ICAS-88-6.2.2 A Review of Requirements, Design Considerations and Resulting Experience for Extended Range Operation of Two-Engine Airplanes

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The purpose of this paper is to briefly discuss some the principal aspects of extended range operations. The sources of information employed in the discussion of requirements are the established standards of the International Civil Air Organization (ICAO) and the national standards of the United States, United Kingdom, France, Canada, Australia, New Zealand and others. Design considerations are based on studies and work accomplished by Boeing Commercial Airplanes in modifying, and achieving extended range type design approval of, 737, 757 and 767 airplanes and associated propulsion systems. Finally, operational experience data is from in-service records of fourteen airlines now using the Boeing twins approved for extended range operations.

I. Requirements for Extended Range Operations

In this discussion the term "requirement" is used in the broad sense to cover the body of statements which vary from established laws to standards to advisories. To differentiate between these categories for the nations that have approved extended range operations would be a major work in itself and would not appreciably enhance an understanding of the engineering and operational issues and results.

There are special aspects of the subject of requirements. First, the level of detail is significant. Most of the individual national requirements listed above are approximately equivalent in level of detail and all are substantially more detailed than those of ICAO. The ICAO standards and guidance fully define extended range operations and list all pertinent type design and operational factors to be considered in an approval process. They do not, however, provide detailed discussion or guidance relative to each of the factors. Second, the equality of requirements, based on the identity or equivalence of words, is not always meaningful. In a few cases the interpretation of nearly identical words by different national certifying authorities has resulted in significant practical differences. For example: what constitutes "new" versus "derivative" engines is a significant interpretation issue. Also, the weighing of "applicable operational experience" as applied to compliance with operational requirements has widely varying interpretations.

Having noted the differences that arise from interpretations and level of detail, it is appropriate to discuss the structure of requirements, and the actual significant differences. The ICAO and all of the national standards are very similar with regard to structure. Airworthiness or type design requirements (requirements to be met by the airframe and propulsion system manufacturers) are clearly separated from operational requirements (compliance to be shown by the airline operator). The list of items to be considered in each area is generally the same. Principal items are identified by Table 1.

Table 1

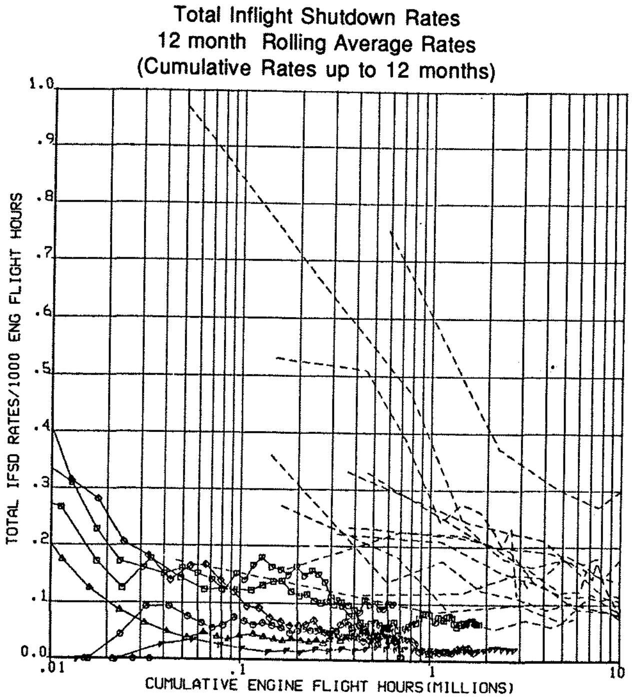
Airworthiness (Type Design) Requirement Items

- Propulsion System Reliability
  - Experience base prior to approval consideration
  - Approval review standards and processes
- Airframe System Reliability including:
  - Hydraulic power
  - Electric power
  - Pnuematic power
  - Equipment cooling
  - Navigation
  - Cargo fire suppression
- Airframe System Performance including:
  - Navigation accuracy
  - Communication system coverage
  - Cargo fire suppression system time capability

