Department of Transport and Communications
Bureau of Air Safety Investigation

AUSTRALIAN AVIATION OCCURRENCES INVOLVING FUEL STARVATION AND EXHAUSTION 1969-1986

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SUMMARY

This study analyzed occurrences involving

- fuel starvation - the state in which the fuel supply to the engine is interrupted although there is adequate fuel onboard the aircraft,

and

- fuel exhaustion - the state in which the aircraft has become devoid of usable fuel.

Fuel starvation has been a more common type of occurrence; however, the probability of the occurrence resulting in an accident has been greater for fuel exhaustion. On average, there have been 6 fuel starvation accidents and 8 fuel exhaustion accidents per annum in Australia since 1969. Fuel-related engine failures have constituted 34% of all engine failure accidents.

Pilot Factors

Fuel Starvation.

The pilot was involved in 45% of fuel starvation occurrences. A very prevalent pilot factor (which occurred in 32% of cases) was mismanagement of the fuel system.

Fuel Exhaustion.

By contrast, the pilot was involved in 89% of fuel exhaustion occurrences. The most prevalent pilot factor was inadequate preparation before flight, although there were typically multiple pilot factors recorded. Common contributing factors were the poor decisions made by the pilot in command. Mismanagement of the fuel system also played a large role in fuel exhaustion.

Flying Experience

There was no relationship found between total flying experience and either type of occurrence. That is, pilots at all levels of experience were involved in both fuel starvation and fuel exhaustion, and so those occurrences cannot be said to be the province of inexperienced pilots alone. The same results were found with respect to pilot currency (hours logged in last 90 days), so those occurrences cannot be said to have arisen from the infrequent aviator alone.

A relationship was found to exist, however, between specific experience on type and each occurrence. That is, pilots with fewer hours on type tended to be involved in a greater number of both fuel starvation and fuel exhaustion occurrences, which suggests that pilot familiarity with the aircraft type has been the most significant category of experience.

Type of Operation

The record of operations in the scheduled transport service area (ie, airline and commuter) and in the training area has been better than in the rest of the aviation sector. That is, RPT, commuter and training operations have experienced fewer occurrences than would have been expected on the basis of the number of hours flown by those operations. The private/business category has been responsible for a disproportionately large number of occurrences.

Aircraft System Factors

Fuel Starvation.

Approximately half of all fuel starvation occurrences were attributed to the aircraft fuel system. Various blockages due to the presence of foreign matter accounted for 27% of the fuel system problems. Improper maintenance of the aircraft was also cited in 13% of cases involving the fuel system.

The fuel system was mismanaged by the pilot in 32% of fuel starvation cases.

Fuel Exhaustion.

The aircraft systems were a factor in only 24% of fuel exhaustion cases. Inaccurate fuel gauges contributed to 12% of fuel exhaustion cases, but cannot be said to have been solely responsible in any instance.

1. BACKGROUND

Under Australia's Air Navigation Regulations (ANR's), all aircraft occurrences which may have safety implications are investigated by the Bureau of Air Safety Investigation (BASI). Aircraft occurrences are classified broadly as either 'accidents' (in which there is substantial damage to the aircraft or serious injury to its occupants) or as 'incidents' (in which safety has been compromised in some way).

One of the major roles of BASI is to determine the factors which contributed to the occurrences. The ultimate goal is to prevent recurrences by making recommendations to the appropriate authorities and by distributing the conclusions of BASI's investigations to the aviation community.

Fuel starvation/exhaustion cases are readily identifiable. When the details of the investigation are entered onto BASI's computerized Accident and Incident (A & I) system, most occurrences are classified as an "engine failure or malfunction". The contributing factors then usually include either "fuel exhaustion", "fuel starvation", or one of a number of forms of fuel contamination.

Fuel exhaustion describes the situation in which an aircraft has become totally devoid of usable fuel.

Fuel starvation refers to the fact that the fuel supply to the engine has been interrupted, although fuel may still remain in the tanks.

Unlike fuel exhaustion, it is possible that fuel starvation may be temporary and overcome by the pilot during flight. Fuel may also be contaminated by water, ice or other substances, and the use of improper grades of fuel could be placed in this category.

The following case histories are illustrative of fuel starvation and fuel exhaustion occurrences :

Fuel Starvation.

In August 1985, a Beech Queen Air departed Brisbane on a night freight run for Mackay. The aircraft differed from other Queen Airs operated by the company in terms of its fuel system, which required the pilot to select between inboard and outboard tanks, instead of there being an automatic selection of those tanks. This flight was the first in that particular aircraft for the pilot, who held a Senior Commercial Licence with a Class 1 Instrument Rating. He had been briefed on the fuel system on the previous morning, but had not actually received a cockpit demonstration.

The aircraft departed with full fuel. Approximately two hours later, the pilot reported the failure of both engines, adding shortly afterwards that he was experiencing difficulty in drawing fuel from the outboard tanks. No further communications were received. The aircraft wreckage was discovered later and investigation revealed that the inboard tanks were exhausted but that fuel remained in the outboard tanks. The fuel selector was found positioned mid-way between the inboard and outboard tanks. No pre-existing mechanical defects were evident, but the placard which described fuel selector settings was found to be obscured.

Fuel Exhaustion.

In April 1986, a Beech Baron departed Kalgoorlie on what was intended to be its last business flight for the company, as the aircraft was to be sold the following day. The pilot held a Senior Commercial Licence with a Class 1 Instrument Rating.

On the return leg about 50 miles from Kalgoorlie, the right-hand tank became exhausted. The pilot chose not to crossfeed fuel but to continue on one engine. The pilot did not report the engine failure but did advise of an alteration to the flight plan which took the aircraft on a more direct route to Kalgoorlie. An altitude of 6000 ft was maintained until near the destination, where a double engine failure was reported. Fortunately, the pilot glided the aircraft to a landing without further incident. In subsequent refuelling, the aircraft took more than the designated usable quantity.

Interviews with the pilot established that he typically estimated fuel quantities before flight by maintaining a log, because it was difficult to perform a visual check unless the tanks were full. Maximum fuel, however, had the effect of limiting the aircraft payload. The pilot's endurance calculations were based upon a belief that the fuel consumption figures contained in the operations manual were unrealistically high. He also claimed that he had been misled by inaccurate fuel gauges during the flight.

