Aerial Suppression of Bushfires

COST-BENEFIT STUDY FOR VICTORIA

I.T. Loane &
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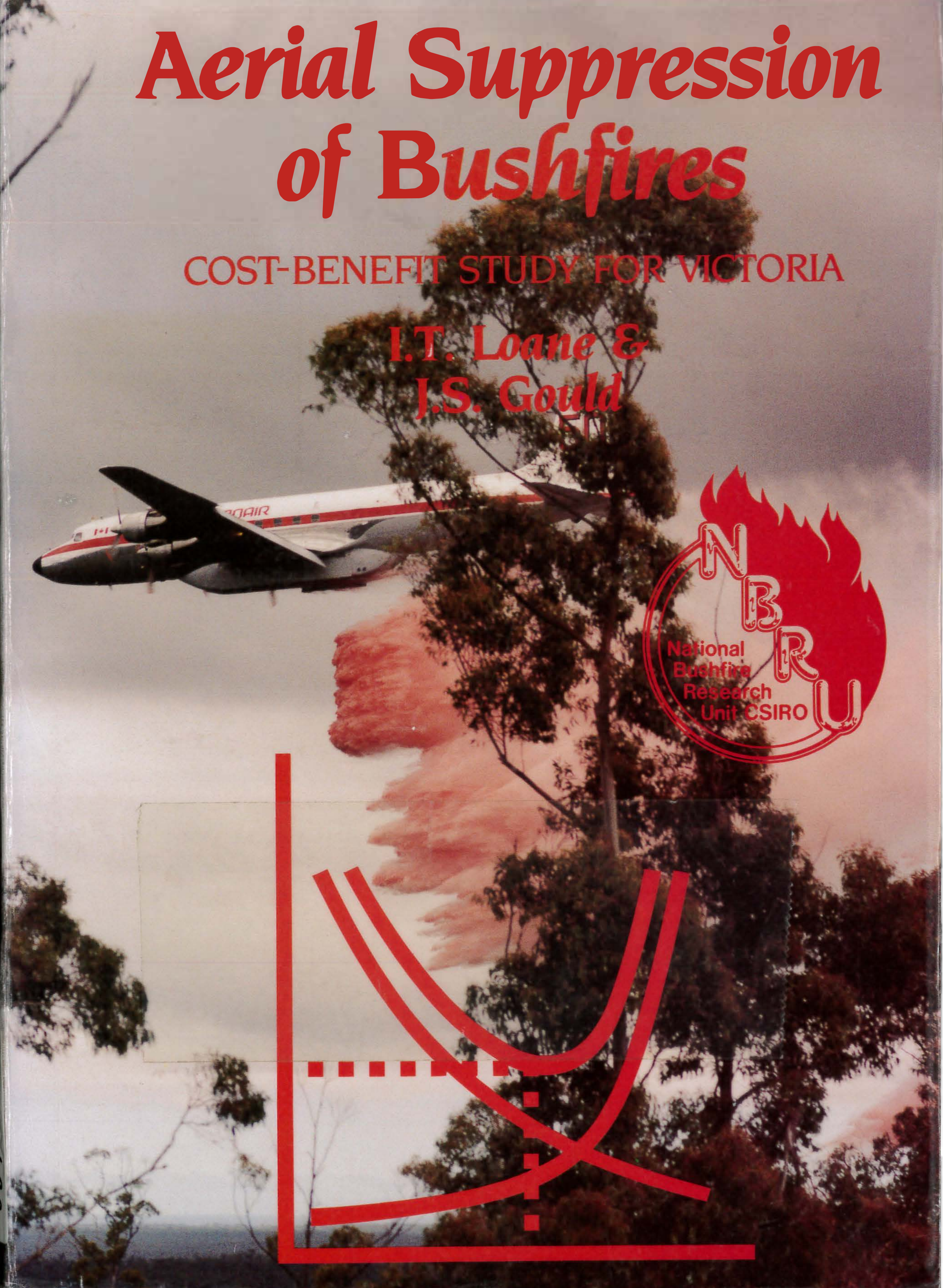

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▲ *Construction of fire-line by rake-hoe crew against low-intensity fire* (*Photo*: CSIRO)

▼ *Medium-intensity fire, around 5,000 kW/m* (*Photo*: CSIRO)

PROJECT AQUARIUS

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NATIONAL BUSHFIRE RESEARCH UNIT
CSIRO DIVISION OF FOREST RESEARCH
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SUMMARY AND CONCLUSIONS

Introduction

Although the south-eastern region of Australia has arguably the most severe bushfire problem in the world, Australia does not make regular use of large airtankers as a part of the suppression armoury.

To help resolve the controversy as to the value of such airtankers in the Australian environment, the Commonwealth Government initiated a scientific and economic study on aerial suppression of bushfires by CSIRO Division of Forest Research under the name of Project Aquarius. This is the report on the economic study which draws on many sources of data but most centrally on preliminary results from the scientific experiments on fire behaviour and suppression undertaken by Project Aquarius. Reports detailing the results from these experiments will be released through the National Bushfire Research Unit following full analysis of data.

The methodology, data and results of the economic study are explained in detail in this report.

Information, data and advice were provided by many other individuals and organisations, in particular the Victorian Department of Conservation, Forests and Lands, and we wish to acknowledge their invaluable contributions.

This study has concentrated on the State of Victoria, but the model developed can be applied to other regions.

The extent and economic consequences of bushfires in Victoria

Using valuation methods detailed in the report, it was estimated that bushfire losses in Victoria amount to $25 million per annum on a long-term average basis, from an area burnt of 150 000 ha. The losses are heavily concentrated in occasional severe seasons. The components of the average loss were: property $19 million, timber $4 million, casualties $1.5 million, conservation $1.5 million, water quality $0.3 million and apiculture $0.1 million, with gains in water yield of $1.2 million. Suppression costs (excluding pre-suppression measures) averaged about $8 million per annum. Costs were brought to a common level based on June 1983, using the Consumer Price Index for Melbourne.

About 85% per cent of the total losses emanate from an average of less than 1 fire per year out of a total number of about 1000 fires per year larger than 1 ha reported by the former Forests Commission of Victoria (FCV) or the Country Fire Authority (CFA), with many more controlled at less than 1 ha. Fire-resilient dry eucalypt and mallee forest types account for about 65 per cent of the average 120 000 ha burnt annually in the FCV area. The value of the timber loss, mainly due to fire-related defect, was estimated as typically between $10 and $40 /ha. In the more valuable and fire-sensitive species, losses may be $50-1500 /ha in mountain ash, and up to $5000 /ha in radiata pine. However, the area of ash burnt in recent years has averaged only 1585 ha per year and of pine 430 ha.

Losses in long-term water yield when mature wet sclerophyll forests are burnt can be very high, with a present value equivalent of perhaps $5000 /ha with equally dramatic **gains** in economic terms when young stands are killed.

The costs of adverse changes in water quality can be high in certain catchment areas, and ecological changes in certain circumstances can be serious from a conservation viewpoint, but in most fires any adverse ecological effects are economically insignificant or even beneficial.

Suppression

Ground suppression costs are greater than losses on most fires. Suppression costs per hectare tend to decrease with larger fire areas, for example, from around $600 /ha for 2 ha to $30 /ha for 1000 ha. Nevertheless substantial savings in total ground costs are made if fire size can be kept to a minimum.

While timber and other losses are higher on fires of high intensity and rate of spread, such fires tend to be beyond the suppression capability of airtankers as well as ground crews. Project Aquarius trials suggested that, while a retardant concentration of 0.5 mm on the eucalypt surface fuel would prevent the fuel from burning, the retardant would eventually be nullified by fires over 3000 kW/m in intensity due to spotting across the retardant line.

Fires susceptible to aerial attack can usually also be handled by ground crews with bulldozers and groundtankers. Nevertheless air attack on fires up to 5 000 kW/m can sometimes achieve a temporary reduction in intensity which is valuable when followed by a second aerial drop or used to support ground crews.

An initial appreciation of the relative capability and costs of different methods of fire suppression may be gained from Table 1, where the comparisons are based on a fire-line effective against a low-intensity (500 kW/m) fire and various other assumptions which are outlined in Appendix 1.

In terms of cost per metre of fire-line held in ordinary terrain, airtankers are clearly far more expensive than ground crews.

However, the value of the different approaches may be affected by many other factors, in particular, the range of operation of each method and the timing of attack, and it was the purpose of the simulation model used in this study to bring into account as many of these factors as possible.

Analyses using a simulation model

The economics of a range of aerial and ground suppression techniques were compared by means of a cost-benefit study, based on a computer simulation model, AIRPRO. AIRPRO was originally designed for the Canadian Forestry Service but has been extensively modified for the Australian study. The model was used to calculate the difference in costs-plus-loss that might occur if each of a number of different suppression tactics was applied to a representative set of historical fires.

Table 1. Comparison of ground and aerial suppression methods on a low-intensity (500 kW/m) fire

	Method of suppression								
	Ground crew		Aircraft						
			Helicopters						
	Hand-tool crew	Machine crew	Bell 206 (water)	Bell 212 (retardant)	Thrush Commander (retardant)	Canadair CL-215 (water)	Grumman Tracker (retardant)	DC-6 (retardant)	Hercules MAFFS (retardant)
Fire-to-retardant distance (km)	-	-	6	10	25	25	75	150	150
Retardant tank volume (litres)	-	4000	340	1362	1500	5455	3545	11 365	11 355
Net length of fire line per load (metres)	-	-	71	217	166	135	241	490	460
Time between drops (min)	-	-	10.5	17.6	28.7	19.0	45.4	72.1	65.6
Rate of line construction (metre/hour)	350	1000	405	740	347	426	318	408	420
Total cost									
$ per hour	115	374	499	2748	1098	3773	3147	6295	9161
$ per metre of fire line	0.33	0.37	1.2	3.7	3.2	8.8	9.9	15.4	21.8

A sample of about 900 fires was drawn from the fire reports of the former Forests Commission of Victoria and the Country Fire Authority during the 4 months November to February for the 5 years 1978-79 to 1982-83. All fires over 10 ha in final area were included, provided adequate details were recorded, and a stratified random sample of smaller fires was taken.

The model uses key features of the fires such as location, times of detection, attack and control, size at attack and control, forest type and property damage. These data, with a number of assumptions and a set of environmental data, generate the growth and suppression of fires in the model.

Fire growth

Each fire is modelled in its free-burning form as an ellipse, segmented into four arcs. Its average rate of spread is based on the observed growth rate, but growth is varied between head, flanks and rear, and varied over time in proportion to the diurnal variation of the McArthur Fire Danger Index.

Ground suppression

The benchmark policy of ground suppression only is simulated first. The overall rate of perimeter containment is made equal to the average rate observed, but the current rate in the model on each arc varies inversely with rate of spread. A build-up function for ground crews is built into the rates of line construction.

Fire growth and suppression are simulated alternately for short periods until the free-burning component of perimeter has been reduced to zero. The final perimeter, area, control time and average intensity are then computed, and from these, ground costs and losses of resources and property. For fires on which aerial attack was reported, an adjustment was made to simulate the area the fire might have reached under ground suppression alone (i.e. to establish 'benchmark' results).

Ground suppression costs for the FCV are derived by a regression equation from area and perimeter, while CFA costs are based on control time and manpower and equipment used.

The simulation is later re-run with two types of additional ground suppression - machine and handtool crew - to assess the effect of increased investment in presently-used types of ground forces.

Losses

Losses were estimated in money equivalents, from the limited information available, for property, casualties, timber, water, National Parks and apiculture.

The main source of data on property losses and human casualties, which occur on only a small percentage of fires, was CFA fire reports. For natural resources, estimation was based on information on forest type and district from the individual fire report, and general data on resource values and physical fire effects.

From a survey of overseas work, human life was valued at $200 000 based on the discounted earnings method. Financial costs estimates for major and minor injuries were based on some typical cases of these injuries. The mid-range values from the estimates were multiplied by a factor of 3 to allow for non-financial costs which gives a value of $500 for minor and $50 000 for major injuries.

Timber losses were valued as the discounted present value of future harvest losses through death, defect or loss of growth, net of salvage revenue. For water supplies, the model estimates the value of the possible short-term gain in yield, the long-term change in yield in ash regrowth catchments, and the cost of quality deterioration.

Evidence on the release of nutrients by fire and the loss of nutrient capital from the site was noted but insufficient data were available to attribute any economic loss to these effects.

Losses relating to beekeeping, mainly due to the loss of future honey yields, were estimated.

Fire losses in National Parks were estimated for loss in visitor enjoyment, with an allowance for loss in scientific conservation values.

Aerial suppression

Suppression of the same fire is simulated for each alternative resource or tactic, including:

- 11 airtanker models
- from 1 to 4 of each aircraft at each home base
- 3 retardant types
- 4 locations of attack.

Only those resources passing preliminary tests are selected to go through the full simulation of suppression. This weeds out, for example, fires that are too small, (where maximum saving is less than the cost of one retardant load), and fires that are too intense for aircraft to be able to hold any effective line.

Rate of fire-line holding by aircraft is based mainly on:

- retardant pattern data from North America
- preliminary data on retardant effectiveness gathered from Project Aquarius
- time between drops, calculated from distance between fire and nearest airfield or lake usable by the aircraft, together with aircraft speed.

Retardant drops are given only a temporary holding role, requiring follow-up by ground crews before they are burnt through. Burn-through time is based on fire intensity and drop width, and allowances are made for canopy interception, placement inaccuracy and evaporation.

Costs of the air attack system include those for airtanker, retardant, retardant base and lead aircraft, and are separated into variable (operating) and fixed (stand-by etc.) components.

Results calculated for each selected tactic include -

- cost-plus-loss (i.e. variable ground cost + airtanker cost + losses), and
- saving in cost-plus-loss vis-a-vis the benchmark policy (i.e. net benefit), which may be negative.

The output from AIRPRO, in the form of results for each tactic on each fire, is analysed by separate programs which

- deduct fixed costs
- weight the sample results according to long-term fire frequencies to give estimates for the whole fire population expected in an average year
- tabulate aggregate results and frequency distributions for any combination of tactics.

The economics of policy variations are assessed by re-running AIRPRO with different base locations or stand-by periods etc.

Results from the simulation model

Under the preferred assumptions and a limited set of basing and dispatch conditions in the model, several types of aircraft, as well as additional ground crews, produced sufficient savings to cover their costs of acquisition and operation (Table 2). The successful aircraft comprised two large land-based airtankers (the DC6 and DC4), an agricultural aircraft (the Thrush Commander), a small helicopter (Bell 206B), and a medium-sized helicopter (Bell 212). Net losses resulted in all circumstances tested for the Hercules, Neptune, Grumman Tracker and the water-scooping aircraft -Canadair CL-215, Canso and Twin Otter.

The savings by the largest airtanker were still less than 3 per cent of historical losses, and savings for all aircraft were heavily dependent on success on a small number of fires. All aircraft failed on the major fires of Ash Wednesday 1983.

Ground crews

Assuming the addition of a ground suppression crew with 9 men, a bulldozer, tanker and light support units to the initial attack force of each of 45 districts, the model predicted gross annual savings of \$713 000, but net savings of only \$115 000.

The addition of a crew of 6 men with hand-tools in all districts increased gross savings by \$372 000 and net savings by \$63 000. These net savings represented a rate of return of only about 2 per cent on the total outlay required each year for wages and other costs for the whole fire season. The savings derived from the same travel times for the additional crews as for historical crews, and relied only on the higher rate of line construction attributed to the extra crews.

Large land-based airtankers

The **DC6**, a large land-based airtanker, provided the best result: annual average gross savings of \$660 000 and net savings of \$136 000 after deducting fixed costs of \$524 000. This result came from the use of a single DC6 at the home base of Mangalore in central Victoria, with fixed retardant facilities at 3 aerodromes -

Mangalore, Hamilton and East Sale. The net savings represent a rate of return on the annual fixed outlay (as opposed to the total capital investment) of 26 per cent.

The addition of a second DC6 at the central base increased gross savings by only about 10 per cent, well short of the additional fixed cost. Similarly, provision of three DC6s - one at each of 3 home bases or, alternatively, all 3 at the central base - was not economic.

A small number of fires (an average of about 8 per year) yielding savings of more than $10 000 accounted for 93 percent of total gross savings. On less than 2 fires per year (averaged over the long run), the DC6 saved more than $100 000 in cost-plus-loss. The sample fires on which such large savings were made included several forest fires over 1000 ha, some grass fires mainly between 100 and 1000 ha, and a pine plantation fire.

Success on these fires usually relied on first attack by the aircraft before the first ground crew arrived, or before the ground forces had built up to full strength, and on attack in the morning before the fire spread rate and intensity had reached their peak.

On most fires the DC6 was not selected on the model's dispatch criteria, usually because the maximum potential savings were insufficient to cover the cost of one load or at the other extreme, the fire was too intense or fast-spreading. The DC6 was selected to fight only about 50 fires per year, and on about 16 of these it returned a loss.

About 70 per cent of the savings by the DC6 were made with the use of long-term retardant (di-ammonium phosphate) mainly in dry sclerophyll forest, but water was economically optimal on a number of CFA fires in grass or scrub with substantial property savings.

Although gross savings by the DC6 were larger than for any other aircraft in each year sampled, most of the overall savings for the DC6 came in the severe fire year 1982-83, in contrast to the water-scoopers and most smaller aircraft. On several historical large fires, the DC6 (with 12-compartment tank) was the only aircraft with sufficient line-holding capability to hold the fire at a manageable size, usually with the first load.

Only 33 per cent of its area savings were achieved with a distance between fire and retardant base of less than 100 km, while 60 per cent were between 100 and 200 km.

The **RAAF Hercules** C-130, equipped with MAFFS unit, was tested as a land-based airtanker of similar capacity to the DC6 but returned a net loss of $373 000, after gross savings of $415 000. The main reasons for the inferior results by the C-130 were the shorter retardant pattern lengths available from the MAFFS at depths above 1 mm, less flexibility in selecting combinations of tank releases, and higher charges for aircraft and crew.

Area savings by the C-130 were nevertheless a substantial 5317 ha per year, about 77 percent of those by the DC6. This result is better than that apparently obtained by the Hercules-MAFFS operation in Victoria in 1981-82 and 1982-83, partly because certain improvements in dispatch, circuit times and accuracy have been assumed in this model.

Table 2. Summary of average annual savings by resource type

Resource type	Number of home bases	Optimal number of aircraft at each base	Area savings (ha)	Gross savings ($'000)	Fixed costs ($'000)	Net savings ($'000)
Airtankers						
DC6	1	1	6907	660	524	136
Bell 212	1	2	4544	306	228	78
Thrush Commander	3	2	3445	237	160	77
Bell 206	2	2	3269	232	204	28
DC4	1	1	4109	344	336	8
Tracker	1	1	3149	227	301	-74
CL-215	1	1	2576	233	511	-278
Hercules	1	1	5317	415	788	-373
Ground crew	No. of districts					
Machine	45		8947	713	598	115
Hand	45		3531	372	309	63

NOTES: The results are based (unless otherwise specified) on

- the number of available aircraft indicated above
- utilisation on any fire of the number of aircraft providing the best savings, up to a maximum of the number available at nearest base
- fixed costs for the number at each base times the number of bases
- the base locations listed in Appendix 12
- exclusive use of each model in turn, i.e. no combinations of different models
- use of whichever retardant type provided the best savings on each fire
- costs and losses are on a common level, June 1983, using C.P.I. for Melbourne.

The **DC4** gave a net annual gain of $8 000, from gross savings of $344 000 and fixed costs of $336 000.

The **P2V Neptune**, a land-based aircraft of slightly smaller capacity, produced net losses. Its costs, based on the depreciated aircraft currently used in the USA, were relatively low. However, it failed to achieve some of the major savings made by the DC6 and DC4 due mainly to shorter pattern length.

Combinations of 1,3 and 6 **Grumman Trackers** were tested, but all returned losses. The lowest net loss was $74 000 with a single Tracker at Mangalore, from gross savings of $227 000 and fixed costs of $301 000. With 3 Trackers at the central base, gross savings increased to $479 000 but fixed costs became $818 000, leaving a net loss of $339 000. Net losses were similarly incurred with the Trackers distributed over 3 home bases (Mangalore, Hamilton and Bairnsdale).

With only a third of the capacity of the DC6, the Tracker frequently had insufficient pattern length to check the fire at a crucial stage. The assumption that it could use any of 31 aerodromes in Victoria as bases for mobile retardant mixers was not sufficient to overcome the initial attack disadvantage.

Like the other medium-sized dedicated airtankers, the costs for the Tracker, based on Canadian rates, are high relative to the smaller aircraft. Whilst the purchase cost of second-hand Trackers is quite low, the main costs for fire-bombing are associated with the tank conversion, crew and infrastructure.

Agricultural aircraft

The **Thrush Commander**, representative of the larger agricultural aircraft, achieved a net savings of $77 000, from gross savings of $237 000 and fixed costs of $160 000. The rate of return over annual fixed costs is 48 per cent.

This result was based on 2 aircraft available at each of 3 home bases (Stawell, Moorabbin and Benambra), with a network of 14 fixed retardant facilities and a total of 84 airfields suitable as a base for a mobile retardant mixer. The aircraft were on stand-by at the home bases only on days of very high fire danger (measured from meteorological records at 3 p.m. at the nearest station), with availability within 1 hour on other days. Fixed costs were based on an average of 8 days of very high fire danger per season.

Net savings with only 1 aircraft available at each base were only $26 000 but net results for either 2, 3 or 4 aircraft were all similar. More than half of the fixed costs were for the base system. The aircraft cost being relatively low under the 1-hour availability system, an alternative under which the aircraft were on stand-by for 30 days of high fire danger per year was tested, but produced lower net savings. The use of mobile retardant mixers did not improve net savings, except at 2 or 3 locations, due to the delay in transport and setting up in the important first 2 to 3 hours of the fire.

Area savings by 6 agricultural aircraft were 3445 ha (only 50 per cent of those for the DC6) with 93 per cent of these savings derived from a fire-to-retardant distance of less than 40 km. Fires with ground attack delays longer than 2 hours accounted for 53 percent of gross savings by agricultural aircraft compared with 25 percent for the DC6. Whilst the quick turn-around time overcomes the disadvantage of short pattern length to some extent, the main advantage of agricultural aircraft lies in the lower cost due to their multi-use nature.

Helicopters

The **Bell** 212, a medium-sized helicopter, produced the best economic results of the small aircraft, although very close to those for the Thrush Commander. Net savings were $78 000 given two Bell 212s at a single home base in the Latrobe Valley, from gross savings of $306 000 and fixed costs of $228 000. The capacity and total costs of these helicopters are several times higher than the Bell 206s, but they were taken to be NSCA helicopters, which are usually on stand-by for a range of emergencies, and therefore more readily available for firework on most days than commercial helicopters.

The **Bell** 206, with 340 litre bucket, produced net savings of $28 000, from gross savings of $232 000 and fixed costs of $204 000. This result was based on 2 helicopters at each of 2 home bases, Latrobe Valley and Melbourne. With only one available at each base, gross savings were $165 000 and net savings $15 000. Net savings increased steadily with each additional aircraft up to 3.

The basic reasons for the economic success of helicopters are similar to those for agricultural aircraft but are more pronounced :

- flexibility of using the most appropriate number on each fire
- long pattern-length (at depths up to 1.5 mm in the open) per litre of capacity
- short turn-around times
- high accuracy
- spreading of fixed costs over a range of uses besides fire-bombing.

Water-scoopers

The amphibious **Canadair CL-215** returned a net annual loss of $278 000 with gross savings of $233 000 and fixed costs of $511 000. The smallest loss derived from a single CL-215 stationed at Mangalore. Increasing the number available, at the central base or other home bases, further increased the net loss.

Just over half of the gross savings by the CL-215 were achieved on grass fires. The water-scooping operation was responsible for 74 percent of the gross savings while 66 percent of the area savings were achieved with water bodies less than 20 km from the fire. On fires where the CL-215 made substantial savings operating from a nearby lake, land-based airtankers usually made similar gains with long-term retardant, or with water from the nearest base.

The CL-215 switched to land-based retardant operations for 26 per cent of its gross savings, mostly on forest fires. However, its savings on land operations were frequently less than for other medium-sized tankers due to disadvantages in, for example, availability of aerodromes, speed or cost. The CL-215 was considered only a single-use aircraft, and all the fixed costs of the aircraft were allocated to water bombing.

The **Canso**, a smaller amphibious aircraft, made area savings about 54 per cent less than those by the CL-215 but because of its lower cost returned a net loss of only $63 000. However, most of these models used in North America are now 40 years old and may not be feasible for Australian operation.

The **Twin Otter**, tested as a small water-scooper dedicated for fire-bombing, returned a net annual loss of $86 000. Significant positive savings were obtained when it was tested in a hypothetical amphibian version but at present Twin Otters in America apparently operate as either a land-based or water-based version.

Combinations

The results above refer to the additional investment in each airtanker model or type of ground crew by itself, but consideration also should be given to combinations of the resource types showing positive savings.

There was considerable overlap in the fires on which the main savings were achieved by each of the DC6, small aircraft and ground crews. Thus, while a DC6 would be economic by itself, it would not be economic as an addition to a fleet of small aircraft, unless it were hired only in the occasional severe fire season (if this could be foreseen).

A combination of small aircraft, with similar total capacity to the optimal-sized pure fleets found in the model, would probably increase total savings, as each type could be allocated to fires or segments of fire according to its particular strength; e.g. a Bell 212, two agricultural aircraft and two Bell 206s.

A small number of hand crews, combined with helicopters for transport to initial attack as well as other fire duties, is also likely to improve total savings.

Qualifications

Although the AIRPRO model is large and complex, it abounds with rough approximations and simplifications of the even more complex reality. To a certain extent these deficiences are inevitable but in some key areas it will be possible to enhance the data and functions at a later stage, in particular following full analysis of data collected in Project Aquarius experiments.

The savings estimated in the model are posited on assumptions of speedy dispatch and fairly high accuracy in selecting fires likely to reward air attack and in drop placement. This efficiency may take some years to develop.

On the other hand, the model underestimates some savings attainable in practice, for example, by concentrating aerial attack on the flank fire before a threatened wind change, or by borrowing aircraft from more distant bases.

Apart from the model structure, many of the data are subject to considerable uncertainty. There could be divergences between the data used in the model and actual values in future years which could have a significant effect on the results, but it has not been possible to define quantitative confidence limits.

Critical variables are:

- the frequency of those potentially-large fires which are susceptible to early control by aircraft
- airtanker accuracy and retardant effectiveness
- costs for large airtanker operations in Australia vis-a-vis Canada
- the share of fixed costs allocated to fire suppression (especially for helicopters and ground crews).

The figures used, however, represent the 'best guess' possible with the information available at the time.

Conclusions

While the limitations of the modelling must be borne in mind, the broad conclusions suggested by the simulation results with Victorian fires over a five-year period can be summarised as follows:

- Acquisition of a single large airtanker with characteristics of the DC6, as an addition to the past level of ground suppression forces, would provide the highest level of economic savings over the long run.
- Two large helicopters or 6 Thrush Commanders would be reasonably economic.
- Additional hand crews in a few key districts, supported by helicopters for transport to initial attack, would be worthwhile.
- Acquisition of other airtankers tested, in particular the Hercules Neptune, Tracker, CL-215 and Twin Otter, would not be economic.

The model was unsuitable for examining combinations of aircraft types on one fire. However, it appears that a combination of helicopters and agricultural aircraft under multi-tier availability arrangements would provide a surer and higher rate of return on the annual fixed outlay than calculated for any single aircraft type alone.

The best saving could be obtained if small aircraft could be supplemented by the DC6 only in very severe fire seasons, assuming these could be foreseen with reasonable accuracy.

1. BACKGROUND

Large-scale aerial attack on forest fires has been common in USA and Canada for over two decades. Drops of water or chemical fire retardant from aircraft are used to assist, although not replace, ground forces. Most other overseas countries with a forest fire problem (e.g. France, Spain, Greece, Chile) now use some form of medium or large airtanker.

In Australia, the former Forests Commission of Victoria* has regularly used light agricultural aircraft for fire-bombing over the past 19 years. The use of helicopters for fire-bombing has also started to become common in all States in the last two or three years. The only operational use of a large airtanker in Australia, however, was in the summers of 1981-82 and 1982-83, when the FCV experimented with a Hercules C-130 hired from the RAAF, carrying retardant in a Modular Airborne Fire Fighting System hired from the USA.

Most bushfire fighting in Australia is done by the State forest services and local volunteer bush fire brigades with traditional ground-attack methods, e.g. water pump and hose, fire-line construction with hand tools or bulldozers, and back-burning from a road or prepared fire-line. These organisations generally operate on a fairly tight budget and have never really considered large airtankers to be within their means or even to be particularly well suited to the Australian situation.

At first sight it might appear strange that Australia, which is generally acknowledged to have virtually the worst wildfire problem in the world, should not have taken up the more modern firefighting technology.

Indeed, in recent years there has been pressure for Australian governments to buy airtankers to fight bushfires. Proponents have pointed to a number of devastating fires in the past few years which show that, although the cost of airtankers may be high, the stakes are also high.

Australian sceptics have argued that, against catastrophic fires which put whole towns at risk, even airtankers would not be effective. With the more common milder fires in forested areas, the potential savings are unlikely to be as high in Australia as in North America, since eucalypts are less likely to be killed by fire than North American trees. Early doubts on the effectiveness of airtankers were expressed by McArthur (1969) at the Royal Aeronautical Society Symposium, 1969.

One of the airtankers suggested for the Australian market is the Canadair CL215, the only plane manufactured exclusively for fire suppression. It specialises in bombing fires with water scooped in flight from nearby lakes. Opponents have argued that the scarcity of suitable lakes or dams in Australia, compared with some Canadian provinces, militates against the use of the water-scooper here.

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* During the course of this project, the Forests Commission has become part of the Victorian Department of Conservation, Forests and Lands, but throughout this paper it will be referred to as the FCV.

To allow thorough investigation of the competing claims, the former Prime Minister, the Rt Hon. J.M. Fraser, requested the CSIRO in 1981 to evaluate the aerial suppression of bushfires. It was agreed that a scientific evaluation of just the physical effectiveness of aerial suppression would not resolve the question, since the sceptics' arguments were largely based on economic grounds implicitly or explicitly.

Accordingly, Project Aquarius was established by CSIRO's Division of Forest Research to evaluate the cost-effectiveness of aerial suppression, with a multidisciplinary staff of eleven, including one economist, most being on three-year contracts. Scientific experiments by Project Aquarius provided data for the economic study, although data from many other sources were also essential. The scientific part of the project centred on field trials in three successive summers:

- studies of high-intensity fire behaviour in Western Australian jarrah forest in 1983;

- trials of the effectiveness of a DC6 airtanker, hired from the Canadian company Conair, on experimental fires near Nowa Nowa, Victoria 1984;

- further studies of fire behaviour and fire-bombing by a helicopter and an agricultural aircraft at Nowa Nowa in 1985.

The economic report was completed in September 1985, at the end of the senior author's period of secondment using the preliminary data available at the time. However Project Aquarius has in a sense been replaced by CSIRO's new National Bushfire Research Unit and further analysis of the data gathered in Aquarius field trials will be carried out by this unit. There could also be further applications of the economic model, to other regions of Australia or other fire management problems.

2. ALTERNATIVE APPROACHES

The nature of the economic study sought by the Government was variously described as a 'cost-benefit study' and a 'cost-effectiveness study'. These two terms have different technical connotations so that some consideration was first given as to which approach would be the more appropriate.

A cost-benefit study of a scheme involves the summation of all the relevant costs and benefits, comparing them in a common monetary unit. A cost-effectiveness study generally calculates the cost in monetary terms per unit of physical output.

Cost-effectiveness therefore does not require the usually subjective valuation of the physical output but this advantage is also its weakness in that it does not address a major aspect of the policy question.

A number of alternative approaches to analysing fire suppression policies are considered further below. Some of these are the cost-effectiveness type, expressing the output in terms of metres of fire-line held, or gallons of retardant dropped. These in fact are only intermediate objectives, rather than the ultimate objective. Another possible physical objective of a fire suppression system is the number of hectares of land saved, but this is still an intermediate objective, albeit closer to the final one.

The final objective really concerns the saving of lives, property and resources of many different kinds. Focussing on any single one as the physical objective would be misleading. Alternatively, the output for each policy could be expressed as a set of physical measures of different kinds of resources. This fails to point to the optimal solution in cases, say, where Policy A results in a higher level of one resource, I, but less of another resource, J, than Policy B. Accordingly, some means of weighting the different outputs for their relative value is needed. Cost-benefit analysis does just that, using market values in a common monetary unit as the method of weighting or, in other words, as the unit of comparison.

Although it tends to involve more subjective judgements in valuing intangible benefits, cost-benefit analysis does attempt to encompass virtually all the relevant considerations for policy making in the public interest. Thus cost-benefit analysis was selected as the approach for the Project Aquarius study.

A survey of other approaches was nevertheless useful, some providing ideas that could be adapted for the current study. Below, some purely physical models of individual fires are outlined; these have provided or could provide the base to which economic factors may be added. Economic analyses at various levels (all from overseas) are then summarised.

Fire shape modelling

A number of models have concentrated on the physical dimensions of growing fires, and some of these have been or could be fitted into more comprehensive economic models.

Elliptical fire growth

Van Wagner (1969) modelled the spread of a fire in uniform fuel, terrain and wind as an ellipse, and defined the area and perimeter for given rates of spread in each main direction.

Anderson, Catchpole, de Mestre and Parkes (1982) extended this, first giving the formula for the fire front in terms of coordinates from the centre, as a function of radial angle. They then gave formulae for the modified fire front after a change of wind direction or a change in slope. These were based on the Huygens principle, under which the fire will grow as the envelope of the small ellipses drawn at each point on the fire front. Applying these to a limited number of points on the edge, empirical examples were simulated by computer and the new fire front plotted. Formulae for the rate of spread and intensity at each point on the ellipse were given in an associated article by Catchpole, de Mestre and Gill (1982). This model may be useful for predicting the movement of individual fires in known conditions, rather than simulating large numbers of fires with little or no data on environmental variations. Considerable extra work would be needed to integrate such a growth model with suppression.

Other shapes such as ovoid and a double ellipse have also been tried. Green, Gill and Noble (1983) found that any of those shapes, and even the rectangle, gave satisfactory approximations to a sample of actual Australian fires.

Flexible fire shape

A model by Albini, Korovin and Gorovaya (1978) incorporates suppression as well as growth of a fire with some flexibility of shape. Their mathematical formulations allow final area, perimeter and control time to be calculated if the following are given:

- fire shape parameter (which can include a shape close to an ellipse, as well as certain other shapes).
- forward, flank and rear rate of spread, each constant over time.
- expression for gradual change in radial rate of spread between head, flank and rear
- rate of line construction (RLC), as a constant length of perimeter controlled per hour assuming direct attack on fire edge
- location of initial attack (as angle between origin and point of attack, relative to major axis)
- attack delay

Alternatively, for indirect attack, where a break is built a certain distance ahead of the fire front, arithmetic examples are given, showing the optimal distance ahead to build the fire-break for various system states.

Simplified arithmetic examples were given. One deficiency of those examples was that the RLC was assumed constant all round the perimeter although the rate of spread varied. The authors say that RLC could instead be formulated as inversely proportional to radial rate of spread, but the mathematics would be complicated.

Suppression is assumed to be continuous, which is unsuitable for airdrops. No economic variables have been incorporated.

Cell models

Kourtz and O'Regan (1977) constructed a model with 2 ha cells and hourly changes in wind speed or direction, from which the location of the fire perimeter at any time could be found. Fuel data at the cell level were not available at the time. No suppression or economics were included.

Kessell, Good and Potter (1982) established PREPLAN, a project involving an inventory of fuels, terrain and resources throughout Kosciusko National Park on a grid with cells mainly 1 sq km and some as small as 5-10 ha. The computer program outputs, for any given location and weather conditions, likely fire behaviour, fire perimeter and area, and effect on resources.