Operational Requirements

- Area of operation (allowed distance from alternate airports).
- Definition of adequate and suitable alternate airports.
- Required weather at suitable alternate airports
- Fuel and oil supply requirements
- Dispatch requirements
  - Crew training
  - Disptach controls and MMEL
  - En route controls
- Maintenance standards
- Control of airplane modifications
- Reliability reporting

These lists are essentially indentical for all of the national standards. However, looking at the details that expand on the listed items, there are several significant national differences. In the airworthiness area the principal difference is the propulsion system experience base required prior to consideration of extended range type design approval. The United States requirements and interpretation require 250,000 engine-hours (world fleet) prior to approval condsideration, with approval allowing operation to 120 minutes from alternate airports. The standards of the Certifying Authority of France (DGAC) allow consideration of extended range approval for incremental times from alternate airports (that is 75, 90, 105 minutes) with lesser levels of engine-hour experience. The DGAC and FAA standards of judgement are similar but the levels of required engine hours are, in the case of France, graduated and in the case of the United States ungraduated. This difference is not casual, in that it reflects two distinct viewpoints toward engine relibility information. This is illustrated by Figure 1. This figure clearly indicates a very large difference in the rate of reliability maturity for engine types entering service prior to 1981 as compared to types entering service after 1981. When the present extended range requirements were formulated (1983-4) it was not possible to account for the reliability characteristics being demonstrated by the recent derivative and new technology engines. In fact, at that time a 250,000 engine hour requirement seemed to many to be quite forward looking. Experience from 1984 to the present indicates that the 250,000 engine hour requirement does not account for the present situation. Thus the maturity requirement deserves further review and update, both to resolve



-------Dashed lines: Early turbojet and turbofan engine types entering service prior to 1981:

JT3C JT3D JT4 AVON
SPEY RB211 JT9D JT8D
CONWAY 805-23 805-3 CF6

□◸◇◸◇△Symbols: Derivative and new technology engines for twins entering service after 1981:

535C 7R4D 80A 80C2
535E4 PW2037 CFM56-3

FIGURE 1

FAA-DGAC differences and to account for presently achievable reliability maturity trends. The real issue to be resolved by a review/requirement-update process is to define factors to be accounted for when considering extended range approval at points much prior to the 250,000 engine hour point. Such factors are known to include: The technology transfer process from prior engine designs, use of improved materials and design techniques, use of advanced ground and air test programs, additional redundancy and self test features, and the distribution of accumulated engine hours to account for factors such as the number of high time engines and the number of operators that have flown and maintained these engines. It is believed important to undertake the review/requirement-update process in the near future to accomodate engines that have recently entered service and those planned to be available in the 1988 to 1995 time period.

There are several differences in operational requirements:

- The Canadian requirements (TP6327) do not differentiate between airplanes with two, three and four engines for most factors, including flight dispatch limitations. The compliance advantages that are available to three and four engine airplanes are only those which are inherent to one engine-out performance and propulsion system reliability. Other extended range requirements (e.g. cargo fire suppression time or communication system reliability) are the same for all airplanes operating more than 60 minutes from alternates at one engine out speed.

- Only the FAA limits both the "mean" and "maximum" single-engine diversion time.

- The British CAA requirement (CAP 513) has en route alternate airport crosswind limitations in addition to visibility limitations.

In summary, the detailed work done by the ICAO Extended Twin Operations (ETOPS) study group in 1983 and 1984 and cooperative work done by a number of national certifying authorities accomplished a great deal toward achieving uniformity of standards. Despite this effort, there are still some significant differences in requirements and in interpretations. The nature of these differences indicate that further work to refine requirements is appropriate.

II. Design Considerations

Prior to commencing extended range operations both the type design and the operations requirements must be met. This portion discusses compliance with the type design requirements. There are several methods of compliance.