Aircraft engine failures are significant events, and have resulted in the second most common type of accident in Australia every year (behind landing accidents). Since 1969, about one-third of all the General Aviation (GA) accidents which have originated with an engine failure have been fuel-related. On average, about 6% of all accidents since 1969 have been fuel-related, which corresponds to 14 accidents per annum. The number of fuel-related accidents has been comparable to the number of accidents arising from either stalls, wirestrikes, overshoots, ground loops, or wheels-up landings.

Those statistics initiated this research. Some related research on fuel starvation only was carried out in the US by the National Transportation and Safety Board (1).

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1. National Transportation and Safety Board. US General Aviation accidents involving fuel starvation 1970-1972. Washington DC, Report No NTSB-AAS-74-1, April 1974.

In addition, a belief exists in the pilot community that most fuel exhaustion accidents arise from pilot negligence. Consequently, a major goal of this report was to identify the human factors (ie, pilot factors) underlying fuel starvation/exhaustion. It was hoped that this identification would permit:

- an estimate of the relative contributions made both by pilots and by aircraft fuel systems to cases of fuel starvation/exhaustion.
- the design of some preventive measures, such as revised pilot education schemes or improved cockpit ergonomics.

Other goals of this research were :

- to estimate the relevance of pilot experience and currency.
- to survey various categories of aviation in order to determine whether some categories of flight operation are more prone to fuel exhaustion/starvation than others.
- to analyze the relevance of fuel measuring devices.
- to investigate the types of mechanical failures which have occurred in aircraft fuel systems.
- to make some human factors engineering recommendations where possible.

2. SCOPE OF THE REPORT

The BASI A & I data-base was interrogated for every occurrence to Australian-registered aircraft between January 1969 and June 1986 in which either fuel exhaustion or fuel starvation was a factor. (Fuel contamination was not included in the research). The justification for including incidents in the research was that many incidents are as informative as accidents with regard to problems in aviation. Those occurrences which were still the subject of investigation were rejected. Those occurrences which were contingent upon another occurrence, such as a collision, were also rejected.

There were 523 cases of fuel starvation and 312 cases of fuel exhaustion.

3. ANALYSIS

3.1 Severity of Fuel - Related Occurrences

Data on the severity of fuel starvation/exhaustion occurrences, ie, including both accidents and incidents, are presented in Table 1. It may be seen that 133, or 43%, of all fuel exhaustion occurrences resulted in an accident, whereas only 19% of all fuel starvation occurrences resulted in an accident. Fuel exhaustion also resulted in higher proportions of injuries, aircraft damage and off-aerodrome landings. Despite these differences, fuel starvation still accounted for 98 accidents.

TABLE 1

Severity of All Cases 1969 - 1986

	FUEL STARVATION		FUEL EXHAUSTION	
	No.	(%)	No.	(%)
Accidents	98	(19)	133	(43)
Incidents	425	(81)	179	(57)
Injuries				
Nil	495	(94)	274	(88)
Minor	15	(3)	17	(5)
Serious	9	(2)	12	(4)
Fatal	4	(1)	9	(3)
Damage				
None	409	(78)	168	(54)
Minor	16	(3)	11	(4)
Substantial	79	(15)	114	(36)
Destroyed	19	(4)	19	(6)
Off-Aerodrome Landing	127	(24)	193	(62)
TOTAL CASES	523	(100)	312	(100)

The phase of flight of all fuel starvation/exhaustion occurrences is presented in Table 2.

Fuel exhaustion.

It may be seen that the majority of fuel exhaustion occurrences were during flight, with a smaller group upon landing. The number of fuel exhaustion cases at take-off was relatively small.

Fuel starvation.

The greatest number of fuel starvation occurrences has also been during flight, but there have been sizable groups at both take-off and landing. A total of 97 occurrences arose at take-off. Of those, 32 (approximately one third) resulted in accidents, which reflects the hazards of experiencing an engine failure during that phase of flight.

TABLE 2

Fuel Starvation Occurrences by Phase of Flight

	Take-off		Flight		Landing		Other/ Unknown		Total	
	No.	%	No.	%	No.	%	No.	%	No.	%
ACCIDENT	32	(33)	49	(50)	16	(16)	1	(1)	98	(100)
INCIDENT	65	(15)	264	(62)	46	(11)	50	(12)	425	(100)
TOTAL	97	(18)	313	(60)	62	(12)	51	(10)	523	(100)

Fuel Exhaustion Occurrences by Phase of Flight

	Take-off		Flight		Landing		Other/ Unknown		Total	
	No.	%	No.	%	No.	%	No.	%	No.	%
ACCIDENT	3	(2)	105	(79)	22	(17)	3	(2)	133	(100)
INCIDENT	6	(3)	127	(71)	36	(20)	10	(6)	179	(100)
TOTAL	9	(3)	232	(74)	58	(19)	13	(4)	312	(100)

3.2 Location

The location of all occurrences is presented in Table 3. The Table includes a very small number of cases which involved Australian aircraft overseas.

From annual surveys of flying activity within the States since 1969, the order from greatest to least has been NSW, Qld, Vic, WA, SA, NT, Tas, ACT. It may be seen from Table 3 that the number of recorded fuel starvation occurrences in each State has also had the order NSW, Qld, Vic, WA, SA, NT, Tas, ACT from greatest to least. The correspondence between flying activity within the States and fuel exhaustion occurrences is similar, except that WA has experienced the greatest number of fuel exhaustion cases.

TABLE 3

Fuel Starvation Occurrences by Location 1969 - 1986

STATE	NSW	Qld	Vic	WA	SA	Tas	NT	ACT	Oseas
	114	104	100	88	49	14	48	1	5

Fuel Exhaustion Occurrences by Location 1969 - 1986

STATE	NSW	Qld	Vic	WA	SA	Tas	NT	ACT	Oseas
	69	58	41	70	36	10	23	4	1

3.3 Relative Contribution of Factors

For every occurrence investigated by BASI, an attempt is made to identify all contributing factors. (It should be noted that BASI, in contrast to the NTSB, does not use the term 'most probable cause'). In the case of fuel starvation/exhaustion, a distinction may be made between factors originating with the pilot, such as inattention to the fuel supply, and factors arising from the aircraft, such as mechanical failures in the fuel system.