Such models are suitable for individual fire analysis in an area small enough to make the mapping effort feasible.

Economic studies

Cost per metre of fire line

One common and fairly quick approach for evaluating different methods of suppression is to estimate the cost per unit length of fire line constructed for each method. This is a type of cost-effectiveness analysis. A good example is provided in an article by Haggarty, Newstead and Stechishen (1983) which concluded that, even with its high cost, the CL215 could be more cost-effective than other airtankers.

Such calculations are based on rather restrictive assumptions about the physical environment. Haggarty et al. assumed a random distribution of fire to base distances between 10 km and 160 km (applicable to the land-based aircraft) and fire-to-lake distances varying over 7,10,16 and 28 km. Line lengths were measured at a depth of 1 mm for chemical retardant and 2.5 mm for water, which were considered to be effective against fires of low to moderate intensity. Calculations were based on the drops made in 95 minutes.

The resultant figures give a useful cost comparison if the assumed fire and lake distributions are realistic and it is already decided that aircraft are to be used.

However, they beg the question as to:

- what the actual distribution of fires, lakes and airfields usable by different aircraft is in the region of interest;
- relative performance against fires of different intensities;
- what savings in area, damages and ground costs etc. would be made, and hence whether the cost of any of the aircraft is worthwhile.

Notwithstanding their limitations, some background comparisons of cost per metre of line for certain ground and air suppression alternatives were made and proved enlightening. The calculations and assumptions are shown in Appendix 1. They indicate that the cost per metre of line constructed against a 500 kw/m fire is in the region of $21.8 for the Hercules-MAFFS, $9.9 for a Tracker, $3.2 for a Thrush Commander $1.2 for a helicopter using water, $0.37 for a machine crew and $0.33 for a hand crew.

Any reasonable variations in the assumptions are unlikely to alter the conclusion that aircraft are economically out of the question as a means of line construction against bushfires in normal circumstances, all other things equal. An important thing that may not be equal, however, is the attack delay. Aircraft may be able to begin attack on fires in remote locations before ground crews can arrive. In these circumstances, the higher cost per metre of line constructed by aircraft may be outweighed by the smaller length of perimeter to be dealt with in the early stage of the fire. The frequency and likely savings in these situations are measured in the cost-benefit model.

Linear programming

A more sophisticated cost-effectiveness analysis is implicit in Maloney's (1973) 'optimising airtanker allocation model'. This uses linear programming to find the minimum cost set of aircraft types and numbers that will meet the required workload or 'quasi-demand'. The latter is measured as the number of gallons to be dropped over the period studied, based on 12 drops per hour times the total number of hours for which fires were burning in the period.

This approach does not consider the effectiveness of the drops or the value of benefits achieved.

A model by Greulich and O'Regan (1975) also used linear programming to find the optimum allocation of airtankers between bases, by the criterion of maximising the number of gallons dropped, within a set budget constraint. All costs were treated as proportional to flying hours, as if fixed costs were excluded.

This approach also takes no account of the value of benefits. None of the approaches above consider individual fires. The remaining approaches take minimisation of cost-plus-loss as the objective, essentially a cost-benefit approach.

Optimisation by calculus

Parkes and Jewell (1962) presented a model which expressed cost plus loss as a continuous differentiable function. Calculus could therefore be used to find the level of suppression manpower that minimised cost-plus-loss, given the following parameters:

- rate of area growth of the fire as a linear function of time
- area at attack
- efficiency of suppression units, in terms of reduction of area growth rate per hour
- suppression cost per unit per hour
- losses per acre.

Whilst computing would be simple for such a model, it has found no practical application, partly because growth rates and suppression rates are not generally measured in practice in terms of area (hectares/hour). Rates of perimeter growth and containment are more likely to be linear functions of time under constant environmental conditions, in which case rates of area growth are related to the square of time. The model also does not distinguish between different parts of the perimeter.

It is not possible to use this approach to select the optimum type of airtanker insofar as they are discrete alternatives and airtanker performance cannot be expressed as a single continuous function. However, if a separate analysis were done for each type, it might be possible to optimise the number of aircraft for a given fire and compare the overall results to find the best airtanker.

The models of this type so far published have not considered the special factors associated with airtakers. Airtanker drops are discrete events, in contrast to the more continuous line-building by ground forces. Ignoring the discrete nature, airtanker rate of line holding could be expressed as an hourly RLC for a given airtanker, fire-to-base distance etc.

If aggregate results on a whole set of fires were needed, it may still be necessary to input the actual variables specific to each fire (rate of spread, distance etc.) and calculate separate results for each, and aggregate them over all fires. Alternatively if some simple mathematical distribution of fire types with given parameters was assumed, it may be possible to calculate the aggregate results and their distribution by the standard formula.

Regression analyses

Some studies have tried to estimate the benefits of increasing fire protection expenditure, not by simulating the effects on a given set of fires, but by comparing observed outcomes across different provinces or different years.

Sackett *et al.* (1967) for example, compared actual losses (in stumpage) over ten years across three different types of region rated as high, medium and low respectively in terms of expenditure on fire protection per year per acre. From these they estimated the reduction in loss per dollar of extra protection.

This approach assumes, however, that the reduction in loss is attributable just to the protection expenditure, whereas in fact many other influences may be operating, some coincidentally in the same direction as the protection/loss relationship, and others in the opposite. For example, higher protection is likely to be associated with higher fire risk and resource values, and hence higher losses from the latter causes. In that case, Sackett's approach would underestimate the contribution by protection.

A multiple regression analysis would in theory be able to estimate the separate contributions of the independent factors involved. But it is unlikely that satisfactory results could be obtained given that the inaccuracies in measuring the other relevant variables could easily swamp the variation in protection expenditure.

The study of total protection expenditure is in any case not relevant to more detailed decisions on optimal expenditure on particular kinds of airtanker, for example. Regression analysis on such problems would also encounter serious data and measurement problems. However, problems might be minimised in comparing losses in a region in the years before and after the widespread use of airtankers - a study perhaps best carried out in North America.

Computer simulation with suppression economics

Several computer simulation models which incorporate both individual fire growth and suppression and economic factors have been built. The United States models include FESIM, FOCUS and FEES, with later versions evolving from earlier ones.

FESIM is the simplest, as far as the fire growth component goes. Davis (1981) outlined the model and an application in Florida. It works on a set of hypothetical fires defined by the 50th and 90th percentile rates of spread for each management zone. Each fire is assumed to have constant rate of spread and rate of line construction around all parts of the perimeter. The steady-state rate of spread is constant but double the initial rate, while RLC builds up with crew or airtanker arrivals. Dispatch of forces is based on rules relating to fire size etc. The model simulates growth and suppression each minute for up to 8 hours.

Airtankers are given a standard rate of line production of 0.4 chains/hour for each 100 gallons of tank capacity, varying to 0.6 and 1.0 for certain lighter fuel types. This is a maximum which is reduced by the proportion that the spread rate bears to 40 chains/hour.

The user has the choice of inputting damages per acre directly, or inputting basic data such as timber type, price, volume etc. from which the model calculates damages.

Planning for FOCUS in the USDA Forest Service began in 1970 and led to a final report in 1981 (Bratten, Davis, Flatman, Keith, Rapp and Storey). It is particularly detailed in modelling alternative types of ground suppression, and requires data on road networks, ground base locations, and travel times and production rates for up to 15 different types of ground resource. Dispatches are based either on (1) fire rate of spread or (2) region, and fire weather index.

A sample of historical fires is used in the model. Fire growth is modelled as an ellipse with initial area, forward ROS and length-to-width ratio specified.

Airtankers operate from the nearest base or water source. Drop lengths for airtankers are based on quantity of retardant and on a table using a fuel load index and ROS index. Air drops are assumed to perform a temporary holding function only. Airtankers are added for each extra 10 chains/hr ROS. There is a complex logic for simulating the effect of drops, depending on the previous air and ground crew activity.

Three modes of attack can be modelled, the mode being specified in input data:

- direct head first - only if RLC/ROS sufficiently high
- direct rear and flank, or
- indirect or back-firing head, with certain parameters specified in input such as time interval between completion of back-firing time and arrival at the line of the fire head.

Burn-through and burn-around of drops is provided for.

Mop-up time and cost are modelled separately. Suppression costs are calculated from hours worked and average cost rates, with fixed costs added separately. Damages are based on input values for 7 damage-potential classes.

Large fires are not modelled by computer but are subject to 'gaming', in which likely results from different tactics are judged by experienced fire bosses.

FEES, which is still being developed by the USDA, uses part of the physical fire model from FOCUS but adds much detail on the probabilities of fire occurrence and damage to resources (Mills and Bratten 1982). This will eventually be the most sophisticated model available.

AIRPRO, a mnemonic for Airtanker Productivity, is the closest Canadian equivalent of the above US models. It was originally designed by Dr Albert Simard for the Canadian Forest Fire Research Institute in Ottawa in the 1970s.

AIRPRO is a large computer-based model, simulating the growth and suppression of individual historical fires, and calculating costs and losses.

AIRPRO is more detailed than FOCUS in its modelling of retardant drops but did not originally consider alternative ground suppression methods. It was preferred as a basis for this Australian study largely because:

- the main emphasis in Project Aquarius is on aerial suppression;
- it was the only detailed model for which we could obtain complete documentation and a program tape, and
- it did not require the detailed road network data used in FOCUS.

Documentation published in 1977-78 described the equations, the program and its application to New Brunswick (Simard and Young 1978). The program on computer tape obtained by Project Aquarius (through Chisholm Institute of Technology, CIT) was a later version (1983) designed for application to British Columbia. Further development of AIRPRO is being pursued by Simard for the USDA Forest Service at its Northern Central Forest Experiment Station, East Lansing, Michigan.

For the Australian application, the central routines modelling physical fire growth and suppression have been largely preserved, but extensive modification or replacement was necessary for the following components:

- transformation of fire report data
- meteorological variables
- fire behaviour
- airtanker basing
- canopy interception
- retardant effectiveness
- additional ground suppression
- costs
- damages

The Australian version is described further in more detail.

ASMI - Relationship with AIRPRO

ASMI (Aerial Suppression Model I) was developed by the former National Centre for Rural Fire Research at Chisholm Institute of Technology, as part of contract work for Project Aquarius. ASMI includes some of the same processes as AIRPRO, in particular fire rate of spread and intensity, retardant effect and airtanker circuit time.

However, there are substantial differences between the models as they are designed for different purposes. ASMI is designed to apply to individual fires burning in a known environment, with a particular type of airtanker available, perhaps to aid decision making on actual suppression. It is a purely physical model, considering only the advance or extinguishment of a given part of the fire edge of undefined length. It takes no account of the total fire size, or economic factors such as resources at risk and suppression costs.

ASMI has an extra component based on the USDA Forest Service model PATSIM which predicts the length of retardant line at different depths resulting from a drop from an airtanker of specified dimensions. The data on line length and width for the 12-tank DC6B, for example, used in AIRPRO, has been derived from that part of ASMI. ASMI also has greater detail on evaporation losses from a drop ahead of the fire front.

AIRPRO is designed to consider large numbers of historical fires and compare the overall area, costs and losses from the application of a number of different airtanker types or methods of suppression. The relevant equations in ASMI, in particular for fire behaviour and retardant effect, have been incorporated in AIRPRO.

3. GENERAL ECONOMIC ISSUES

Before continuing with the description of the modelling techniques and assumptions used in this particular study, the approach taken on several pervasive economic issues is first discussed.

Social scope

The diversity of the potential benefits from bushfire suppression makes it essential to view the aggregate costs and benefits at a broad community level rather than from the viewpoint of any one agency. For example, although forest services commonly manage and fund the aerial suppression forces, the potential benefits range beyond the direct responsibilities of the forest service, e.g. to private property owners. In a sense, such other benefits are 'external' to the forest service but must be internalised in a single cost-benefit analysis.

Distribution issues

This study aggregates values at market prices without any attempt to place different weights on benefits accruing to or costs borne by particular groups in society. Weighting is usually recommended only where there is a significant issue of redistribution between rich and poor, particularly in less developed countries. Such issues do not arise in this case.

The decision as to whether or not to acquire airtankers could reasonably be based just on aggregate social costs and benefits, regardless of the distribution of the benefits. However, for any expenditures on bushfire control that are undertaken, the question of how the cost burden should be shared depends significantly on the distribution of benefits, and this is discussed further below.

Accounting prices

The accounting prices used to value costs and benefits in this study are, in almost all cases, typical market prices. There is no attempt to adjust for distortions to competitive pricing such as result from tariffs and subsidies, nor for monopoly, price controls and under employment of resources that could cause a divergence between actual prices and opportunity costs. Such distortions are far too prevalent and complex to measure comprehensively.

The main exceptions are for certain items for which actual prices may bear virtually no relation to opportunity costs, namely, capital and water. In addition, imputed values in dollar equivalents are accorded to certain intangible items such as recreation, conservation and human life. These are discussed in the relevant section, as are the issues of the appropriate valuation of timber and volunteer labour.

The study generally does not account for any change in market prices which might be caused by the effects of bushfires. The estimate of net benefits may be accepted as the change in total consumers' and producers' surplus on the assumption that changes in quantities traded due to fires are small relative to total markets. The only exception is for timber where provision is made for the effects of non-zero price elasticity of demand.

Optimising criteria

The optimising criterion used in this study is essentially the net present value of benefits less costs. Prima facie, the policy with the highest positive net present value is preferred.

Present value of net benefits

Net benefits in any one year from a given suppression policy may be defined as:

Net benefit = Gross benefit minus cost of suppression = B-C
= (Loss without suppression - loss with suppression)
- cost of suppression
= Loss without suppression -
(cost of suppression + loss with suppression).

'Loss' in this context refers to losses of property and resources, less any benefits due to the fires.

'Loss without suppression' is the benchmark, (i.e. when C = 0 and B = 0), and could refer either to the situation of completely uncontrolled fire or, more realistically, the situation with traditional methods and level of suppression forces. 'Suppression' in the latter context refers only to the additional suppression effort.

The net benefits in each year can be discounted back to the initial period, and aggregated to give the present value of net benefits.

Annualised net benefits

The results here, however, are presented in terms of the criterion of average annual net benefits or savings. Since we have no knowledge of variation in results between particular future years, it can be assumed that the average expected net benefits are equal each year. In this situation, the two criteria are equivalent, and comparison of policies in terms of either criterion will give the same ranking and ratios, as shown below.

$$V = B * A_{\overline{n|}\,i} - F \qquad \text{(See Footnote *)}$$

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* $A_{\overline{n|}\,i}$ is the present value of an annuity (ie. a set equal periodic payments) of an amount 1 per period for n periods, discounted at i.

$$A_{\overline{n|}\,i} = \frac{1 - (1 + i)^{-1}}{i}$$

$A^{-1}_{\overline{n|}\,i}$ is the periodic payment under an annuity of n payments, present value of this is 1, at an interest rate i.

$$A^{-1}_{\overline{n|}\,i} = \frac{1}{A_{\overline{n|}\,i}}$$

If the initial capital cost is F, and the resultant annual net benefit = B for n years, and the appropriate discount rate is i, then the present value of net benefits. Alternatively the initial cost F can be converted to an equivalent set of equal annual amounts (i.e. an annuity), $F.A^{-1}_{\overline{n|}i}$ comprising an interest component (at i) and a principal component equivalent to depreciation. The present value of the set of amounts equals the capital cost, F. Using this method, annualised net benefits are:

$$A = B - F * A^{-1}_{\overline{n|}i} \qquad V = \frac{B * A_{\overline{n|}i} - F}{B - F * A^{-1}_{\overline{n|}i}} = A_{\overline{n|}i}$$

$$\frac{V}{A} = \frac{B * A_{\overline{n|}i} - F}{B - F * A^{-1}_{\overline{n|}i}} = A_{\overline{n|}i}$$

Thus A is proportional to V, since $A_{\overline{n|}i}$ is a fixed number for all policies evaluated at the same n and i.

The annualised net benefit is a more convenient criterion in this case, where use of airtankers would not necessarily involve a large initial capital outlay by the government, but perhaps instead a series of regular hire payments to private operators. Annualisation also reduces the numbers to a more manageable and meaningful size.

Cost-plus-loss

Cost-plus-loss (C + L) is a criterion commonly used in the economics of forest protection. In this case, it means cost of fire suppression plus actual loss due to fire, with all terms discounted to present values. There is a trade-off between the two components in that, as expenditure on suppression goes up, losses should come down. As expenditure on suppression increases, the combined total is expected first to fall, to reach a minimum, and then to rise again (see Figure 1).

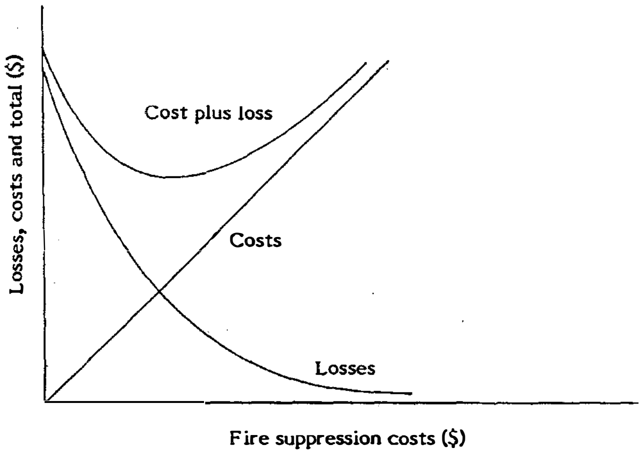

Figure 1. Cost-plus-loss from fire suppression

The minimisation of the present value of cost-plus-loss is in fact logically equivalent to the maximisation of present value of net benefit, as can be seen from the earlier equation which can be rewritten:

Net benefit = B - C = Benchmark (C + L) - (C + L) with suppression alternative

Since the benchmark is invariant with respect to policy alternatives, the policy which minimises C + L must maximise B - C.

Internal rate of return

The internal rate of return of a particular scheme is that discount rate at which the present value of net benefits equate to zero. This is another criterion sometimes used in expenditure evaluation but can provide misleading rankings of options and is not used here.

Under certain time patterns of costs and benefits, the internal rate of return is not uniquely defined, although there is no problem here with equal annual amounts.

A small project yielding a high internal rate of return may not necessarily be preferable to a large project with a lower internal rate of return, since as long as the latter internal rate of return is above the cost of available capital the larger project would be economically superior if it yielded a greater total surplus above the cost of capital than the smaller one.

Thus net present value is generally a superior criterion in such cases.

Discount rate

As in any social cost-benefit analysis involving initial capital outlays and future benefits, the controversial question arises of the appropriate rate for discounting future amounts back to present values.

Relevant precedents in Australia range from 4 per cent per annum used by some forest services to 10 per cent recommended by the Commonwealth Treasury (with sensitivity analyses at 7 and 13 per cent).

Two different concepts (and hence approaches to estimation) of the discount rate can be distinguished:

- the social rate of time preference (SRTP), indicating the extent to which society views a given benefit in the future as worth less than the same benefit today.
- the social opportunity cost of capital (SOCC) indicating the return that could have been earned by investing capital in its best alternative use. The SOCC itself reflects individual rates of time preference, as well as the productivity of capital.

In perfect competitive markets, these two values would both be equal to the market interest rate. Because of numerous distortions, however, in particular the presence of taxation, the SOCC is higher than the SRTP. Some economists have suggested the use of a 'synthetic' discount rate derived as a weighted average of SOCC and SRTP. More recently, Feldstein (1972) and others have argued that it is is preferable to use both rates in an analysis in their appropriate roles:

- the SRTP should be used to discount future benefits and costs to the present, and
- a shadow price should be applied to each dollar of scarce capital used, reflecting the loss incurred by not using it elsewhere to earn the SOCC.

Ferguson and Reilly (1975) have applied this concept to an Australian forestry project and estimated appropriate rates as 5 per cent per annum for the SRTP and $2.73 as the shadow price for each dollar of capital. The shadow price is a composite reflecting the idea that the capital used could have been drawn from a mixture of other uses (private investment, public investment or consumption), each with a different rate of return: i.e. the shadow price is the present value of the additional return that could have been obtained if the dollar had been used in perpetuity in these other areas.

In this airtanker study, application of a shadow price is not straightforward, as most of the costs involved are not capital costs invested by a public agency but annual hire costs charged by private operators. These in turn have been set by the private operators to cover their own required rate of return.

Therefore in this study, other capital costs (e.g. for retardant bases) are converted to annual rates using a real interest rate of 10 per cent per annum which is taken to be the SOCC and similar to the private rate of return.

However, for discounting future benefits (such as for timber saved) occurring up to 100 years from now, a SRTP of 5 per cent per annum is applied.

Price level

All costs and prices have been expressed in terms of a constant price level, namely around $A June 1983 when most of the data were compiled. Where necessary, prices obtained from other years were adjusted to that date according to the movement in the Consumer Price Index for Melbourne.

Since then price indices have been rising at around 5 per cent per annum so that for the equivalent dollar values at December 1985 for example, 10 per cent could be added to all values.

In those cases where a real increase in price for certain goods in future years is assumed, the money price will rise faster than the general inflation rate. For example, if the price of timber rises in real terms by 1 per cent per annum, and if the inflation rate turns out to be 8 per cent per annum in future, the money price of timber will rise by 9 per cent per annum

Security

There is a question as to whether an additional benefit by way of increased security or reduced risk should be included. An analogy is that, in order to remove the risk of one major loss, people are prepared to pay regular insurance premiums which in total amount to a sum greater than the average expected value of their losses. The additional amount paid meets the operating cost and profit of the insurance companies, but also can be taken as the measure of the premium that clients are prepared to pay for security against a large one-off loss. This seems to be in the region of 20-30 per cent of expected losses.

Whilst a community desire to purchase airtankers may partly reflect this concept of insurance against catastrophic loss, no extra premium for security has been included in this study. The main reason is that, judging from the analysis, there is no real security provided by airtankers. They merely increase the probability by a small margin that any potential bushfire disaster will be averted.

A straightforward cost-benefit analysis, based on expected values, seems adequate to handle this, provided adequate values are accorded to the catastrophic losses.

A better way to express this desire for security may be to include not just the market value of the tangible losses but also allowances for the intangible emotional losses suffered with the destruction of homes, lives and parts of our national heritage.

Inter-industry effects

The economic impact of bushfires, particularly individual disasters, can also be viewed in terms of the effects on different industries. For example, T.J. Mules has compiled an input-output analysis of the 1983 Ash Wednesday bushfires in South Australia (Healey et al. 1985). This showed that the biggest direct production losses occurred in the agriculture and forestry sectors, with significant flow-on effects reducing output in the manufacturing, finance and trade sectors. Positive effects from reparation activity were modelled separately showing substantial increase in building, manufacturing, transport, trade and finance. The output gains from replacement activity and forestry stockpiling were estimated as $188m while losses stemming from the agricultural and forestry sectors' losses were estimated as $34 m.

These inter-industry effects, however, are not necessarily relevant in a cost-benefit study of bushfire suppression which aims to aggregate all costs and benefits for different policies. Unless it were thought that some particular industries or classes of people affected were more deserving than others, and their benefits should be weighted more heavily, the distribution will not affect the aggregates used for policy comparison.

The input-output tables show the main visible effects on economic activity after the fire, and their distribution between industries. However, the measured net increase in output and incomes after the fire obviously should not be interpreted as an overall gain in economic welfare from the fire. The apparent paradox arises partly because items such as houses and public assets shown on the positive side in reconstruction activity have not been included as an equivalent reduction in value or imputed services on the negative side.

The gains in economic activity in some industries can alternatively be viewed as costs to society as a whole. For example, the replacement of burnt houses has an 'opportunity cost' in that it absorbs scarce resources, some if not all of which could presumably have been employed otherwise, building entirely new assets of benefit to society. Instead, they must now be employed merely to replace what existed before.

A cost-benefit study measures these effects mainly in terms of the change in market or capital values brought about by the fire.

Sharing the cost burden

If airtankers are to be used, regardless of the results of a cost-benefit study, the question arises as to who should fund them, with a separate but related question as to who should manage the service. Some possibilities include:

- State or Commonwealth governments
- semi-government fire protection agencies
- insurance companies
- private operators, through charges levied on beneficiaries.

There is in fact a whole spectrum of types of agency from pure government to pure commercial, with those like the CFA and NSCA somewhere in the middle.

A semi-government agency may be a vehicle for funds passed on by a higher level of government. The main question lies in the ultimate source of funds.

Two different criteria for financing government programs should be considered:

- the 'benefit' or 'user pays' principle; i.e. costs should be shared in the same proportions as benefits are received.

- 'capacity to pay'; i.e. revenue should be extracted according to individuals' capacity to pay, e.g. through income tax or general tax revenue.

The user pays principle is appropriate if the beneficiaries can be clearly distinguished and, of course, if they are not intended to benefit specifically because of their low income. In the case of airtankers (or bushfire suppression generally), however, the potential beneficiaries are diverse and difficult to identify, being, to a large extent, hypothetical. They could include for example, farmers, travellers, rural and semi-urban home owners, timber consumers, water users, etc. In particular areas there may nevertheless be large individual stakes, e.g. in private pine plantations.

Government finance

Given the general characteristics of bushfire protection as a 'public good', there is a good case for financing from general revenue of Commonwealth, State or Local Governments.

Local rates would be quite suitable as a basis for funding, being fairly well related to potential property losses, but a local government unit would be too small to be a suitable basis for management of the service. Corresponding to the levies on private property, there could be levies on public land-holding agencies. This system could be combined with levy differentials based on bushfire hazard ratings for different areas.

However, regional hazard ratings can be very subjective and variable and such a rating system may not be worth the administrative expense. An alternative solution would be general government financing, whether through a government department or a new agency. This spreads the cost burden widely, like the benefits, with no pretence or administrative effort to match the two.

Whilst ideally such funds might be raised by taxation according to ability to pay, there is no guarantee in reality, and it is conceptually not possible to link any small government expenditure to any particular source of finance, out of the many types of taxes, charges and loans used to finance the budget as a whole.

The State Government level may be the most appropriate level for management, both from the viewpoint of Constitutional responsibilities and efficient use of local knowledge. However, there could be justification for some Commonwealth involvement in that:

- The Commonwealth bears the major share of the burden for natural disaster relief payments and thus has a financial interest. For example, after the Ash Wednesday fires in 1983, out of the $44m paid from the Victorian Natural Disaster Relief Account, $23m came from the Commonwealth and $21m from the State Budget.

- Optimal deployment of large airtankers could involve decisions as to their allocation between several different States according to the greatest benefit.

Insurance levies

Given that insurance companies bear the burden for a substantial proportion of bushfire losses, there is a case for the companies to help to finance efficient control measures, in their own interest as well as the public's. For example, in Victoria's Ash Wednesday fires, insurance payouts were expected to amount to $138m of the total costs of $236m estimated by the Government.

Insurance levies in fact have already provided a large share of the finance for country and city fire brigades in past years. In Victoria, 21 percent of home insurance premiums and 42 percent of non-domestic premiums have gone to the upkeep of fire brigades. This source provided two-thirds of the funds of the CFA, while the other third came from the State Government.

An increase in fire levies would be largely passed on to policy holders so that people would share the burden in accordance with the size of their insurance premiums. However, there is a poor relationship between the risk of bushfire losses and insurance premiums, for two reasons:

- A uniform levy on all policy holders would discriminate against city dwellers who are at little risk from bushfires. This could be alleviated if a reasonable differentiation in levies according to local risk could be made, but the same problems would arise as in the case of levies on local rates.

- There is a substantial degree of under-insurance. The great bulk of farm fences, livestock and crops, in particular, are not insured. While home insurance is more widespread, it has been estimated that 13 percent of homes are under-insured and a further 20 percent grossly under-insured. Overall, only 28 percent of assets on rural properties are insured. In the 1985 Maryborough fire, only 16 percent of the value of assets destroyed was insured. Publicly-held resources such as timber and National Parks are not insured.

It can therefore be viewed as inequitable to load the burden of fire protection for all on only those citizens who insure. This inequity could be aggravated as raising premiums would provide a futher disincentive for people to insure, reducing the premium base and throwing a greater burden onto those still paying premiums.

Whilst individuals have every right to opt not to insure and to bear their own losses, inequity arises because of the general practice of governments of subsidising those who lose uninsured property in a natural disaster. As a one-off measure, on compassionate grounds such relief is justifiable, but the expectation that such aid will always be forthcoming presumably acts as a disincentive to insure fully. One aspect of this is that insurance companies lose business from what is, in a sense, subsidised government competition.

For such reasons, the Victorian Government is currently planning to shift the main source of fire brigade funding from insurance companies to an additional tax on property values. Most other States either have or are planning to adopt a similar system.

Regardless of the method of funding of fire control agencies, there is still a good case for encouraging insurance companies to offer discounts to those who live in low fire-risk areas or who take effective hazard reduction measures (D A Lee in Healey et al. 1985). South Australia's Government Insurance Office has taken up this method. The Insurance Council of Australia has opposed the idea on the groun~~ds of th~~e high costs of regular inspections of every insured property to assess the current state of risk (House of Representatives 1984, p.1411-3).

However, by encouraging individuals to take measures which reduce the hazard for themselves and also for their neighbours, the benefits of the scheme could be very high, and further investigation of it seems warranted.

Commercial enterprise

If the airtanker service is supplied by a commercial enterprise (or a non-profit company like NSCA), the 'user pays' principle tends to be automatically fulfilled, since only likely beneficiaries have the incentive to pay the voluntary charges.

It would be difficult however, for a commercial enterprise to run an airtanker service at the optimal level because it may be unable to extract appropriate charges from the wide range of people and organisations who might benefit from the reduced risk. There would be a tendency for some potential beneficiaries to act as 'free riders' and decline to pay.

Despite this it is interesting to note that the National Safety Council of Australia (Vic. Division) has greatly expanded it helicopter fleet for aerial suppression, funded by fees (for 'protection service') paid by a number of organisations, including government agencies. Many of these organisations may view their role as contributing in the general public interest rather than just for benefits strictly within their own domain.

To realise the full potential benefits, it is desirable that any suppression service be managed in a way that looks to the broad social interest, allocating the scarce resources to the highest return area in cases of conflict. This would require that the service either be run by an independent government or semi-government agency, or at least with close co-operation between the bodies representing the main interest - FCV, CFA, etc.

4. COST-BENEFIT MODELLING

Estimating the total costs and benefits flowing over time from each policy alternative involves first identifying and quantifying the significant physical changes that result and then valuing each effect in terms of a common monetary unit.

System overview

Each policy alternative involving investment in airtankers or units of ground equipment gives rise to an initial cost and then a series of operating costs and benefits resulting from each application to a fire. For each fire, the benefits comprise basically the reduction in damage to life, property and other resources in the path of the fire. This in turn depends on -

- the reduction in area burnt - which depends on the speed and effectiveness of the suppression technique vis-a-vis the growth rate of the fire
- the quantity and value of susceptible resources in the area
- the extent of damage that would have occurred to resources in the area, which depends on fire intensity and the susceptibility of the resources.

The flow chart in Figure 2 shows how the main variables in the system interact.

The results depend on a vast range of environmental conditions beyond our control, and also on a host of related policy decisions including pre-suppression, dispatch and suppression tactics. Human reactions and productivity also have an important influence.

The overall economics of each policy depend on how the initial cost compares with the aggregate of net benefits on all fires it is used on. This in turn depends on the total distribution of fires within its operating scope - i.e. their number, locations, timing, behaviour etc.

Practical modelling

Of course none of these future events can be predicted with certainty, the variables are too numerous and relationships too complex to fully quantify, and many of the desirable data are unavailable. Hence a compromise must be reached between fire reality and modelling simplicity. The model used is based on a mixture of reality and abstraction, with relationships simplified to involve only a few quantifiable variables. It processes a sample of fires drawn from past fire reports.

The relationships are too complex and involve too many discontinuities to allow a continuous objective function to be formed and optimised by calculus or marginal analysis. Instead, computer simulation techniques are used to compare the results of a finite number of suppression expenditure alternatives.

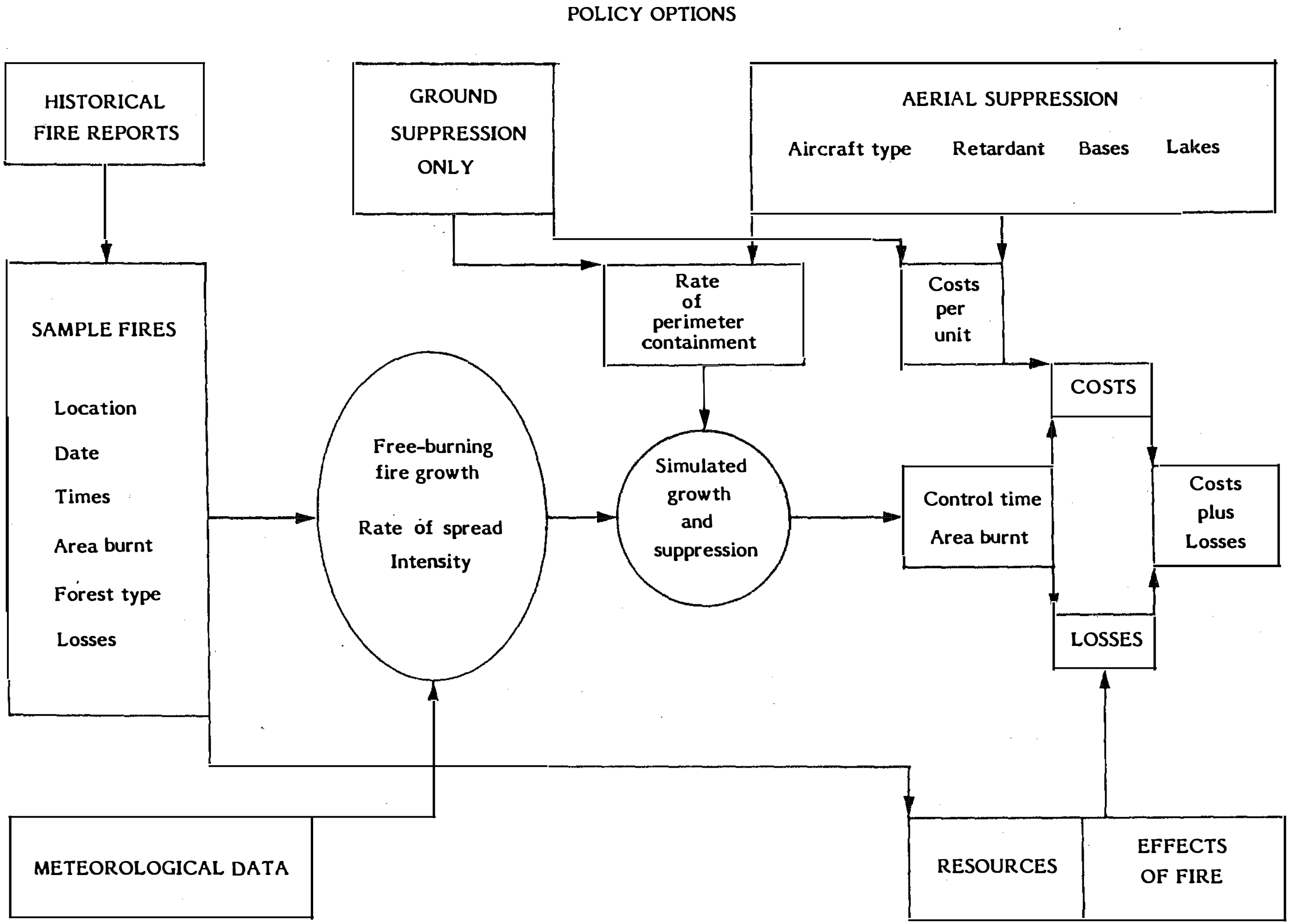

Figure 2. Flow-chart of main relationships in model

Other indirectly-related policies such as pre-suppression activity have to be taken as given, rather than optimised within the model. The optimal policies with respect to certain technical aspects, such as drop height and drop speed have been estimated by separate experiments and taken as given in the model.