For propulsion systems the methods of compliance are very direct. First, the propulsion system must have accumulated a satisfactory number of hours for judgement of its reliability. Generally, this is 250,000 engine-hours of world fleet experience and approximately half of that on the particular airplane/engine combination being considered for extended range operation. Second, the record of all events which suggest possible facets of unreliability must be investigated (inflight shutdowns, unscheduled maintenance, malfunctions during ground operation, flight events resulting in thrust reductions, etc.). Third, the corrective actions (configuration changes, maintenance procedures, and operations procedures) taken in response to the record of events must be identified and evaluated. Fourth, considering the record of events and corrective actions taken, a projection of expected inflight shutdown rate is made. This rate must meet numerical reliability requirements (probability of loss of all thrust due to all independent causes should be 10^{-8} per flight hour or less and the probability of loss of all thrust due to design related causes should be 10^{-9} per hour or less). Finally, the process outlined by the four items above leads to the definition of configuration, maintenance, and operations standards that must be accepted as a precondition for extended range type design approval.

A similar process is followed for essential airplane systems (hydraulic power, electric power, cabin pressurization, equipment cooling, communication and navigation, cargo fire suppression and others). As with the propulsion system process, the review of airplane systems may result in the definition of required standards for modifications, maintenance and operations procedures. In addition, for airplane systems, the process may also lead to the addition of added system capacity (for example, more fire suppressant), or to the incorporation of added redundancy (for example, an added electric generator capable of powering essential instruments). It might also lead to the addition of added monitoring systems (for example, a device to check electronic equipment cooling air flow), or changes to the requirements for equipment that must be operational at dispatch (Master Minimum Equipment List).

The results of the propulsion and airplane system reviews lead to definitions of configuration, maintenance and operations requirements for extended range operations. The three figures provided below summarize the configuration changes for extended range approval for 737, 757 and 767 airplanes (Figures 2, 3 and 4).