Scanning of fuel starvation and exhaustion records, however, suggested that this two-way classification between pilot and aircraft factors was inadequate to explain some occurrences. That is, there were instances in which circumstances beyond the pilot's control existed, although the aircraft was not implicated in isolation either. For example, if a pilot is given misleading fuel consumption figures, has no opportunity to independently verify those figures, and fuel exhaustion ultimately results, then it is more appropriate to use a third classification of contributing factors (ie, operational documentation) than to attempt to allocate responsibility between the pilot and the aircraft in broad terms. The factors in this third category included :

- support manuals and directives, including servicing instructions, fuel management instructions and fuel consumption figures (as described above).

This third category was labelled 'environment', although it should be recognized that the description refers to more than just the physical surrounds, and as such included :

- weather
- the actions of maintenance personnel
- production or design flaws

Figures 1&2 depict the balance found between pilot, aircraft and so-called environmental factors in fuel starvation/exhaustion. The contribution of each category alone is shown, as well as the major joint influences. It should be noted that aircraft factors denote malfunctions in either the fuel system or the engine instruments.

It may be seen that the pilot played a greater role in fuel exhaustion than in fuel starvation. Although not obvious from Figures 1&2, pilot factors were implicated in 89% of fuel exhaustion cases but only 45% of fuel starvation cases. Conversely, the aircraft played a greater role in fuel starvation than in fuel exhaustion. Aircraft factors were implicated in 54% of fuel starvation cases but only 24% of fuel exhaustion cases.

FIG. 1 FACTORS - FUEL STARVATION

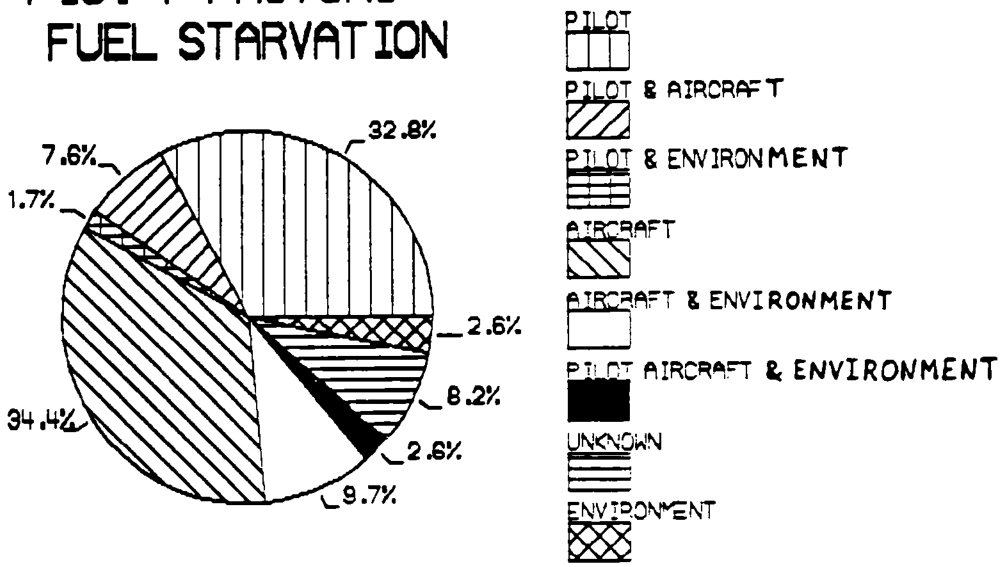
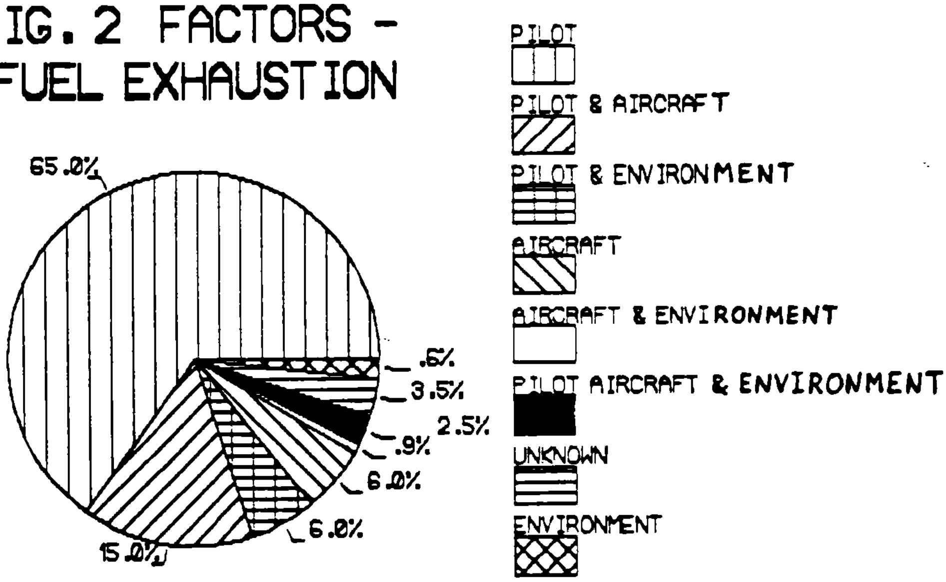


FIG. 2 FACTORS - FUEL EXHAUSTION



The majority of occurrences were assigned multiple factors within a particular category. Only a relatively small proportion of cases involved factors from more than one of the three categories - pilot, aircraft or environment. Fuel exhaustion had only 24% of such multiple categories, whilst fuel starvation had only 22%. However, there were some significant combinations.

There were a greater number of pilot - aircraft cases in fuel exhaustion than in fuel starvation (where, for example, the pilot contributed to a fuel system malfunction). There were also a greater number of pilot - environment cases in fuel exhaustion than in fuel starvation (where, for example, the pilot did not allow for the effect of strong headwinds). Fuel starvation, however, had more aircraft - environment cases than fuel exhaustion (eg, where maintenance personnel contributed to or overlooked a fault in the fuel system).

3.4 Analysis of Pilot Factors

Table 4 gives a breakdown of the most commonly-occurring pilot factors, for those cases in which pilot factors contributed to the occurrence. It may be seen that most pilot factors implicated in fuel starvation were also implicated in fuel exhaustion, although the pattern differed between the two types of occurrence.

TABLE 4

Pilot Factors

(This table only includes cases which recorded pilot factors. A recorded case was usually assigned more than one factor; therefore, the sum of the percentages is greater than 100%).