Data limitations

Quantification of all aspects of the fire suppression process is the essence of this study, but at the offset reservations about the accuracy of the data and relationships involved should be made clear. In parts it may appear to be an exercise in quantifying the unquantifiable. Some of the reasons for the data limitations are:

- The natural processes involved in fire behaviour and effects are highly complex and variable over space and time. Even in the course of a single fire, there may be great variation in environment, weather conditions, fire behaviour and effects, and suppression effectiveness. In addition, this economic study, concerned with a long time span and large regions of Australia, faced great variability on the broader scale.

  Wide variability in the economic environment also make it difficult to place consistent values on the effect of given resource changes.

  Because of these problems, research studies quantifying the factors are relatively few, covering only a small part of the full range of situations and variables ideally required.

- Official reporting of actual fires is often scanty. Many agencies' fire report forms do not provide a space for all items of interest and often the items that are on the form are not filled in comprehensively by informants. These problems are in turn partly due to the difficulties of measurement mentioned above. Volunteers, in particular, understandably place a lower priority on filling in forms than on practical fire fighting.

For all the main factors involved in the model, nevertheless, the best data that were reasonably available were used. Many gaps had to be filled by interpolation, extrapolations and 'guesstimates' based on qualitative judgements. Variability in factors generally had to be handled by estimating an average value, implicitly weighted by the probability of different values in different situations. Even when data were available for particular estimates, they frequently could not be used directly in the model because they were known to be derived from an atypical situation. Ad hoc adjustments in the light of other information were therefore made.

In seeking information, the importance of particular data items to the study has to be sometimes traded off against the cost of acquiring them. Accordingly the quality of data varies through the model and there may appear to be detail in some parts that is not justified by comparison with the rough estimates and assumptions in other parts. The model might be likened to a chain that is only as strong as its weakest link.

However, there are several reasons justifying this situation: where detailed or exact information is readily available there is no advantage in reducing its quality to a lowest common denominator. The data used in these parts may be of interest in themselves to particular readers. Further, a better base is thereby provided for re-evaluations if data in the weaker sections can be improved at a later date.

The above qualifications should be taken as implicit in all the estimates discussed later in this paper.

Structure of AIRPRO program

AIRPRO is a fairly large FORTRAN program, consisting of a main program and 44 sub-routines. The program has about 4500 lines, and in compiled form requires 0.28 megabytes, so the program was run on CSIRONET's mainframe Facom M-180 computer. Certain mini-computers such as the Digital PDP-11/73 would also have sufficient capacity.

Running the program requires two input files:

- FIREIN, containing details specific to each sample fire, in format set out in Appendix 2;
- DATAIN, containing the general system data, e.g. concerning airtankers, airfields, resource values etc.

Output consists of:

- EVERY, a file containing the results, for each fire, of each resource combination selected to fight the fire;
- BEST, a file containing, for each fire, just the results for the resource combination giving the best saving;
- A summary table showing the distribution of optimal resources by various categories, and certain other totals;
- Optional detailed diagnostics, showing the value of numerous intermediate variables during the course of the program's calculations.

Additional programs have been written to analyse the EVERY and BEST output in more detail.

The simulation of fires in AIRPRO involves several levels of space and time.

Space

At the broad level, the geographic coordinates of each fire and airfield are used to calculate distances between each. The district determines certain aspects of costs and damages.

At the next level, the changing dimensions of the fire under growth and suppression are tracked.

Time scheduling

AIRPRO keeps track of the time on the 24-hour clock, as well as elapsed time since detection and time between events.

The model uses two different methods of representing the change in systems variables over time.

i) The following are events which occur at specified points in time or after specified intervals:

- crew arrival
- airtanker drop
- burnthrough
- sunrise
- sunset

In addition, the change in the diurnal weather cycle, although a more gradual process, is modelled as an hourly event.

ii) Fire growth and ground suppression, although continuous simultaneous processes, are modelled here as discrete separate events, currently alternating every 15 minutes. This interval can be readily reduced in running the program; as it approaches zero, the system comes closer to a continuous process but the computing costs also increase substantially.

5. FIRE INPUT DATA

Frequency distributions

The economics of airtankers depend largely on the number and characteristics of fires over the time period and area in which the tankers will be applied. Whilst we ideally wish to predict future fire patterns for an economic study concerned with future policies, virtually our only indicator lies in past statistics. Hence this study is based on fire data from historical records.

Distributions of fire occurrence and effects have a strong random or stochastic element, and thus one approach would be to generate hypothetical distributions, using an appropriate probability distribution and random numbers. The shape of the assumed distribution and its parameters would nevertheless be preferably derived from actual statistics. The approach taken here, however, is a simpler one, based on a deterministic model with a fixed set of historical fires. Results are weighted by long-term fire frequencies over past years, which represent future probabilities of occurrence, so that the results can be viewed as average expected values.

The data were used in two ways:

- A sample of fires, representing the relative distribution of different combinations of characteristics affecting suppression, was input to the simulation model.
- Long-term data on the total number of fires in various broad groups were used to expand the sample results to estimates for the whole population.

A flow-chart showing the stages in computer processing of the fire records is shown in Appendix 3.

Sources

Fire data were drawn mainly from the records of the (former) Forests Commission of Victoria and the Country Fire Authority, the two authorities responsible for fire suppression in Victoria. The FCV records include a larger proportion of fires in more remote timbered locations, while the CFA's include more grass fires and cover the major fires where private property losses occur. Computerised records are available since 1972-73 for the FCV and since 1979-80 for the CFA. Some non-computerised data from the National Parks Service were also added.

Sampling period

The sample of representative fires used in the simulations were drawn from the last five years' records, whereas the population numbers used to expand the sample results were based on the longest period for which reliable records were available. The representative fires were drawn from more recent years because:

- computerised records were available, which reduced data preparation time when thousands of fires used to be processed.

- the quality of reports for more recent years was expected to be greater than for earlier years.
- the patterns of human behaviour underlying the recent fire records are more relevant to those in future years. For example, detection, dispatch and travel delays should be shortening, ground suppression resources are improving, and the distribution of population and resources at risk is changing.

Long-term fire patterns

Variations in weather conditions, on the other hand, cannot be adequately represented by data from the last few years. A catastrophic fire season such as 1982-83 appears to come once every few decades rather than once every five years, although every sixth or seventh year often brings serious fire losses. The basic weather patterns underlying such fire cycles should be reflected in frequencies of large fires over the last century which will probably indicate as much about future fire weather patterns as we can hope to know.

The background factors subject to human influence may evolve further in future years, e.g. control burning may be extended and more successful; efforts to prevent electricity lines causing fires may be increased, while, working in the opposite direction, the prevalence of arson might increase, or the number of people building in high fire-risk bushland settings may further expand. No attempt has been made here to project or predict their extent, although the model allows testing to explore what difference in results would flow from given general changes in say attack delays, rates of spread and number of fire starts in different land-type zones.

Population data for FCV fires from November to February were taken from the 11 years 1972-73 to 1982-83, classified by area class by main forest type cell. For fires over 1000 ha, the number was to be adjusted on the basis of the relative number of fires over 1000 ha since 1918 but in fact the number appeared to have remained constant at about 19 over 1000 ha per year. The rise in total number of fires of all sizes reported between 1918 and 1983 is shown in Table 3.

Table 3. Average annual number of FCV fires

Period	No. of fires
1918-38	163
1939-56	248
1957-72	378
1973-83	472

However, the figures are probably distorted by a tendency to not report many small fires in earlier decades; significance was only placed on the number of large fires reported. The fire statistics are also influenced by changes (mainly increases) over the years in the size of the area protected by the FCV.

Long-term damage statistics, which might better reflect the frequency of disaster situations, are not available on a comprehensive basis but rough estimates from various secondary sources (e.g. Foster 1976 and Cheney 1976, summarised in Appendix 4) were compiled to supplement the above statistics. These indicated that annual damage from severe fires over the last 70 years was only about 62 percent of that over the last 11 years. The weights for fires costing more than $500 000 were therefore adjusted downward by this factor.

Before running the fire data through the simulation, several preliminary processing programs were necessary.

Sampling stratification

Fires for each year 1978-79 to 1982-83 were divided into three groups according to which authorities were present and reported on each fire:

- pure FCV
- pure CFA
- both FCV and CFA

The sub-set of fires in the four-month summer period November through February was used as being the period during which the airtankers would be available.

The aim of sampling was to restrict the number of fires processed in AIRPRO to a few hundred for Victoria so as to limit computing costs, bearing in mind that the fire set has to be processed a number of times with different policy variables and assumptions.

Before sample selection, the population was stratified by:

- fire season (5)
- area class (5)
- for FCV, main forest type/height class (11)
- for CFA, damage class (6)

The fires were stratified so as to ensure that the categories of fires most likely to affect the results were sampled most heavily, and that no significant category of fire was omitted. Fires with key data items missing were excluded from the sampling procedure. Fires which were actually controlled at a small size by ground forces unaided by air attack would be unlikely to show savings from addition of airtankers, so relatively few in this category were included in the sample.

For the pure FCV and Both sample, all fires over 10 ha were automatically selected (averaging 60 a year), and fires under 1 ha excluded, eliminating an average of 250 a year). For fires between 1 and 10 ha one fire was randomly selected from each of the 11 main forest type cells (unless void). However, all fires on which air attack was used, including those under 1 ha, were selected.

For the pure CFA sample, all fires over 10 ha and none under 1 ha were selected. All fires between 1 and 10 ha on which any property damage was reported were selected.

Appendix 5 shows the population in each FCV category, expressed as averages per year. The total sample number processed in AIRPRO was 918, consisting of 272 FCV only, 557 CFA only, and 89 Both.

Other variables such as travel time and district could significantly affect the results but were not used for stratifying variables since the number of cells expands rapidly with each extra stratifying variable and the extra complexity did not seem worthwhile. The complete enumeration of all fires over 10 ha should in any case capture the great majority of bushfires which could be worthwhile for air attack in the sampled years.

Items recorded on fire reports

The items recorded and the design of the fire report vary between agencies, as is indicated by Appendix 6. Many of the reports do not include key information needed to assess the economics of alternative suppression techniques either because there is no provision for them on the form, or because the spaces are not filled in, or because the information is inherently too complex to summarise. Values for the missing data were nevertheless estimated as system averages, and incorporated in DATAIN or in the main program.

Record structure

Considerable changes to the Canadian version of AIRPRO were needed to adapt it to the structure of the FCV and CFA records. The program has since been adapted to accept a generalised form of fire input data from any agency, but the original data must first be transformed into the required format by means of preliminary processing programs or hand-coding. This approach has the advantage of limiting interference with the complex main program but has the disadvantage of not taking advantage of some special details available on some agencies' reports.

AIRPRO now provides for three different record structures in FIREIN:

- pure FCV or general format - 2 cards
- pure CFA - 3 cards
- both - 5 cards (2 FCV + 3 CFA)

The 58 items on the FCV record are extracted directly from the original record, which has 4 cards and 102 items, by a SAS program. As for the 55 items on the CFA record, some are taken directly from the original records and some derived by preliminary programs, both by the CFA's computer section and Project Aquarius staff. For example, the CFA aggregated the suppression forces used by supporting brigades on a major fire onto the report for the primary brigade.

Matching reports

Fires in the Both category were separated by means of a matching program, the aim being to avoid double counting reports which were really of the same fire. The program basically compared FCV and CFA fires on the same day, identified those which appeared to be the same (reported locations within about 15 km of each other, and final areas within 75%) and output a file combining the matching records.

On 'Both' fires, the model uses the FCV data for the basic characteristics of the fire rather than the CFA's. The ground costs and loss reports of each agency are combined. Other agencies involved in fire suppression, usually in a secondary role, such as the National Parks Service (NPS), Melbourne and Metropolitan Board of Works (MMBW), State Electricity Commission (SEC), etc. and private companies such as APM Ltd also keep fire reports. However, it has been assumed here that their significant fires are already covered in the FCV or CFA records, and their unique kind of damages are covered in general routines for damage calculations.

In the case of NPS, however, extra details for about 40 of their largest fires in the last 4 years were added to the matching FCV fire record. Items added were identification number of Park, area of Park burnt, and NPS expenditure on suppression, rehabilitation and replacement.

Meteorological data

Weather and fuel data are no longer provided for on FCV fire reports, and have not been provided in most CFA reports since 1981-82, partly because of the variability of these factors over the course of a fire. Since meteorological factors have a role in the model (e.g. for redistributing the average spread rate of a fire over time), data was obtained from the Bureau of Meteorology records and input to the model via both FIREIN and DATAIN.

The computerised meteorological records were purchased from the Bureau for:

- the 6 stations in or near Victoria with 7 or 8 observations per day
- 25 other stations, widely distributed throughout Victoria, with at least 3 pm observations daily.

A new FORTRAN program was written to compute McArthur Fire Danger Indices from these records in either their Hourly Surface (Bureau Card 7) or Daily Surface Observation (Card 18) formats. The FDIs were calculated with the equations set out by Noble, Bary and Gill (1980) for Forest FDI Mark V and Grasslands FDI Mark III. Several preliminary calculations were necessary:

- Relative humidity was calculated from dry bulb temperature and either wet bulb temperature or dewpoint and pressure.

- The Soil Dryness Index (SDI) (in millimetres) was calculated from an abbreviated program used by the FCV, based on the model set out in Mount (1972). This was used in place of the Keetch-Byram Drought Index to calculate the Drought Factor.

- The Grassland Curing Percentage was approximated from a rough model, using the month of the year, SDI and lagged rainfall.

All the main equations used are set out in Appendix 7.

For all 31 stations, the 3 pm FDI for the last 5 years was calculated and the resultant file was matched against the fire report files. To each fire record was added the 3pm FDI for the day the fire started and the following day at the nearest station.

For 5 stations with 7 or 8 observations a day (Mt Gambier, Nhill, Tullamarine, East Sale and Wagga Wagga), the 3-hourly FDIs were calculated and averaged over a 10-year period for each hour, month and station. Values for the hours in between the 3-hourly observations were filled in by interpolation. The typical daily movement in the FDI, peaking in early afternoon, is illustrated in Figure 3. These data, representing the typical diurnal movement in the FDI for five different climatic zones in Victoria, were entered in DATAIN. It seemed desirable to include also a station in the highlands of Victoria but there are no such stations with 3-hourly readings. In any case the variation between the stations was not significant in the context of the model.

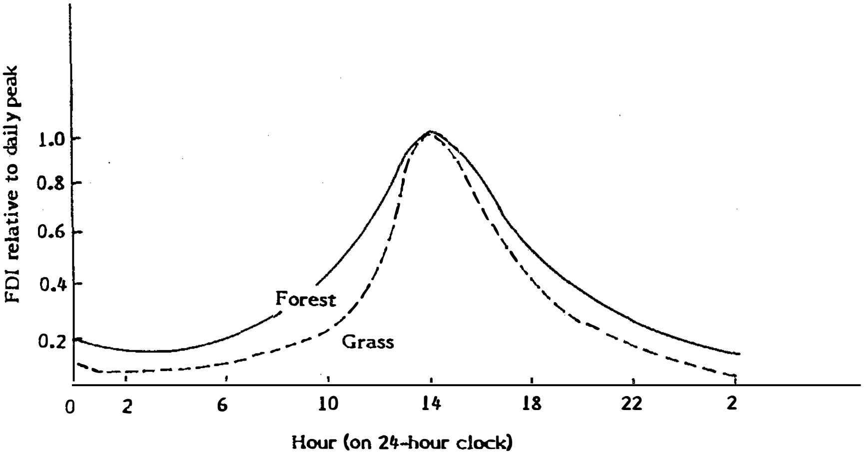

Figure 3. Diurnal variation in Fire Danger Index (Mean 1973-83, February, Tullamarine)

The files of FDIs now compiled are available for other analyses of historical fire weather, independent of AIRPRO.

Besides the FDIs, two other variables from the meteorological records were added to the fire file:

- wind speed
- rainfall intensity index, derivation and use of which is discussed in Chapter 17 on water catchment effects.

6. FREE-BURNING FIRE MODEL

The model combines the reported characteristics of each fire with various assumptions to simulate the free-burning growth of the fire. The main calculations are described below:

Location

The location of each fire is described by its latitude and longitude. These are derived for FCV fires from the map sheet number (1:250,000 scale) and easting and northing grid reference number of the ignition point, using a linear interpolation routine.

The location of each CFA fire is taken to be the latitude and longitude of the brigade in whose area the fire started. Since there are about 800 rural brigades in Victoria, the distance between brigade centres would average about 17 km and would be much less in more populous areas, so the estimate should usually be within a few kilometres.

Shape

The fire is assumed to be elliptical, as if burning in a uniform environment (fuel, slope and wind direction). Whilst variations in fuel, slope and wind direction are important in determining rates of spread and shape of actual fires, it is not practicable to obtain and use all this information in simulation modelling of a large number of fires.

The only information on fuel available and used is the FCV main forest type. Types 1 to 6 are taken as forest, while 7 (grass, heath, scrub) is taken as grass (see Table 17). All CFA fires are assumed to be in grass, unless otherwise specified on the report.

Length-to-width ratio (R)

This is estimated by empirical formulae.
Forest fuels:*

$$R = \frac{1}{\exp\ (-0.0162\ V^{1.2} + 0.0029)}$$

Grass fuels:**

$$R = 1.1\ V^{0.464} \qquad \text{if } V \geqslant 1.$$

where V = wind velocity (km/hr)

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* Simard AIRPRO Program 1983 ** McArthur, Cheney & Barber 1982

Length-width ratios are higher for grass fires than bushfires for a given wind speed since the influence of the wind is dampened below the forest canopy. (See comparison in Figure 4. It should be noted that the equations are from two different sources and are not strictly comparable at higher wind speeds.)

Perimeter

Perimeter at control is estimated from final area burnt, and perimeter at attack from area at attack, using the formula:

$$P = c\sqrt{A}$$

where
P = perimeter (metres)
A = area (ha)
$c = 46.05R + 297.2$ if R is greater than 1.5
$c = 21.87R + 332.6$ if R is equal to or less than 1.5

R = length : width ratio of fire

The formula was estimated by regression analysis on Canadian actual fire data by Simard (1969), and gives results close to those for a perfect ellipse, often used to represent a fire burning in uniform conditions. The relationship between A and P (for R = 2) is illustrated in Figure 5.

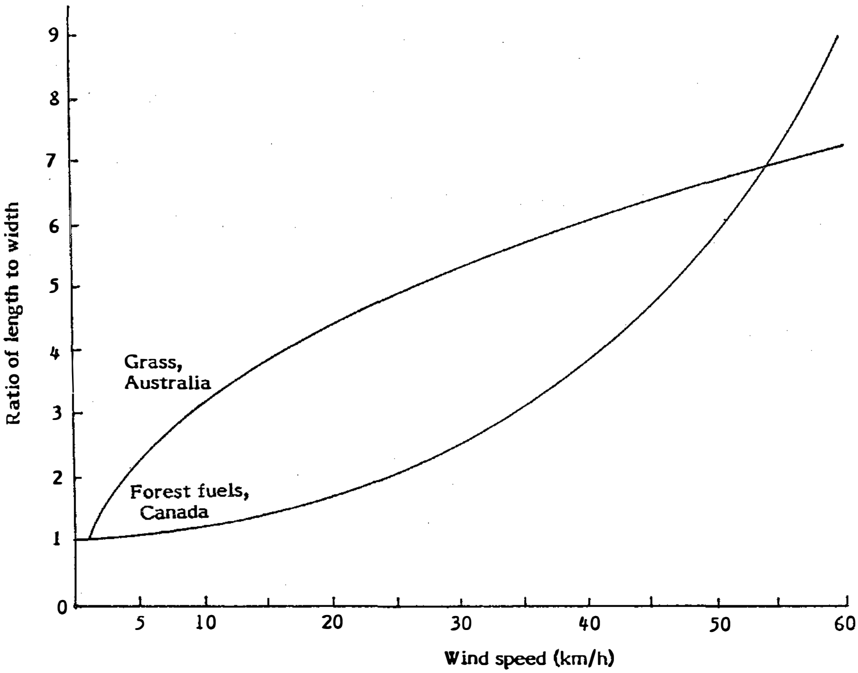

Figure 4. Ratios of fire length-to-width at different wind speeds

The changing perimeter is important for suppression calculations, while the final area is important for damage calculations.

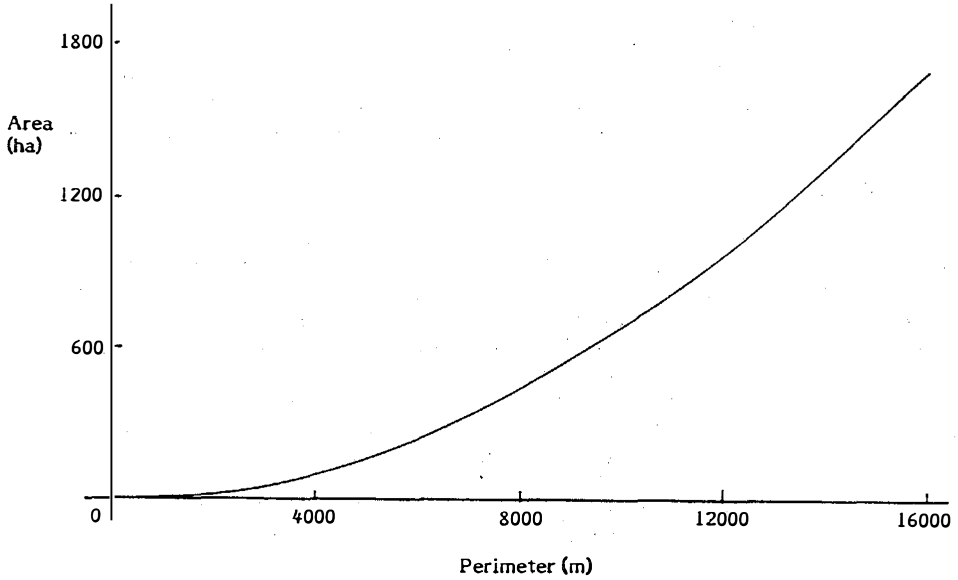

Figure 5. Area and perimeter of fire ellipse

For FCV fires area at attack is available, and this is also substituted in the above equation to find perimeter at attack.

Perimeter growth rate

The average growth rate after suppression began is:

PGS = (Perimeter at control - Perimeter at attack) / Time to control

If the time-to-control is used to calculate rate of growth of the fire, it should ideally represent the period over which the fire was still actively growing. On some reports, however, the control time is the time that a secure line was completed around the fire, although the fire may have been substantially checked some time earlier. Consequently, on FCV reports, 'Time checked' was used in preference to 'Time controlled' although the problem remains in part even with this.

This PGS represents growth in the actual perimeter, controlled plus free-burning, with the proportion of the latter gradually decreasing over the course of suppression.

We need to estimate, however, the rate at which the fire would have grown over this period without suppression i.e. the free-burning rate, RPG. The rate of growth of actual perimeter begins at the free-burning rate at the start of suppression and is gradually reduced to zero at the end of suppression. Therefore, if the free-burning rate were constant and the rate of containment were constant, PGS above would be the average of RPG and O.

i.e. PGS = RPG/2
so RPG = 2 PGS

However, because of variations in the rate of growth and containment, both over time and on different arcs of fire, the above extreme assumptions are not fulfilled. Instead, the average RPG is estimated in the Australian model by a three-step iterative process, searching for the average RPG which is consistent with the differential growth patterns used in the model.

A first guess at RPG is made, based on 2 PGS with adjustments according to the position in the diurnal FDI cycle, the ground crew delay and initial arc of attack. The simulation for ground suppression is then run, and the size of the discrepancy between the observed perimeter and simulated perimeter is used to generate a second guess. The results of the first and second simulations are then used as the basis for interpolation and for a third and final guess. Any earlier guess which results in a discrepancy of less than 15 per cent in simulated area is accepted as satisfactory. Using this approach, the total simulated area for each year's fires is generally within 5 per cent of the total reported area.

Area at attack is not available for CFA fires so, as a basis for growth calculations, the perimeter at detection is assumed to be just 100 metres.

Using the assumption mentioned above that RPG = 2 PGS, the free-burning rate of perimeter growth is first calculated as:

RPG = Increase in perimeter from detection to control /
(Attack delay + $\frac{1}{2}$ control time)

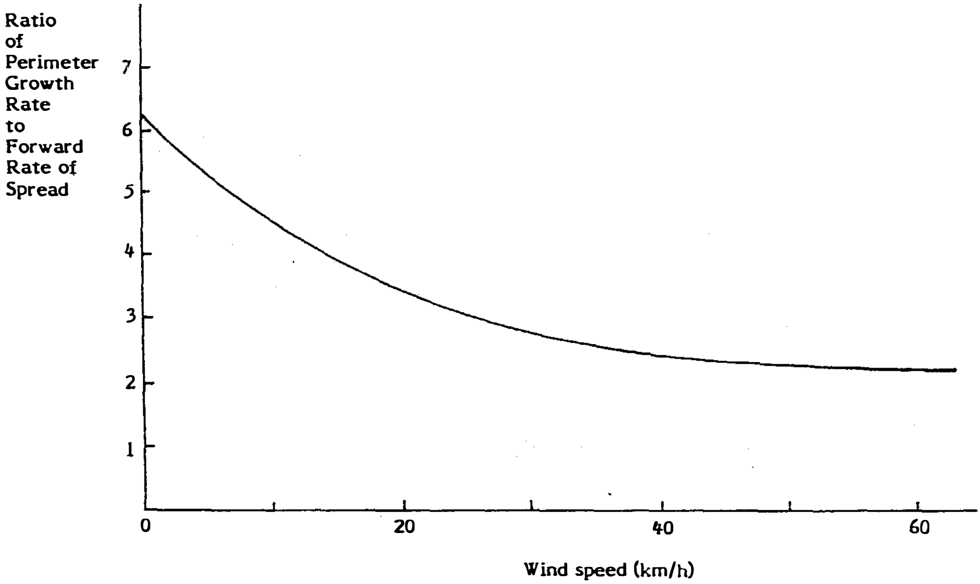

Figure 6. Perimeter growth to forward rate of spread ratios

Forward rate of spread

This is estimated from the perimeter growth rate and length-to-width ratio by a series of equations representing the geometry of an ellipse (Simard and Young 1978, pp. 66, 185). The equations are set out in Appendix 8, and the decrease in the ratio of perimeter growth rate to forward rate of spread as wind speed increases is illustrated in Figure 6. The rate of spread calculated in this way should reflect the various influences of fuel, topography and weather known to be important in determining fire behaviour. It also implicitly captures any increase in fire size due to spotting, or back-burning for control purposes.

The FCV fire report until several years ago had provision for an estimate of forward rate of spread and fire danger variables. These have been deleted in revised forms because the rates are so variable and difficult to estimate during the course of a fire that they were not thought to be useful. Some other agencies' fire reports include such estimates but they are bedevilled by the same problems.

Another indirect way of estimating the rate of spread would be by applying the McArthur meter or equations (see theoretical forward rate of spread below). However, this also involves much approximation of meteorological conditions and fuel weight, as well as the form of the relationships, and is unlikely to be more accurate.

Flank and rear rates of spread

AIRPRO calculates rates of spread on the other arcs by the following formulae based on Canadian empirical work (Simard and Young 1978).

$$\text{Flank ROS} = (\text{Rear ROS} + 0.00156V) * \text{Forward ROS}$$

$$\text{Rear ROS} = (e^{-0.047V}) * \text{Forward ROS}$$

Figure 7 illustrates the decrease in the ratio of flank and rear to forward rate of spread as wind speed, V, increases.

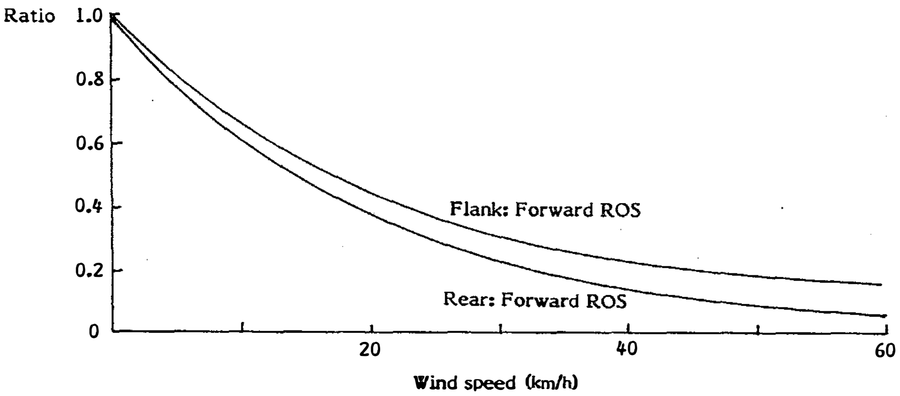

Figure 7. Flank and rear to forward rate of spread ratios

Two other variables needed to determine growth rates for each flank are calculated as follows:

Rate of growth of semi-major axis of fire ellipse (m/hr):

$$GM = (\text{Forward ROS} + \text{RearROS}) / 2$$

Rate of forward movement of centre of ellipse:

$$FC = (\text{Forward ROS} - \text{RearROS}) / 2$$

Size at detection

Area at first attack is given as input for each FCV fire but it is necessary to estimate the size at detection in order to simulate the results from airtankers which may arrive earlier than the ground crew. To do this, the fire is in effect shrunk back to the time of detection with the formula:

$PD = PFA - RPG*TT$

where PD = perimeter at detection

PFA = perimeter at first attack

TT = attack delay = dispatch delay + travel time

The RPG here is actually derived from the growth rate after attack and since this may differ from the actual growth rate before attack, PD in the above formula can be negative on occasions. In such cases, PD is assumed to be 100m, and a new value of RPG is inferred:

$$RPG = (PFA-100) / TT$$

During the simulation the fire is grown forwards again until suppression begins when, in the case of ground suppression only, it will have reached almost exactly the same size as that in the input data.

Intensity

Intensity (I) is calculated from the Byram formula:

$$I = HWR$$

where H = heat value of fuel

W = fuel weight

R = rate of spread

A value of H = 17000 kJ/kg for eucalypt fuel was used by Packham (unpublished 1984) in his Aquarius ASMI model, with I in kW/m of fire front, W in kg/m^2, R in m/sec.

This has been translated to $I = 0.47\ WR$ where W is in t/ha and R in m/hr.

Assuming also W = 15 (t/ha) for forest fuel, gives the approximation:

$$I = 7R$$

Intensity is used in the model to calculate rates of line construction and damages.

Variation in spread rate

Information on changes in the sample fire's rate of spread (e.g. because of weather or fuel changes) is not available in the model. However, the rate of spread is assumed to vary from hour to hour around the actual average, in proportion to the variation in the long-term mean for the hourly FDI for the appropriate climatic zone and season of the year.

The 3pm FDI for the fire is used to calculate a 'theoretical forward rate of spread' (TFRS) from the equation based on McArthur's meter in Noble, Bary and Gill (1980):

Forest: $TFRS = 1.2 * FDI * W$
where $TFRS$ = theoretical forward ROS in m/hr.
W = fuel weight (t/ha), assumed to be 15t/ha.

Grass: $TFRS = 0.13 * FDI$

However, in the Australian version of AIRPRO, this TRFS is only a base for calculating the percentage diurnal changes to apply to the actual ROS and so is not essential to the model. Only the proportionate change in FDI between the first and second day is really used in the model - not the absolute levels of FDI. (In the Canadian version the Fire Weather Index was more critical because in their equations, ROS is a non-linear function of FWI.)

Initial rate of spread

The ROS at the start of both the period of free-burning growth and the period of suppression is calculated so that, with hourly adjustments in proportion to the diurnal cycle, the average ROS equals that calculated from the input data.

Initial rate of perimeter growth = AI * Average rate of perimeter growth

where

$$AI = \frac{FDI_h * TT}{\sum_{i=h}^{TT+h} FDI_i}$$

FDI_h = FDI at hour h
= $FDID_h * FDI$

$FDID_h$ = diurnal factor = mean FDI at hour h relative to 3pm, from DATAIN
FDI = FDI at 3 pm, from FIREIN
TT = period of free-burning growth = attack delay
h = hour of detection

Hourly change

Thereafter, rate of perimeter growth at hour i, $RPG_i = RPG_{i-1} * FDID_i/FDID_{i-1}$

Rates of linear spread and intensities on each arc are adjusted in line with RPG each hour.

Daily change

For fires burning beyond midnight, the diurnal FDI cycle is imposed on the day-to-day change. The FDIs for the first two days are given in input data, but to avoid a sudden change at midnight, the transition from the first day's to second day's levels of FDI is spread over the 16 hours from midnight to 4 pm:

$$FDI_h = FDI_{h-1} - (FDI1 - FDI2) / 16$$

where $FDIi =$ FDI at 3pm on i^{th} day, $i = 1,2$

For the third day, the afternoon FDI is set to 90 per cent of the previous day's, and on the fourth and subsequent days to 50 per cent of the previous days to reflect the increasing probability of rain. In accordance with this, an upper limit of 72 hours for the estimated control time has been imposed.

The modelling of fires extending over many days is weak but the model is mainly intended to test initial attack and this procedure captures the main periods of active spread and prevents costly computer calculations from going on too long.

Large fire growth pulse

In Canada, Simard found that the simulated area burned on fires over 40 acres was consistently low compared with the observed area. He argued that this was because large fires tend to spread very quickly for a few hours before settling down to more moderate growth rates. If the actual fire is not controlled by initial attack forces, there is a subsequent influx of men and equipment. If average rates of growth and suppression over the whole course of the fire are applied at the start of suppression, the model controls the fire much quicker than in real life.

One of the modelling adjustments made in the Canadian version was to apply a large fire growth pulse, so that the initial growth rate (after the arrival of the first crew) was increased and then gradually decreased so that the total simulated growth over the life of the fire was still approximately equal to the observed growth.

This was not considered necessary in the Australian version for several reasons:

- Although there is a phase of acceleration of a fire from a point ignition source, this is generally achieved within the first half-hour*. It would therefore usually be completed by the time of attack.
- There are already two factors in the model which may provide for an early escape - the morning build-up in the diurnal weather cycle, and a crew build-up function.
- The iterative procedure for estimating the average PGS provides an alternative method for obtaining closer agreement between real and simulated area.

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* See functions in Cheney's chapter in Gill et al. 1981, pp.157-8.

Imposition of the diurnal weather pattern on the fire means that fires which are detected in the morning and burn throughout the day could have an initial rate of spread of only about one third of their average rate. This provides an important advantage to airtankers if they are able to begin attack before the ground crews arrive.

Fire segmentation

The free-burning fire ellipse is aligned in the direction of the wind or slope. The coordinate geometry is calculated with the origin at the centre of the ellipse (not the ignition point of the fire), with the vertical axis being the direction of forward spread and thus the major axis of the ellipse.

The perimeter is divided into four arcs or 'flanks', namely the head, two equal flanks, and rear (equal to head), each of which is processed separately. The point of intersection between the head and flanks is defined so that the tangent to the ellipse at that point has a slope (i.e. angle relative to horizontal minor axis) equal to the length-to-width ratio.

D is point where head intersects flank.
Tangent at D is parallel to AB with slope equal to length/width.

E,F and G are defined symetrically.
Head is DE.
Flanks are EF and DG.
Rear is FG.

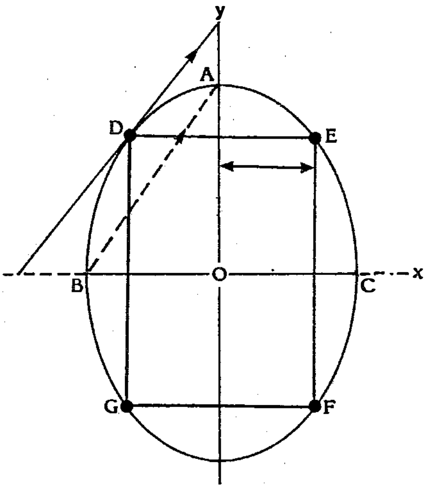

Figure 8. Arcs of fire ellipse

The relative length of each arc, which remains constant as the absolute size of the ellipse grows, is given by a series of equations based on the geometry of the standard ellipse (whose semi-major axis has unit length). The absolute arc lengths are derived by multiplying these relative lengths by the ratio of current perimeter to perimeter of the standard ellipse.

