check duct amplifier output
6	Pack controller	Override sensor bridge output with signal to produce full on heating output	Zone controller	Same as pack
7	Pack controller	Override sensor bridge output with signal to produce full on cooling output	Zone controller	Same as pack
8	Pack controller	Drive actuator in more heat direction (as in 6)	Zone controller	Same as pack
9	Pack controller	Override sensor bridge output to produce nulled output	Zone controller	Same as pack
10	Pack sensor	Check output of bridge for proper sensor input	Check inlet (duct) sensor	Check output of bridge for proper sensor input
11	No test	--	Zone sensor	Check output of bridge for proper sensor input
12	No test	--	Zone sensor	Check selector output signal

4.1.3.3 In-Service Operation: From the preceding data, the complete flight crew and ground maintenance crew manuals are devised that are used in-service for system fault isolation to the LRU level. Figures 1, 2, and 3 show the appropriate pages of the manual that pertain to the fault pattern example in 4.1.3.1. Figure 1 is from the flight crew manual showing the pattern of cockpit indications observed during the example fault and the code assigned to that pattern. Figure 2 shows the associated ground crew manual page dealing with location of BITE hardware and accessibility. Figure 3 shows the formal step-by-step procedure the ground crew is to follow to isolate the faulty LRU.

4.2 Automatic BITE Example:

A second example is presented of automatic BITE implementation for a system very similar to that described for manual BITE. The subsystem operation is similar to that described in 4.1.1. The fault isolation preliminary design analysis (4.1.2) information is also similar. The difference is in the implementation. This example uses a digital microprocessor architecture with the microprocessor software performing the BIT functions.

4.2.1 Hardware Design: This example based upon controller electronics that are built with digital, microprocessor architecture provides a higher level of automatic BITE operation. Much of the maintenance manual procedure from the manual BITE example (4.1.3.1) are implemented in embedded software (called firmware) in the controller computer memory.

The example controller is the cabin zone temperature controller. One cabin zone controller controls four cabin zones, commands the pack temperatures required, and controls the required APU airflow. The cabin temperature controller includes BIT functions to fault isolate and identify components associated with the controller (including the controller itself). The controller provides fault isolation for the respective components as shown in Figure 9.

The BIT operates in two basic modes; continuous monitoring and initiated BIT.

4.2.1.1 Continuous Monitoring: During normal system operation, in-flight or on the ground, the controller monitors the associated components on a periodic, on-line basis such that all BIT tests are performed at least once every 5 s. This continuous monitoring mode functions without interfering with normal system operation. The controllers do not provide fault isolation information to the flight crew but do provide fault status indication. System malfunctions are determined from these control panel indications and flight crew deductions.

At regular intervals, key signals are sampled, digitized, and read into the controller microcomputer. The microcomputer, under control of software programs in nonvolatile read-only memory (ROM), is used to isolate faults in the system to a LRU. All parameters read in by the microcomputer are compared with fixed values stored in nonvolatile memory. If a value is out of tolerance, a fault is recorded in a random access memory (RAM). Suitable software filtering is employed to prevent nuisance fault recording. Each fault detected must be similarly detected on two or three additional successive passes before it is logged and displayed as a fault. In this way both continuous and intermittent faults are detected and recorded. All LRUs associated with the