FUEL STARVATION	No.	(%)	FUEL EXHAUSTION	No.	(%)
TOTAL CASES	235	(100)	TOTAL CASES	277	(100)
Mismanagement of Fuel System	166	(71)	Inadequate Pre-Flight Preparation	192	(69)
Inadequate Pre-Flight Preparation	78	(33)	Mismanagement of Fuel System	118	(43)
Inattention to Fuel Supply	59	(25)	Improper In-Flight Decisions or Planning	89	(32)
Improper In-Flight Decisions or Planning	32	(14)	Inattention to Fuel Supply	78	(28)
Lack of Familiarity with Aircraft	28	(12)	Miscalculated Fuel Consumption	73	(26)
Operated Carelessly	25	(11)	Operated Carelessly	30	(11)
Fuel Selector Set Between Tanks	24	(10)	Lack of Familiarity with Aircraft	21	(8)
Miscalculated Fuel Consumption	15	(6)	Improper Operation of Powerplant Controls	15	(5)
Improper Operation of Powerplant Controls	13	(6)	Navigation Error	14	(5)

A large number of cases of fuel starvation were attributed to pilot mismanagement of the fuel system (ie, that factor was recorded on 71% of occasions in which any pilot factor was present). That factor included such actions as :

- failing to check the position of the selector before take-off.
- positioning of the fuel selector to a near-empty tank which was mistakenly believed to be full.
- mistaken positioning of the fuel selector to the "off" position, or between tanks.
- running a tank 'dry' before switching to another tank (which, although an accepted practice, has been considered to compromise safety on some occasions).
- inappropriate use of main and auxiliary tanks.
- with multi-engine aircraft, inappropriate crossfeeding technique.
- inappropriate use of auxiliary fuel pumps.

A similarly large number of cases of fuel exhaustion were associated with inadequate pre-flight preparation on the part of the pilot (ie, that factor was recorded on 71% of occasions in which any pilot factor was present). That factor frequently occurred in conjunction with other factors and included:

- failure to check visually or by use of a dip-stick the fuel level before departure.
- undue reliance on inaccurate fuel gauges.
- undue reliance on the directions of the previous pilot.
- performance of the visual fuel check on sloping ground, which led to erroneous conclusions.
- miscalculation of endurance and/or range. It should be noted that there was a negligible number of fuel exhaustion cases (ie, 8) in which the actual flight plan was judged to be deficient, because only 55, or 20%, of pilots were recorded as having submitted a flight plan. Thus, the majority of miscalculations took place in the absence of a formal plan. Some miscalculations resulted from errors in converting between either litres and gallons, or between volume and weight measures.
- failure to attend to deficiencies in the fuel system, such as leakages.
- failure to secure fuel caps or drains after checking fuel level or moisture content, respectively, which resulted in venting of fuel.
- performance of the pre-flight check some time before departure, with a change in fuel quantity occurring in the interim, eg, due to venting of fuel overboard from an aircraft parked on a slope.

Improper decisions made by the pilot during flight were a feature of both fuel starvation and fuel exhaustion, but particularly of the latter. The following scenarios apply:

- the pilot realized en-route that refuelling would be prudent, but opted not to make an unscheduled landing.
- the pilot failed to realize that endurance or range was less than anticipated.
- inadequate evaluation of the effects of unanticipated conditions, such as headwinds or diversions around weather, etc.

Inattention to the fuel supply was a significant factor in both fuel exhaustion and fuel starvation, and usually occurred in conjunction with other pilot factors. For example, if a pilot failed to ensure adequate fuel before flight, then inattention to the fuel supply during flight would compound the situation.

The improper operation of powerplant controls was a lesser factor implicated equally in both types of occurrence. This factor most frequently involved improper operation of the mixture control ,ie, failure to lean the mixture sufficiently. There were also instances of mistaking the mixture control for the carburettor heat control.

Navigation errors contributed to fuel exhaustion only. The typical scenario was that the pilot became lost, possibly during adverse weather conditions, and the total quantity of fuel consumed increased beyond original expectations.

The factor "operated carelessly" denotes an act of neglect which is unintentional. This factor was most often used to amplify the fact that the pilot had either prepared for the flight poorly, or mismanaged the fuel system. This factor was evenly distributed over both fuel starvation and fuel exhaustion.

Lack of familiarity with the aircraft was another pilot factor common to both types of occurrence. This factor was often used to describe the circumstances which had increased the probability of mismanagement of the fuel system or inadequate preparation.

3.5 Type of Operation

Air Navigation Regulations, in their classification of operations, distinguish between general aviation (GA) and regular public transport (RPT), the latter including the domestic and international airlines. Within GA, a distinction is also made between those who provide regional scheduled transport (operating under either a Supplementary Airline Licence or an exemption from ANR 203 and henceforth described as 'commuters') and the rest of the industry, including charter, private, business, agricultural, training and other aerial operations.

Those operations which provide scheduled transport services, ie, RPT and commuter, are subject to more stringent regulations than the rest of the industry and have very good safety records generally. This finding was reinforced in the context of fuel starvation/exhaustion. Table 5 presents data on the incidence of both fuel starvation and fuel exhaustion across the aviation industry. Based upon the number of hours flown for each category of operation during the period 1969-1984, it was possible to calculate an expected number of occurrences. That is, the presumption was made that the expected number of occurrences should be proportional to flying activity.

Scheduled transport operations experienced a very low number of fuel exhaustion cases and far fewer than expected. On the basis of flying activity, scheduled transport operations were also under-represented in the fuel starvation statistics.

On the basis of flying activity the following observations were made regarding the non-scheduled GA sector:

- the private/business category experienced more occurrences (in both fuel starvation and fuel exhaustion) than expected.
- the training sector, however, had a better record than expected (in both fuel starvation and fuel exhaustion).
- agricultural operations experienced more fuel exhaustion cases than expected.
- charter operations experienced fewer fuel exhaustion cases than expected.