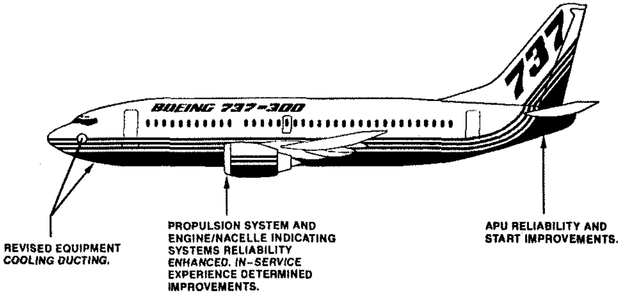


FIGURE 2

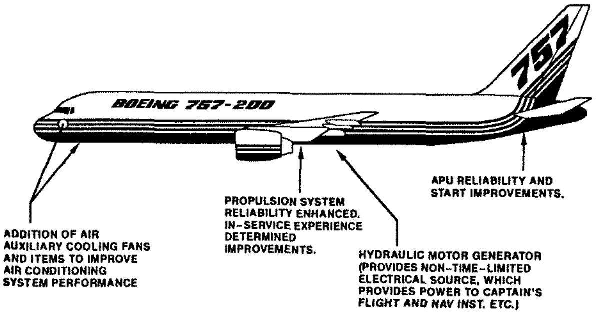


FIGURE 3

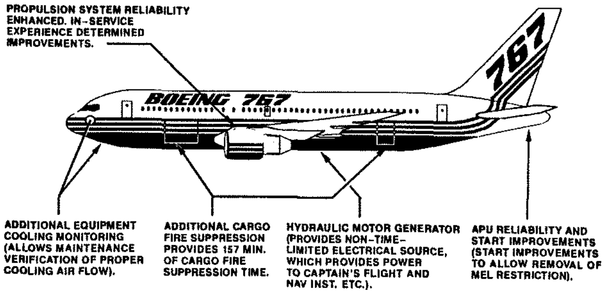


FIGURE 4

III. Extended Range Operation Experience

There were a number of extended range operations with 737, 767, BAC111 and A300 airplanes prior to FAA issuance of Advisory Circular 120-42 in May 1985. These included, but were not limited to, the use of 737 in the southwest Pacific regional area by Air New Zealand, Air Nauru, and others; the use of 737s and A300s on Caribbean routes; the use of 767 in Caribbean service by Air Canada and use of 767 in North Atlantic service (February 1985) by TWA. All of these operations were successful. But, in-service experience data, of the type required to provide a quantified evaluation backed up by an engineering evaluation of specific events of interests, was not formally brought together.

In May of 1985 extended range operations with the 767, conducted in accordance with the requirements of Advisory Circular 120-42, were begun and a thorough database has been kept ever since. A similar database has been kept for the 757 starting in January of 1987. For each of these airplane models a complete fleet (all airplanes) database and a database just for those airplanes equipped and maintained in accordance with extended range configuration and maintenance standards has been kept. Since the number of configuration and maintenance changes required for extended range operations is small (see Figures 2, 3 and 4) in most cases the whole fleet data can be employed in assessing the reliability of airplane and propulsion systems used for extended range operations.

The following series of paragraphs illustrate some of the steps taken to evaluate the reliability of extended range operations.

A. Total 767 Fleet and Extended Range Experience.

Figure 5 indicates the size of the 767 fleet and the number of airplanes equipped for extended range operations as of December 31, 1987. Forty-two percent of the fleet is extended range equipped and the percentage is increasing rapidly. It also indicates the total accumulated fleet flight hours and the number of extended range operations (31,951). The rate of accumulation of extended range operations is approximately 1500 per month.

767 Fleet Data

Total and Extended-Range Operations (EROPS) Equipped Aircraft

As of December 31, 1987

767 Fleet Operators	Number of Airplanes		Total Estimated Flight Hours	Total Estimated* EROPS Flights (Preliminary)	EROPS Usage (Flights/Month) November 1987
	Total	EROPS Equipped			
American	29	16	260,600	5,662 North Atlantic Crossings	364 North Atlantic
Air Canada	14	4	174,042	1,390 North Atlantic Crossings 1,950 Caribbean	69 North Atlantic 35 Caribbean
All Nippon	29	0	172,689		
Ansett	5	0	45,718		
Air New Zealand	4	4	19,600	5,300 Tasman and Pacific Regional	320 Tasman, Pacific
CAAC - (Bej)	4	4	13,926	197 China Sea	17 China Sea
Britannia	5	0	54,055		
China Air	2	0	23,465		
Delta	24	0	241,700		
Egypt Air	3	3	33,632	128 Trans-Sahara	17 Trans-Sahara
El Al	4	2	44,101	Over 590 North Atlantic and Africa	
Ethiopia	3	3	22,700	980 Indian Ocean, Trans Himalayan	35 Indian Ocean, Himalayan
Japan Air Lines	11	5	25,100		
Kuwait	3	3	9,400		
Lan Chile	2	2	12,969	Has Flown South Atlantic	
Piedmont	4	4	6,000	434 North Atlantic, Begin 6-15-87	60 North Atlantic
Qantas	7	7	46,706	9,600 Tasman and Pacific Regional	251 Tasman, Pacific
TACA	1	0	8,569		
Transbrasil	3	0	49,079		
TWA	10	10	161,361	5,560 North Atlantic Crossings	268 North Atlantic
United	19	0	327,562		
Varig	6	5	12,430		
Former Operators	0	0	20,051		
Total: 22 Operators	192	80	1,787,575	31,951 EROPS Operations	761 North Atlantic 588 Tasman and Pacific 87 Others 1,436 EROPS Flights per Month

* Actual count or conservative estimate

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FIGURE 5

B. Events Occurring during Extended Range Operations.

Reports from airline operators and from Boeing field service support organizations indentify significant in-flight occurrences. In the 31,951 extended range operations, 67 such events have occurred. Distribution by phase of flight and effect on flight plan is indicated in Figure 6. A reasonably detailed evaluation of each event has been accomplished.