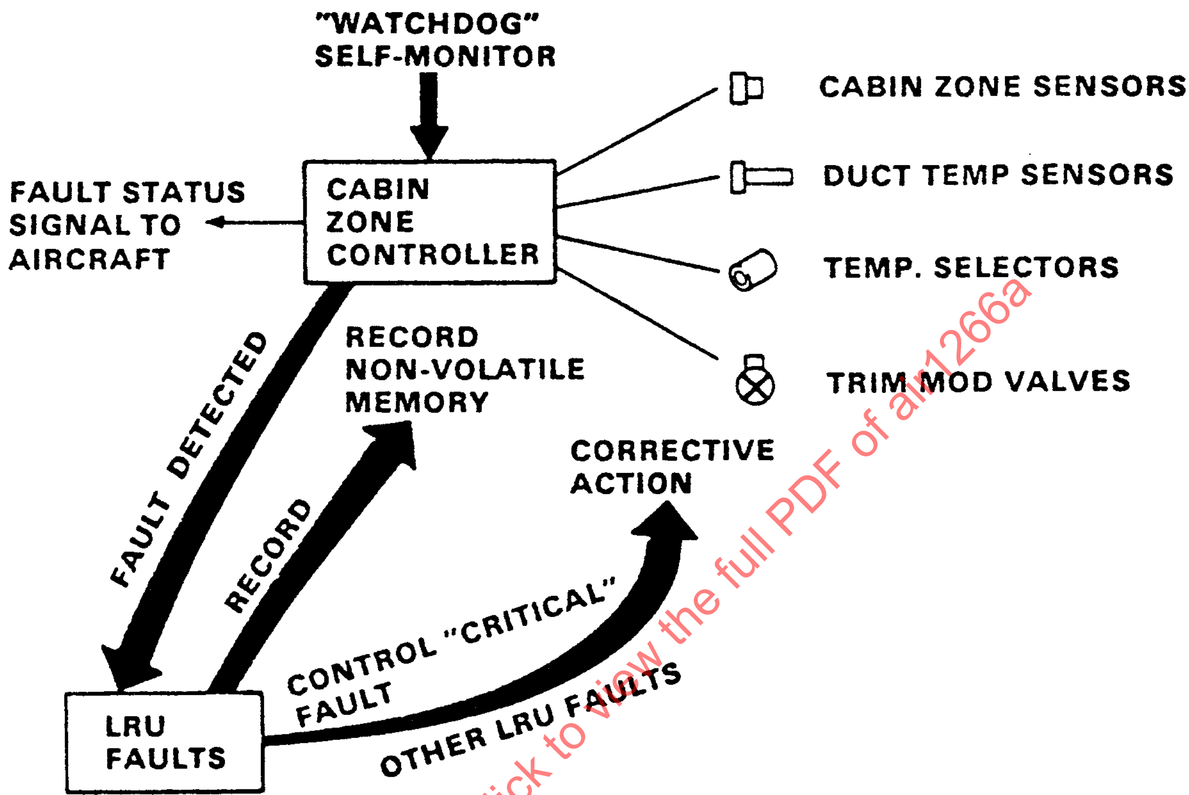


FIGURE 9 - BITE Continuous Monitoring Mode
Cabin Zone Subsystem

4.2.1.1 (Continued):

controller are tested, including the controller itself. The tests consist of monitoring the temperature sensors, temperature selectors, and valve and actuator motors for open and short circuits. When all tests are complete, the fault is isolated to a particular component and this information is stored in an electrically alterable read only memory (EAROM) for later interrogation. One section of the memory will store faults detected during nine previous flights or since the memory was last cleared. Oldest information is automatically dropped from memory. The aircraft squat switch is connected to the controllers to indicate the start of a new flight.

Adaptive fault tolerant operation of the system is also provided for certain system failures. During continuous monitoring, certain faults will cause the controllers to eliminate various control signals. For faults within any cabin zone control loop (selector, sensors, trim air valve, controller), that zone demand is eliminated from pack and APU command discrimination. Drive signals to the trim air valve are shut off, but the other zones continue to operate normally. If a controller critical fault occurs, all drive signals are shut off and the controller automatically signals backup control functions to operate.

4.2.1.2 Initiated BIT Mode: The initiated BIT mode is used to interrogate fault memory and to verify that a replaced LRU passes the appropriate electrical tests. This mode functions when the aircraft is on the ground, no pneumatic source operating, and the pushbutton controls on the controller front panel are pushed in proper sequence (see Figure 10). In this mode the controllers do not perform their normal function. Pushing the pushbuttons will cause controller self-tests to be performed and faults stored during continuous monitoring of the last and previous nine flights to be displayed as shown in Figure 10 and described in Table 3. This ability to distinguish between last and previous flight faults allows maintenance crews to determine whether the fault just occurred or whether it may have been occurring during previous flights as well. Nine previous flights were chosen so that intermittents which do not cause flight crew action but were detected by BIT will drop out of memory and not cause maintenance crew confusion. The nine flights, however, does allow sufficient storage time of data for faults causing flight crew action so that the aircraft can return to a facility where maintenance is to be performed and the BIT data interrogated. The number nine represents a typical maximum number of flight legs between maintenance bases for this type of aircraft, although numbers up to 64 have been considered for other aircraft.