TABLE 5

Fuel Starvation Occurrences by Type of Operation (2)

TYPE OF OPERATION	RPT	Commuter	Charter	Agricultural	Training	Other Aerial	Privt/ Bus.	Total
OBSERVED	30	18	85	27	54	51	245	510
(%)	(6)	(3)	(17)	(5)	(11)	(10)	(48)	(100)
EXPECTED	92	31	71	31	87	60	138	510
(%)	(18)	(6)	(14)	(6)	(17)	(12)	(27)	(100)

Fuel Exhaustion Occurrences by Type of Operation (2)

TYPE OF OPERATION	RPT	Commuter	Charter	Agricultural	Training	Other Aerial	Privt/ Bus.	Total
OBSERVED	0	2	27	27	20	47	185	308
(%)	(0)	(1)	(9)	(9)	(6)	(15)	(60)	(100)
EXPECTED	56	19	43	18	53	36	83	308
(%)	(18)	(6)	(14)	(6)	(17)	(12)	(27)	(100)

There were also differences in the types of pilot factors recorded for the various categories of operation. Table 6 presents data on the incidence of six selected pilot factors across the non-scheduled operations. Expected frequencies of occurrence were once again calculated under the presumption that those frequencies should be proportional to flying activity. Both charter and training operations had a better record than expected with regard to all six pilot factors. In contrast, the private/business category was consistently over-represented in all six human factors. The only other notable trend is that agricultural operations contributed a greater proportion of the factors "inattention to the fuel supply" and "operated carelessly" than expected on the basis of flying activity.

2. See Appendix A for a statistical analysis of this data. The table does not include a small number of cases in which the category of operation was unknown.

TABLE 6

"Inadequate Pre-Flight Preparation" by Type of Operation (2)

TYPE OF OPERATION	Charter	Agricultural	Training	Other Aerial	Private/ Business
OBSERVED	20	25	25	36	161
EXPECTED	55	21	59	38	94

"Improper In-Flight Decisions or Planning" by Type of Operation (2)

TYPE OF OPERATION	Charter	Agricultural	Training	Other Aerial	Private/ Business
OBSERVED	6	5	5	23	79
EXPECTED	25	9	26	17	41

"Mismanagement of Fuel System" by Type of Operation (2)

TYPE OF OPERATION	Charter	Agricultural	Training	Other Aerial	Private/ Business
OBSERVED	38	22	26	25	165
EXPECTED	57	22	61	39	97

"Miscalculation of Fuel Consumption" by Type of Operation (2)

TYPE OF OPERATION	Charter	Agricultural	Training	Other Aerial	Private/ Business
OBSERVED	6	3	4	16	57
EXPECTED	18	7	19	12	30

"Inattention to Fuel Supply" by Type of Operation (2)

TYPE OF OPERATION	Charter	Agricultural	Training	Other Aerial	Private/ Business
OBSERVED	12	17	12	17	76
EXPECTED	28	11	29	19	47

"Operated Carelessly" by Type of Operation (2)

TYPE OF OPERATION	Charter	Agricultural	Training	Other Aerial	Private/ Business
OBSERVED	7	9	3	10	23
EXPECTED	11	4	11	8	18

2. See Appendix A for a statistical analysis of this data. The table does not include a small number of cases in which the category of operation was unknown.

3.6 Role of Pilot Experience and Currency

The experience of all pilots involved in fuel starvation/exhaustion was assessed by two means:

. total hours flown (which measures general experience), and

. hours flown on type (which measures experience specific to the model of aircraft)

Table 7 shows the relationship between general experience and occurrences, for those cases in which pilot factors contributed. It may be seen that pilots at all levels of experience were involved in both fuel starvation and fuel exhaustion. In other words, it was not novice pilots who were mainly responsible for the occurrences. It should be noted that pilots may receive both dual-flight and ground-based supervision (including debriefs, etc) for approximately the first 50 hours flying experience. This supervision may account for the relatively small number of occurrences in that experience category.

TABLE 7

Fuel Starvation - Occurrences by Total Hours (3)

TOTAL HOURS	0-50	51-100	101-300	301-500	501-1000	1001-3000	3001-5000	5000 +
NO. (%)	2 (2)	2 (2)	24 (25)	11 (12)	10 (11)	24 (25)	6 (6)	16 (17)

Fuel Exhaustion - Occurrences by Total Hours (3)

TOTAL HOURS	0-50	51-100	101-300	301-500	501-1000	1001-3000	3001-5000	5000 +
NO. (%)	1 (1)	6 (4)	39 (24)	18 (11)	27 (17)	31 (19)	16 (10)	23 (14)

Table 8 shows the relationship between specific experience on type and fuel starvation/exhaustion; once again, for those cases alone which were assigned pilot factors. With regard to fuel starvation, there is strong evidence that those persons with low experience on type were more likely to be involved in an occurrence, ie, pilots with less than 50 hours experience on type accounted for 45% of occurrences. The trend was similar for fuel exhaustion but less definite, ie, pilots with fewer than 50 hours specific experience accounted for 33% of occurrences.

3. This data was collected for only a small cross-section of incidents, but most accidents.

TABLE 8

Fuel Starvation - Occurrences by Hours on Type (3)

TYPE HOURS	0-50	51-100	101-300	301-500	501-1000	1001-3000	3001-5000	5000 +
NO.	42	9	22	7	9	7	0	1
(%)	(45)	(10)	(18)	(8)	(10)	(8)	(0)	(1)

Fuel Exhaustion - Occurrences by Hours on Type (3)

TYPE HOURS	0-50	51-100	101-300	301-500	501-1000	1001-3000	3001-5000	5000 +
NO.	45	14	29	15	11	16	5	2
(%)	(33)	(10)	(21)	(11)	(8)	(12)	(4)	(1)

A difficulty with investigating the relationship between pilot experience and aircraft occurrences arises from the lack of data on the experience of pilots who have not been involved in an occurrence. As the proportion of pilots in GA who have fewer than 50 hours experience on type is unknown, it is not possible to calculate an expected number of occurrences in that experience category. It is possible (but unlikely) that the relatively large number of occurrences which have been observed at low levels of experience on type is a reflection of the proportion of pilots who have been flying with that degree of experience at a given point in time.

However, as support for the conclusion that experience on type has been influential, lack of experience on type resulted in characteristic pilot factors. There was a trend for the presence of the pilot factor "mismanagement of the fuel system" to be inversely related to the degree of pilot experience. That is, whenever fuel system mismanagement was a factor, the pilot tended to have fewer hours on type than when fuel system mismanagement was not a factor (4). Similarly, there was a trend for the presence of the pilot factor "miscalculation of fuel consumption" to be inversely related to the degree of pilot experience. That is, whenever fuel miscalculations were a factor, the pilot tended to have fewer hours on type than when fuel miscalculations were not a factor (4).