One approach to use of the accumulated information is to review the 12 events occurring during the EROPS portion of flight (See Figure 7).

This data and others indicate that, although all events deserve careful scrutiny, propulsion system and electric power system events should be, and are, subjects of special review. These reviews and the resulting corrective actions have led to a process of continuing improvement (note the time distribution of events).

A Summary of the 67 Events Occurring on 767 EROPS Flights

May 1985 through Dec 1987

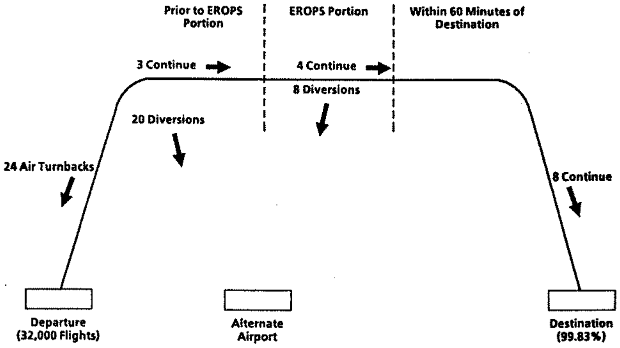

FIGURE 6

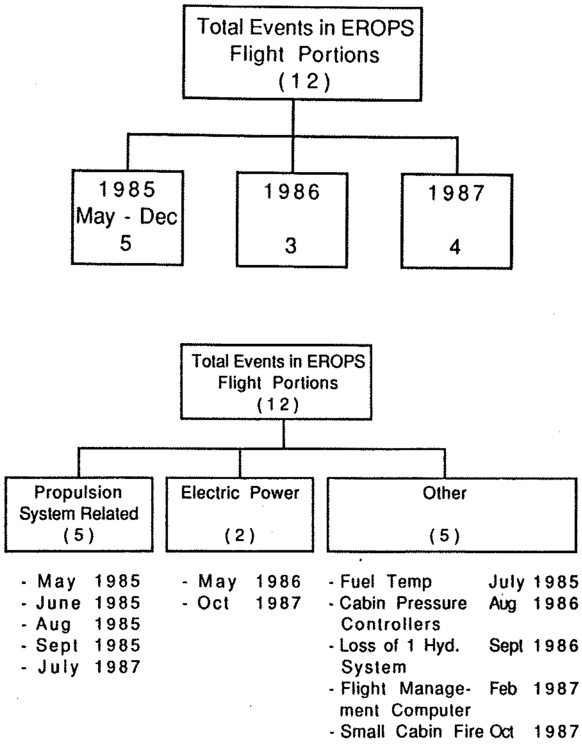

FIGURE 7

The above illustrations are provided to show a few of several ways employed to evaluate and take advantage of in-service experience.

C. Use of in-service data to evaluate reliability predictions.

One of the processes for approval of extended range operations is to show that, considering the route segments to be flown (length and distance to alternates), propulsion and airplane system failures that would lead to loss of safe fight and landing capability are extremely improbable (less than 10^{-9} per flight hour for airplane systems). The difficulty of using in-service experience in this regard is obvious: A few million hours of experience is a low level for evaluation of the analyses of systems designed to meet "safe flight and landing requirements" (loss of safe flight and landing capability less than once in a thousand million flight hours). This situation is eased substantially by use of conservatism in making safety analyses and by the method of use of in-service data to evaluate these analyses. The following discussion illustrates this.