The chord lengths (e.g. DE for the head) or arc-to-chord ratios are similarly determined.

The size and position of the chords are important in the mechanics of modelling fire growth under suppression. They are determined initially by the rates of spread of each flank, as outlined below.

Chord growth components

The horizontal and vertical components of the movement of the ends of each chord are determined as follows:

The lateral growth rate of the head (and rear)chord GL, either side of the major axis, is given by:

$$GL = IX * GM$$

where
IX = x coordinate of point where head meets flank in standard ellipse,*
GM = growth rate of semi-major axis of fire ellipse
(Forward ROS + Rear ROS) / 2

The total growth rate of the head chord is therefore 2 * GL, and the growth rate of the head arc, AGI_I, is given by:

$$AGI_1 = 2 * GL * RC_1$$

where RC_1 = head arc-to-chord ratio.

The forward rate of growth of the flank chord from the fire origin, GF, and the rearward rate of growth of the flank GR, are given by:

$$GF = IY * GM + FC$$
$$GR = IY * GM - FC$$

where IY = y coordinate of intersection of head and flank in standard ellipse

FC = forward growth rate of centre of fire ellipse
(Forward ROS - Rear ROS) / 2

Then total growth rate of flank chord is GF + GR, and growth rate of flank arc is given by:

$$AGI_2 = (GF + GR) * RC_2$$

where
RC_2 = flank arc-to-chord ratio from standard ellipse

Applying this series of calculations to the estimated perimeter at detection establishes the initial dimensions and growth rate on each side of the fire at the time suppression begins.

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* Equations to determine IX are given in Simard and Young (1978) p.65.

7. GROUND SUPPRESSION

Benchmark

While the primary purpose of AIRPRO is to study airtanker productivity, it is first necessary to establish a benchmark of suppression without airtankers, against which alternatives can be compared and the net benefits (i.e. savings in cost-plus-loss) measured.

The benchmark policy is ground suppression only, with rates of perimeter control based on those achieved on the historical fires in the sample - basically the status quo.

In testing the alternative airtanker policy, it is assumed that airtankers are additional to the historical level of ground forces for initial attack, rather than replacing it. Even with airtankers, ground forces are needed on all fires to consolidate and mop-up, as well as for the many fires on which airtankers are not used. Airtankers are likely to contribute only a fraction of the total length of fire line constructed over a season. Hence the size of the initial attack and specialist ground forces is unlikely to bear reduction. Nevertheless, the use of airtankers can reduce total ground suppression costs, in the model as in practice, by reducing the overall control time.

Another alternative policy tested was an increase in the level of ground suppression forces in the form of:

- hand crews and
- machine crews,for initial attack.

For each sample fire, the model first goes through the simulation with original ground suppression only, then with additional ground forces, then with airtankers. Although the main features of the fires are drawn from historical records, the model cannot capture all aspects of the historical fires and many assumptions have to be made. The modelling process has managed to obtain fairly close agreement between the observed and simulated final areas but the assumptions and possible inaccuracies relate mainly to the variations over space and time in the growth and suppression of individual fires.

Times of attack and control

For FCV fires, the following times are calculated in the model from the input data:

Attack delay = time crew arrived at fire minus time fire detected (including despatch delay and travel time)

Table 4 indicates that travel times on FCV fires are less than 1 hour on 85 percent of fires and are over 2 hours in only 6 percent of cases.

Control time = time fire checked or contained minus time crew arrived.

Table 4. Number of fires by travel time class and main forest type

(FCV 1972-73 to 1982-83)

Main forest type	Travel time class (minutes) 0-20	21-40	41-60	61-120	121-180	>180	Total
Ash, HEMS	30	19	25	20	13	34	141
Mixed species	464	329	226	189	53	111	1372
Redgum, box, ironbark	183	104	65	30	3	2	387
Softwood	85	21	8	2	0	1	117
Alpine	2	1	3	13	4	12	35
Mallee, native conifer	2	4	5	19	3	5	38
Grass, heath, scrub	409	141	54	38	9	8	659
Not reported	1563	576	260	174	48	56	2677
Total - number	2738	1195	646	485	133	229	5426
Fraction of total (%)	51	22	12	9	2	4	100

This does not include the subsequent time to completely control and mop-up, but is intended to measure the time before the fire size stops growing significantly.

CFA fire reports do not provide time or size at first attack or travel time. However, the distance from brigade building to fire is given and this is used to estimate travel time, assuming a standard 30 km/hr speed. Attack delay is then calculated as time between call (detection) and turn-out from brigade building, plus travel time. Control time is taken as Time to Contain if this item is filled in but since it often is not, Duration of Incident is the second preference.

The time suppression begins in the simulation is taken as the crew arrival time from FIREIN, and the fire size at attack is calculated by applying the free-burning growth rates to each side of the fire size at detection, for the intervening interval.

Rate of line construction

Average RLC on each fire is calculated simply as:

RLC = Perimeter at control/Time to control

RLC is thus strictly the rate of perimeter containment rather than rate of line construction, in that it reflects any factors which contributed to holding the fire, including natural breaks or rain, as well as the efforts of the suppression crew.

An alternative approach would be to base the rate of line construction on:

- the number of men and suppression appliances reported, and
- RLC per unit based on measurements on fire trials.

However, this is unlikely to be more accurate, given the great range of RLCs possible in different types of terrain and by different workers. The formula above automatically captures such variations as well as exigencies on the actual fire.

Rate of line construction is assumed to vary inversely with the intensity on each flank, according to the following formula for the RLC on flank f of:

$$\mathrm{RLC}_f = \mathrm{RLC} \sqrt{\frac{\text{Average intensity over 4 flanks}}{\text{Intensity on flank f}}}$$

Similarly, with each change in overall fire intensity in line with the diurnal FDI, the current RLC is adjusted according to the inverse relation:

$$\text{New RLC} = \sqrt{\frac{\text{Old RLC}}{\text{New Int. / Old Int.}}}$$

This function dampens RLC to give a less-than-proportional response to intensity. This appears to contrast with evidence that RLC by direct attack (i.e. at the fire front) varies more than proportionately to intensity in the higher intensity range and eventually becomes impossible. However, the above function is probably more representative of indirect suppression in such circumstances, where some progress towards containment can still be made some distance ahead of the fire front giving a positive RLC over the longer run.

Adjustment for air attack

Since RLC is intended to refer to line construction by ground crews only, an adjustment is necessary for those historical fires on which air attack was also used. The length of line held by aircraft is estimated from the volume of retardant dropped, average intensity of fire, and typical length of pattern available at the required depth. The perimeter growth rate is then adjusted upwards in accordance with the aerial contribution. The objective is to estimate how far the fire would have spread without aircraft, so as to establish the ground suppression only benchmark against which other tactics can be tested.

Crew build-up

The other adjustment made to the average data was to incorporate a suppression crew build-up sequence on fires over 9 ha. This was done by reducing the early RLC below the observed average and gradually increasing the current RLC to above the average over a calculated build-up period, so that the average RLC remained as observed.

The total RLC is allocated to up to 4 crews which arrive at evenly spaced intervals, not exceeding four hours, during suppression. For every 150 m/hr of line construction rate, an additional crew is assumed to be on the fire. The shape of crew build-up function is illustrated in Figure 9.

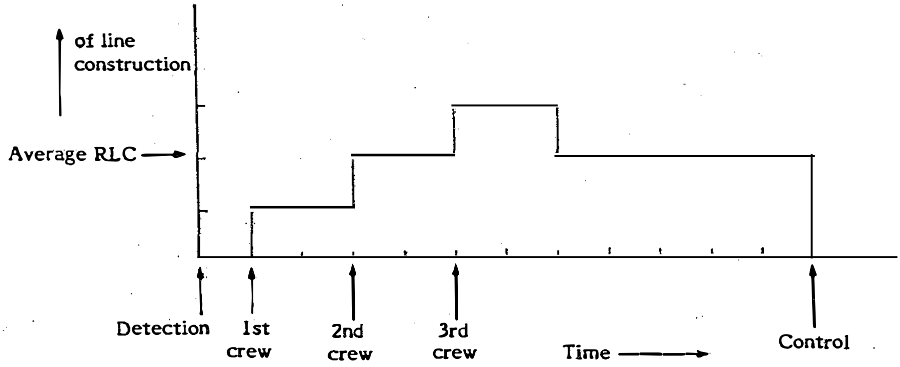

Figure 9. Ground crew build-up function

Order of attack on arcs

The initial arc and direction of attack by ground crews can be specified in DATAIN. The model user can also specify whether the crews work together, or split in two (as at present) and work in opposite directions from the same starting point.

Presently, for low intensity fires (up to 1500 kW/m), one crew begins on the head, working clockwise in the order 1, 2 etc. while the other works anticlockwise in the order 3, 4 etc. until they meet.

For higher intensity fires, the crews start at the intersection of arcs 3 and 4, split and work in opposite directions, and so generally finish on the head.

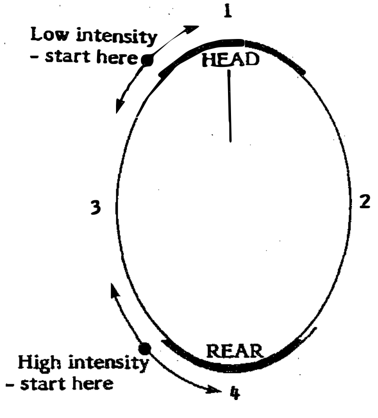

Figure 10. Order of ground attack on arcs

Perimeter containment

As mentioned earlier, the model simulates growth and suppression alternately in separate bursts, each for a maximum of 15 minutes.

The model calculates TL, the time left in the period for suppression before the next event or call to fire growth, and TW, the time it would take to finish the arc at the current RLC:

$$TW = AL_f/RLC$$

where

AL_f = free-burning arc length.

If TL is less than TW, line is built until the next event, and the perimeter controlled by ground forces on arc f working in direction d is increased by:

$$PCG_{f,d} = TL * RLC$$

If TW is less than TL, line is built until the end of the arc, and PCG is calculated by substituting TW for TL in the last equation. In the time remaining before the next event, the crew begin building line on the next arc.

The free-burning arc remaining, FL, is $FL_f = AL_f - PCG_{f,d} - PCG_{f,o}$

where $PCG_{f,o}$ = perimeter on flank f controlled by crew from opposite direction.

The fire is contained when the crews meet each other.

Modification of free-burning growth by suppression

When suppression begins at one end of an arc, growth is assumed to stop at that point and the symmetry of growth for the ellipse is lost. The chord length becomes the primary variable in calculating growth.

The arc and chord growth rates and the arc-to-chord ratio, must all be modified. As is shown below when one or both ends are held as in cases B and C, the arc length at time t+1 is longer (being stretched out) than if free-burning, although the chord length is shorter and area burnt smaller.

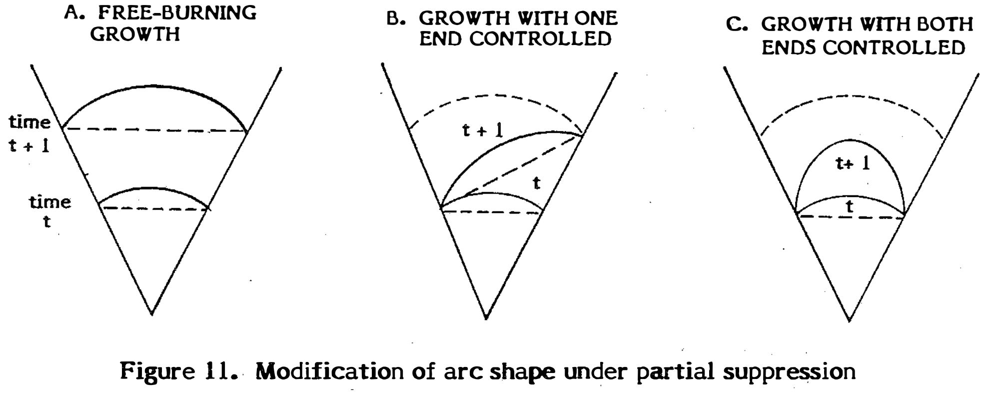

Figure 11. Modification of arc shape under partial suppression

In Figure 12, suppose suppression starts at A between arcs 1 and 3. Since the chords will be swung diagonally, their 'horizontal' (i.e. parallel with original chord) and 'vertical' components need to be defined. They are initialised by setting the horizontal components of chords 1 and 3 equal to current chord length, and the vertical components to zero:

$CH_1 = CL_1$; $CH_3 = CL_3$;

$CV_1 = CV_3 = 0$

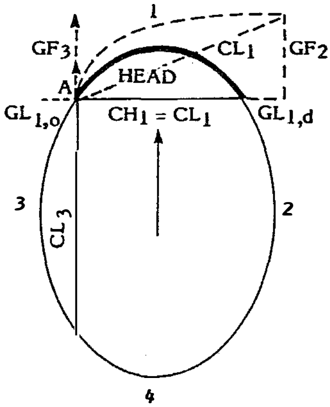

Figure 12. Growth sectors under partial suppression

With half the crew proceeding clockwise on the head from A, the forward growth rate of chord 3, GF_3, and the lateral growth rate of chord 1 on the left hand side, $GL_{1,o}$, are set to zero. On the right hand side, the forward growth rate of chord 2, GF_2, and lateral growth rate of chord 1, $GL_{1,d}$, are determined as in free-burning growth.

The equation for modifying the arc growth rate AG at the start of suppression is:

$$AG_f' = AG_f + RI\,(GC_{a,d} - GC_{f,o})\,RC_f(AL_f/AB_f)$$

where

RI = current-to-initial spread rate
GC = chord growth rate
f = arc of attack
a = adjacent arc
d = direction of attack (i.e. where one would finish if moving in the direction of attack)
o = opposite direction
RC = arc-to-chord ratio

AL = total arc length
' = updated value of variable
AB = free-burning arc length

In Figure 12,

$GC_{a,d} = GF_3$

and

$GC_{f,o} = GL_{1,o}$

(before terms on right hand side are set to zero).

Basically, the vertical component of the arc is stretched further to the extent of GF_3, and the horizontal component is shortened by $GL_{1,o}$.

The growth rate for the arc adjacent to the one attacked must also be adjusted.

$$AG_a' = AG_a + RI * (GC_{f,o} - GC_{a,d})$$

The arc growth is added to the arc length, AL

$$AL_f' = AL_f + AG_f * (AB_f/AL_f). TI$$

where

AB_f = free-burning part of arc f
= $AL_f - PCG_f$
TI = time interval for growth

This stretching of the new arc when suppression starts at one end effectively transfers the spread from the old arc to the new arc. In certain circumstances in the original model, this could cause airtankers starting on a rapidly spreading head to <u>increase</u> the final size of the fire. To prevent this unrealistic result, the suppression model has been modified. The component of the arc length due to the stretching is calculated, and the ground crew starting on that part of the head are assumed to work at the higher rate appropriate to the previous flank until they reach the 'original' head component.

Chord length is calculated during suppression as follows. If both ends are controlled, the chord length is fixed. If only one end is controlled, the horizontal and vertical components of chord growth at the free end are calculated:

$$CH_f' = CH_f + TI * RI * GC_{f,d}$$

$$CV_f' = CV_f + TI * RI * GC_{a,o}$$

Chord length is then given by Pythagoras:

$$CL_f = \sqrt{CH_f^2 + CV_f^2}$$

Then arc-to-chord ratio is calculated : $RC_f = AL_f/CL_f$

Final fire size

Throughout the growth process the model has increased the size of each arc independently of the remainder of the perimeter. When all arcs have been controlled, they are summed to give the total perimeter:

$$P = \sum_{f=1}^{4} AL_f$$

The shape of a typical simulated fire at various stages is illustrated in Figure 13.

Although the shape has been modified by suppression, the final area is now approximated by averaging chord lengths and using a formula based on an ellipse to calculate the length-to-width ratio, RL:

$$RL = \sqrt{\frac{R(CL_2 + CL_3)}{(CL_1 + CL_4)}}$$

where R = original L:W ratio

Then the area is calculated using the same empirical relationship between area and perimeter as earlier (page 46), in reverse: $A = (P/c)^2$

Mop-up

Mopping up and making the fire safe may take considerably longer than it did to contain it, although the forces are gradually scaled down. This does not need to be physically modelled here, but the costs are included in total suppression costs.

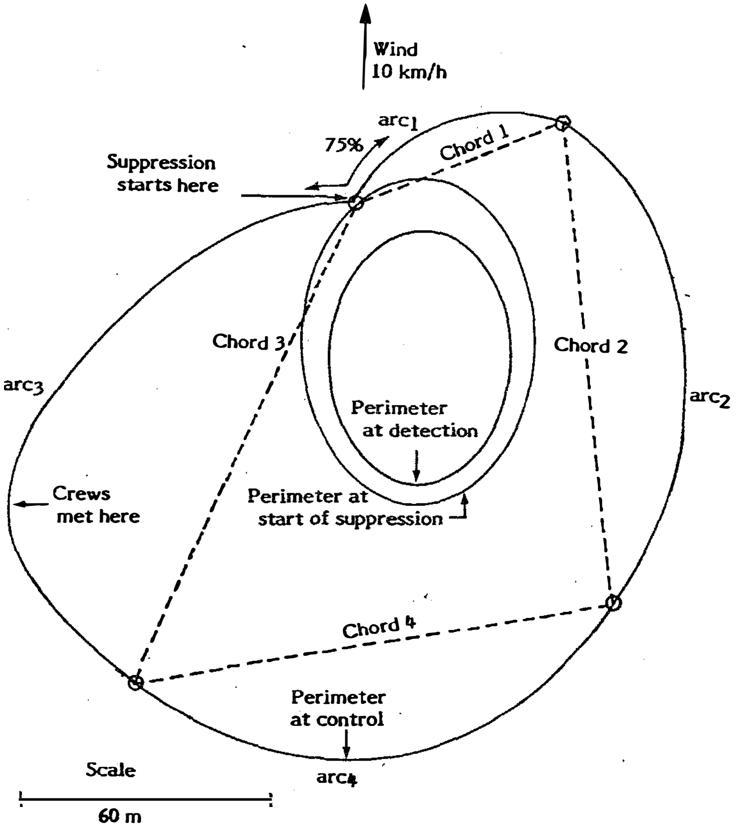

Figure 13. Shape of a typical simulated fire
(from Simard & Young
'AIRPRO - The equations' 1978)

Additional ground suppression

Having established the benchmark simulation with ground suppression only, the model re-initialises the fire and proceeds to simulate what might happen with two types of additional ground forces, namely:

- a machine crew consisting of a D6 bulldozer, a 4-wheel-drive 4000 -litre tanker, 3 4-wheel-drive utilities with small tanks, various hand tools, 2 personnel vehicles and 9 men including drivers.

- a hand crew consisting of 6 men with rake-hoes and other hand tools.

The additional ground crews are assumed to be available for initial attack, with the same travel time as on the historical fire. However, they are allotted rates of line construction based mainly on Project Aquarius trials which differ from the average rates derived for the historical crew. This may involve inconsistencies in some cases but is justified on the basis that, although the overall RLC on a large fire may be affected by sundry factors such as natural fire breaks on part of the perimeter, it would often be possible to put an extra crew to work on a segment in typical bushland where their contribution is maximised. The RLC for the additional crews is added to the benchmark RLC.

The Project Aquarius trials* were conducted in Mixed Species forest at Nowa Nowa, Victoria with the above two types of crews. Although evidence of environmental and human factors (terrain, fuel type, fitness etc.) was gathered in the trials, these variables are not available in the model. Therefore for the purposes of this model, the resulting RLCs were averaged across all those factors and distinguished only by fire intensity. The Project Aquarius trials covered only a limited range of conditions so the data had to be supplemented from other sources.

In the trials, the ground crews were set to work on experimental low-medium intensity fires, with the objective of minimising area burnt. Their rates of progress related to line constructed and held. For the hand crew the line measured was about 1 m wide cleared to mineral earth near the edge of the fire. Clearing was done mainly with rake-hoes, using the step-up method. Rakehoers were preceded by a slasher, and logs and trees were removed with a chain-saw, or debarked, where necessary. The line was patrolled and, where necessary, new lines made around spot-overs and burn-throughs. Rests were included in the time taken.

The RLC is expected to fall as fire intensity rises as:

- a wider line may have to be built
- a greater amount of time is spent patrolling and controlling spot-overs
- the rate of work falls, or rest breaks increase, as the crew suffer from greater heat exposure.

Usually the crew work at a greater distance from the flames as intensity increases, in which case measured RLC may not fall much. In terms of the resultant fire area, working at a normal rate some distance from the fire edge (i.e. indirect attack) is equivalent to working at a lower rate close to the edge. However, the

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* conducted by Mark Dawson & Tony Crichton of the S.A. Country Fire Service.

RLC data were based on crews working usually within 0 to 20 m of the flames, a situation fairly close to direct attack in terms of the final area. The assumption of direct attack in the model thus seems reasonable.

At times the observed RLC seemed to increase as fire intensity rose, but this sudden concentrated effort could not be sustained so that, notwithstanding, a negative relation between RLC and intensity has been assumed. An inverse function has been used, based on the few observations available:

- maximum RLC for no-fire situation (i.e. where intensity = 0)
- maximum intensity beyond which crews would not engage in direct attack (i.e. where RLC = 0)
- observed RLCs on typical going fires.

The following function, illustrated in Figure 14, was used:

$$RLC = b \left[1 - \left(\frac{I}{a} \right)^2 \right]$$

where I = fire intensity (kW/m)
b = max. RLC (m/hr) (1100, machine crew; 500 , hand crew)

a = intensity limit (2000, machine crew; 800 , hand crew)

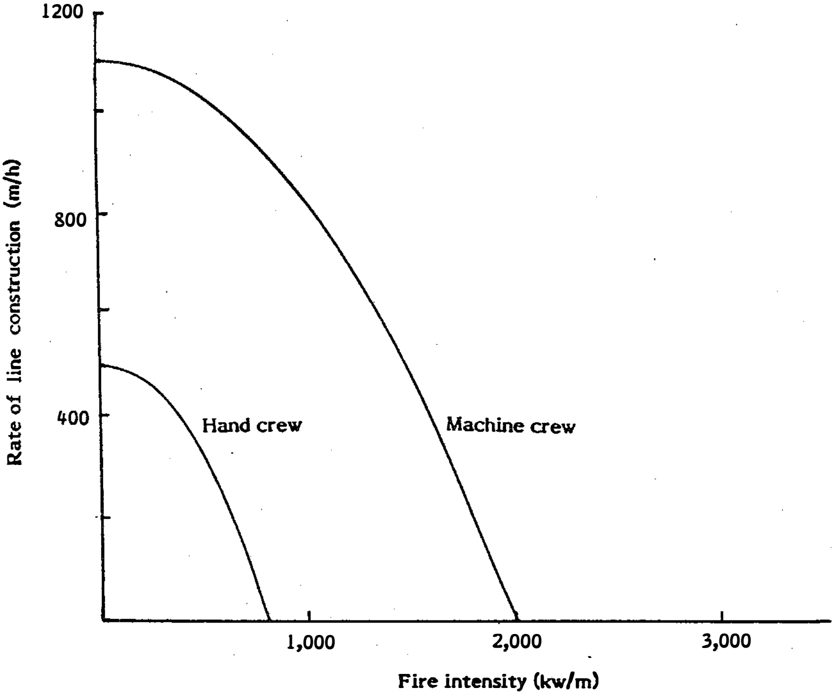

Figure 14. Rate of line construction in relation to fire intensity

8. GROUND SUPPRESSION COSTS

Fixed versus variable

The ground suppression costs for labour, equipment and materials ideally have to be separated into the variable element, which is directly related to the amount of work done on fires, and the fixed element which must be incurred for the season regardless.

In economic terms, the variable labour cost is not the cash cost but the opportunity cost of the employee's time. Hence, if the fire crew can be employed on other productive work when not fighting fires, with marginal value equal to their wage cost, then the variable cost of their time on fires can be measured by their wages. If on the other hand, they are hired only as a fire crew on permanent stand-by the variable labour cost can be taken as zero, and their wages cost allocated entirely to fixed costs. The former situation has been assumed here.

Similarly, general-purpose items, such as bulldozers and utilities, may be assumed to be drawn from other work for a fire, and their variable cost is approximated by their hourly charging rate (with capital costs spread over their working hours). For items largely dedicated to fire work, such as tankers, their variable cost per hour would be better measured by their operating expenses (petrol, oil) and additional repairs, maintenance and depreciation related to use.

Fixed cost data are not needed for the ground suppression benchmark, since the base level of forces used in the historical benchmark is assumed to be common to all the policy variations tested. Hence the addition of equal fixed costs to all alternative policies tested could not alter the net benefits or ranking of any. Fixed costs are nevertheless needed for additional ground crews, discussed further below.

Different approaches to calculating suppression costs were used for FCV and CFA crews, partly because of the different availability of data.

FCV

FCV fire reports contain an estimate of direct suppression costs. This cannot be used alone in the model since a procedure is needed to simulate how ground suppression costs would change if airtankers assisted, and the effort and time required from ground crews were correspondingly smaller. In this study regression analysis was used to derive an equation expressing suppression cost (GC) as a function of variables that are output from the simulation model - namely area and perimeter. Perimeter was thought to be significantly related to containment costs, and area more related to mop-up costs. Area in the model is in fact proportional to the square of perimeter.

The linear function used was:

$$GC = 1.87*P + 3.26*A; \quad R^2 = 0.69$$

where P = perimeter (m)
A = area (ha)

The cost of ground suppression estimated from that formula and expressed per hectare falls from $262 for a 10 ha fire, to $85 for 100 ha, $29 for 1000 ha, and $11 for 10 000 ha (assuming a length:width ratio of 3:1).

The corresponding Canadian version employed a collection of up to 8 independent variables including Fire Weather Index, RLC, control time and mop-up time, and non-linear transformations of them. However, while all these variables may bear some relation to ground costs, they are also often closely related to each other, so that multicollinearity may be present in the regression and the coefficients tend to lose meaning.

The FCV's reported costs include the direct costs of the time of wages of employees and charges for machines and vehicles, and special materials such as food and accommodation on campaign fires.

The reported costs exclude 'overheads' such as salaried staff time (for supervision, accounting etc.) and use of items purchased from the annual Head Office fire budget, e.g. radios, rake-hoes, chainsaws.

An additional general allowance of 15 per cent was made for the component of such costs varying with fire size, e.g. staff time, and depreciation of radios and tools.

An alternative approach to estimation of FCV costs would be to input for each sample fire the estimate of suppression costs given on the fire report, and use a general function based on fire size or control time merely to estimate the variation for different tactics. That approach would have the advantage of reflecting any special features influencing costs on individual fires.

CFA

Suppression costs are not provided on CFA fire reports but the number of people turning out and appliances used on the fire are recorded, and were input to the model in FIREIN. The hourly costs for each resource were input in DATAIN.

There is no cash cost for the CFA volunteers but this is not relevant to a cost-benefit analysis which must account for the economic cost to society. Here it can be argued that the volunteers' time has an opportunity cost based on the interruption to their work (or leisure) and the value of lost production. This personal cost is doubtless taken into account by citizens in deciding how much time to devote to the fire brigade, but those who volunteer presumably judge that the benefits, particularly in the form of protection for their own property in either the short or long run, outweigh the costs.

The average rate used for all CFA officers and volunteers was $5 per hour. This may be compared with average weekly earnings of $7.50 in 1983, and farm income per person employed equivalent to around $3 per hour in recent years.

The 12 appliance categories used in CFA fire reports (see below) may be more appropriate to urban brigades than bushfire fighting, and did not always give a good indication of the size and cost of the appliance. Nevertheless, average hourly costs were estimated for each, using basic data supplied by the CFA. The method and assumptions used are outlined in Appendices 9 and 10 and the results are shown in Table 5 for the categories used most commonly on bushfires.

Table 5. CFA appliance costs

Appliance	Variable cost ($/hour)	Fixed cost ($/yr)
Small town tanker	24	5050
Emergency tanker	26	6000
Trailer tank	17	-
Rescue/salvage van	11	6000
Quickfill trailer	3	1060
Private appliances	17	-

Private appliances can include many types but are assumed here to comprise 75 percent utilities with slip-on tanks, and 25 percent plant such as bulldozers, graders or tankers.

Only the variable hourly cost was used in the model. It should be noted that a major reason for the hourly costs appearing to be quite high is that fire appliances are idle for most of the year. Tankers average only about 1500 km per year, but when in use are subject to considerable wear and tear.

A total hourly rate for the combined CFA resources on each fire is calculated in the model. Hourly costs for road travel time from brigade to fire are estimated separately from suppression time. The costs related to kilometres travelled are higher on a per hour basis for road travel, although the component for repairs and maintenance is lower.

Then the total cost is calculated for each suppression tactic generally by multiplying the hourly rate by the sum of containment time and one tenth of mop-up time. This implies that an average of one-tenth of the total numbers turning out remained during mop-up. Since the number of volunteers turning out is the maximum number present, it is assumed that for larger fires the average number present is only two-thirds of the maximum, to allow for arrival delays and shift work.

On fires where both the FCV and CFA are present, only half the normal FCV costs are added to the CFA cost.

Additional ground suppression

The cost of ground crews additional to the benchmark level (assumed to be FCV) had to be estimated separately. A regression equation based purely on fire size is not appropriate for this. In this case a variable cost-per-hour for both travel and suppression was calculated for each type of crew (machine and hand), based on the composition of each crew and current wage rates and prices (see Appendix 1b).

The relevance of fixed costs for additional fire crews is arguable, as it depends largely on whether productive work could be found for them when not fighting fires. If so, only their wage cost during the period of firefighting need be counted as an additional variable cost, with their wages for the remainder of their period of employment being charged to non-fire jobs. That is, fixed wage cost would be zero. However, with each expansion of the summer crew primarily for fire fighting, it might be expected that it would become more difficult to employ the extra employees as productively on other work, assuming a normal diminishing marginal productivity of labour input. In the extreme situation of a crew employed purely to fight fires, their labour cost for the whole fire season should be treated as a fixed cost of fire suppression, and the variable cost per hour of actual fire suppression would be zero.

Under the existing system, most FCV fire fighters are permanent forestry employees or casuals hired for summer, with many of the latter being taken on regularly each year. They are thus mostly trained and experienced in fire work, and are integrated into the normal work schedule of the forest service, for example working on road maintenance and seed collecting. Summer is a busy time for most forest services and it is expected that there would be no shortage of useful work for an additional crew.

Therefore in this study, the full hourly labour costs of the ground crew during suppression have been allocated to the variable costs of the fire, and only 10 percent of the total wage bill for the four-month summer period has been allocated to fixed costs of fire suppression. This fixed cost is deducted from gross savings in the output analysis.

Fixed costs included a share of administrative costs and capital costs on communications and fire fighting equipment. The fixed costs for additional ground crews is estimated to be about $13 000 per machine crew and $7000 per hand crew, comprised as shown in Table 6. With one additional crew in each of 45 districts, fixed costs would total $597 600 for machine crews, and $308 700 for hand crews.

Table 6. Fixed cost components for machine and hand crews

Cost component	Machine crew ($)	Hand crew ($)
Stand-by or unproductive labour time (at 10% of wages)	7710	4820
Fixed cost of specialised equipment (tankers)	2530	-
Ancillary equipment (mobile camps, radios etc.)	1150	780
Training	1070	710
Administration	820	550
	13 280	6 860

Fire-trail maintenance

There is a potential saving in fixed costs of road maintenance for ground suppression which could be offset against airtanker fixed costs. The National Parks Service of Victoria spends about $400 000 per annum on construction and maintenance of trails, mainly for access to fires. The trails are considered undesirable on environmental grounds but necessary for fire control. If a reliable system of air attack were available, however, NPS considers that a reduction in road expenditure by about one-third would be feasible. Basic trail construction in key areas would still be necessary, for potential control lines as well as access, but less regular maintenance would be necessary. This would provide savings of $133 000 to offset against fixed costs of airtankers. However, helicopters are the only really suitable means of air attack for this purpose as they can also be used for transport and reconnaissance. Half the fixed costs of small helicopters are already written off in the model against these non-suppression functions which are largely related to lack of road access. No further allowance for reduction in road costs has been made.

9. AERIAL SUPPRESSION

After computing results for ground suppression options, AIRPRO proceeds to simulate the effects of adding aerial attack on the same fire.

On any one run, a particular configuration of retardant bases and the various airtanker models and retardants to be tested must be specified. For each fire, AIRPRO tests each separate combination of the following resources and tactics:

- up to 32 models of aircraft (presently limited to 11), classified into 9 broad types
- numbers from 1 to 4 of each model at each home base
- 3 types of retardant
- 4 locations of attack.

Many of these combinations are weeded out by preliminary tests.

Aircraft types and models

Eleven models of airtankers have been tested in the Australian version. Table 7 shows their classification into (up to) nine broad types.

Table 7. Aircraft types, models and capacities with retardant tank capacity in litres

Size	Land	Water	Helicopter
Small	Thrush Commander (1500)	Twin Otter (1818)	Bell 206(Jet Ranger) (340)
Medium	Grumman Tracker S2G (3545)	Canso PBY5A (3637) Canadair CL-215 (5455)	Bell 212 (Iriquois) (1362)
Large	DC6B (11365) Hercules C-130 (11355) Neptune P2V (9092) DC4 (7570)	--	--

Their characteristics,as entered in DATAIN, are listed in Appendix 11. AIRPRO takes account of the advantages of the larger aircraft in the form of their bigger pay-loads, longer range and faster cruising speeds, as well as the disadvantage of higher costs, lower manoeuverability and a more limited set of airfields which can accommodate them.

Most of the above models are commonly used for fire-bombing in the USA and Canada and most have also been flown in Australia in a civil or military role at some time in the past. However, the older aircraft which have not been flown regularly in Australia for some years, such as the Neptune and Canso, may have difficulty obtaining certification by the Department of Aviation, and spare parts and servicing would be expensive.

Other ex-World War II aircraft which are cheaply available overseas and are still used for fire-bombing include the A-26 Invader, B-17 Flying Fortress, F7F, JRM-3 Mars, PB4Y Privateer and TBM Avenger*. Not having been flown in Australia, they are excluded here.

Notes on the reasons for selecting the 10 aircraft are given below:

Land-based aircraft

- The Thrush Commander with retardant tank volume 1500 litres is one of the larger, relatively modern agricultural aircraft regularly hired by the FCV for fire-bombing.
  Others hired include:
    - Bull Thrush (1930 L) - no longer operating
    - Air Tractor (1210 L)
    - Fletcher (910 L)
    - Beaver DHC-2 (850 L)
    - Piper Pawnee (540 L)

  The FCV has moved towards a preference for the larger agricultural planes, of which the Thrush Commander is a good example. Data have been gathered, nevertheless, to allow a comparison of the above models.

  The agricultural planes are all privately owned. Unlike the larger fixed-wing planes, their primary use is not fire-bombing but spraying weedicide, fertiliser, pesticide etc.

- Grumman Tracker A fleet of Trackers was used for many years by the Royal Australian Navy, but the rights to dispose of them were sold in 1984 to overseas interests which reportedly intended to sell them for use as fire-bombers in Europe. Amongst the unsuccessful bids were proposals to convert them to fire-bombers in Australia, with the aid of North American know-how.
  Trackers are widely used in Canada and USA for fire-bombing, with various tank designs.

- DC6B DC6s were in civil use in Australia in past years although none remain now. Like most of the other fixed-wing aircraft, DC6s are structurally altered to incorporate the retardant tank and then become virtually restricted to fire-bombing.