The currency, or recency, of pilots was defined as the number of hours flown in the previous three months (or last 90 days). Table 9 shows the relationship between currency and fuel starvation/exhaustion, for those cases in which pilot factors were present. It may be seen that the most current pilots were responsible for the majority of occurrences. With regard to fuel starvation, pilots with more than 40 hours accounted for 57% of occurrences; whilst with regard to fuel exhaustion, pilots with more than 40 hours accounted for 56% of cases

3. This data was collected for only a small cross-section of incidents, but most accidents.
4. For a statistical analysis, see Appendix B

TABLE 9

Fuel Starvation - Occurrences by Hours in Last 90 Days (3)

HOURS 90 DAYS	0-10	11-20	21-30	31-40	41-60	60 +
NO. (%)	10 (10)	16 (17)	10 (10)	6 (6)	6 (6)	49 (51)

Fuel Exhaustion - Occurrences by Hours in Last 90 Days (3)

HOURS 90 DAYS	0-10	11-20	21-30	31-40	41-60	60 +
NO. (%)	11 (9)	11 (9)	21 (16)	12 (10)	11 (9)	59 (47)

These results contradict any suggestion that it may have been pilots who did not fly regularly who were largely responsible for the occurrences. In fact, it is likely that the highly current group represents professional aviators. This conclusion is reinforced by an inspection of Table 5 in part 3.5 of this report, where it may be seen that professional categories of operation accounted for approximately half of all occurrences, the other half deriving from the private/business sector.

3.7 Analysis of Aircraft Factors

Table 10 gives a breakdown of the most commonly-encountered aircraft factors, for those cases in which aircraft factors contributed.

3. This data was collected for only a small cross-section of incidents, but most accidents.

TABLE 10

Aircraft Factors

(This table only includes cases which recorded aircraft factors. A recorded case was usually assigned more than one factor; therefore, the sum of the percentages is greater than 100%).

FUEL STARVATION	No.	(%)	FUEL EXHAUSTION	No.	(%)
TOTAL CASES	273	(100)	TOTAL CASES	77	(100)
Foreign Matter Affecting Normal Operations	74	(27)	Vents, Drains, Tank Caps and Tanks	33	(43)
Excessive Vibration	59	(22)	Overload Failure	25	(32)
Material Failure	52	(19)	Leakages	16	(21)
Pumps	48	(18)	Excessive Vibration	10	(13)
Lines and Fittings	47	(17)	Material Failure	9	(12)
Vents, Drains, Tank Caps and Tanks	42	(15)	Fuel Syphoning	5	(6)
			Lines and Fittings	4	(5)
Fuel Injection System	40	(15)			
Inadequate Maintenance or Inspection	36	(13)			
Obstructions	36	(13)			
Leakages	30	(11)			
Pressure Low	28	(10)			
Selector Valves	27	(10)			
Filters, Strainers and Screens	24	(9)			
Carburettor	19	(7)			
Overload Failure	15	(5)			
Loose Part/Fitting	14	(5)			
Fuel Control Unit	11	(4)			
Fuel System Instruments	17	(6)	Fuel System Instruments	37	(48)
Reciprocating Cases	257	(94)	Reciprocating Cases	73	(95)
Turbine Cases	16	(6)	Turbine Cases	4	(5)

It may be seen that a variety of aircraft fuel system components were implicated in fuel starvation. There was a significant contribution from the presence of foreign matter in the fuel system, which typically impeded fuel flow. (Note : as fuel contamination was not included in this research, 'foreign matter' does not include water, ice, improper grades of fuel, etc, but usually refers to solids.).

Note that the maintenance of the aircraft, although not strictly an aircraft factor, has been inserted in Table 10 for the purposes of information. Inadequate maintenance or inspection (whether by the pilot or by professional services) was cited in a number of fuel starvation cases. Those cases include instances in which maintenance personnel actually initiated the problem, eg, by installing selector valves incorrectly or by introducing foreign material into the fuel system.

A high proportion of fuel exhaustion cases resulted from drains or tank caps allowing a loss of fuel.

Fuel system.

Whilst fuel-injected systems were represented in fuel starvation cases more frequently than carburettor systems, it is difficult to make a comparative analysis of the reliability of those two systems without further data (in particular, the activity of aircraft which use either system). It is also difficult to compare the performance of reciprocating engines with turbines for the same reasons.

Fuel system instruments.

Inaccurate fuel system instruments played a much greater role in fuel exhaustion than in starvation cases. The instruments were never the sole factor in any incident, because standard aviation procedures specify that the pre-flight preparation should ensure sufficient fuel for flight, including all reserve requirements. Aircraft of a take-off weight greater than 5700 kg require a cross-check of the fuel quantity by two separate methods.

Thus, the majority of cases of inaccurate fuel system instruments occurred in conjunction with pilot factors. The most common scenario was that the pilot unwittingly relied on inaccurate gauges (usually in conjunction with other oversights) and exhausted the fuel supply. A second distinct scenario, however, was that the pilot was aware that the fuel system instruments were inaccurate but then either chose to ignore their indications completely or made an incorrect compensation.

A second issue pertaining to fuel measuring instruments is both their visibility and ease of interpretation. That issue is addressed in part 3.8 of this report.

3.8 Human Factors Engineering Considerations

Following on from the NTSB report (1), it was hypothesized that a number of fuel mismanagement cases could be attributed to the design of the fuel selector switches. That report had suggested that the more complicated the switching mechanism, ie, the greater the possible number of selector positions, the higher the probability of fuel management errors.

In this analysis, a distinction was made between the simplest type of selector, in which there are only two possible positions (ie, 'on' or 'off'), and other mechanisms. The on-off design is rare on fixed-wing light aircraft, occurring notably on the Cessna 150/152 series and the Piper 25 series. The on-off design is the norm on a number of single-engine helicopters (and on most home-built aircraft). The design necessarily constrains the pilot to drawing fuel from all tanks simultaneously. The majority of fixed-wing aircraft have the facility for selecting lateral tanks individually, whilst some permit the optional selection of all tanks simultaneously.

1. National Transportation and Safety Board. US General Aviation accidents involving fuel starvation 1970-1972. Washington DC, Report No NTSB-AAS-74-1, April 1974.