TABLE 3 - BITE Tests of Subsystem Component Output Functions

LRU Type	Tests Performed
Sensors	Checked for open or short circuit-level beyond possible -65 to 200 °F sensed ambient temperature.
Selectors	Open potentiometer wiper arm, open or shorted windings. Check for selection inaccuracy beyond ±2 °F.
Controller-APU/Pack Demand	Inject inputs into pack and APU demand amplifier and check for proper output.
Controller-Zone or Pack Temperature	Check bridge power supplies, inject inputs to control amplifier and check proper outputs, inject input and check output drive circuitry performance (assuming valve is operating properly from prior manual test).

In addition to tests performed during continuous monitoring, certain components are automatically put through a preprogrammed sequence when the verify button is pressed to facilitate testing their operation. This is used for verification after maintenance, as well as for flight readiness. The controller has indicators on the front panel, one for each of the LRUs associated with the controller, and one for the controller itself. A GO indicator provides a positive indication that a test has been completed and no faulty LRU detected.

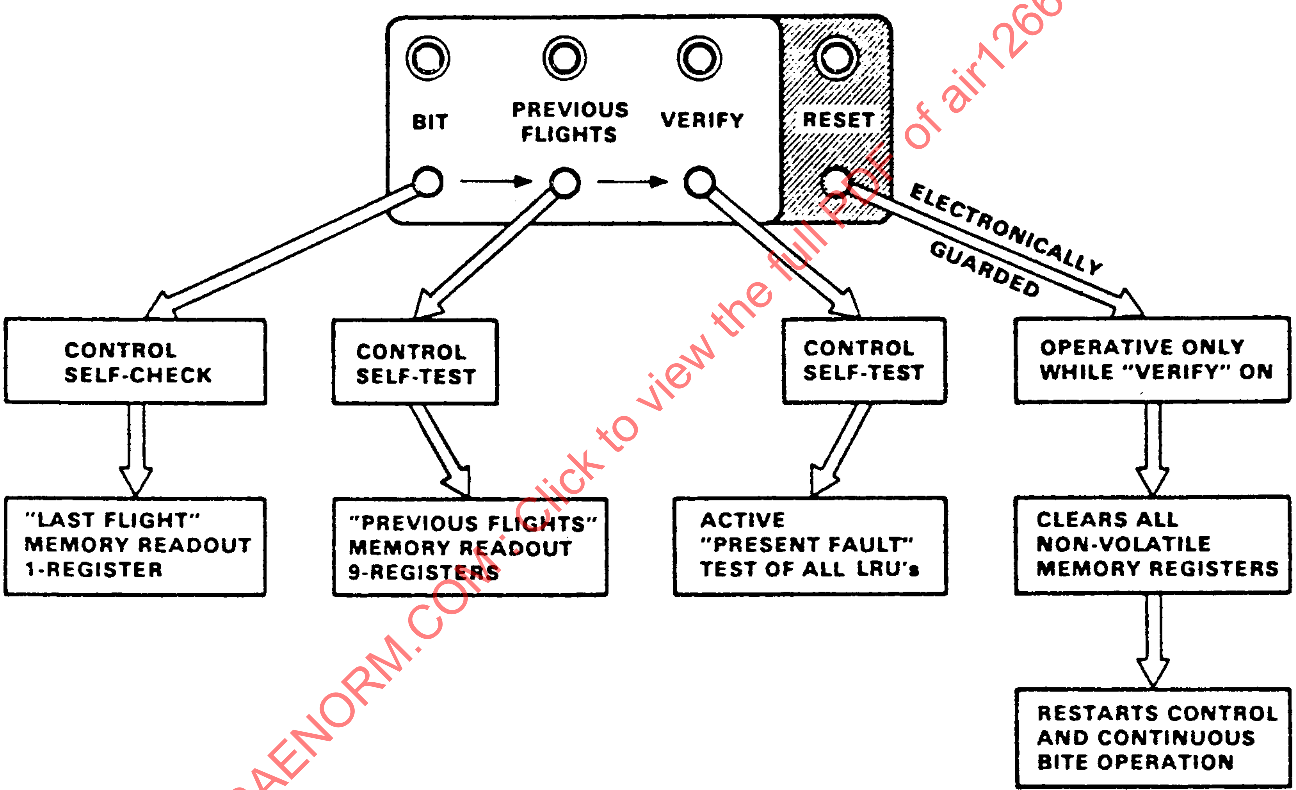


FIGURE 10 - BITE Initiated Mode Pushbutton Operation