  A DC6B provided by the Canadian company Conair Aviation was used in Project Aquarius trials in January-February 1983 at Nowa Nowa, Victoria, to obtain experimental data on retardant effectiveness.

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* See Simard & Forster (1972) for details of aircraft used.

- Hercules C-130 An RAAF Hercules, temporarily fitted with a Modular Airborne Fire-Fighting System (MAFFS), was hired by the FCV for operational fire-bombing in 1981-82 and 1982-83. The MAFFS was hired from the USDA Forest Service. Unlike the normal fixed tanks, the MAFFS can be bolted in place or removed in 2 - 3 hours and ejects the retardant under pressure through a set of nozzles, rather than dumping its load when the doors are opened.

  After an evaluation of its use (Rawson and Rees 1984) the FCV decided that it did not appear to be cost-effective and did not extend its use to the 1983-84 season.

  This (CSIRO) study reflects many of the same factors leading to the FCV's conclusion, but differs somewhat in assuming faster circuit times and better accuracy, based more on American experience, and a restructuring of hire rates.

  Hire of an RAAF aircraft might be expected to be an efficient use of a multi-purpose resource, but the dual role also means that conflicts of use could arise and future availability for fire-bombing in any period has to be negotiated with the RAAF.

- Neptunes These have been used in the 1960s and 70s by the RAAF although none is presently flying in Australia. They are used mainly by the USDA Forest Service for fire-bombing.

Water-scoopers

Whilst the above land-based planes can take on water from a hose at any airfield, only the amphibians or water-based planes can pick up water by scooping over the surface of a lake or other large water body. This has never been tried in Australia and is popular mostly in Canadian provinces where lakes are abundant.

- Twin Otter Only a land-based version is currently operating in Australia, but Twin Otters are widely used in America for fire-bombing in a water-scooping mode.

- Canadair CL-215 This amphibian is the only aircraft designed especially for fire-bombing and water-scooping although it has supplementary uses such as spraying oil spills and transport.

  Because of its high capital cost (about $7 million when new), its overall economics have so far not been as attractive as those of older, depreciated aircraft. Out of 64 CL-215s manufactured by 1980, 47 were sold for use outside North America, and 15 were used in Quebec, whose government had taken over the Canadair company. Other Canadian provinces have leased or purchased CL-215s more recently under a federal government subsidy program involving low-interest loans.

  Over past years, Canadair agents have made various representations to Australian governments, pressing for the use of CL-215s in this country.

- The Canso (or Catalina) is unique as a cheap medium-sized water scooper. Although mostly 40 years old, Cansos are still used as the work-horse of many Canadian fire-bombing fleets.

  Cansos were flown in Australia in the war years. They may now have difficulty getting registration in Australia unless particularly well maintained, but they are tested in the model here because of their unusual features.

Helicopters

Helicopters have the advantage of being multi-purpose so that only part of their fixed costs need be counted against fire-bombing. They are becoming widely used in Australia for fire-bombing by some of the National Parks and forest services, and also for fire reconnaissance and personnel transport.

They have the virtue of great manoeverability and accuracy and being able to land or take on water in places that can usually be found within a few minutes flight of any fire. On the other hand they are relatively slow and carry a small pay-load.

The National Safety Council of Australia (Victorian Division) has built up a fleet of helicopters including Bell 205, 206 and 212s that can carry water in either a detachable belly tank or a suspended bucket.

Other aircraft

Certain other aircraft which could be suitable for Australian fire-bombing were not included in the AIRPRO simulations as they were thought to be represented fairly closely by other types already included.

- Helicopters Other small or medium-sized helicopters will perform similarly to the Bell 206 and Bell 212 included in the model. For example, the ACT Bushfire Council has used an Aerospatial Squirrel helicopter with a bucket of 550 litre capacity, compared with the Bell 206's 340 litre bucket.

- Caribou A prototype removable retardant tank has been designed for the Caribou, an RAAF small transport aircraft. The tank could be installed or removed within an hour, and would hold about 2300 litres, between the capacity of the agricultural aircraft and the Tracker.

  The Caribou has a short-take-off-and-landing capacity and could probably use the same strips as agricultural aircraft. The cost, at Department of Defence's full charging rates, is several times greater than the agricultural aircraft.

- Fokker F-27 The F-27, an aircraft widely used for passenger services in Australia, could be converted to a specialised airtanker carrying about 5000 litres of retardant. The capacity and the cost would lie between that of the Tracker and DC6.

No details of retardant footprints for either the Caribou or F-27 are available.

Multiple aircraft

The model can test for the optimal size of fleet of aircraft. It first computes the results of using just one aircraft of a given model on the fire, then tries two of the same model from the same base, then three and so on. The number tested is presently limited to four although this limit can readily be changed in the model. The aircraft for individual fires are all assumed to be drawn from the home base nearest to the fire. There is no provision for the more complicated simulation, but probably more realistic situation, where supplementary airtankers from a more distant base are brought in, nor for the use of different models together on one fire.

Retardants

Three types of retardant are tested in the model:

- **water:** obviously cheapest, available at any airport without mixing facilities, having no adverse effects, but least effective.
- **short-term retardant:** water is still the retarding agent, with added thickener (e.g. gum or clay-based) to reduce dispersion.
- **long-term chemical retardant:** inhibits the combustion process in cellulose fuels. Diammonium phosphate (DAP), which was used in Project Aquarius trials, is the retardant tested in AIRPRO. It is mixed in a ratio of about 12 kg powder to 100 litres water, expanding the volume of liquid by about 10 per cent. Gum thickener, corrosion inhibitor, anti-caking agent and orange colouring agent are usually added.

Location of attack

Four tactics are tested in the following order:

- head only
- head and one flank
- head and both flanks
- head, both flanks, rear.

The four locations of air attack tested all begin with the head and differ only in where the airtanker finishes, leaving the remainder to the ground crews. An airtanker failing to make any impression on the head is failed in the model. This aspect of the model could underestimate the value of aircraft in situations where an attack on a flank could still be useful, particularly on large fires before a threatened wind change. However, where the head is too intense and fast spreading for air attack, flank attack would also be hindered by rapid burning around of drops.

Bird-dog

The airtanker may be guided by a light command aircraft (bird-dog) to improve drop accuracy and usefulness. It is presently assumed in the model that a bird-dog is used on all drops, but there is a variable in DATAIN that specifies the number of airtankers on a fire required before a bird-dog is used.

Bases

An important policy decision for fire-bombing concerns the number and location of fixed retardant bases to be set up.

Establishing more bases, appropriately spaced, means more effective attack, by reducing fire-to-base distance and hence first drop time and time between drops. However, it involves higher fixed costs for setting up and maintaining the bases.

The Australian version of AIRPRO has been modified to allow the user to specify the number and location of bases available for a particular run. One configuration tested is illustrated in Figure 15, which corresponds to the list in Appendix 12. On other runs, different base configurations can be tested on the same fires. In the post-AIRPRO output analysis, the results of the different runs are compared after subtracting corresponding fixed costs to find the optimal base locations.

There are several types of base to be specified in the model:

- home bases for each aircraft, where they start each day at first call to a fire, and return each night.
  The number of home bases times the maximum number of aircraft available at each determines the total number of aircraft available and hence their fixed cost (whether used or not).

- fixed retardant bases which, if closer to the fire, will be used by the airtanker for supplies of mixed retardant.

  Retardant bases are generally more numerous than their home bases, since bases are cheaper than aircraft. The dedicated aircraft have retardant facilities at their home base where they are on stand-by. For agricultural aircraft, however, home base may be the base for their agricultural or other operations, unrelated to fire danger areas, and not equipped for retardant mixing.

- other airfields which do not have retardant mixing facilities but can be used to supply water or as a site to set up portable retardant facilities.

- 'mobile' bases, i.e. the depots (usually district forest offices) at which portable mixing facilities are based. The portable can be loaded onto or behind a truck and driven to the nearest airfield.

- lakes and water bodies - not actually bases but points of pick-up for water-scooping airtankers. Their location is largely a given part of the environment and is subject to only limited policy manipulation.

Airfields

Each type of aircraft is limited to airfields that are physically capable of handling them. A sub-routine in the model determines which airfields can be used by which aircraft.

The latitude, longitude and suitability characteristics of 84 airfields in Victoria are listed in DATAIN and Appendix 13. These include all 32 aerodromes licensed by

Department of Aviation* and a further 52 airstrips listed by NSCA which are assumed to be capable of taking only light planes.

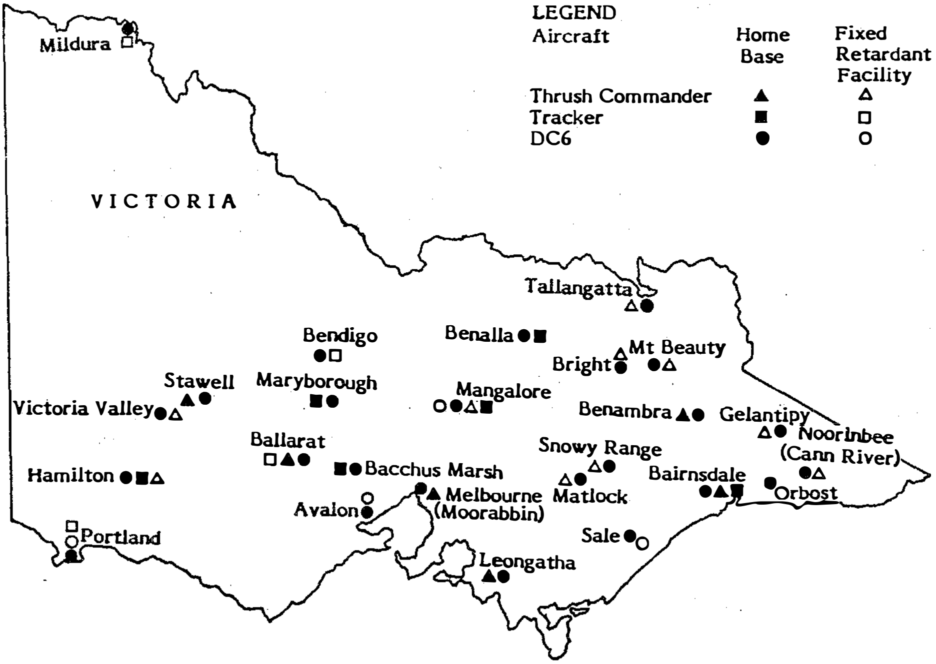

Figure 15. Selected base configuration - home bases and retardant bases for three types of aircraft

There are many other strips known to be capable of taking agricultural planes including 150 listed by NSCA and many paddocks which could be used in emergencies. Their omission therefore causes over-estimation of the average turn-around time for light planes with a portable mixer, particularly in the flatter western areas. However, the 84 strips already give a fairly good distribution of bases and, say, doubling the number would add significantly to computing costs.

Aircraft I can use airfield J in the model if it passes three tests, based on Department of Aviation (DoA) standards, namely:

- take-off run required by I is less than take-off run available at J,
- tyre pressure of I is less than 1.3 x 'maximum' tyre pressure at J,

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* Commonwealth Department of Aviation, Aerodrome Directory (AGA-3)

- aircraft classification number (ACN) of I for the particular sub-surface strength of J is less than 2 x Pavement Classification Number (PCN) of J.

The 1.3 and 2 factors used above are estimates of the general concessions that might be allowed by DoA for a limited number of movements for fire-bombing during the summer months.

For unrated pavements (i.e. no PCN rating), DoA criteria based on weight and tyre pressure of aircraft have been incorporated in the tests.

Appendix 14 is a printout from this routine showing which tests are passed by each aircraft at each airfield in the model.

On these criteria, the DC6 could use just nine airfields, while the CL-215 could use 16 and the Tracker 31. For the Tracker, this represents an average radius of 42 km per base, but the airfields are not evenly distributed. A large area in the eastern highlands has no airfields.

Lakes

Water-scoopers have certain requirements for safe operation. For example, Canadair pamphlets say that the CL-215 requires a clear stretch of water at least 1.2 km long, 90 m wide and 1.2 m deep, with a further 0.5 km at each end clear of obstacles to 15m (see Fig. 16).

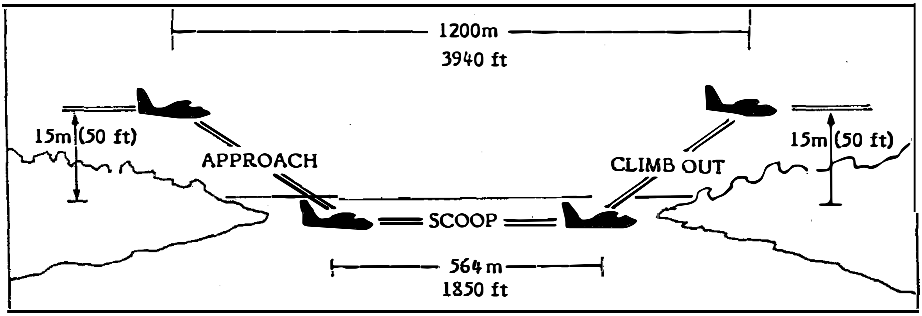

Figure 16. Water-scooping requirements of CL-215

All inland water bodies with apparent straight stretches of at least 1.2 km were identified from maps and listed (see Figure 17 and Appendix 15). Several coastal locations were added. The Victorian Department of Water Resources and other controlling agencies (viz. SECV, NPS, MMBW, PHA, River Murray Commission) were asked to indicate whether any problems might bar any locations from use by water-scoopers. This exercise confirmed 87 water bodies and ruled others out, but left 34 in a doubtful category because, without an expensive survey, the agency could not be sure about underwater obstructions, or because the water level in dry summers was variable. These doubtful ones, indicated in Appendix 15, are currently still in the model.

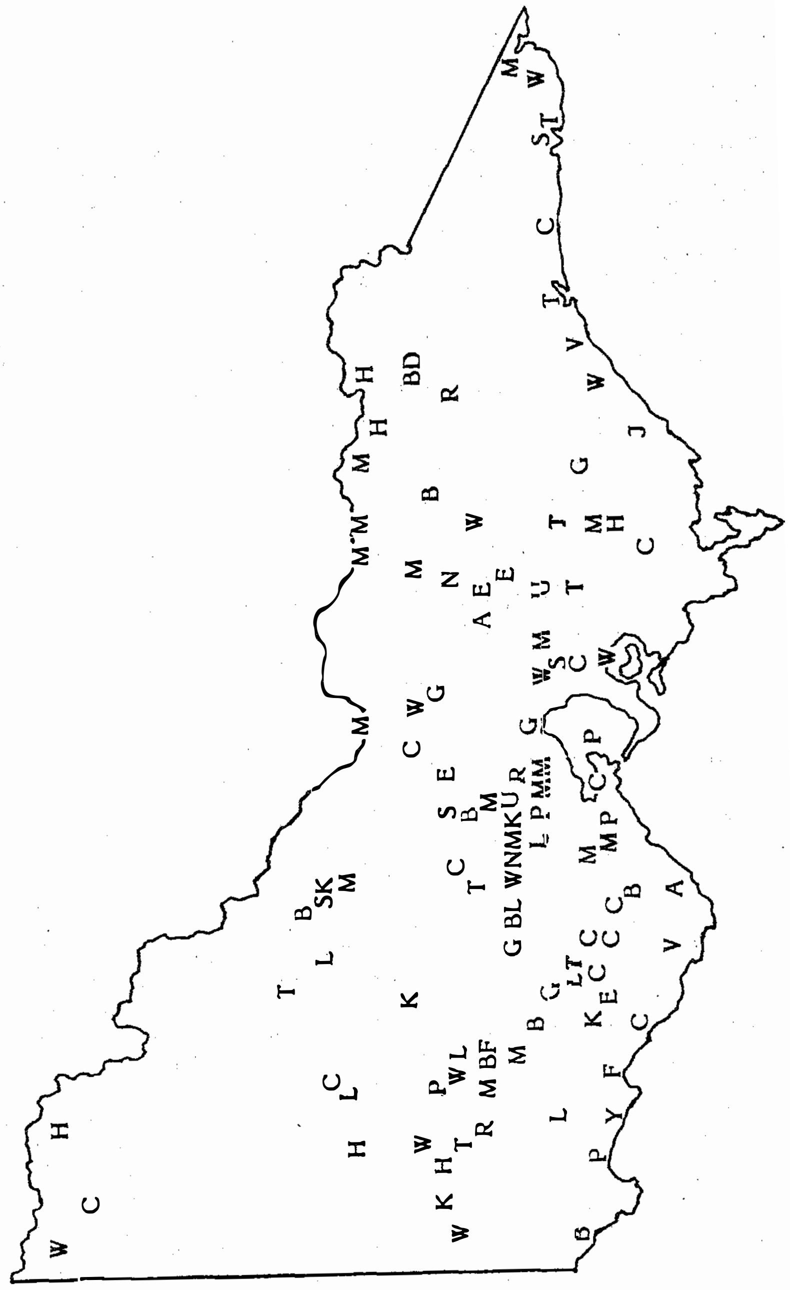

Figure 17. Distribution of possible water bodies for water-scooping airtankers

Circuit times

Airtanker times are made up from the following components:

Initial take-off delay

The dedicated airtankers (i.e. all except agricultural planes and helicopters) are assumed to be waiting at their home retardant base on stand-by during the summer months of highest fire danger. This was initially taken as the four months from 1 November to 28 February. They are assumed to be ready to take off with just 10 minutes delay ('scramble time') between fire detection time and take-off, which allows for engine warm up, flight plan etc. and simultaneous loading of retardant.

Prior mixing of retardant is normal, particularly on days of high fire danger, although some deterioration of the gum thickener in mixed retardant occurs over time. Aircraft are not loaded until necessary so as to avoid excessive weight on the tyres and the need to clean out unused loads.

For multi-purpose agricultural aircraft and helicopters, the user specifies on any run of AIRPRO one of three possible states of readiness:

- 'availability', with delay 1 hour 10 minutes. This approximates one level of the FCV arrangements where aircraft operators are committed to remain within one hour's flight of a specified base, although they may be flying on other jobs in the meantime.
- stand-by, with take-off delay 10 minutes
- stand-by on days of very high fire danger (FDI over 24 in model), and 'availability' on other days.

In practice the fire manager would take into account a range of factors for stand-by decisions, including the forecast FDI and the occurrence of lightning, but the model uses the above simple criterion.

The time the aircraft is activated is taken as the time of detection of the fire, although this may be on the early side. There is often a delay of even half an hour between detection and ground suppression crew dispatch which might be partly due to a delay for sizing up the situation before dispatch. However, to the extent that it is due to the time required to assemble the ground crew and equipment, it is appropriate to assume it does not apply to airtankers on standby.

A system based on immediate dispatch reaps the benefits of attack when the fire is small but is likely to have an associated cost for dispatches which subsequently prove to be unnecessary. These costs would be minimal if fire managers are able to make immediate accurate judgments on the basis of such factors as fire weather, resources at risk and ground forces available. Whereas foresight is required by the fire manager, this study has used hindsight to exclude historically small fires from the sample, and to avoid full simulation of tactics on fires where the cost of one load would be in excess of the historical loss.

One option to allow for the problem of dispatch decisions would be to include an allowance in fixed costs for unnecessary missions. However, the alternative adopted here was to assume that, except on days of high fire danger, aircraft are not activated until the fire has reached a minimum perimeter of 200 m.

Cruising time, fire to base

This is simply fire-to-base distance divided by speed of model. At the start of testing a particular airtanker on a fire, AIRPRO identifies the closest usable home base, closest usable retardant base and closest other usable base to the fire. This is done by comparing approximate distances (based on Pythagoras) between all usable bases and the fire and choosing the shortest for each type of base. The model then calculates the distance more exactly by a sub-routine of geophysical formulae.

Climb time

Where the elevation of the fire is not available, as is the case with the Australian bulk data, the default assumption of a climb height of 660m is used, so

Climb time = 660/(Rate of climb for model in m/hr).

Drop time

This covers circling, lining up etc., and is calculated from a standard drop time for the aircraft type divided by a manoeeverability factor for each fixed-wing model.

In the Victorian MAFFS operation, the average time over the drop zone was 13 minutes for one drop plus 8 minutes extra for each drop if a second or third drop was made from the same load. However, it is assumed here that, with more experience, times similar to those in North America would be achieved (Table 8).

Take-off and landing times

After the first drop, these are calculated from the standard times (Table 8), divided by the manoeeverability factor. Manoeeverability factors (explained below in section on accuracy) vary from 0.56 for the DC6 to 2.4 for agricultural aircraft.

Table 8. Aircraft circuit times (minutes)

Element of circuit	Aircraft type		
	Land-based	Water-based	Helicopter
Take-off time	5	1.5	0.5
Landing time	4	1.0	0.5
Drop time	3	3.0	0.5

Loading time

Loading time for land-based aircraft is tank volume divided by loading rate. Loading rate is assumed to be 1900 L/min at bases for medium and large airtankers, and 500 L/min for small ones. For water-scoopers, loading time is fixed at 10 seconds, and for helicopters at 1 minute.

Time for first drop

If the home base is also a retardant base, the aircraft flies directly to the fire, so the time between take-off and first drop is the sum :

climb time + cruising time + 1/2 drop time

If the base is not a retardant base, the time of first drop covers the time to fly to the retardant base nearest the fire, load, fly from there to the fire, and drop.

Time between drops

To pick up for the second load, the aircraft flies to the nearest usable retardant base for chemical retardants, or the nearest usable airfield for a land-based aircraft using water, or the nearest lake for a water-scooper. Helicopters are assumed to be able to pick up water, whether from a dam, stream, tanker etc., within 6 km of the fire.

If an agricultural plane is being used and the nearest airfield to the fire has no fixed retardant facility, and the fire is of sufficient duration, it is assumed that the portable mixer is driven from its base to the airfield. The time between drops is based on the distance between fire and nearest fixed retardant facility until the portable mixer is ready, after which it is based on distance from the fire to the nearest airfield. The delay before the portable is available is road time (base-to-airfield distance divided by average speed of travel) plus preparation time of 100 minutes. The speed (relative to straight-line distance) is given for each base, depending on local topography and varies from 33km/hr for Orbost to 67km/hr for Beaufort. Helicopters are also assumed to be able to pick up retardant from a mobile mixer within a maximum of 10 km from the fire; e.g. from a clearing by a road, or an airfield if closer.

Time between drops after the first becomes:

2 * fire-to-retardant base cruising time + landing + loading + take-off + climb + drop times

Refuelling

Land-based aircraft are assumed to refuel concurrently with loading retardant. For water-scoopers, however, just before the total time flown by the aircraft would exceed its endurance on the next delivery, the model allows an extra delay for diverting to the nearest base and refuelling. For medium aircraft, 15 minutes refuelling time is allowed, and for small ones 10 minutes.

Sunset

If the next delivery would mean that the airtanker would return after sunset, it is retired for the night and ground crews alone continue suppression.

If the fire is still burning the next morning, the airtanker is assumed to be loaded ready to take-off at sunrise and resume dropping.

Sunset and sunrise times for each fire are computed from the latitude, longitude and date by a series of equations used in the Canadian version of AIRPRO, with certain parameters altered to suit the southern hemisphere.

Retardant drops

AIRPRO computes the depth of retardant required to check the fire and finds the length of pattern at that depth available from the airtankers, if any, so as to calculate the length of perimeter held. The various steps are explained below.

Retardant effect

AIRPRO assumes that up to two drops may be made on the same segment of fire front. If a single drop is not sufficient to hold the fire, double-drop suppression is tried, whereby the first drop reduces intensity to a level low enough for the second to hold.

Holding: One of the prime aims of Project Aquarius was to gather evidence on the effect of retardants on the intensity of fires in Australian eucalypt fuels.

In the 1984 tests with a DC6 at Nowa Nowa, Victoria, the fires were of low intensity and easily stopped by either aerial or ground suppression. In 1985 tests with a helicopter and a Thrush Commander, fires of higher intensity were encountered. The retardant drops checked some of these fires, but were ineffective on others.

Other data were obtained from small-scale laboratory tray experiments by CIT and from field studies in grass in the Northern Territory.

Australian data are supplemented in the model with those used in the Canadian version of AIRPRO for pine fuels and short-term retardant. The Canadian data were derived by Stechishen and Little (1971) from tray experiments. The equations used for holding effect are shown in Table 9.

Table 9. Retardant 'holding effect' parameters

Fuel type		Water	Short-term retardant	Long-term retardant
Eucalypt	Q =	$0.63\ I^{0.89}$	$0.56\ I^{0.79}$	$0.24\ I^{0.87}$
Grass	Q =	$0.35\ I^{0.89}$	$0.31\ I^{0.79}$	$0.17\ I^{0.79}$
Pine	Q =	$2.64\ I$	$1.98\ I$	$1.10\ I$

Q = depth of retardant (mm) required to 'hold' the fire, i.e. to stop it burning through a treated zone for at least an hour.

I = fire intensity in MW/m.

These equations are based on experimental observations at intensities below 2000 kW/m, so cannot be validly extended to higher intensities. The CIT data indicate a much greater effectivenes of the retardant than the Canadian figures for pine fuels. A comparison is shown in Figure 18. However, it has not been possible to check the figures under consistent experimental conditions.

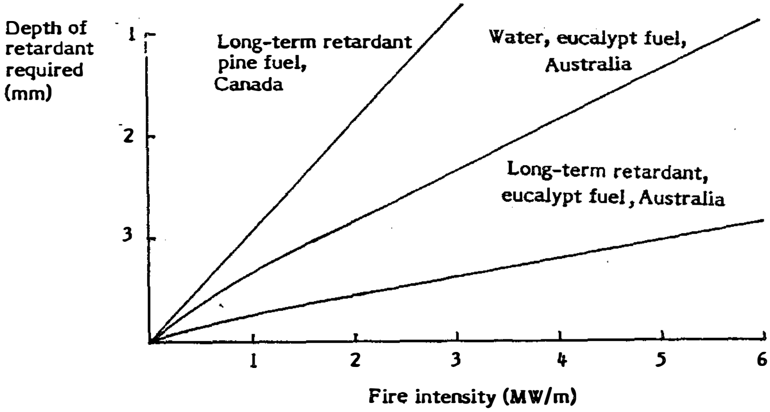

Figure 18. Depth of retardant required to hold fire at different intensities

The Australian equations above indicate the depth required to stop the fire burning through the coated fuel in the drop zone. However, this does not take account of the situation where the fire spots over the drop zone and resumes its progress on the other side. If the fire is of sufficiently low intensity, the retardant drop may provide a valuable check to its progress even if the fire eventually trickles through the drop or throws a few spots to the other side.

Operationally, very seldom do drops completely extinguish the fire front. Thus, in the model, the depth given by the above equations is assumed to hold the fire for only an hour without ground follow-up.

Limits: Aquarius trials indicated the fire intensities beyond which single retardant drops were ineffective due to heavy spotting across the line. In Mixed Species eucalypt forest, this limit was around 2000 kW/m for unsupported drops. It is assumed here that the limit would be 3000 kW/m with ground crew follow-up within an hour although it was not possible to obtain any experimental evidence on combined air and ground attack on medium-intensity fires.

These limits of air attack, however, are well below the head intensities typical of 'disaster' fires and are also within the capability of machine crew attack.

Reduced intensity: For double drop suppression, AIRPRO uses data from a theoretical study of the cooling effects of retardants on high-intensity fires in Canadian fuels presented by Swanson and Helvig (1973), with adjustments for higher-intensity fires based on preliminary data from Project Aquarius. An array ER (I,J,K) in DATAIN gives post-drop intensity as a proportion of pre-drop intensity for retardant I, intensity class J and retardant depth class K, illustrated in Figure 19. Four intensity classes are used (Table 10).

No useful retarding effect was judged possible for forest fires over 5000kW/m, i.e. those having a rate of spread of about 700m/hr at a fuel weight of 15 t/ha. Although the first drop may have a temporary dampening effect on the flames, heavy spotting across the line would still occur before or after the drop. A second drop may achieve a further retardation but it is unlikely that the line would be secure enough to allow ground crews to take advantage of the respite.

Table 10. Fire intensity classes

Fuel type in Swanson & Helvig study	Equivalent intensity class assumed for Australian study
1. Crown	Above 3000-5000 kW/m
2. Brush, slash	1,700 - 3000 kW/m
3. Litter, duff	0 - 1,700 kW/m
4. Grass	Grass-all intensities

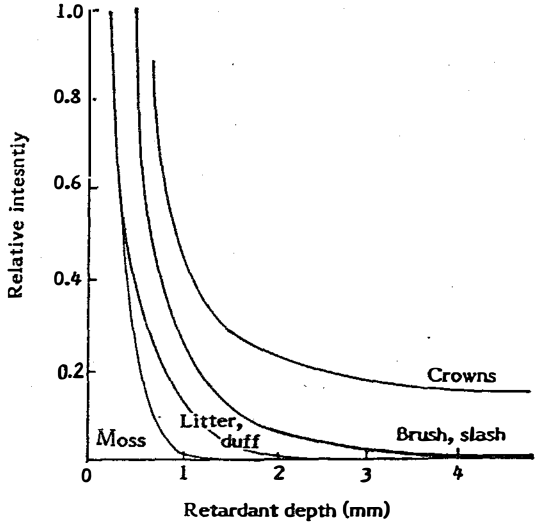

Figure 19. Proportion of original fire intensity remaining after first retardant drop

Given the fire intensity on the arc of attack, the model computes, by an iterative process, the lowest retardant depth class on the first drop such that the fire can be extinguished with a second drop of the same or lower depth than the first.

The model attributes half the length of perimeter eventually held to the first drop and half to the second.

This can also be taken to represent the situations where retardant drops are used to quieten 'hot spots' on the fire front (say 2000-5000 kW/m) to allow ground crews to approach.

Burn-through: The 'holding' equations were based on drops holding the fire front for at least an hour under the experimental conditions but beyond this further allowance for variation in burn-through time has been provided.

The holding effect of the drop may be achieved by only a portion of the drop on or nearest the fire, leaving the rest of the drop zone as a further line of defence against the weakened fire.

Burn-through time then depends mainly on the time over which the water content of the drop evaporates and the time for any remaining flames to accelerate and join in a moving fire front. These in turn depend mainly on fire intensity, retardant type, concentration and width, and fuel type.

Drying: Drying the surface of a eucalypt fuel bed from saturation to the point where it is again dry enough to burn could take around 40 minutes in typical wildfire conditions (say 35% humidity, 35% initial fuel moisture content and 10% equilibrium moisture content). The drying time in grass could be as low as 10 minutes.

Re-ignition: Low-intensity fires may be completely extinguished by a retardant drop, or perhaps held until fire danger conditions rise the next day. The higher the fire intensity, however, the more likely there are to be sources of re-ignition such as burning bark and logs to allow revival of the fire front shortly after the water content of the drop has evaporated. This is also more likely in forests with heavy fuel loads.

When a drop of pure or gum-thickened water has dried out, no barrier is left, and there could be a general burn-through along the drop line with immediate re-establishment of the fire front.

Long-term retardant, on the other hand, provides a barrier even after drying out, although there is still generally room for the fire to creep through between the spots of retardant salt.

Acceleration: If the fire has been reduced to a number of separate spots burning through at intervals along the drop, there is a further lag before these accelerate and rejoin to form a front spreading at the former rate. This lag is typically less than half an hour.

A rough allowance for the above factors was made in AIRPRO by expressing burn-through time in terms of the following function of intensity and drop width, the shape of which is indicated in Figure 20.

For long-term retardant in forest fuel

$$\mathrm{BTT} = 1 + \exp(2.5 - 2.0*I)*(1+(W-10)/20)$$

For water in forest fuel

$$\mathrm{BTT} = 0.6 + 0.3 \exp(2.5 - 2.0*I)*(1+)W-10)/20)$$

where

BTT = burn-through time (hours)
I = fire intensity (MW/m)
W = drop width (m)

BTT for grass is set at half BTT for forest.

The model allows the airtanker to counter burn-through by redropping on the same section of fire line.

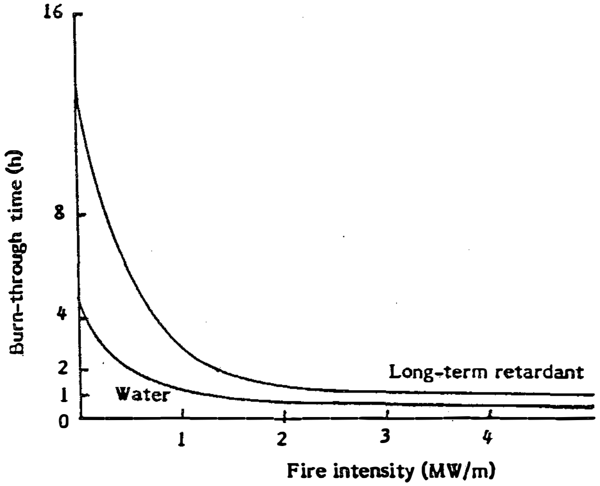

Figure 20. Retardant burn-through time

Another sub-routine being developed for AIRPRO by Simard provides for the fire to burn around the end of an airdrop where it is not linked to another controlled section. This has not been adopted in the Australian version, as it is not clear that ~~it improves~~ the working of the model which already provides for additional fire growth at either end (implicitly) of a free-burning part of an arc.

Relationship of aerial to ground suppression

Final suppression of a section of fire front held by an airdrop in the model still requires a ground crew to work around the same edge. While working through an air-drop, they are assumed to build controlled line at an augmented rate, namely, twice the rate applicable at the rear of the fire.

Retardant pattern

For each airtanker in the model, data are provided for the length of retardant pattern achievable on the ground in the open at each of 10 depth classes for each basic combination of tank release. The contours of a typical retardant pattern (or footprint) on the ground show how line lengths tend to decrease for higher concentrations. Figure 21 illustrates the pattern for a Thrush Commander. The latter produces about 66 m line at 0.5 mm depth but no useful line above about 1.5 mm depth. The DC6 can produce up to 1000 m at 0.5 mm and 545 m at 1.5 mm.

The number of compartments (usually simply referred to as tanks) in an aircraft's overall retardant tank determines the tank combinations that can be released in

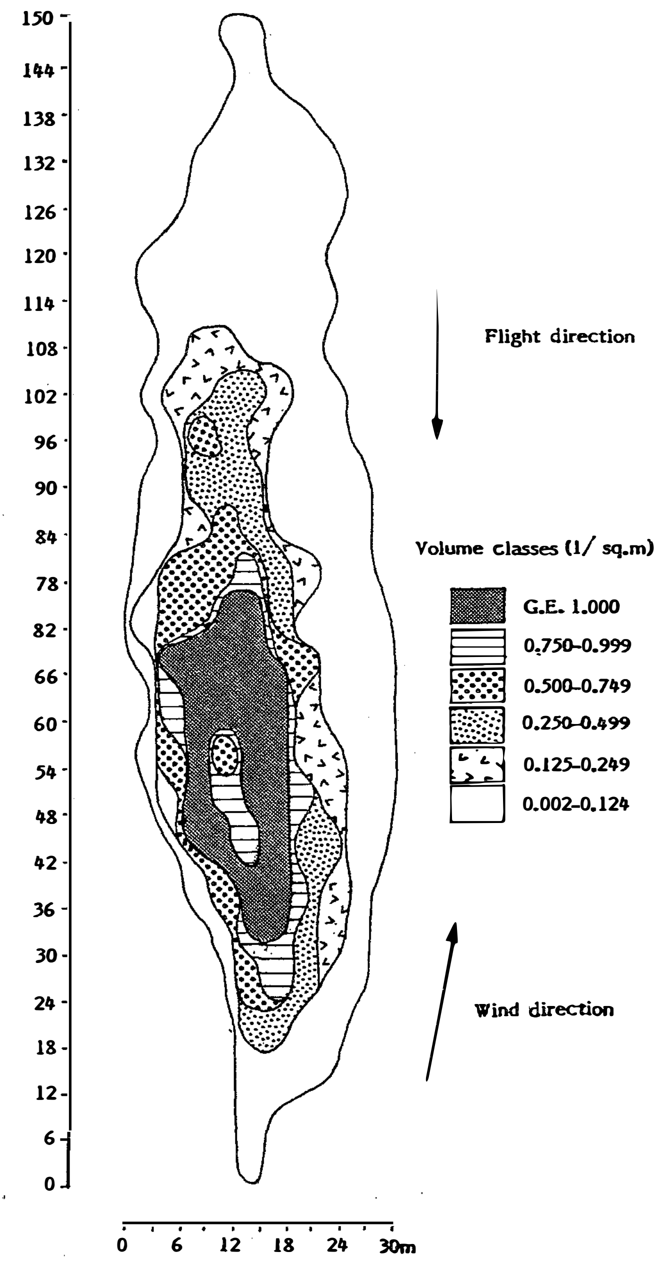

Figure 21. Thrush Commander drop pattern
Source: B. Rees (1983), 'Retardant distributions from six agricultural aircraft', FCV

one drop. It is necessary to distinguish here between a load, a drop and a release. For example, a Grumman Tracker could leave its base with a full load of 3410 litres in its 4 tanks. On arrival at the fire it could make two separate drops each of 2 tanks, 5 minutes apart, on separate flanks. One drop could consist of a single release of two tanks simultaneously, known as a 2T x 1R salvo. The other drop could consist of two releases, each of one tank, 0.7 seconds apart, known as a 1T x 2R sequence. The pattern for the sequence drop would be longer but shallower.