Whilst the on-off fuel selector was the type employed in 6% of the aircraft involved in fuel starvation/exhaustion, it was only associated with 2.5% of cases in which fuel mismanagement was a factor, which indirectly supports the NTSB conclusion. One probable advantage of the more common designs, however, is that the requirement to switch tanks ensures that the pilot remains at least partially attentive to the fuel supply, and thus reduces the chance of fuel **exhaustion**. As support for this conclusion, the more common designs accounted for 99% of fuel starvation cases but 92% of fuel exhaustion cases.

The probability of selection errors may also be increased by selectors which have ambiguous settings. For example, some Cessna models possess a rotary fuel selector which is double-ended, with the lugs at each end pointing to two different settings which are 180° opposed. A detent ensures that the selector is aligned with those two settings. The lug pointing to the correct setting is the longer lug which is held by the pilot when activating the selector. In some models however, a correctly pointing lug obscures the markings which indicate the setting, so that the pilot cannot see immediately which tank has been selected and must employ a process of elimination. Such designs have the potential to cause problems for pilots not current on the type.

As regards design standards for fuel selectors, the US standards for GA light aircraft (see FAR 23) effectively specify that :

- all selections should be visibly marked.
- a tank setting should be distinguishable by feel from an intermediate setting by a detent or other mechanism.
- a separate and distinct action should be required to select the 'off' position.
- the selector should be moved right in order to select a right-hand tank.
- rotary selectors should be turned clockwise in order to select a right-hand tank.
- the switch should not pass through the 'off' position when selecting a tank from the opposite side.
- if the fuel selector also functions as the sole emergency shut-off valve (as occurs with most reciprocating-engine light aircraft), the 'off' position should be marked in red.
- double-ended rotary selectors are approved, provided that the longer lug (measured from the centre of rotation) indicates the selection.

Another reasonable hypothesis was that multi-engine aircraft would be conspicuous in the fuel mismanagement statistics, due to :

- the necessity of managing the fuel supply to more than one engine simultaneously.
- the possibility of cross-feeding fuel from the wing on one side to an engine on the other, which adds complexity to the task.

This prediction was not supported by the data. It was initially thought that a possible explanation for this result was that scheduled transport operations (ie, RPT and commuter) make greater use of multi-engine aircraft and, because of greater pilot training and familiarity, fuel mismanagement would be less likely to occur. The analysis was then repeated for non-scheduled GA operations, but the same conclusions resulted.

As introduced in part 3.7 of this report, the design of fuel gauges has potential human performance implications. It was speculated that some instances of "inattention to the fuel supply" could have arisen from poor instrument design, ie, errors may have resulted from the gauges being either difficult to read or difficult to understand. This prediction could not be tested directly, as the necessary data were not collected.

The final design-related hypothesis was that wing height could have an influence on the pre-flight preparation of the pilot. More specifically, it was predicted that pilots of high-wing aircraft would be more likely to neglect the physical check of the fuel level, due to the need to climb upon the wing-struts (if present), or to obtain a foot-stool to climb sufficiently high enough to reach and open the fuel caps.

Little support was found for this prediction. High-wing aircraft comprised 47% of all occurrences, and correspondingly accounted for 56% of cases of inadequate pre-flight preparation or planning.

Another pilot factor which would have been interesting to analyze in relation to aircraft model was "improper operation of the powerplant controls", as some of those cases arose from substitutions of the mixture, carburettor-heat and throttle controls for each other. Small sample sizes prevented a meaningful analysis. A previous FAA study (5) found that controls which are in close proximity may be confused, especially by persons unfamiliar with the aircraft type. Greater standardization between aircraft models was recommended as a partial solution to this problem, with the US legislation being enacted in July 1986.

5. Federal Aviation Administration. National Aviation Facilities Experimental Center. General aviation (FAR 23) cockpit standardization analysis. Washington DC, Report No FAA-NA-77-38, March 1978.

4. CONCLUSIONS

1. The greatest need for prevention of fuel starvation/exhaustion occurrences exists within the GA category of operation.

2. Fuel exhaustion is an area of particular concern due to the relatively severe outcome of the average occurrence, and the potentia: for disaster contained in every occurrence. This research supports th proposition that most fuel exhaustion occurrences have been avoidable because inadequate pre-flight preparation by the pilot was a contributory factor in many instances. However, this research does no support the proposition that all fuel exhaustion occurrences have arisen from pilot negligence, as there have often been a variety of factors involved.

3. The most needless fuel exhaustion occurrences have been those which arose from either neglect of the pilot to perform a physical fuel check before flight, or from determination of the pilot to continue a flight knowingly with marginal fuel reserves. A common element of both these types of occurrence has been a lack of direct appreciation by the pilot of the hazards involved, often coupled with haste to reach a destination.

4. Miscalculations of fuel consumption have also contributed to a number of unnecessary occurrences. This problem has a number of sources, including lack of pilot knowledge and lack of inclination to apply the required knowledge. There is also what could be described a a procedural component. That is, lack of consistency of fuel volume measurement units has caused problems for some pilots despite the advent of the Metric standard within Australian aviation. Miscalculations typically have arisen when pilots must convert betwee various units. For example, although fuel is sold by the litre, the fuel consumption figures given in the flight manual may be in gallons If the instruments record the actual amount of fuel onboard the aircraft, they may also be calibrated in gallons, or in pounds. (For weight and balance purposes, fuel is calculated in kilograms, which results in an additional conversion between units).

5. Unreliable fuel system instruments have also contributed to some in-flight miscalculations of fuel consumption. Current US standards for GA aircraft (see FAR 23) specify that the fuel gauge for each tan should read 'zero' in level flight whenever the quantity of fuel remaining is unusable. Those standards do not address the accuracy of measurement of partially full tanks. Anecdotally, there is widespread scepticism towards the reliability of fuel system instruments in the pilot community. Scepticism which induces pilots to interpret the instruments cautiously is commendable; however, scepticism which induces pilots to disregard the instruments without obtaining alternative fuel measurements is an area of concern.

6. Fuel starvation merits attention as a widespread cause of engine failure occurrences. As approximately half of BASI's recorded occurrences in this area may be attributed to mechanical problems within the fuel system, there would seem to be scope for preventive measures. In principle, most blockages of fuel system lines, injectors, filters or vents which have been due to the presence of foreign matter could have been anticipated by a thorough inspection, rather than being detected at the time of the occurrence. A difficulty with making recommendations in this area is that responsibility for aircraft maintenance is distributed across the owner, the operator, servicing personnel and the LAME.