The 767 electric power system, configured for extended range operation, is shown by Figure 8. It includes five basic sources of power:

1. A generator driven by the left engine (90 KVA)
2. A generator driven by the right engine (90 KVA)
3. An Auxiliary Power Unit (APU) driven generator (90 KVA)
4. An Hydraulic Motor Generator (5KVA AC + 50A DC)
5. Batteries (Standby and APU)

767 EXTENDED RANGE OPERATION

ELECTRICAL POWER SYSTEM

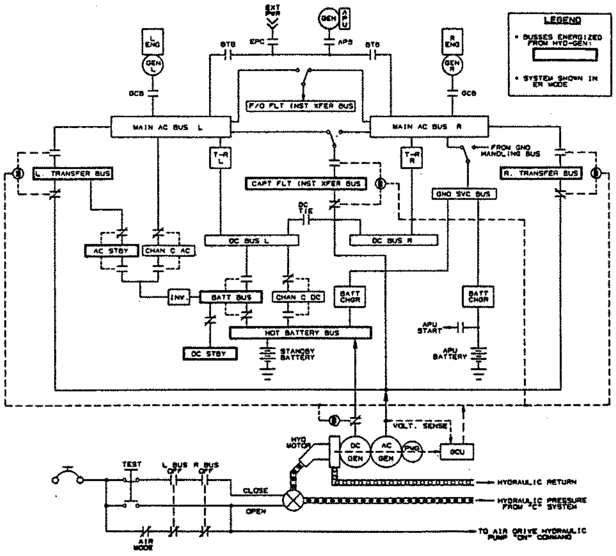

FIGURE 8

The APU driven generator is only used to supply inflight power when one of the engine driven generators is not available, and the Hydraulic Motor Generator (HMG) is only used to supply inflight power when no main generators (90 KVA) are available. Power from these sources is distributed to electric devices in the airplane via a set of inter-tied busses. If only an Hydraulic Motor Generator is available the power loads are those which are most essential to efficient completion of flight. These include (the complete list contains more than sixty items):

- Pilots attitude director indicator
- Pilots horizontal situation indicator
- Pilots airspeed indicator
- Pilots altitude indicator

- Standby engine instruments
- Standby attitude, altitude and airspeed instruments
- 1 Flight Management computer
- 2 Inertial Reference systems
- Captain's and auxilary pitot heat
- 1 air data computer
- 1 VHF communication system
- 1 HF communication system
- Warnings (Master, Stall, Fire)

Finally, it is noted that if only battery power is available just those loads essential to safe flight and landing capability are powered.

Prior to analysis of the electric power system it is necessary to define the associated operational conditions. For extended range operation these include:

1. Dispatch with any three of the four principal sources (2 engine driven generators, 1 APU driven generator and 1 hydraulic motor generator) is allowed.

2. None of these sources are allowed to be unserviceable for more than three flight days.

3. Diversion to the nearest suitable alternate will always occur when one engine is lost.

4. Diversion to the nearest suitable alternate will normally occur when only one of the three 90 KVA sources is available.

5. Whenever an engine driven generator is not available at dispatch or is lost in flight the APU driven generator will be used.

6. Whenever the hydraulic motor generator is not available at dispatch the APU will be started and run (electric load not drawn unless an engine driven generator is not available) for the extended range portion of flight.

7. The flight lengths to be considered will be in the range of five to twelve hours. The maximum flight time to an alternate airport will be two or three hours.

With a system design, a set of operational conditions and a database of reliability information for each of the major components of the system it is possible to make a system reliability analysis. This analysis (fault tree structure) has branches that account for loss of each source and combinations of sources. Levels from the top down are listed in Table 2.

The analysis described above is initially made on the assumption that all sources are available at dispatch, and then made to account for each dispatch situation allowed (1 engine driven generator unserviceable, APU unserviceable, etc.) The results of these individual analyses are then combined to account for the likelihood of occurrence of each dispatch situation (all four sources serviceable, each combination of three sources serviceable). The result of this process is the prediction of the likelihood of events that fall in each of the levels described in Table 2.