The pilot has some control over several factors affecting the drop pattern according to the requirements of the fire front - drop height, speed, number of releases and tank delay. Greater drop heights are safer but generally suffer from greater dispersion and hence shorter line. The USDA Forest Service recommendation is for a minimum drop height of 150 ft, but in Canada this tends to be the upper limit used in practice.

For a deep coverage, slow speeds (say 100 km/hr) are optimal if they can be managed safely without stalling, while for a longer but shallower line a faster speed can be chosen.

The delay between tanks for a sequence drop should be optimised relative to the aircraft drop speed, so that the pattern from the two tanks forms the longest possible continuous line on the ground at the required depth. If the maximum line on a long free-burning flank is desired, all available tanks may be disposed of in one drop, but if half a load is sufficient to finish one flank the other half may be reserved for a pass on another flank.

AIRPRO does not attempt to optimise drop height, speed or tank delay; instead they are implicit, underlying the line length input data. Ideally each length could be based on the optimal height, speed and delay for the particular depth desired. This has been done in calculating lengths for the helicopters and agricultural planes for the Victorian study but it is not clear whether the Canadian data for other airtankers was calculated that way or from patterns with a fixed height and speed.

DATAIN contains for each airtanker the line lengths for each number of tanks, n, that can be simultaneously released for:

i) a salvo release of n tanks, and
ii) a sequence of 2 releases with n followed by n tanks separated by the optimal delay.

The pattern width for each combination and depth is also provided so that burn-through times may be estimated.

The data for a 4-tank Tracker for water-like retardants are shown in Table 11.

The zero depth class indicates the smallest trace of retardant and is used in the model not for any effect on the fire but to measure the maximum pattern length and hence the degree of overlap required to tie in drops at greater depths.

Due to the graduated contours of a typical footprint (i.e. drop pattern), the line length for a sequence of 2 releases each of n tanks at a given depth is always greater than or equal to twice the length for a salvo of n tanks at the same depth, as in the data above. The zones containing the required depth d (i.e. A and B in Fig.22) need not be abutted exactly, but can be separated by a gap C within which the patterns from each release at half the required depth, d/2, overlap so the total depth equals that required.

Table 11. Grumman Tracker retardant pattern (length and width in metres)

No.of simultaneous tanks	Depth (mm)									
	0	0.25	0.5	1.0	1.5	2.0	2.5	3	4	5
Feature of drop pattern										
1 Length-salvo	82	60	42	14	0	0	0	0	0	0
Length-sequence	164	124	88	47	27	14	0	0	0	0
Width	11	7	5	3	2	0	0	0	0	0
2 Length-salvo	104	73	59	44	28	15	4	0	0	0
Length-sequence	208	147	122	90	66	48	37	30	15	4
Width	15	12	9	6	6	6	3	3	2	2
4 Length-salvo	116	84	73	59	50	44	37	29	12	3
Length-sequence	232	169	147	121	103	95	75	62	45	37
Width	14	11	9	8	6	6	6	6	6	6

Figure 22 also indicates how the model uses the basic data for 1 or 2 releases to compute line lengths for sequences with 3 or more releases. The equation is:

$$L_{d,n,r} = L_{d,n,1} + (r-1) * (L_{d,n,2} - L_{d,n,1}) \quad (r \geq 3.)$$

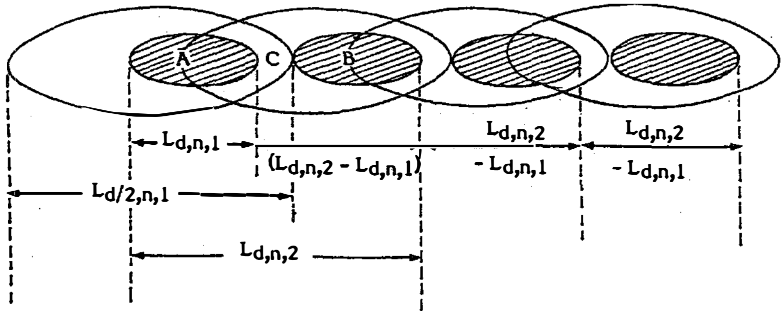

Figure 22. Pattern overlap on sequential drops ($L_{d,n,r}$ = length at depth d from r releases, each of n tanks)

Given the depth required to extinguish the fire (on the current arc at the current time), the model computes the line lengths at that depth achievable from all possible tank combinations (ranging from 1 for an agricultural aircraft to 14 for a 12-tank DC6).

The model selects that tank combination which gives the maximum perimeter held per hour (equal to perimeter held per drop divided by average time between drops). Since splitting a load into two or more drops means greater losses for inaccuracy and increased flying time, full loads will be preferred unless a partial load is sufficient to complete one arc, or double-drop suppression is more effective.

For the first drop on any arc, the model computes the drop length either directly from the input data (if 1 or 2 releases) or from the above formula (if 3 or more releases). For all subsequent drops, for any number of releases, some overlap will be gained, and the formula below is used for $P_{d,n,r}$ - the extra line held by a drop of nT x rR at depth d:

$$P_{d,n,r} = r*(L_{d,n,2} - L_{d,n,1})$$

If double-drop suppression is being used, half the length from the above formula is attributed to each drop.

Pattern length adjustments

The pattern depth and length in the open are adjusted for four factors which influence effective length: canopy interception, accuracy, evaporation and retardant viscosity.

Canopy interception: Simard developed a fairly complicated method to calculate the proportion of a pattern length penetrating the tree canopy to reach the burning fuels. It was given as a function of 3 stand age classes, 3 stocking classes, 9 species types, 5 release quantity classes and 10 depth classes.

Information structured in this way relevant to Australian species was not available, but broad estimates for canopy interception had been made by CIT and incorporated in ASMI. CIT's data, translated into the required forest types, and some information from FCV tests, were used in AIRPRO as shown in Table 12.

Table 12. Canopy interception parameters

	Throughfall as proportion of depth dropped (P)	Interception as proportion of depth dropped	Canopy capacity (mm) for water (S)
Ash	0.50	0.50	1.50
Mixed Species	0.65	0.35	0.75
Redgum, Box	0.80	0.20	0.50
Softwood < 15m	0.30	0.70	2.50
Softwood ≥ 15m	0.40	0.60	2.00
Alpine	0.65	0.35	0.75
Mallee	0.80	0.20	0.50
Heath, Grass, Scrub	1.00	0	0

If the depth of retardant required on the ground is D, the nominal amount required before canopy interception is $Q = D/P$, and nominal interception is $(1-P)*Q$.

An upper limit for canopy interception, S, is set, where S is taken from Table 12 for water, or 6 times that amount for thickened retardants. Canopy interception is then calculated as the minimum of S and (1-P) * Q.

Canopy interception is then added to the depth required on the ground to derive the amount required from the airtanker. Interception is thus modelled as a uniform layer left in the canopy, rather than a percentage deduction from the line length as in the Canadian version.

Accuracy: An allowance for the average misplacement per drop, E, is subtracted from pattern length under canopy, to give perimeter held. In this context, E relates only to under-or over-shooting in the line of flight. Excessive overlap with pattern already laid wastes line, while leaving a gap will allow the fire to burn through unless the gap is filled with another drop which will also give unnecessary overlap.

In relation to cross-range error, retardant dropped inside the fire edge on burnt ground is wasted, while retardant dropped too far in front of the edge will be subject to some evaporation before the fire reaches it. However, experienced pilots can generally place the drop at a satisfactory distance from the edge to avoid either of these extremes, if chemical retardant is used. Wastage on water drops is considered below under the evaporation factor.

Simard's inaccuracy component (in metres) is:

$$E = AC + 0.09 * V + 0.6$$

where AC = accuracy parameter for each airtanker
V = wind speed (km/hr)

This formula combines five types of error, based on both theory and Canadian operating experience, namely:

i) target identification error
ii) pilot and equipment reaction time
iii) drop speed and height
iv) wind speed
v) aircraft reaction

Each of these independent errors can be positive or negative and thus has a chance of partially cancelling out. Using the binomial distribution, the average absolute error is calculated to be 37.5 per cent of the total error.

The component for aircraft reaction is based on a standard error of 3 m divided by an index of relative manoeverability (Rm) for each aircraft constructed as follows (Simard & Young 1978, p.125):

$$Rm = 30G / (Lw + 2.5\,Lp + 0.33\,Lx)$$

where G = design load factor
Lw = wing loading (lb/ft^2)
Lp = power loading (lb/hp)
Lx = control surface loading (lb/ft^2)

The average accuracy parameter, AC, was 11 m in the Canadian context *. For DC6, for example, AC was 13m, so that with a 20 km/hr wind, the average loss would be 16 m. This represents 17 per cent wastage on a typical 4T x 1R drop at 1 mm depth. Simard indicates that this is consistent with observed Canadian practice, but it seems to be better than the accuracy achieved in operations in Victoria. Out of 65 rated drops from the Hercules or agricultural aircraft, FCV observors rated 70 per cent as accurate and 30 per cent as inaccurate. Helicopters were generally rated as accurate (Rawson and Rees 1983). In a Canadian evaluation, 70 per cent were rated accurate, 24 per cent close and 6 per cent poor. (Hodgson 1968).

Evaporation: Cross-range error, placing the drop too far from the fire edge, may allow some evaporation before the drop is reached by the fire but this is relatively insignificant for long-term retardant since the main effect derives from the retardant salt. Pure water drops from fixed-wing agricultural aircraft, however, have been observed in FCV operations to be largely ineffective, since evaporation from a drop placed too wide is substantial. In addition, a significant proportion of the water may drain off the fuels (particularly standing fuels) to the ground. Evaporation from surface fuels at an ambient temperature around 35°C has been roughly estimated at 1 mm/per hour**. This is equivalent to 0.02 mm per metre from the fire front at a rate of advance of 50 m/hr. However, the wind and the heat of the fire itself add considerable drying effect.

Accordingly, an amount of wastage for drainage and evaporation is deducted from the depth penetrating the canopy, namely 0.05 mm for each metre of average misplacement of drops (E), the latter being a function of aircraft manoeverability. Given an average error of 9 m for an agricultural plane, the loss amounts to 0.45 mm, leaving little effective line. For larger aircraft such as the CL-215, however, a significant concentration still remains. For long-term retardant, loss of effective concentration due to evaporation is assumed to be only 20 percent of that for water.

Table 13. Relative pattern lengths of water and thickened retardant
(expressed as a ratio water:thickened retardant)

	Depth class (mm)									
Quantity released (litres)	0	0.25	0.50	1.00	1.50	2.00	2.5	3.0	4.0	5.0
500	1.02	1.00	0.90	0.85	0.80	0.75	0.75	0.75	0.75	0.75
1000	1.00	1.06	1.03	0.90	0.85	0.80	0.75	0.75	0.75	0.75
2000	0.99	1.00	1.07	0.95	0.90	0.85	0.80	0.75	0.75	0.75
4000	0.98	0.99	1.00	1.09	1.08	0.98	0.85	0.80	0.75	0.75
8000	0.97	0.98	0.99	1.01	1.05	1.06	1.08	1.06	0.94	0.90

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* Simard & Young (1978), p.148

** CIT data from Aquarius trials

Retardant viscosity: Gum or clay thickeners in retardants have the advantage of increasing adhesiveness of the load and hence reducing drift losses, and increasing canopy penetration by way of greater momentum. On the other hand, these effects tending to increase line length have to be weighed against effects tending to reduce it - more retardant sticking to the canopy and a more compressed pattern. The net effect should be reflected in data used by Simard, based on Swanson et al. (1975) for relative water pattern lengths of thickened retardant (Table 13) as a function of quantity released class and depth class.

It can be seen that pattern lengths for water are significantly shorter at the higher concentrations, particularly for smaller load sizes.

The line lengths input for each airtanker therefore are for water drops, and these have to be divided by the above figures when thickened retardants (i.e. both short and long term) are tested in the model.

Operational constraints: There are a number of constraints on fire-bombing aircraft which can prevent them from operating safely in the required areas, e.g. smoke, wind, broken terrain or rough water. These are not modelled in AIRPRO but some are reflected to a limited extent in other variables. For example, where winds are so strong or gusty as to trouble aircraft they will generally fail in any case because of excessive fire intensity, while the drop wastage is supposed to reflect average accuracy in different types of terrain.

Selection tests

The maximum number of combinations of resources/tactics that could be tested on any fire was 528 (i.e. 11 aircraft models x 4 fleet sizes x 3 retardants x 4 locations of attack). To avoid unnecessary computing, the model carries out a number of preliminary tests before fully simulating any combination, and rejects any that are clearly unlikely to be worth dispatching. This procedure may result in the selection of as few as 1 per cent of the possible combinations over a number of fires.

Maximum savings: An aircraft model is not selected if the maximum savings it could achieve if it controlled the fire immediately are less than the minimum delivery cost of one load. Maximum savings are calculated from the damage routines assuming the final area as equal to the area at detection.

Smaller aircraft are processed first and if any fail this test, larger types are also skipped.

Secondary models: For each of the 9 airtanker types, (e.g. large land-based, medium water-scooper etc.), the aircraft model thought most likely to be effective is classed as primary and the others secondary. If the primary model fails the tests or generates a net loss, secondary models of that type are skipped. This involves pre-judging likely effectiveness, and runs some chance of eliminating superior solutions, but probably not often.

Number of aircraft: In general, if the minimum cost of using n aircraft of a given model from the same base (namely, n times the cost of one delivery from one aircraft) exceeds maximum savings on the fire, the model does not proceed further to test n or any greater number of aircraft.

If savings from n aircraft are greater than or equal to savings from (n-1) aircraft, after taking account of bird-dog costs, testing for (n+1) aircraft proceeds. Otherwise, marginal savings from additional aircraft are negative and numbers beyond n are skipped.

Retardant: If maximum saving is less than the delivery cost of one load, including retardant cost, the retardant is skipped.

Location: If savings after extending air attack to flank f are greater than or equal to savings after flank (f-1), attack is extended to flank (f + 1). Otherwise no further flanks are tested.

Perimeter: If three or more airtankers have been tested, and the total length of line held for the next number considered exceeds the perimeter at detection, the proposed trial is skipped.

Line holding: If the rate of line holding is not greater than zero, or is not greater than rate of arc growth, the proposed trial is skipped.

Drops to control flank: If the maximum possible savings are less than the minimum cost of the number of drops needed to hold the flank being considered and the drops made on previous flanks, the proposed trial is skipped.

Combinations passing all tests are selected to go through the full simulation.

The selection tests mirror to some extent the dispatch decisions that must be made by a fire manager. He may have fairly automatic pre-planned dispatch criteria, or may subjectively weigh up the flying costs against the values at risk and fire danger etc.

Perimeter held by air attack

The order in which the arcs are attacked by air at present is:

> clockwise on the head (1), then one flank (2); then anticlockwise on the other flank (3), then the rear (4).

The two flanks are treated symmetrically in AIRPRO, although in the Australian situation it is typically more critical to control the eastern flank before the wind changes to the west. This may mean that in practice it is desirable to attack the rear (to anchor the eastern flank) before the western flank. Before a proposed drop on an arc, the length of free-burning arc, the perimeter held by air and the perimeter controlled by ground are calculated. The arc is skipped if already controlled by ground. If not, the drop is placed, tying into the end of any previous drop or line made by ground crew working in the same direction, and the length of effective line is added to the cumulative perimeter held. The actual perimeter held is reduced by any spillover in excess of the arc length or any overlap onto line built from the opposite direction. The spillover is counted as perimeter held on the adjacent arc if it is not already held.

Airtanker totals

After each load, flying time is incremented by the time interval between loads, plus the extra time for dropping partial loads. When the fire has been controlled by ground forces, aircraft times and costs are totalled.

> Total airtanker time includes initial take-off time, circuit time and flying time for all drops by all airtankers. This is multiplied by variable airtanker cost per hour to give airtanker cost.
>
> Bird-dog cost = bird-dog time *cost per hour.
>
> Retardant cost = number of loads dropped * tank capacity (L) * retardant cost per litre.

Total airtanker cost is the sum of the last three totals.

10. AIRTANKER COST

Sources of data

Details of airtanker costs for the aircraft of interest for Australia were sought from several agencies and companies, overseas and in Australia. Whilst more tractable than data on benefits, the cost data nevertheless present problems, particularly in relation to comparability of rate structure, cost items included, quality of service, national currency and year of price level.

No single agency could give authoritative data on more than two or three of the selected aircraft models. However, where data from more than one company for the same model were available, a link between different costing methods was provided.

Hire and ownership data

Two different approaches to cost data are possible:

- costs incurred by owner of aircraft
- hire rates charged by owners for use of aircraft by fire authorities.

For most aircraft in this study, hire rates charged by commercial operators were used for cost data.

These were more readily available for most aircraft (from the leasing agency or the operators) whereas ownership costs were generally kept confidential. There is also the advantage that commercial hire rates should cover all real costs, whether cash or imputed (e.g. owner's labour and capital etc.), whereas costs based on government accounting systems cannot be relied on to do similarly.

Costs for the large land-based specialist airtankers were based on North American hire rates. Canadian agencies supplied rates for the DC6, S2 and Canso, while the USDA supplied rates for the P2V and DC4. Canadian stand-by rates tended to be two or three times higher than US rates for the same model; this may be due to use of newer aircraft, more rigorous back-up requirements (e.g. guaranteed replacements) and/or less competition in Canada. It is assumed here that the situation and rates in Canada would be more applicable for Australia.

For agricultural aircraft and helicopters, which are already widely used in Australia, local hire rates were used. The FCV supplied rates for agricultural aircraft, and NSCA and ACT Bush Fire Council for helicopters.

Cost structure

To compare the economics of airtankers at different levels of operation, it is necessary to split costs into categories of:

- variable costs, which are proportional to operating hours
- fixed cost, which must be incurred regardless of use of the aircraft.

Total costs, both fixed and variable, are important in the initial decision as to whether to acquire airtankers. However, when the aircraft are already available, the main question is whether to dispatch them on particular fires and how long to fly them for. In this case, only the variable or operating costs should be weighed against savings, since the fixed costs can be considered 'sunk'.

Cost structure is discussed below, first for hire rates and then for ownership costs.

Hire rates

Hire rates charged by commercial operators of specialist airtankers usually have two components:

- cost per flying hour
- cost per day or week of stand-by or availability.

The two-tiered structure presumably reflects to some extent the variable and fixed costs incurred by the operator. In other industries, fixed costs are usually recovered as part of the per unit price but there is a good case for separate charges in the airtanker industry where fixed costs must be incurred to make the airtankers available, yet actual flying hours could be negligible in a wet season.

For agricultural aircraft hired by the FCV there is a three-tier cost structure of:

- flying charge per hour
- stand-by charge per day
- availability charge per week, i.e. for arrival at retardant base within one hour of call.

Since agricultural aircraft have other uses beside fire-bombing, the stand-by charges should partly reflect their earnings forgone in other uses. The availability charges similarly reflect the opportunity cost to the operators of restricting their other work to within a radius of 1 hour's flying time from the retardant base.

In Canadian hire rates, the stand-by rate per day is typically around 2.5 times the rate per flying hour. However, the USDA quoted stand-by rates per day as low as 0.5 times the rate per hour. In rates quoted by companies tendering for Project Aquarius, the ratio varied from 0.7 to 20. One agency charged only an hourly rate but with a minimum payment for 3 hours to ensure a contribution to fixed costs. Clearly there is a wide variation in different operators' approaches to recovering fixed costs, making comparison on a consistent basis difficult.

Where the charge per flying hour is so high as to recover a significant part of fixed as well as variable costs, less efficient use of the aircraft may result. The fire-fighting agency paying the bill may be reluctant to dispatch the aircraft even in situations where it could save enough to cover the variable cost. Similarly, in the AIRPRO model, such aircraft might not pass preliminary tests based on variable cost.

For efficient resource use, rates should be based on the true underlying costs, and similarly a social cost-benefit study should use the true costs. In this study, the private hire rates for most airtankers were accepted as indicating the true cost structure. However, some with very different rate structures (e.g. USDA, Defence, NSCA) were restructured to a basis more comparable with the others.

Cost to owner or operator

Variable costs to the owner clearly include operating costs such as petrol and oil. They also include a per-hour apportionment of repairs and maintenance costs, both regular short-term and long-term, such as engine overhaul, and part of depreciation.

Fixed costs include stand-by crew salaries and fringe benefits, training, hangar rent, registration fees or air navigation charges, and the bulk of capital charges (interest and depreciation). Insurance is also a fixed cost to the owner although it really represents an annualised amount to cover irregular losses, the probability of which is related primarily to flying hours.

The division of capital charges needs particular care to ensure consistent treatment. The original capital cost includes the purchase price of the basic aircraft and conversion to airtanker, and may include spare parts inventory. This gives rise to two periodic components, depreciation and interest:

- **Depreciation:** In economic terms, this is the reduction in real capital value of the asset each year. For accounting purposes it is often approximated by the straight line method, i.e. equal amounts per year over predicted life.

- **Interest:** Interest is imputed at a common rate here since actual interest payments vary according to whether the asset was financed by loan or owner's equity, whether the interest rate was subsidised, when the loan was taken out etc. The rate of 10 percent p.a. used is intended to be the long-term opportunity cost of capital as discussed in an earlier section. Actual interest payments decline over the life of the asset as the interest rate is applied to a declining capital amount.

Capital charges have been divided into their variable and fixed elements and converted to a constant annual equivalent by a method explained in Appendix 10. Depreciation and interest are combined in a single annuity value. The formulae resulting are:

$$\text{Fixed capital charge p.a.} = C\left(1 - \frac{S_1 + u(1 - S_1)}{(1 + i)^n}\right)A^{-1}_{\overline{n|}\,i}$$

$$\text{Variable capital charge per hour} = C\left[\frac{u\,(1 - S_1)}{(1 + i)^n}\right]\frac{A^{-1}_{\overline{n|}\,i}}{V}$$

where: C = initial capital cost
S_1 = salvage value after n years
u = proportion of depreciation due to usage
V = normal usuage rate (hours per year)
i = interest rate (%/100)

Special calculations were made for the CL-215, C-130 and helicopters for reasons explained below.

Canadair CL-215

Being an airtanker built specially for fire-bombing, the capital cost of the CL-215 is high compared with that of depreciated aircraft formerly in military or civilian use. However, none is operated by private companies (as far as we could ascertain) so no comparable hire rates are available.

One of the estimates made was based on ownership costs for the Manitoba Department of Natural Resources, with an estimate of capital charges added to the recurring cash costs. The annual fixed cost turned out to be well above that for any other airtankers, mainly due to the capital charge. This was based on an interest rate of 10 percent p.a., and an 18-year life, with 20 percent residual value. Capital charges allowed by private operators could be even higher. For example, in an article favouring the economics of the CL-215, Haggarty et al. (1983) calculate a private ownership option based on capital repayment over only 5 years and 15 percent profit rate.

The calculated cost was well above the 'full cost per hour' charged by Manitoba and also the ownership costs quoted by the Quebec Government (which now owns the Canadair factory). This was presumably because they omitted certain hidden costs, as commonly occurs with government accounting systems. The Manitoba hire rates would thus be implicitly subsidised. However, because of the possibility of some double-counting in the variable and fixed charges calculated by the first method, another method was used, resulting in rates intermediate between the Manitoba ownership and hire rates. The variable cost was based on the data for fuel consumption, maintenence requirements etc. quoted by Canadair, and the fixed cost on the charge for extension days beyond 60 days given in Canadair's tender for Project Aquarius trials.

Here it should be borne in mind that the rates tendered by most companies were lower than normal rates for the North American fire season, since the trials offered work during an otherwise idle period.

RAAF Hercules

The RAAF Hercules might be expected to involve economies since the bulk of its fixed costs can be allocated against its defence role. Normal use is 800 hr per year, compared with a typical 80 to 200 hr per year for North American airtankers.

In its operations for the FCV in 1982-83 the Hercules was charged at a rate of $4633/flying hr (Rawson and Rees 1983). For reasons discussed earlier, the rates were restructured for use in AIRPRO, shifting more costs into the fixed component,using data for cash costs of ownership supplied by the Department of Defence. Capital charges were handled in a way similar to that for the CL-215. For the Hercules, additional costs for a MAFFS unit, which has a capital cost of $1.4 million (FCV), and compressor, were included. The overall costs by this method were similar to those experienced by the FCV, about $1.1 million per annum.

The Hercules turned out to be substantially more expensive than all other airtankers, including those of equal retardant capacity.

This makes it unattractive for fire-bombing, unless the defence authorities were to take a different view of civilian fire suppression and revise the cost structure accordingly. For example, if fire work were seen as a beneficial exercise for the crew rather than a diversion from normal defence duties, there would be a case for charging lower rates for fire-bombing and gaining more use for the Hercules. However, the defence authorities are constrained to avoid charging subsidised rates which would provide unfair competition to private operators.

Helicopters

The cost of ensuring availability of helicopters for fire-bombing depends on the nature of their other roles. NSCA helicopters in the Latrobe Valley are generally on stand-by for a range of possible emergencies, but a part of their fixed costs should still be allocated to fire-bombing. It may not be feasible to reserve any exclusively for firework but in most cases they are likely to be ready for action at least as quickly as agricultural aircraft.

Helicopters owned by forest or National Park services should be able to be used on a variety of other work to defray capital costs, while remaining readily available for fires in the summer.

Helicopters (usually of similar size to the Bell 206) based in Melbourne or other large cities carry out various other jobs such as personnel transport and photography which are generally more difficult to leave in the event of a fire call than is the work of an agricultural aircraft.

In this study, the same dispatch delays have been allocated to helicopters as to agricultural aircraft, but it has been assumed that the opportunity cost of guaranteeing availability at 1 hour's call would be 50 percent of the full stand-by rate, compared with 14 percent implied in some contracts for agricultural aircraft. For commercial helicopters, the total fixed cost could be reallocated to some extent from days of low fire danger to pay for full stand-by on days of high fire danger. For the larger helicopters operated by NSCA, a figure of 25 percent was used.

When locations other than the normal bases of Melbourne and Latrobe Valley were tested as alternative home bases, additional costs for ferrying and/or accommodation were added.

Because of the diverse uses of helicopters, they are seldom used purely for fire-bombing all day. Other roles associated with fire control for which they are well suited include transport of personnel and equipment, reconnaissance, command post, and back-burning with aerial incendiaries. Hence it would be invalid to charge the whole the of fixed cost for helicopters against line-holding of the type modelled in AIRPRO.

Greater specialisation may occur on large fires where a number of aircraft are operating. Larger expensive helicopters are more efficiently used primarily for fire-bombing and transport, leaving the smaller ones to concentrate on reconnaissance etc.

Although the proportion of their time spent on different tasks is quite variable, it is assumed here that, during fires, half the time of small helicopters is spent on fire-bombing and half on other work. Hence only 50 percent of stand-by costs for 30 days a year have been included in fixed costs. For medium or large helicopters (including the Bell 212), 75 percent is allocated to fire-bombing.

Stand-by period

One of the policy decisions to be taken concerns how long the aircraft should be maintained on stand-by through the fire season. The forest agencies generally negotiate a hire rate which includes a rate per day of stand-by for the normal period, say 90 days, and a lower rate per extension day (typically 35 to 65 percent of the standard rate).

Looking at the actual costs underlying these rates, certain costs would be variable with period of stand-by, although fixed with respect to flying hours. Thus extending the period for a month may make no difference to some parts of rent, administration and salaries for permanent staff, but require additional payments for casual staff who otherwise would have been released.

However, in Canada the specialised airtanker companies pay an annual salary to their staff, even though the pilots may be only needed for a few months of the year. Hence the cash cost to the company of an additional month of stand-by may be negligible.

However, during their holidays the pilots are free to, and encouraged to, obtain work elsewhere, so it can be argued that the cash cost of extension days to the agencies reflects the social opportunity cost of retaining the pilots.

In the study, the fixed airtanker costs are specified in terms of a stand-by rate per day for a standard season of 120 days (November through February). These are typically the most fire-prone months for Victoria, although large fires sometimes occur in September, October and March, as indicated in Appendix 17. Where variations to longer or shorter seasons are tested, the cost of extension days is taken to be 50 per cent of the normal stand-by rate.

Agricultural aircraft are assumed to be normally on availability through the fire season, but an option is tested in which they are placed on stand-by whenever the fire danger is very high (FDI over 24). Costs for this are based on the assumption that there are 30 such days in the average 120 day season. This is derived from data on the distribution of 3 pm FDIs over the last 5 years at East Sale meteorological station, shown in Appendix 16.

Comparing hire and ownership

It is difficult to compare ownership costs and hire costs on a common basis, since the basis for the companies' rate setting has not been revealed. The private hire rates superficially seem to be much higher than the expected equivalent for a government-owned aircraft. Some companies are said to pay off the aircraft in 5-8 years, and allow 15 percent for financing and profit (Haggarty et al. 1983). A government user, on the other hand, could reasonably write the capital cost off over 20 years and allow 10 percent in real terms for financing.

However, such comparisons may exaggerate any advantage government ownership would bring. For example, private operators may not always realise their desired return in a risky or more competitive environment. Assumptions of a long operating life have to be matched with an adequate allowance for repairs and maintenance. Other costs and risks fully accounted for by a private enterprise may be hidden in a government bureaucracy and allocated elsewhere.

Particularly in Australia, a government agency with little experience of similar aircraft may find problems and higher unit costs in trying to manage and service the aircraft itself. For any owner in Australia the cost of spare parts and servicing for several of the aircraft not in common use here would be higher than in America.

Other adjustments

Currency: US and Canadian dollars were converted to Australian dollars at the exchange rate prevailing at the time quoted.

Year of price level: Costs were brought to a common level around June 1983, using the Consumer Price Index for Melbourne.

Overseas hire

Another option costed was the hire of airtankers from North America for the Australian summer months only.

It might be thought that this would produce economies since the airtankers are otherwise largely idle (or undergoing routine maintenance) in America at this time. Australia would not expect to pay the full fixed costs of aircraft availability since these are already recovered from American work.

However, there is substantial additional cost for ferrying both ways e.g. $80 000 for a DC-6 from Canada to Sydney return. Only the larger aircraft are suitably equipped to fly this distance under their own power.

Further, it can be assumed that the operators' own crew, including ground and administrative staff, would have to be brought to Australia for the whole period.

Overall, the cost quoted for summer hire appears close to the average annual cost for an aircraft retained in Australia. It could be more economic if it were possible to predict which years the airtanker would be particularly needed. However, this would require a level of medium-term fire weather forecasting that is not possible at present.

Other uses

It has been found in America that converted airtankers find few or no other uses apart from fire-bombing, which means that the whole capital cost must be allocated to about 80 to 200 hours of use in summer.

Possibilities of off-season use that have been considered in Australia include:

- freight
- air photography
- scientific applications
- tourist trips to Outback
- coastal surveillance

However, the markets for most of these services are already over-supplied. The unavailability of the aircraft in the summer would also handicap it for freight or surveillance roles requiring regular service. December-January is in fact the time of peak requirements for general freight.

Controlling oil spills is another use for airtankers being seriously investigated by the Federal Government. It is similar to fire suppression in the nature of the operation, the need for early attack, and the intangible nature of the benefits. On past experience, the frequency of use on oil spills in Australia would be much lower than for bushfires. If a financial commitment by the government department concerned with oil spills were made, it could provide a useful contribution to defraying the costs of airtankers.

Agricultural aircraft and helicopters have a natural economic advantage in regard to multiple use.

Airtanker accidents

The probability of casualties in airtanker accidents should ideally be incorporated in the analysis as an offset to the possible savings in ground casualties. In the United States, over 50 airtanker accidents, including 31 fatalities, in the 11 year period 1964-1974 were reported to the National Transportation Safety Board. * On the basis of an average of 7000 flying hr/annum **, this represents 0.0004 fatalities/hr. This could be costed at $80/hour, using the same figure of $200 000 per life used in the losses section. An implicit component for accident compensation is probably included in hire rates charged by operators.

Administration

To cover administration and support services, an allowance of 10 percent has been added to direct costs.

Environmental effects of retardant

The chemical ingredients of fire retardant may have some effect on the natural environment where they are dropped. The main ingredient of retardant - ammonium phosphate or sulphate - is widely used as a commercial fertiliser. It may have a minor fertilising effect where dropped, but in the high concentrations used for fire-bombing it tends to be destructive of vegetation. National Parks services are reluctant to use chemical retardants because of the changes to vegetation that may follow, and prefer the use of water in fire-bombing.

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* George et al. 1977

** Gale & Mauk 1983

Retardant may be particularly damaging to fish and aquatic life if dropped in or near streams.

However, the total area coated with retardant in fire-bombing operations is a very small fraction of the area burnt in bushfires. No economic valuation is accorded to environmental effects in this study.

11. RETARDANT BASE COSTS

Four different levels of retardant base facility are provided for in the model: the first is the mobile facility; the others are fixed bases for small, medium and large aircraft respectively.

Dry v liquid retardants

The facilities are assumed to be for the mixing of dry powder retardants such as Phos-Chek and Amgard, since this is the form used in Project Aquarius trials and predominantly used in FCV and USDA operations.

An alternative is the use of induction mixers for retardant in liquid concentrate form, such as Firetrol 931. There are differences between the dry and liquid retardant types in relation to storage, handling and mixing costs, and viscosity, and both types have strong proponents (e.g. see Howard 1980).

Cost components

Retardant base costs are here divided into four components according to which variables they are most closely related to. The items included in each component are explained below, while the assumptions on operating levels, establishment costs and unit costs are detailed in Appendix 18.

Fixed annual costs

The initial capital cost is assumed to range from $14 000 for a small mobile mixer to $45 000 for a large base. It is assumed that 50 percent of capital depreciation is fixed, irrespective of use. The average effective life of the base components is assumed to be 10 years, over which time their capital value depreciates to zero at normal usage rates, but at minimum usage rates there would still be depreciation over that period of 50 percent of original value, due to corrosion or obsolescence etc. The present value of this depreciation is converted to an annual equivalent including interest. Appendix 10 explains the method used for apportioning the capital charge (combined depreciation and interest) between fixed and variable components.

An amount for preventative maintenance is also included as an annual fixed cost.

Stand-by costs per day

These comprise travel and labour costs for the crew maintained at the base for each 9-hour day of airtanker stand-by. It is assumed that, even for the largest base, two people can handle the initial mixing and loading, but that additional labour would be called if a fire occurs.