7. Fuel starvation has a human factor component which has been responsible for about half of BASI's occurrences. That component has three sources : failure of the pilot to attend to details such as the position of the fuel selector, lack of pilot currency on type, and poor fuel selector design.

8. Whilst this research has not found there to be a large operational problem arising from fuel selector design, there is scope for other ergonomic considerations which are discussed in part 6 of this report.

9. It was found that aircraft may possess a flight manual which does not necessarily record the effective fuel system capacity (if, for example, long-range tanks are an option). Whilst this research did not find a significant operational problem arising from inaccurate flight manuals, a potential safety hazard exists.

5. RECOMMENDATIONS

Various aviation Divisions and Sections of the Department of Transport and Communications have, as a continuing responsibility, addressed problems of reported fuel starvation and fuel exhaustion occurrences.

The Aviation Safety Digest has featured numerous articles on fuel planning and management. Other documentation of both an advisory and mandatory nature has been widely circulated within the aviation community. However, the incidence of fuel starvation/exhaustion does not appear to have abated. Therefore, the following recommendations and suggestions are brought to the attention of the Department and the industry -

An education programme specifically aimed towards improving awareness and attitudes related to existing operational standards and requirements (prescribed in the ANO's) would appear timely. This should emphasise the importance of the pilot's responsibility for fuel management checks which include :

i) Cross-checking of fuel quantity by two separate methods for aircraft exceeding 5700 kg MAUW - as per ANO requirements. This is also recommended for aircraft below 5700 kg MAUW.

ii) Calculating fuel quantity required as per the statutory requirements laid down in AIP RAC/OPS and the VFG.

iii) Monitoring the fuel state in flight at regular intervals. Logging of all tank selection changes is recommended.

iv) Demonstrating fuel system management procedures (including the operation of the fuel selector) to pilots under supervision, especially when those pilots lack recent experience on an aircraft type.

Fuel system management knowledge and skills should be demonstrated as an essential requirement during the Biennial Flight Review or routine flight check as appropriate. This assessment should include the following topics :

i) Knowledge of the particular aircraft and its systems and instrumentation.

ii) Calculating aircraft endurance and range under varying conditions of power settings and altitude.

iii) Making in-flight compensations for changes to the original flight plan, such as those brought about by diversions.

iv) Determination of fuel state of the aircraft at any point in flight.

Aircraft operators should consider fleet standardization with regard to fuel selection and management systems. Two recent accidents have arisen from problems in this area : Queen Air VH-FDR at Biloela on 7th August 1985, and Beaver VH-AAY at Walcha on 22nd December 1986.

In the determination of future Australian airworthiness standards (implemented either prospectively or retrospectively), such as those embodied in the US FAR 23 specifications, the following additional ergonomic and procedural considerations should be addressed :

i) No fuel selector should obscure any of its positional markings during the entire range of its operation.

ii) Double-ended rotary selectors should clearly distinguish between the 'pointer' and 'tail' ends.

iii) No selector positions should be 180° opposed.

iv) It is advisable that fuel selectors should be visible and accessible to both pilot seats.

v) Fuel system instruments should be calibrated over the entire range of the instrument, not solely at the zero position.

vi) Where fuel system instruments have a history of demonstrated unreliability or inaccuracy, an alternative visual method of assessing fuel quantity should be provided for that model.

vii) Each aircraft flight manual should specify the fuel system capacity applicable to that particular aircraft. Optional systems fitted to the particular aircraft should be clearly listed as such.

viii) Operators should ensure operations manuals reflect the specific status and operating criteria of specific aircraft in their fleets. Particular attention should be given to ensuring that fuel system and selector placards are legible.

APPENDIX A

Chi-square statistical analysis

A chi-square analysis provides a formal means of determining whether one or more observed frequencies differ significantly from their expected frequencies, respectively. In this report, expected frequencies (of aviation occurrences) were calculated under the presumption that occurrences are proportional to flying activity.

The analysis yields a probability that the differences between observed and expected occurrences were due to chance. By convention, a probability less than 0.05 indicates a statistically significant difference.

Section **Analysis**

3.5 Fuel starvation occurrences by all operations

$(X^2 = 158.79, df = 6, pr < 0.000)$

Fuel exhaustion occurrences by all operations

$(X^2 = 239.63, df = 6, pr < 0.000)$

As discussed in part 3.5 of this report, commuters operate in a different environment to the rest of GA. Thus, in order to make meaningful comparisons of safety performance across GA, commuter operations should be excluded. The following chi-square tests are based upon a sample which excludes both RPT and commuters.

Fuel starvation occurrences by GA non-scheduled operations

$(X^2 = 71.88, df = 4, pr < 0.000)$

Fuel exhaustion occurrences by GA non-scheduled operations

$(X^2 = 109.78, df = 4, pr < 0.000)$

Inadequate pre-flight preparation by GA non-scheduled operati

$(X^2 = 91.12, df = 4, pr < 0.000)$

Improper in-flight decisions or planning by GA non-scheduled operations

$(X^2 = 69.30, df = 4, pr < 0.000)$

Mismanagement of fuel system by GA non-scheduled operations

$(X^2 = 79.54, df = 4, pr < 0.000)$

Miscalculation of fuel consumption by GA non-scheduled operations

$(X^2 = 46.75, df = 4, pr < 0.000)$

Inattention to fuel supply by GA non-scheduled operations

($X^2 = 41.20$, df = 4, pr < 0.000)

Operated carelessly by GA non-scheduled operations

($X^2 = 15.40$, df = 4, pr < 0.005)

APPENDIX B

Point biserial correlation statistical analysis

A correlational analysis provides a formal means of determining whether two variables are statistically associated, ie, the strength of the linear relationship between the two variables is measured. The point biserial statistic is appropriate when one of the variables has only two possible values, such as a factor which may either be present or absent.

The absolute size of "r" indicates the strength of the association, and may vary between 0 and 1. Negative values indicate an inverse relationship.

The analysis yields a probability that the observed association was due to chance. As there were no advance reasons for predicting the direction of the association, the test is two-tailed. By convention, a probability less than 0.05 indicates a statistically significant association.

Section	Analysis
3.6	Mismanagement of the fuel system by hours on type ($r = -.14$, $df = 275$, $pr < 0.02$)
	Miscalculation of fuel consumption by hours on type ($r = -.13$, $df = 275$, $pr < 0.03$)