Level	Description	Predicted Probability Range
1st	Loss of all instrument power (all main generators and the hydraulic motor generator (HMG))	Extremely improbable (less than 10^{-9} per flight hour)
2nd	Loss of two main sources: 2 engine driven generators, or 1 engine driven generator and 1 APU driven generator, etc.	Improbable (generally in the range of 10^{-5} to 10^{-9} per flight hour.
3rd	Loss of one main source on associated drive system.	Probable (generally in the range of 10^{-3} to 10^{-5} per flight hour.
Lower Levels	Channel components	

TABLE 2

Reports of events occurring in airline service are used to assess the reasonableness of the analysis described above. The figure below summarizes all reported electric power system events that occurred in the time period May 1985 through December 31, 1987. In this time period service reports indicate the occurrence of 79 events (it is likely that in this time period there may have been a number of single source loss events that were unreported since the system is designed so that such events result in no inconvenience to the flight or cabin crews). Flight hours accumulated in this period are 1,250,000. The 79 events are categorized as indicated in Figure 9.

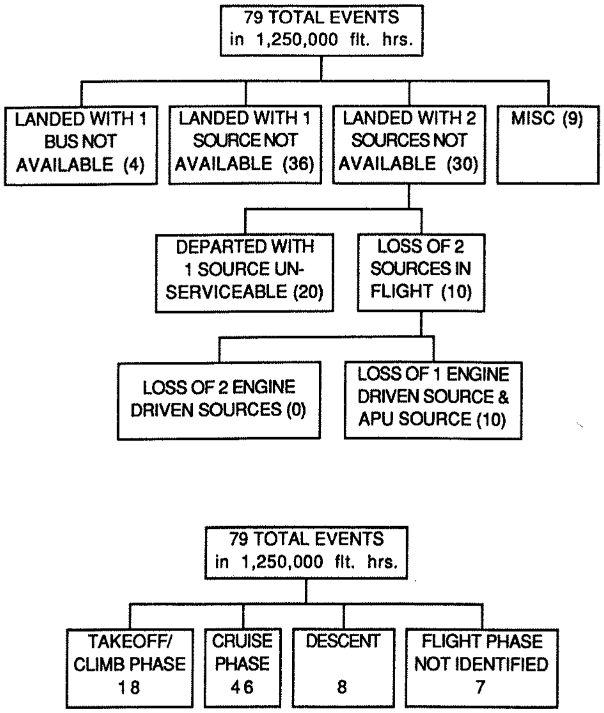

FIGURE 9

Rates taken from Figure 9 are compared to rates predicted by the system analysis. To date there is good correlation. That is, the analysis predicted rates for all event categories are greater than those experienced in airline service.

Similar analyses and comparisons to in-service data are accomplished for other airplane systems which are considered to be essential to the safety of extended range operations. The results indicate that the design and analysis approach taken is sufficiently conservative. Specifically, the number of in-service losses of two main sources (see Level 2 of Table 2) is less than the number predicted by analysis. Also, there have been no in-service losses of three main sources. This in-service experience indicates that, to date, the prediction of compliance with extended range requirements is justified.

IV CONCLUSION

The development of extended range requirements and work accomplished by airframe and engine manufacturers to meet those requirements have led to a considerable and growing level of extended range operations. Experience from these operations is periodically and systematically employed to verify compliance with the requirements and to define changes for futher improvement of the reliability of propulsion and airplane systems and operations. The benefits of the process are threefold. First, airline operators can use twin-engine airplanes along with three- and four-engine airplanes to provide safe, efficient and economic airline service. Second, the high level of attention to all technical details affecting safety and reliability that is a requirement for extended range operations of two-engine airplanes has led to a substantial number of improvements that are applied to three- and four-engine airplanes and to two-engine airplanes which are not currently employed for extended range operations. And three, the system assures that twin engine airplanes in extended range operations are carefully monitored and improvements are being made to ensure their continued compliance with extended range requirements.