Two operators are assumed to be on stand-by only at aircraft home bases, and only on days of high fire danger. However, when the airtankers are on stand-by, but the base crew are not, the initial take-off delay is assumed to be increased by 10 minutes. If the aircraft has to use a fixed retardant facility closer to the fire, operators are sent to that base to provide all loads after the first for the duration of the fire. Daily travel and clean-up for 2 hr is added. For mobile mixers stationed at district forest offices, it is assumed that the crew can be employed nearby while waiting for fire calls, so no stand-by cost is allowed.

Additional labour

This is the hourly cost for additional labour to bring base crew to full complement. Labour included in stand-by costs on days of high fire danger is converted to variable hourly labour on other days for the hours the base actually operates.

Operating cost per kilolitre of retardant

This includes:

- that part of capital cost variable with use, i.e. depreciation due to wear and tear
- repairs and extra maintenance related to use
- fuel and lubrication.

Ideally the bases are designed at the outset to accommodate the number and size of aircraft expected, but future demand is uncertain, and it is cheaper up to a point to build spare capacity into the original base design than to expand it later.

The level of facilities assumed in the model represent a compromise between those used in the past by the FCV and those used commonly in the USA. Figures for medium and large bases assume slightly bigger tank sizes and much faster mixing and loading rates than those achieved in the FCV-MAFFS operation, partly so as to accommodate more than one aircraft. The fixed small base is assumed to be able to handle up to 4 agricultural aircraft each on a 40 minute turn-around. Flexibility to handle more aircraft can be provided up to a point by pre-mixing a larger volume, which becomes a stock to be run down over the day if the rate of withdrawal exceeds the rate of mixing.

The average investment per USDA base is about $720 000 (US 1981) for annual use of 1000 kL (Gale and Mauk 1983). Some of the higher expenditure is for items such as runway works, buildings and underground storage not allowed for in the basic infrastructure assumed here.

Total annual costs

The rates charged by individual companies were mostly obtained on a confidential basis and so cannot be published. However, Table 14 indicates typical total annual costs for one aircraft of each of seven broad types.

Table 14. Total annual costs by type of aircraft ($A)

Aircraft size and cost category	Land-based	Water-scooper	Helicopter
Small			
- Aircraft	65 000	148 000	53 000
- Retardant and base	82 000	-	-
- Total	147 000	148 000	53 000
Medium			
- Aircraft	308 000	532 000	166 000
- Retardant and base	142 000	-	-
- Total	450 000	532 000	166 000
Large			
- Aircraft	619 000		
- Retardant and base	290 000		
- Total	909 000		

The costs are based on a typical number of flying hours and stand-by days. For small land aircraft and helicopters, stand-by costs are only allowed for 1 in 4 days. Retardant costs for a typical number of loads are included only for land-based aircraft. Bird-dog costs of $20 000 could be added.

12. FIRE EFFECTS

Losses from wildfires are difficult or impossible to quantify and value, especially damage to the less tangible natural resources which are not traded in the market.

The USDA Forest Service has established estimates of protected resource values under its Resources Planning Act program but its system leaves much to be desired, and no similar valuation system is available in Australia (USDA Forest Service 1975; Althaus and Mills 1982)

Nevertheless an attempt has been made for this cost-benefit study to establish methods of valuing damage to timber, water, recreation and apicultural resources from first principles.

Benefits from fire

The major concern lies with the potentially large losses of property and resources that can result from bushfires. However, as at least a partial offset to these losses, some fires may also bring benefits.

Farmers, and aborigines before them, have long used deliberate burning for purposes such as clearing scrub and invigourating pasture. More recently, forest managers have been practising prescribed burning in order to reduce fuel loads and thereby aid the control of future wildfires. It is also accepted that fire, being a natural part of the environment and an agency of renewal, can be beneficial at times for conservation objectives.

Since the optimal use of fire for these beneficial purposes generally requires a particular timing and intensity, it is increasingly being carried out through deliberate burns under the appropriate regime. Wildfires are then likely to be undesirable additions to the planned regime. Nevertheless, some areas burnt by wildfire, particularly at low intensities, may accidentally benefit.

In this study, gains from wildfires are included explicitly only for water yields. Other benefits of the kind discussed above are taken into account only implicitly by the zero or low net losses from low-intensity fire for other resources such as timber and environment.

13. PROPERTY

Over the long term, the property losses on major bushfires probably outweigh the more regular small losses of natural resources. They are not reported and aggregated, however, in any consistent comprehensive way.

Private property

Data sources

In Victoria most property losses, particularly those involving private property, could be expected to occur in fires fought by the CFA. Hence, apart from the 1982-83 large fires where wider sources were covered, this study relies on CFA figures for property losses. These were derived from the following sources:

- computerised reports, available since 1979-80, which include quantities and values of various items lost - in particular, buildings, livestock, crops, equipment and fencing.

- Major Fire Reports (non-computerised) which should be completed for fires in excess of 100 ha. These carry more detail on fire weather, but do not provide specifically for losses. Nevertheless, losses are often added in the Other Comments space.

  There were about 80 of these reports for the last 6 years, which were used to supplement and fill gaps in the computer records. Generally, only quantities lost were reported. These were multiplied by per unit values representing average depreciated values. Values were derived from the Department of Agriculture, a stock and station agent, and an insurance loss adjustor experienced in bushfire claims.

  Examples of these values for the major items are set out in Appendix 19 along with estimates of losses on the Ash Wednesday fires of 1983 in Victoria.

- the published CFA report on Ash Wednesday fires

- Victorian Department of Agriculture estimates of farm losses in 1982-83.

Basis of valuation

The valuation of private property losses, for which market prices for similar assets are usually available, should be more accurate in theory than those for natural resources which are not tradeable or are sold by the government at non-market prices.

The appropriate economic concept of fire damages was identified by Sinden and McArthur (1968) as the cost of replacement to the pre-fire level of productivity.

The market price of similar new assets, or used ones if a market exists, is a useful starting point, but it is ideally necessary to know the condition and value of the particular asset destroyed. The true loss due to the fire is the reduction in the net present value (NPV) of future services expected from the asset. The NPV should be approximated by the (depreciated) market value if a market existed. For example, a 50-year-old fence which is on its last legs and needs replacement or continuing costly repairs, would have a low NPV relative to a new fence. In this case, if it is destroyed by fire, the loss is the lower NPV rather than the full replacement cost which would have to be paid soon regardless of the fire.

Any salvage value should be deducted to obtain the net loss.

In many cases the asset is not totally destroyed, in which case a better approach to loss valuation may be to measure the expenditure necessary to restore the asset to its previous value (e.g. repairs, restoration and rehabilitation expenditure).

Either the reduction in capital value, or replacement cost, or loss in production income may be the most appropriate method in different circumstances, but it is important to avoid double-counting of inputs and outputs. For example, suppose all the sheep on a farm are killed and the pasture is burnt, taking six months to recover. The loss could be counted as the full market value of the sheep when killed, plus the value of the pasture (at least as much as its agistment value). However, it would be invalid to add the lost income expected from wool and lambs from those sheep. The value of the outputs should be largely reflected in the inputs already measured.

Estimates in CFA reports of the financial losses suffered were accepted where available. These ideally should reflect the particular value, state of repair and degree of damage of assets affected by the fire. However, there could be significant under-estimation due to failure to report or include values for some fires. On the other hand, where losses are reported, it is conceivable that there could sometimes be over-estimation in line with optimistic claims for insurance.

Another possible source of information about property losses lies in the data base of insurance payments held by the Insurance Council of Australia. However, this has a limited coverage of insurance companies, and apart from major fire disasters, claims due to bushfires are not readily separable from other fire claims. Further, while insurance cover on homes is high, cover for agricultural assets such as crops, livestock and fencing may be as low as 10 percent.

On certain severe fires where large compensation or insurance claims are involved, careful estimates of losses on individual properties are made. As well as the value of stock, buildings, trees, materials and equipment destroyed, these may include post-fire costs for rehabilitating pasture, interim costs for hand-feeding or agisting the remaining stock, clearing up and disposing of burnt animals and debris, and additional management expenses. No centralised data on these detailed evaluations are available.

Pasture losses

Extensive losses of grass or other pasture usually occur in country fires even if no valuable property is burnt. The economic loss resulting depends on the recovery time and value of the pasture. Recovery time usually ranges from four months with good post-fire rains, to ten months with unfavourable weather. The value of pasture depends on its condition and, like most other rural assets, on weather and market conditions. Improved pasture at a time of low availability could be worth $40/ha, and unimproved around $15/ha. The value is indicated by rates for agistment and additional transport costs.

Pasture losses are usually omitted from fire reports, so an arbitrary allowance of $5/ha of 'grass, heath or scrub' has been added for this study.

Public property

Public property losses include telephone and power poles, bridges, buildings, road signs and research plots. There is no general centralised system for recording such losses, which could be spread over a wide variety of Commonwealth, State and Local government agencies. CFA reports provide only for private property and SEC poles, and FCV reports provide only for timber losses.

However, for the 1982-83 fires, such losses for State and Local assets were channelled through the Victorian Natural Disaster Relief Account which gave an aggregate figure for about 10 damaging fires in that year. These figures included relief payments to private victims of the fire, and special fire-related expenditure by the Police, Department of Emergency Services, etc.

Since they were not classified by fire, the ratio of total estimated losses from this source to total itemised losses on individual fires (about 2:1) was used to expand the itemised losses on each fire, i.e. public losses and expenditures were spread proportionately to other identified losses.

Property loss and area savings

A study of the Southern Tablelands fire in 1965 by Sinden and McArthur (1968) found that there was some evidence that the greatest damage occurred in those properties nearest the start of the fire. Property owners further away apparently used the warning time available to take protective actions such as moving stock, hosing buildings and constructing firebreaks, but the effect was not clearcut. If true, it would suggest that reducing fire area by aerial attack could mean a less than proportional saving in property.

On the other hand, by concentrating on protecting property, airtankers might achieve property savings more than proportional to area savings. Against this should be set the point that ground crews have already probably made special efforts to save individual buildings and property.

In conclusion, the simplest assumption was adopted - that losses are reduced in proportion to area burnt.

14. HUMAN CASUALTIES

As on the CFA fire report, three broad classes of casualty were provided for: minor, major and fatal. Data were handcoded on FCV fires where extra information was available.

Human life

Loss of human life is seen by the general community to be the most important and terrible consequence of bushfires. Accordingly any comprehensive study of the costs and benefits of fire suppression must somehow take account of the value of possible saving of lives.

This does not necessarily mean that human life must be included in the monetary aggregates of costs and benefits. As an alternative, the technical study could confine itself to estimating the net monetary benefits for those effects that can reasonably be given a monetary equivalent, whilst estimating changes in number or quantity for those effects that are not so amenable. It is then left to political judgements to make any necessary trade-offs between monetary and non-monetary amounts.

However, this study includes human life in the economic calculus, drawing on overseas work on the subject.

One relatively simple method that was used in early studies of the value of life was the 'earnings' method. The value was calculated as the sum of a person's future earnings, with each year's earnings weighted by the probability of survival to that year, and discounted back to the present. Using a simplified form of this formula, for an average person earning $20 000 p.a. and half-way through their working life, the present value of future earnings discounted at 5 percent p.a. would be about $200 000.

This might be acceptable as a lower limit but is unsound in principle. It focuses only on the person's value to society as measured by their contribution to national income, which has many deficiencies as a goal of economic policy, and ignores the person's own feelings and their non-economic role in society.

Another approach is to take the values implicit in political decisions that involve the saving of lives, e.g. the expenditure on search and rescue missions for lost people, or expenditure in hospitals to save lives. Where such actions have a general community acceptance the implicit values are useful indicators. However, they beg the question as to how much governments should be prepared to spend in order to save lives.

Another simple method, which has little to justify it, is to value life at the value of a life insurance policy. The insured amount, however, relates more to how the insured person values his or her surviving kin (if there are any), rather than to the value of his/her own life.

The attempt to put a value on individual lives is not very palatable and, in any case, is not really necessary. Public programs such as improved bushfire suppression do not save any particular lives, named individuals, or even a given number of people. All they do is to slightly reduce the risk of death in a particular period for everyone.

The value we are seeking then depends more on what people are prepared to pay for an equivalent marginal reduction in the probability of death. Economists have made several attempts to measure this, both by studies of observed behaviour and through direct questionnaires.

The approach used in studies of wage-risk trade-offs is to estimate a multiple regression of the form:

$$W = a + b_i X_i + c\,p + d\,q$$

where W = annual wages
b_i and X_i = explanatory variables such as age, education, unionisation
p = annual risk of death at work
q = annual risk of non-fatal injury

The coefficients c and d estimated indicate the implicit value of life and injury respectively.

The range of figures estimated is listed in Table 15 (summarised by Blomquist 1981 and Viscusi 1983). Values have been converted from $US1979 to $A1983.

The first eight figures were based on studies of earnings for occupations with different accident or mortality risks, and the apparent premium attributable to higher risk. There were, however, considerable problems in isolating the risk factor from various other factors contributing to earnings differentials.

Table 15. Estimates of value of life saving

	Author of study	Value of life savings ($'000)	Discounted future earnings ($'000)
1.	Dillingham	561	201
2.	Thaler and Rosen	731	168
3.	Brown	1 582	n.a.
4.	Smith	4 082	155
5.	Viscusi	4 252	158
6.	Leigh	6 900	n.a.
7.	Marin and Psacharopoulos	2 000	n.a.
8.	Olson	8 100	n.a.
9.	Blomquist	697	277
10.	Ghosh, Lees and Seal	527	76
11.	Acton	85	66
12.	Jones-Lee	15 139	141
13.	Carlson	800	n.a.

The next two studies were based on analyses of seat belt use and highway speeding, respectively. The next two were based on surveys of people's willingness to pay for coronary care systems and improved airline safety. The last examined the US Air Force's policies on ejector seats for pilots.

The range of estimates is so wide that these studies may not seem to help in selecting a practical figure. However, it is notable that all are greater than values calculated by the earnings method for the same set of people.

The figures over $2 million superficially seem considerably higher than the values implicit in government decision-making. Although no careful studies on this subject have been carried out, governments generally do not seem to be willing to spend millions of dollars for road safety improvements or hospital facilities that would allow an expected saving of only one life. In another field, search and rescue missions involving aircraft, patrol boats and teams of men working for several days to save a single life could cost several hundred thousand dollars but not as much as $1 million. A more typical cost of search and rescue missions is around $20 000. The amount that the community is willing to pay in such cases would presumably be higher if it were certain that the effort would be successful.

There are good reasons to be cautious about applying the higher figures for value of life in this bushfire study. If higher figures are used in evaluation of expenditures on bushfires than for other life-saving programs, there would be a bias in the allocation of funds. Alternatively, if the government used a figure of several million dollars as the value of lives saved in evaluation of all expenditure programs, it could quickly encounter a budgetary constraint, as a vast array of programs in health, transport, education etc. could appear worthwhile. This effect would be moderated, however, if the higher value of life were used consistently on both sides of the cost-benefit calculations. That is, as well as a higher benefit from lives saved from a particular program, there would also be a higher opportunity cost, since the funds used could otherwise have been applied with some small but positive probability of saving lives in other areas.

Nevertheless, it could be that citizens as taxpayers are not willing to pay the amounts for life saving that seemed implicit in the occupational decisions of citizens as employees.

In conclusion, it was decided to use in this study one of the lower figures for value of life: $200 000 based on the discounted earnings method.

Non-fatal injuries

Minor casualties, as reported for CFA fires, covered temporary eye problems (grit and smoke irritation), sprains and minor injuries requiring first-aid or medical attention but little if any time in hospital. Major casualties covered broken legs, severe burns, etc., requiring hospitalisation.

Injuries involve financial costs for medical treatment and loss of earnings, as well as less tangible costs of pain and suffering.

For the same reasons as discussed above, valuation should be based on individuals' willingness to pay to reduce the probability of injuries, or equivalently the premium they demand to face an increased risk of injury. This measure should in theory cover both the financial costs of injury and the pain and suffering.

Several overseas studies of wage premiums in risky occupations pointed to an average value of around $30 000 per non-fatal injury at work, which was several times the amount of earnings lost, mainly due to the intangible elements of suffering. In US workers compensation settlements for bodily injuries, payments at the lower end of the scale (up to $50 000) tended to be several times the financial loss, although above $100 000 there was little difference. The average pay-out for burns injuries was $80 000. Compensation payments after the event, however, would tend to underestimate people's willingness to pay to avoid injury before the event. The seriousness of possible bushfire injuries varies across the whole spectrum from trivial to near-fatal, but for a few typical cases, financial cost estimates are shown in Table 16.

Table 16. Costs of bushfire injuries

Injury	Medical costs	Lost earnings	Total financial cost
Minor			
Eye irritation	1 hr/first aid x $30/hr	4 hr x $8 = $32	$62
Sprained ankle	1 hr first aid $30 2 G.P. visits $30	2 days x 8 hr x $8 = $128	$188
Major			
Limited burns	3 weeks hospital (single room) x $230/day = $4830	6 weeks x $300/wk = $1800	$6630
Serious burns	12 weeks hospital (single room, including 6 days intensive care x $230/day) = $19 320 2 specialist consultations at $(43 + 22) Major skin graft - surgery $158 - anaesthetic $99 Scar surgery $257 Total Medical = $19 899	20 weeks x $300/wk = $6000	$25899

If we take mid-range estimates for the two CFA categories, and multiply by a factor of 3 to allow for non-financial costs, the costs could be $500 for a minor and $50 000 for a major injury. These figures were used in the model.

As for property, casualties were assumed to be proportional to area burnt for different tactics.

15. TIMBER

Formula

The DAMAGE subroutine in the model computes timber losses as the discounted present value of losses at the planned harvest time, less salvage revenue. The formula is given below, before discussing each of the components in turn and some alternative valuation methods:

TLOSS = D - S
where TLOSS = timber loss
D = discounted value of losses at harvest time

$$D = ROYC * (1 + RAI)^N \left[\frac{(SDK * VH) + (1 - SDK) * [(YGL * CAI) + (DEF * VH)]}{(1 + i)^N} \right]$$

S = net salvage revenue
= (ROYC - CSAL) * SAL * SDK * VS

SDK = proportion of timber severely damaged or killed in burnt area
SAL = proportion salvaged out of severely damaged or killed timber
VS = salvageable volume (m^3/ha)
ROYC = current royalty at harvest (\$/m^3)
CSAL = additional costs of salvage (\$/m^3)

RAI = rate of annual increase in real value of royalties
I = discount rate
N = number of years between fire and planned harvest time
VH = merchantable volume at harvest (m^3/ha)
YGL = number of years growth loss
CAI = current annual increment (m^3/ha)
DEF = additional defect at harvest due to fire, as proportion of merchantable volume

The various components of physical damage are examined first below, before discussing the effect on the harvesting regime and economic variables.

Physical damage

Three sources of physical loss at harvest time are allowed for:

- timber killed or severely damaged
- loss of growth
- defect

Each component is estimated, using parameters given in look-up tables in DATAIN, as functions of up to three variables:

T = forest type
H = height class
I = fire intensity class

(The classes are shown in Table 17 and the total areas burnt in different classes in various Victorian regions are shown in Appendix 20.)

Table 17. Forest composition and height classes, Victoria

1.	Ash, High Elevation	Mountain ash (Eucalyptus regnans), alpine ash (E.delegatensis), shining gum (E. nitens). High-elevation mixed species (HEMS) e.g. messmate (E. obliqua) in higher, moister stands.
2.	Mixed Species	Stringybarks, messmate, peppermint, gums, silvertop ash (E. sieberi)
3.	Red Gum, Box-Ironbark	
4.	Softwood	Mainly Pinus radiata
5.	Alpine	Snow gum (E. pauciflora), alpine heath
6.	Mallee, Native Conifer	Includes cypress pine
7.	Heath, Grass, Scrub	

Height classes

I.	Over 52 m
II.	40-52 m
III.	27-40 m
IV.	15-27 m
V.	0-15 m

Forest type and fire intensity are the only relevant variables available in the computerised fire data, and serve as proxies for other correlated variables. A number of other factors are known to be important, e.g. pre-fire tree health, drought index at time of fire and post-fire conditions for recovery, but as there is no information available on bulk fire data the damage parameters have to be estimated for average or typical values of these other variables.

Recorded measurements of timber damage through fire were surveyed, but it was not possible to use all of these figures directly, since frequently crucial variables were not recorded, or the conditions quoted were not typical in some regard. Hence, estimates and adjustments based on other qualitative information were also applied. The data used are listed in Appendix 21.

The parameters used reflect the following factors which directly influence the physical effects of fire:

- Forest type
  - essentially broad species groups recorded on FCV fire reports;
  - biological protective mechanisms, e.g. bark thickness, bark texture, reserve buds;
  - fuel load and structure.
- Tree height
  - age, and hence diameter and thickness of protective bark, and also likelihood of past fire damage and eventually over-maturity;
  - height of canopy above ground and hence susceptibility to crown scorch
  - likely availability, in the crowns of the trees, of seed which might permit regeneration.
- Fire intensity (Byram's formula)
  - heat generation;
  - duration of burning;
  - amount of fuel consumed;
  - height of flames and hence extent of crown scorch.

Mortality

Tree death can be viewed in economic terms as the end of a spectrum of degrees of damage. The figures used here for mortality (SDK) are intended to include not only those trees killed outright but also those recognised as so severely damaged that they are salvaged soon after the fire. They also include eucalypts which are killed to the ground but survive by producing coppice shoots.

Tree death from fire generally occurs through either:

- complete radial killing of the live tissues in the stem in the cambium layer just below the bark by the heat of the surface fire, or
- death of apical meristems (growing buds), through scorching or consumption, causing loss of photosynthesising ability, or death of reserve buds capable of replacing these.

Death causes the trees, over time, to lose their main value for sawtimber and pulp. Eucalypts, as they dry out, develop faults such as radial checking (splitting), and pines are subject to insect and fungal attacks which stain and weaken the timber within a year or two. Hence, if the timber has developed to a merchantable stage at the time of the fire, there is an economic incentive to salvage this value as soon as possible and before it is lost.

If not killed, the tree may still be damaged sufficiently to suffer a temporary set-back to normal growth, before resuming normal growth rates, but probably never attaining the absolute size of its original growth path. The damage also tends to set in train a process of increasing defect which worsens with age.

The likelihood of mortality in different species is discussed below.

Ash, HEMS: This group contains the more fire-sensitive and valuable eucalypts, generally grown in moist climates at higher altitudes (wet sclerophyll forest).

Mature mountain ash (Eucalyptus regnans) have rough bark on the lower bole which gives some protection against low-intensity fires. The upper branches, however, are clothed only with thin gum-type bark and the growing tips, leaves and branches are killed by fires which are intense enough to throw great heat into the crowns. Scorching of the crown may occur by convection from surface fire, with scorch have their lowest branches 25 m above the ground, however, which helps avoid damage from surface fires.

Alpine ash (E. delegatensis) are somewhat more fire-resistant, due to thicker bark, but their crowns may be burnt by flames being transmitted up the rough bark and particularly by the ribbons of loose bark that often hang from the trunk or accumulate in any fork.

Like most eucalypts, ash can produce new shoots from epicormic or reserve buds below the bark, but they are not as vigorous in this regard as some species. Hence, ash having the majority of their crowns burnt are generally not expected to recover, although their ultimate fate may not be clear until the following spring. Mortality is near 100 percent in high-intensity fires.

Another form of tree death in ash has been studied by Cremer (1962) in the moist forests of E.regnans, E.obliqua and rainforest in southern Tasmania. Where the deep humus typical of these forests has dried out sufficiently, it will continue to burn for days and eventually kill the cambium layer around the base of the trees ('girdling').

In most seasons, ash forests tend to be too moist to burn, but they accumulate heavy fuel loads over a period of years, so that fires occurring when the drought index is high frequently reach high intensities.

Mixed Species: This broad category in the drier eucalypt forests contains the stringybarks. These are the most fire-resilient of trees, with a thick protective outer bark layer, extending to all branches, and a great capacity for vigorous recovery after leaf scorch or even total defoliation, through the activation of previously dormant epicormic buds beneath the bark. Hence most stringybarks survive even intense crown fires.

The category also includes a proportion of somewhat more sensitive species such as gums with deciduous outer bark, and silvertop ash. The gums have thinner bark but there is some offset to this in that their smooth bark prevents the flames from running up the trunk as occurs with stringybarks. Gums which accumulate shed bark at the base of the tree may be killed by girdling, but other species with fibrous bark are not susceptible in this way.

An allowance of 10 percent mortality for mature Mixed Species in high-intensity fires has been made here because of:

- a proportion of over-mature or unhealthy trees, including those whose bark has already been so reduced in thickness by previous fires that it is too thin to protect the tree against the next fire;
- individual trees with particularly high accumulations of fuel around them (e.g. old logs, bark and branches) which may burn for long after the main fire front has passed;

- a proportion of the more sensitive species.

This allowance is increased to 50 percent for height class V (0-15 m), reflecting the high probability of death in the low end of this height range, e.g. seedlings and saplings.

One published observation was that, after a fire in a dry sclerophyll forest near Eden (silvertop ash 40 percent, stringybark 30 percent, 25-30 m dominant height), 15 - 20 percent of trees in areas severely burnt were either killed during the fire or died in the drought conditions which followed (519 mm rain in following year) (Mackay and Cornish 1982).

Some of the mixed species regenerate readily by coppice (suckering) from lignotubers at the base of the tree. This is counted here as mortality since it sets the tree back to the start of growth, although growth may be twice as fast from coppice as originally from seed (Abbott and Loneragan 1983), but defect may also set in.

Red Gum, Box-Ironbark: These species are often found in drier, flat woodland settings, but there are a number of differences between them. Red gum are considered fire-sensitive, more like ash species. Box trees, with rough lower bark and smooth upper branches, may be of medium sensitivity, while ironbark, with thick tough bark, appears well protected.

Intense fires are seldom experienced in these forest types because of their wider spacing and lower fuel loads. Their damage parameters are here placed mid-way between ash and mixed species.

Softwood: Pinus radiata, the main plantation softwood in Victoria, is the most fire-sensitive of the forest types. It can survive low intensities with little damage (e.g. careful prescribed burning at less than 250 kW/m) but fires which scorch most of the crown are generally fatal. This occurs more readily than with ash, say, as pine branches tend to occur at lower heights unless pruned, and accumulated suspended needles offer a ready ladder for the fire to climb. Medium as well as high-intensity fires, and even low-intensity ones in unpruned stands, may therefore kill most of the trees, especially younger ones. These pines lack the ability to recover through epicormics. Certain species, such as P. elliottii, are reasonably fire-resistant (van Loon 1967) but these are common only in northern NSW and Queensland.

Other types: The other types are reckoned not to be of significant timber value, so damage functions have not been prescribed. They may nevertheless have a small local timber value.

The alpine type includes snow gums which are easily killed by fire although they regenerate by coppicing or from seed. Mallees and native conifers are also easily killed, particularly as they tend to be low-growing. Mallees are rarely killed outright, however, and tend to regenerate by vigorous coppicing.

Effects on growth

The growth loss assumed here is based on observations of Victorian timber trees, although certain other studies have found a growth increase after fire.

Attiwill (1985) found zero growth in 70-year-old messmate for the first 16 months after a high-intensity fire at Mt Disappointment, despite crown rejuvenation in the meantime.

Hodgson (quoted in McArthur 1968) found that, after a fire in E. obliqua (messmate) pole and spar stands 80-100 years old, the volume increment for unburnt sites in the second year after the fire was 3 times that for severely burnt ones, and in the third year was 2.5 times greater . The decreased increment could persist for 6 or 7 years. The figures imply a loss of 1.27 times the current annual increment (CAI) in the second and third years alone. However, the first year loss would have been higher than that in the second year - perhaps the whole normal CAI - while the losses after the third year would have tailed off. A cumulative loss of 3 years' CAI may have resulted.

Kellas and Squire (pers. comm. 1983) found that messmate suffering 50-100 percent crown scorch had a volume loss of $3.8m^3$ after 6.5 years compared with a CAI of $1.6m^3$ for unburnt trees, implying a total loss of 2.4 years CAI. For trees with less than 50 percent crown scorch, the loss was $1.8m^3$ or 1.1 years.

A study for 50-60-year-old messmate by Wright and Grose (1970) found that basal area increment (BAI) in the first 17 months after a fire for defoliated trees was 17 percent of that for unburnt trees, while for those partially scorched BAI was 75 per cent of unburnt ones. The trend was similar in the next 15 months but there was little loss after that. This implies a loss of 1.7 years' BAI for defoliated trees but the loss in merchantable volume increment would presumably be a little greater.

The above results contrast with those for E. marginata (jarrah) in Western Australia. Podger and Peet measured growth for 3 years after the Dwellingup fire of 1961, and found an increase in BAI in areas where the fuel load was high and the fire severe that was equivalent to 3.5 years' pre-fire growth (quoted in McArthur 1968). The growth in the first year was not significantly different from pre-fire growth but in the second year it trebled. Areas with lower fuel loads showed an overall increase in BAI corresponding to about 1.4 years.

The growth effect seems very variable, however. More recent studies in jarrah have indicated zero growth in the first 18 months after fire, followed by an increase in growth for the next 3 years until normal growth is restored (N.D. Burrows, pers.comm.).

Banks (1982) recorded apparent growth increases in E.pauciflora (snowgum) in the ACT in the years following fire.

The studies showing growth increases, however, seem less relevant to wildfires in Victorian timber trees than those showing losses.

The only other data on growth effects found were those of van Loon (1967) for young southern pines (about 6 years old) on the NSW North Coast with average height 7 m. Pinus elliottii proved quite fire-resistant and there was no evidence of loss of growth for fire damage class 2 (i.e. losing virtually all green needles), although for damage class 1 (most severely scorched) there was 70 percent mortality and a light initial reduction in growth in the others. For P. taeda survival rates were very poor in all but the lowest damage class where the green needles at the top were still clearly visible, and the leader erect. For P.taeda, insufficient data were available for growth comparisons.

For this model, the number of years' growth loss is assumed to be nil for low-intensity fires, rising to 3 years CAI for high-intensity fires. It is assumed to be similar for all forest types and heights in Victoria. While smaller trees may be affected more initially by the fire, recovery seems to be more rapid since they are in a vigorous growing phase.

Defect

In contrast to the temporary growth loss, the loss due to additional defect often increases with tree growth after the fire. The main forms it takes are occlusion of dead wood, secondary damage by insects etc., deformed stems, and persistent epicormic shoots.

Where only part of the cambium layer is killed, the tree may survive and grow, eventually putting on new wood around the dead tissue, giving rise to dry sides. The occluded dead wood greatly reduces the sawlog potential of the tree, as it is generally in a key area in the lower trunk. The 'dry sides' are often found on the leeward or uphill side of burnt trees where the most intense heat is concentrated by a 'chimney' effect.

Gum vein and kino, which degrade wood quality, may form, and decay tends to spread around any scar.

Scars provide an entry point for attack by termites and other insects as well as fungi. McArthur (1968) has termed this secondary damage. The decay and other defects tend to gradually radiate out from the initial scar, spreading into the heartwood as well as up and down the stem. Rate of spread may be of the order of 0.3 m per year.

Greaves et al. (1965) compared a stand of alpine ash protected against fire for 60 years with nearby stands 90-150 years old with a long history of fires. The former had a 15 percent loss in royalties due to termites and degrade, while various compartments in the latter had losses of 25, 29, 34, 35, 55 and 57 percent respectively. Greaves attributed most of the latter losses to the primary or secondary effects of fire. There is no record of the number and intensity of fires that did the damage, but if we assume there were three or four wildfires of medium-high intensity, the average contribution to loss from each would be about 10 percent of volume.

Ten years after a fire in 18-year-old P. radiata, Billing (pers. comm. 1984) found that 77 percent of the trees had dry sides with decayed wood, and the scars covered an average of 46 percent of stump circumference in small trees and 22 percent in larger ones. The scars commonly extended 5-7 m above the ground, and may have been responsible for a 60 percent loss in volume and a 50 percent reduction in unit royalty, implying an 80 percent loss in total values. These pines were burnt by a low-intensity backing fire, with flame heights about 1 m, but on a day of high fire danger.

In a superficially similar situation, Nicholls and Cheney (1974) studied P.radiata 5 years after a fire of about 100-340 kW/m when the trees were 22 years old. The overall loss in sawn volume was only 0.4 percent . The large discrepancy between this result and Billing's was attributed to the presence of much logging slash amongst the pines studied by Billing, giving a longer residence time for the fire.

The FCV has apparently conducted some studies of defect after fire in eucalypts but no results have been reported, partly owing to the great variability between individual trees, and the expense necessary to take a sample large enough to be statistically valid.

When the leading shoot of a eucalypt is killed, a new leader generally develops from the uppermost epicormic shoot, but a stem kink and overgrowth is formed as the new tip grows past and occludes the base of the dry spike remaining from the old leader (Incoll, pers. comm.). The more severe the fire, the further down the dieback extends, and hence the shorter the potential sawlog available. Research in silvertop ash (E. sieberi) near Orbost has suggested that a moderate fire in 10-year-old stands may result in a loss of 50 percent of the volume, due to low forking, reducing to 15 percent for 30-year-old stands (Featherstone, pers. comm.).

In well-stocked mature stands of eucalypts, it is expected that the stem epicormics resulting from fire will not persist, as the crowns above and adjacent to them regenerate and shade the boles. However, where stocking is low (as in the 'shelterwood' management system practised in Trentham district), the epicormics on the stem may persist, ultimately reducing sawlog value (Harris, pers. comm. 1983).

After a severe fire in Wombat State Forest, the sawlog loss after 20 years due to such epicormics was estimated as up to 20 percent. This applied only to the less damaged stems, as the worst had been removed in salvage. The total damage would therefore be higher than 20 percent (Harris pers. comm. 1983).

Spatial variation in fire intensity

Within the total fire area, the intensity varies widely between:

- different segments of the fire (e.g. head or backing fire)
- parts burnt at different times when fire weather and conditions were varying, and
- areas with different local fuel loads.

To make general allowance for these variations, the final area burnt by each fire is here divided into up to three categories: low, medium and high intensity. The proportion in the higher categories is an increasing function of average forward rate of spread, as shown in Appendix 21(b).

On an evenly spreading fire, the zone burnt by the head fire could be about 60 percent, as shown in Figure 23. However, data available suggest that even on the highest intensity fires, the proportion of area severely burnt seldom exceeds 50 percent (Cheney 1976). For example, in the Warburton fire which started on 16 February 1983 and burnt 43 000 ha, 44 percent of the area suffered greater than 75 percent crown scorch, and another 17 percent between 50 and 75 percent scorch.

One problem of basing damage estimates on the average rate of spread is that, where the rate of spread varies greatly over time during a large fire, the average is implicitly time-weighted rather than area-weighted. For example, many large fires may burn for many days before being contained (giving a low overall rate of spread), but the great majority of the area is burnt on one day of extreme fire danger. Accordingly, any fire over 1000 ha is here put in the maximum intensity class, as well as all those with average rate of spread exceeding 700m/hr.

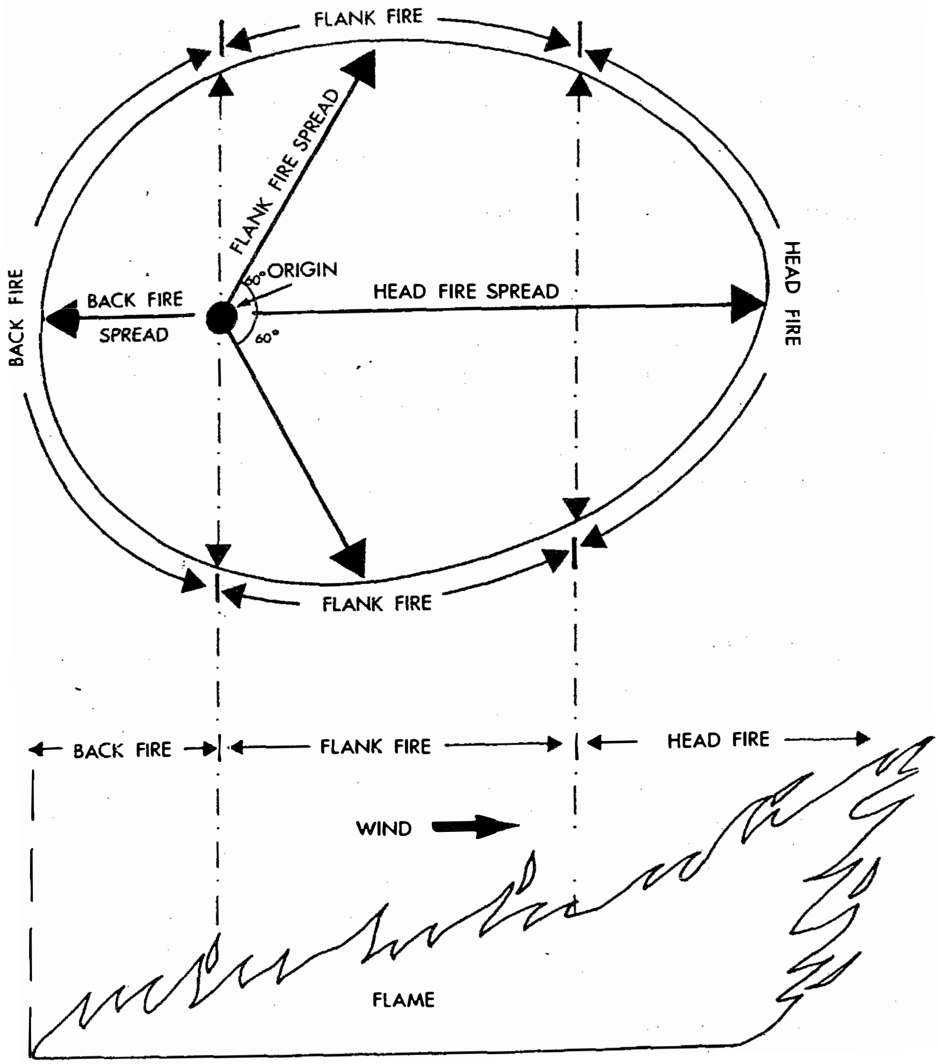

Figure 23. Zones burnt by head, flank and back fires
Source: N.D. Burrows (1984). Describing forest fires in Western Australia
Forest Department of W.A. Tech. Paper No. 9.

Economic effects

The economic significance of timber damage depends not purely on the physical loss but on how that loss affects production and consumption in the timber and related industries. Depending on forest management policies and demand and supply factors, a given physical loss can have widely differing economic effects, both in magnitude and timing.

The basic approach taken here is to estimate the economic loss as the discounted present value of the future losses at planned harvest time, less net salvage value.

This involves a simplification in some cases compared with the true cost which is the net present value of the complex set of changes in costs and revenues in the years after the fire. In particular, efforts to replace the lost timber by

- substitution of other timber, and
- replanting,

set in train a series of economic changes.

Alternative management responses, and the corresponding methods of measuring the net cost, are discussed below. An illustration of the difference in timber sales over time between various extreme approaches is shown in Figure 24. The different management responses involve different ways of distributing the losses over time or space, but under certain assumptions discussed below, the overall net loss will be the same under all methods.

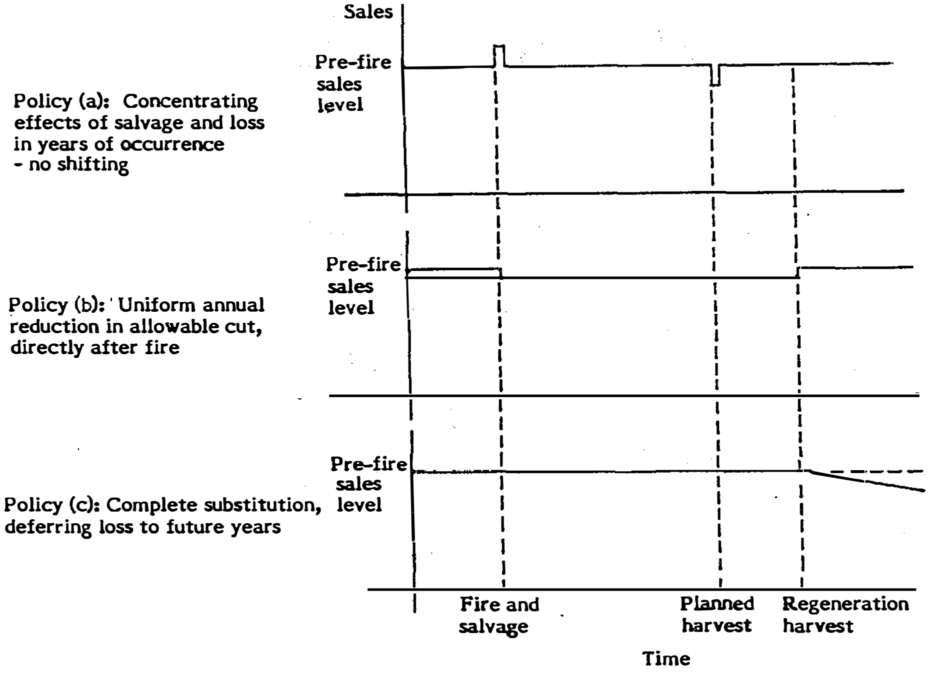

Figure 24. Distribution of effects of fire on timber sales under various management policies

Direct transmission of resource loss to sales loss

This is the assumption behind the method used here, i.e. the reduction in volume at harvest time is reflected in a reduction in overall sales in the same year. Similarly, the salvage of timber is reflected in an increase in sales in the year of salvage, assumed here to be within the first year after the fire.

Since the loss at planned harvest time occurs some years after the fire, it must be discounted to its present value, which greatly reduces the nominal value for young stands.

This type of response could occur implicitly, particularly in a small forest district, without management necessarily being aware of the size of the loss, e.g. if harvesting plans dictate that a certain area be logged, the resulting volume will depend on the effects of past fires. However, on a larger scale, management is unlikely to allow fire losses to be reflected in same-year market effects, because of the potential disruption both to consumers and producers.

Assuming the normal downward-sloping demand curve (DD in Figure 25), implying that marginal utility of timber diminishes with increasing consumption, or that consumers substitute timber for other products as its price decreases, the cut in supply from S1 to S2 forces the equilibrium price up from P1 to P2, to equate supply and demand. The price is represented by the royalty or stumpage rate if this is set in a way that simulates market forces.

Consumers suffer an increasing marginal loss of utility, the further they are forced back up the demand curve.

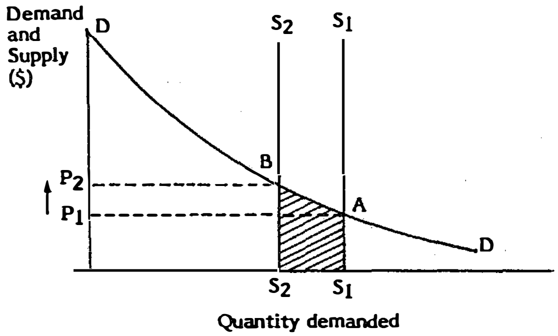

Figure 25. Timber demand and consumer surplus

The loss (for the purposes of a cost-benefit study) equals the combined loss in 'consumer surplus' and 'producer surplus' which is the area ABS_2S_1 under the demand curve, and approximates the loss in volume times the average of the pre-fire price and the higher post-fire price i.e. Loss = $(S_1 - S_2) * (P_1 + P_2)/2$

Consumers may adjust by substituting other products for the burnt timber, but still incur a loss through the need to move to less preferred or more expensive alternatives.

The analysis is in terms of the basic resource at the stump, before any processing stages. There will be local social costs to employees and producers in industries which would have processed and used the lost timber if no redeployment or substitution is arranged. Generally, however, cost-benefit analysis does not count 'down-stream' production losses in addition to the consumer losses, as it is assumed that, directly or indirectly, the resources involved are redeployed to increased production of other kinds, or employment of resources in other areas of the economy is increased by an equivalent amount. The redistributions may be important from a regional point of view but are netted out in an economy-wide view.

Conversely to the above, if salvage timber is sold in addition to normal market supplies, the increased supply tends to drive the price down. For example, after the 1983 fires, the smaller logs available from salvage eventually became unsaleable, implying a shift to the right along the demand curve until zero price was reached.

Deferral of effects

One extreme in the range of possibilities for spreading the effects is to maintain harvest and sales levels unchanged (at pre-fire levels) as long as possible, by substitution of other timber.

That is, fire losses are covered by:

- bringing forward the harvest of other timber, with a loss of interim growth or
- substituting timber that is less accessible or of inferior quality.

Either alternative involves costs, which will be highest in a situation of timber scarcity.

In a situation of ample reserves of mature timber, such as prevailed in the early days of Australian forest exploitation, these costs would be negligible, as the burnt timber could be readily replaced by stands of similar quality and accessibility. Royalty values would similarly have been negligible.

Nowadays, when the remaining forests are managed on a tight rotation basis, the cost of fire losses is significant whichever substitution option is taken. Indeed, if we assume that forests are being managed for harvest at financial maturity, the gain in discounted value obtained by bringing harvest forward by one year, would be just equal to the loss of one year's growth in royalty terms. If current harvesting is exceeding the sustainable yield of the forest system, however, bringing forward harvests to replace the fire losses will shift a greater burden to later generations who will eventually have to bear a reduction in consumption.

Similar considerations apply in reverse to salvage timber. For example, the Forests Commission of Victoria, after the disastrous fires of 1983, adopted a stated policy of substituting salvaged timber for green timber that otherwise would have been cut, and broadly maintained saw-log harvesting quotas at the same level. This was done to avoid an over-supply of timber and associated depression of market prices, as well as to avoid over-taxing the capacity of processing industries. (Local sawmills were in any case stretched beyond capacity, necessitating the transport of logs to more distant mills).

Where harvesting is deferred, extra growth accumulates, and indeed compounds if the volume of annual cut remains unaltered. If this accumulated growth is carried forward to the year of planned harvest of the burnt timber, it provides a partial offset to the losses then encountered.

Reduction in allowable cut

Under this approach, a reduction in annual allowable cut is made after the fire, thus spreading the effect uniformly over the entire rotation. This could be implemented even straight after the fire, despite the temporary increase in timber availability from salvage operations, to soften the transition to the reduced availability in later years. This approach avoids subjecting consumers in any particular year or generation to particular shocks.

Allowable cuts are unlikely to be adjusted for individual fires, unless the losses are large relative to the forest management unit involved. However, the estimation of regional allowable cuts on a uniform annual basis can be expected to reflect a deduction for total losses over time due to wildfires, based on past experience. This could be merely implicit, particularly for native forests, as assessed merchantable volumes are the result of, inter alia, an unknown amount of fire losses over past years.

This method effectively converts a one-off fire loss into an annuity (series of regular equal payments). Converting this back to an equivalent present value for the purposes of the cost-benefit study should give a value similar to that obtained by the first method (discounted value at harvest). This assumes that the allowable cuts are based on rotation at financial maturity.

Regeneration

Regeneration of forest stands after fire is another response which can redistribute or limit the effects.

Replanting after fire deaths is typically practised with plantation softwoods, and assisted regeneration of valuable eucalypts is becoming more common. A variable amount of natural regeneration from seed or coppice will in any case follow the killing of fire-sensitive eucalypts. Regeneration is generally carried out, on the same site, after salvage and/or clearing.

Where the fire losses take the form of defect found at harvest time, replacement cannot take the form of planting on the same ground straight after the fire. However, the losses could be anticipated, and provision made for them by planting new stands (of the same or different species) on other sites. It could be argued that the large-scale planting of pines in Australia was in part necessary to replace timber losses through past fires in native forests.

Since the stands burnt are likely to have been at least semi-mature, replanting straight after fire cannot be expected to provide mature timber in time to fill the gap at the time the burnt stand would have been harvested.

This gap could be filled by bringing forward harvests due for cutting later, and continuing to shuffle harvests forward in a 'holding capacity' until the new timber matures. It can then fill the gap and restore the original pre-fire equilibrium. There is nevertheless an interim loss of growth on the harvest brought forward.

Comparison of valuation methods

The formula for the discounted value of future harvests lost is based on the first approach of direct transmission of resource loss to sales loss in the year of harvest.

For the approach based on regeneration and interim substitution, the loss formula would comprise the following:

- re-establishment costs of new stands (initial establishment plus later costs), less
- costs saved after loss of burnt stands, plus
- value of interim cumulative growth loss on harvests brought forward, with all future amounts discounted to present value.

A similar method is used by some forest services (such as Forestry Commission N.S.W.) to value fire losses in young plantation trees up to merchantable age (about 15 years). Their measure is the sum of past costs invested in the trees, with accumulated interest, up to the time of their demise.

Sunk costs are, of themselves, irrelevant to future decisions, but the past costs method will give the same result as the future costs methods if several assumptions are fulfilled, in particular:

- past planting methods and costs will be continued
- both past and future costs are converted to the same price level
- the discount rate is the same as the interest rate *
- the discount rate equals the rate of increment in value on harvests deferred (or value loss on harvests brought forward).

Both methods, involving past or future regeneration costs, will give the same loss as the discounted value of lost harvests provided that the internal rate of return accruing on the plantation equals the discount rate, i.e. they are economically just worthwhile (see Appendix 22). This should be a reasonable assumption on average if forest management is aiming for economic optimality. Studies by the FCV have indicated a real rate of return of 6-9 percent per annum on pine plantations, compared with a social discount rate of 5 percent and social opportunity cost of capital of 10 percent used here.

However, in some individual situations, the plantation cost method could give misleading results. For example, it will undervalue the loss on a stand accruing an above-average return, while it would over-value the loss if a failed plantation is burnt.

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*The discount rate is used to reduce future amounts to present values, while the interest rate is applied to accumulate past amounts to present values.

The main reason for using the past costs method is that it is based on known data whereas with young trees there is considerable uncertainty about future harvest value. However, the stands were presumably planted on the assumption that they would earn at least the normal rate of return, based on predictions of harvest value. If the further knowledge of their progress since they were planted has caused the expectation to change, this knowledge should ideally be used in valuing fire losses.

Anomalous gains due to fire

The application of normal discount rates (e.g. 5-10 percent in real terms) can have a striking effect in forestry studies, with their long investment times, by producing present values that are only a fraction of the future value of timber.

The issue is important in valuing fire losses, particularly in native forests with a rotation age of the order of 120 years. Indeed, in some cases anomalous results could be produced, as the salvage value could exceed the present value of the losses at harvest age, giving an apparent economic net gain from fire. This is more likely to occur with old-growth stands in native forests, where the volume of stands scheduled for harvesting in 15 years time may be no higher at harvest than now. The present value of the future harvest, discounted at 5 percent p.a., would be only 48 percent of the salvage value now.

If fire, by forcing immediate sale, produces a financial gain, the superficial implication is that a similar gain could be realised without a fire, just by accelerating the cutting rate. This could be a fair interpretation in some cases but there are a number of reasons why such an interpretation could be misleading:

- The analysis may fail to take account of non-timber values (e.g. conservation and water yield) which increase with forest age even after timber values have stopped growing. These values should also be included as losses from fire.

- In other cases where the forest is mature but still growing, the unit value of the sawlogs may be increasing significantly due to the increasing diameter or wood quality, so that it may be economically preferable to reserve the trees for another 15 years. However, if royalties set for the larger trees do not properly reflect the differential in market value, the salvage value may be greater than the present value of the future harvest. This anomaly would be purely due to the royalty system, highlighting the principle that valuation of fire losses (as well as forest management generally) should ideally be based on market value (or 'residual value') of timber, rather than on royalty rates where they differ.

- In Australian native forests at present, the cutting of old-growth forests (mature and over-mature, and often inferior or remote from markets) serves the purpose of allowing time for the potentially superior regrowth forests to grow to merchantable size. For mature stands killed by fire, the volume loss at harvest may be no higher than their standing volume when burnt but there could be a significant loss of increment on regrowth forest whose harvest is brought forward to fill the gap. The annual loss of increment (in value terms) on timber that is cut before it has reached financial maturity would be higher than the discount rate. This suggests that in unregulated * forest systems such as most Australian native forests, use of the simple discounted future harvest method could underestimate fire losses, as it does not take account of the indirect effects on increment due to substitution.

- Another reason why large-scale fire salvage or earlier cutting may not produce a real gain, is that switching a large volume of timber from future supply to current supply may drive the current market price down and future price up. This can be provided for by taking account of price elasticity effects in loss calculations.

- It might be argued that the discount rates typically used in other economic calculations are inappropriate, being too high, for forestry. Indeed, in past years it was held by many foresters that discounting was out of place in forestry.

The view taken here is that discount rates must be applied uniformly throughout all sectors of the economy. However, there is an argument that the rate used to discount benefits due far in the future should be considerably lower than the opportunity cost of capital often used in cost-benefit studies (commonly around 7-10 percent p.a.), as explained below.

Discount rate

The subject of the appropriate rate is controversial in economic as well as forestry circles and is surveyed here only briefly.

Two different concepts of the discount rate suitable for cost-benefit analysis have been put forward:

- the social time preference rate (STPR), which reflects the idea that people regard a benefit of a given amount in a future year as worth less than the same amount in the current year.

- the social opportunity cost of capital (SOCC), i.e. the rate of return to society that could be obtained if the funds invested in the project were instead invested in their best alternative use. Projects with a net present value (discounted at the SOCC) less than zero should not be undertaken because the funds could be invested for a better return elsewhere.

Rather than seeing the two concepts as alternatives, it has been argued (Feldstein 1972) that future benefits should be discounted at the social time preference rate, while capital used in the project should be valued at a shadow price based on the social opportunity cost of capital. Ferguson and Reilly (1975) estimated suitable values at 5 percent p.a. for the STPR, and $2.73 as the shadow price for each dollar of capital invested.

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* A perfectly regulated forest is one where there is an equal stock of each age class from zero up to the rotation age.

Ferguson's estimate of the STPR was based on interest rates for riskless government bonds, but these are also influenced by rates of return on capital in the private sector. The STPR is quite a subjective matter. Use of a low STPR implies a belief that governments have an obligation to protect the interests of future generations, regardless of individuals' attitudes to time in regard to their own benefits. A higher STPR may reflect uncertainty about the future, or an assumption that living standards will continue to increase into the future and accordingly that the marginal utility of a given benefit to people in the future will be less than for the same benefit to people today.

The estimate of 5 percent p.a. is accepted here as suitable as a STPR for discounting benefits. A higher rate of 10 percent p.a. has been used as the shadow price of capital. This is the social opportunity cost of capital recommended by Commonwealth Treasury (1981) for use in evaluating public projects, based on a study of private sector rates of return. Some of the cost figures used in this study that were obtained from other sources (e.g. airtanker hire rates) implicitly reflect a similar or possibly higher rate of return.

Timber resource data

Sources of data and methods of estimating timber resource data are outlined below. The data used are listed in Appendix 21(a).

Years to harvest

These figures were mostly derived as an estimate of rotation age minus age when burnt, but adjustments were made for discontinuities in age class distributions.

Age when burnt

The age when burnt refers ideally to average age over the period of the analysis, i.e. the next 15 years when airtankers might be used.

An initial guide was obtained from tree growth functions relating height to age for different species, for a typical site quality. A typical growth curve is shown in Figure 26.

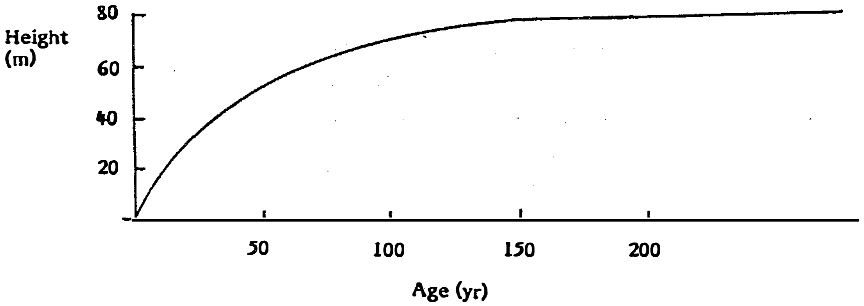

Figure 26. Tree height/age (mountain ash)

The age/height distributions, however, do not follow a simple rule as they might in a perfectly regulated forest system. There are discontinuities due to natural factors and past cutting practices. For example, the bulk of Ash in height classes II and III (27-52 m) are regrowth from the 1926 and 1939 fires, whilst most Ash in height class I could be old-growth forest, perhaps 150 years or more. Mixed species and red gum etc. are slower growing and rarely attain height class II or I. Even height class III and IV contain much mature and over-mature timber (e.g. 150 y.o.) which was not worth cutting in earlier years, as well as some vigorous regrowth stands (e.g. 30 y.o.)

Harvest age

For plantations and regrowth native forests , the harvest age for a given species is becoming more standardised. Rotation ages suggested by the F.C.V. (Victoria, Task Force 1983) were: Ash 80 yr; Mixed Spp. 120; Red gum, box 150; Softwood 35.

However, the over-mature old-growth stands remaining are already much older and it is assumed here that they will be cut out over the next 20 years. Since the majority of Ash height class II is of even age (45 yr now), it will be cut in a staggered fashion over the next 60 years or so.

Plantation conifers are on more uniform rotations, although the normal period has been reduced from around 45 to 35 years in Victoria.

Harvest volume

This refers to total merchantable volume, including sawlog and pulp, per hectare. Where only one harvest is obtained, from clear-felling at maturity, the amount is straightforward. Where harvests occur at different stages in the life of a stand (e.g. three commercial thinnings in pine) the equivalent amount is found by summing the various contributions, with interest accumulated to rotation age.

Volume data are intended to be broad-acre averages over sites of differing quality e.g. ranging from superior sites carrying more than 1000m^3/ha for mountain ash, to areas that are inoperable because of steep slope or rock etc.

Table 18. Mean annual increment, Forests Victoria

Forest type	MAI (m^3/ha)
Ash	7
Mixed sp.	
- mature	0
- regrowth	2
Pine	18

Victoria, Task Force (1983), Options, pp. 59,69)

Current annual increment

The data for current annual increment in merchantable volume reflect the sigmoid growth curves typical of trees, as illustrated in Figures 27 and 28. The relevant data, it should be noted, are for current increment at the time burnt, not mean annual increment. The mean annual increments (MAI) for the different forests in Victoria are shown in Table 18. While mountain ash on the best sites may be faster growing than pines, they are more variable, particularly in natural stocking rates, and hence have lower MAIs.

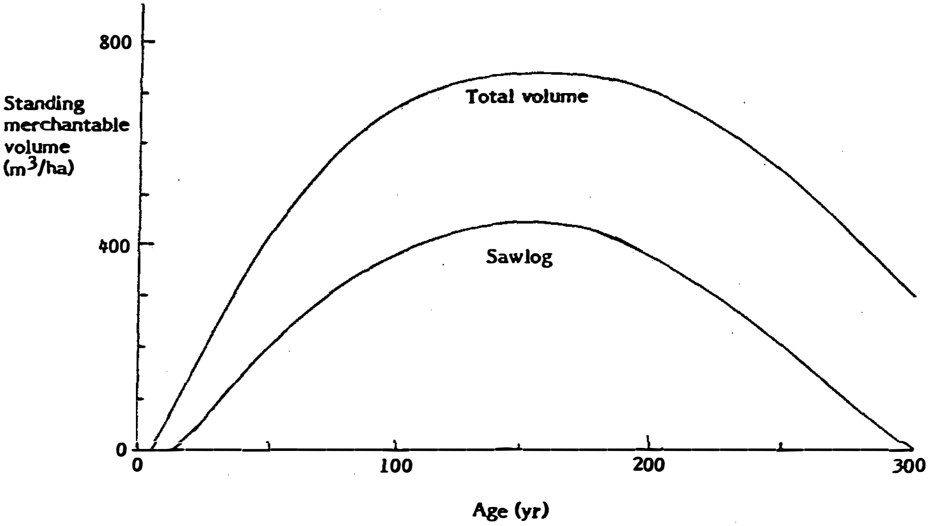

Figure 27. Timber volume/age (medium quality mountain ash)

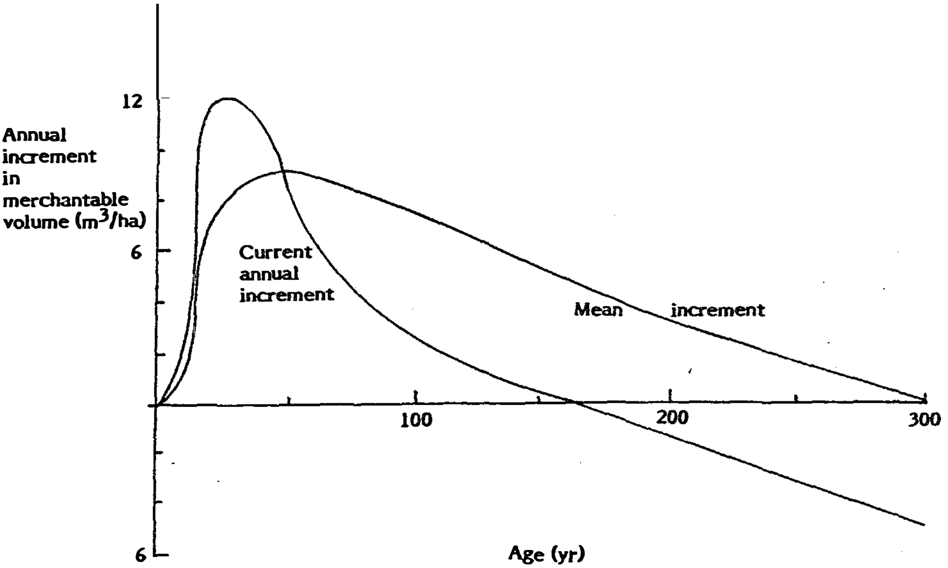

Figure 28. Annual volume increment/age (mountain ash)

Timber value data

Royalty (ROYC)

The value of timber on the stump is based here on the royalty rates charged by the FCV. The royalties are set according to a formula which takes into account the main factors affecting market value (viz. size, quality, distance from market) but the standard amounts allowed are not necessarily appropriate in all cases.

An example of the use of the FCV formula (as at 1983) to calculate one of the royalty figures used in the model (for Ash, height class II) is given below, followed by some discussion of whether these rates adequately reflect market values.

Royalty Formula

Ash, Height class II e.g. mountain ash, 47 m:

Standard mill formula - 'Other Hardwoods'	(\$/m^3)
- Zone 1, (East and Central Regions), 1984:	59.79
less Sawn haul allowance for road freight from PRD (point of royalty determination) to railhead, plus rail freight to Melbourne - for Marysville*	**9.66
	50.13
Divergence	
- Ash, bush grading Category C (Lower grades of mature forest)	
20% Select x + 7.45 =	+1.49
20% Standard x + 1.09 =	+0.22
45% Scantling x + 0 =	0
15% Inferior x - 4.80 =	-0.72
	+0.99
	51.12
Recovery (sawn timber out of log)	x 50%
	25.56
less Log haul allowance for 20 km between bush and PRD on Class C road at 5.3 c/km:	-1.06
Residues	
Assume 50% sold as chips at rate of 30% x pulp rate of \$6.00:	+ 1.00
Roading charge, thinning allowance and residual logging - assume not applicable	0
Sawlog royalty:	25.50
Pulpwood royalty	6.00
Weighted average royalty at 40% sawlog, 60% pulp =	\$13.80

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* a district mid-way between Melbourne and the State border

** estimate from Ward & Kennedy (1983)

Market value

The value of timber used in this study ideally would be the amount buyers are willing to pay for marginal supplies in a free market.

Although the royalty rates are administered by the FCV, a government agency, they cannot be totally unrelated to market values because of the following factors:

Rates were at one time calculated with reference to the residual value of timber, i.e. market value of timber products (such as sawn timber) minus costs (such as falling, transport and processing) incurred between stump and product sale.

The FCV rates are limited at the upper end by competition from other States and countries and private forest owners, and the ability of millers to pay in the economic climate of the time. They are limited on the lower side by the desire of the FCV to obtain sufficient revenue to cover forest management and increasing pressure from the Government to make an adequate contribution to Treasury funds.

Nevertheless, it is possible for the formula at times to yield royalties out of line with the market. Byron and Douglas (1981) gave evidence that royalties in most States were well below market value in the past, although Victorian rates were not explicitly calculated. They quoted Reilly's estimate that residual prices for NSW sawlogs were 2 and 3 times the stumpage levied by the NSW Forestry Commission in 1972-73. The general conclusion from several comparisons was that the actual prices at which sawlogs have been sold are much less than, in some cases only half of, the residual value. Pulpwood royalties for individual companies are confidential and Byron's conclusion from the limited evidence was more guarded, namely that higher pulpwood prices may be possible.

Prices below market value are reflected in unsatisfied demand for timber which can be constrained for example, by sawmill licensing.

The market values estimated in the above studies are based on the actual supplies placed on the market by the forest services. It is implicitly assumed that these supplies derive from economically rational policies, and the price at which supplies are offered for sale approximates the marginal cost of supplies. If supplies are being offered at implicitly subsidised prices which do not cover long-term opportunity costs (including land and capital), however, the true value would be underestimated by current market bids.

Since 1983 free-market auctions for a limited amount of wood have been tried by the FCV and the bids accepted were around $3-5/m^3 above the formula rate for fire-salvaged regrowth ash, even though market supplies tend to be above average due to salvage availability. However, these premiums may largely reflect the current unusually buoyant demand conditions in the industry. In depressed conditions, on the other hand, as recently as 1980, royalty rates appeared to be above marginal values in the market in that a 25 percent fall in log sales resulted.

In recent years there have been sharp rises in FCV royalty formula rates (in excess of the general inflation rate). Further, a new royalty structure is to be introduced in July 1985, using the same formula as before but with substantial changes in the allowances. In particular, the softwood price differential for log size and quality will be widened, better reflecting market values and royalties in other States. The new price range for logs from 15 cm up to 33 cm diameter will be \$14-38/m^3, compared with the old range of \$25-30/m^3.

In conclusion, the general level of FCV royalty rates as at 1983 has been accepted for timber values in AIRPRO, with adjustments to widen the differential between height classes.

Increase in royalty

The value in the harvest year of timber due to be cut many decades into the future may be significantly different from the current royalty, due to intervening changes in supply and demand.

A long-term upward trend in real price (i.e. relative to the general inflation rate) might be expected for a diminishing natural resource, all other things equal. In the United States, for example, the real price of timber increased at an average rate of 3.3 percent p.a. over this century (Convery 1977).

The upward price tendency due to supply reduction is moderated by changes in technology and tastes which promote substitution of other materials for timber in certain uses, shifting the demand curve downward. However, greater consumer demand for 'natural' products has been noticeable in recent years.

An analysis of the Western Australian hardwood timber market (Edquist 1982) indicated a potential long-term rise in hardwood timber prices, from an index of 100 in 1979-80 to 119 in 1991-95, then down to 112 in 2001-2015. Softwood trade, which was not included in the analysis, could moderate those price tendencies.

In Victoria, the supply of old-growth native hardwood will be virtually exhausted over the next few decades, and similarly the supply from Asia and America will decrease*. In the medium and longer term, the supply of regrowth eucalypts will increase, but the new sustained yield level will be less than past levels which included liquidation of old-growth reserves.

In the medium-term (10-30 years), there will be a major increase in supply of plantation softwoods, both from Australia and overseas (NZ, Chile, New Guinea etc.) with the possibility of a market glut.

It is assumed here that native species will increase in real value due to increasing scarcity at the rates of 1 percent per annum for ash and redgum, and 0.5 percent for mixed species, while softwood prices will not change.

Elasticity

The price elasticity of demand for stumpage is a measure of the responsiveness of demand to price changes. Higher elasticities result if it is easy to substitute other products for the one in question. Conversely if there is an independent change in quantity supplied due to bushfires, a low elasticity or substitutability means a higher response in price (in a free market). Thus, consumer losses are higher if prices are driven up by a shortfall in supply after a bushfire.

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* FCV, Options, pp. 14, 23 etc.

The formula for elasticity, which holds for relatively small changes, is:

$$E = \frac{\%\text{ change in quantity}}{\%\text{ change in price}} = \frac{\Delta Q}{Q} * \frac{P}{\Delta P}$$

On the assumption that the demand curve is linear between the pre-fire and post-fire price-quantity combinations, the average price, ROYC, applying to the reduction in output is:

$$\text{ROYC} = P + \frac{\Delta P}{2}$$

$$\therefore \text{ROYC} = P + \frac{\Delta Q * P}{2 * Q * E}$$

where P = pre-fire royalty
ΔP = change in price
Q = total market
ΔQ = change in output

There is no real evidence on elasticity for stumpage. One related study by Edquist (1982) for sawn hardwood in WA estimated an elasticity of (-) 2*. Factors affecting substitutability and demand for sawn timber would be transmitted back to demand for its major input, stumpage, so that their elasticities might be similar. In relation to pulpwood, demand for paper products may be less elastic. Hence the average elasticity for stumpage may be lower than 2, and is here assumed to be just 1.

The size of the price elasticity depends on the size of the total market, i.e. normal quantity supplied, to which the change in quantity is related. Here the market is taken as the total wood supply to the State or 2 000 000 m^3 for Victoria.

Salvage

Standing volume

The standing volume at the time of the fire is relevant to the salvageable volume. Merchantable standing volume is estimated for each forest type and height class, rising with age or height according to a growth function (see Fig.27).

Most species have no merchantable volume in the lowest height class (0-15 m). The timber at that stage is unsuitable for sawlogs (which generally require a small-end diameter of at least 25 cm) but the larger stems may have a limited market as pulp or poles. Merchantable volume, especially for sawn timber, rises sharply as the timber matures, but eventually stabilises and begins to decline in the over-mature phase as defect increases.

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* Price elasticity of demand is technically negative but for convenience we refer here to the absolute value.

Fraction salvaged

This fraction for each forest type and height class, is applied to the area killed or severely damaged. Burnt stands will be salvaged only if:

- salvage revenue exceeds costs, and
- no greater gain can be made by leaving them to grow further.

Salvage of less than 100 percent reflects the following factors:

- killed trees may be scattered or access poor, so that salvage is not worth the costs. This type of loss is low for pine plantations where the value per hectare is high, stand size and damage is fairly uniform, access is good, and unit costs of salvage harvesting low. By contrast, Mixed Species in native forests may be scattered or difficult of access, and have a low salvage rate. Ash species are intermediate in these regards. Redgum, box and ironbark, although widely spaced, are easier of access and are assumed to have a higher salvage rate.

  Even for pines, however, the fraction salvaged falls on large fires when the rate of harvesting required is beyond the industry's capacity to achieve before standing timber degrades.

- Merchantable volume may be reduced on burnt trees. In particular timber which is saleable for pulp if unburnt (younger or over-mature classes) may have no market when burnt because paper pulp is highly sensitive to contamination by carbon.

- High-intensity fires may cause a minor loss by charring the wood beneath the bark or burning the tops so that some log length is lost at the small end. Generally, however, only bark and branches are directly burnt. This involves a small loss to those who sell bark as a by-product (50c/m^3).

- The fires in the SA pine plantations on Ash Wednesday also destroyed trees when the trunks snapped in the tornado-force winds, but this phenomenon is exceptional. More generally, there may be some volume losses due to breakage as fire-killed timber tends to be more brittle.

Salvage costs

These are extra costs incurred on the volume salvaged, additional to normal logging costs.

These costs may be borne at any of the stages in the processing chain, e.g. by the forest service in the form of royalty discounts, by the loggers, the millers or the consumers. The costs may be passed backwards or forwards along the chain according to bargaining power but the total of these costs is of relevance here, rather than their distribution. Extra costs may result from the following factors:

Logging charred timber: Fallers may demand extra compensation for

- dirty conditions
- danger from falling branches and heads

- greater wear on chainsaws, or time for sharpening chains or axing bark off trees
- wear on tyres due to saplings being burnt to sharp edges.

As a partial offset handling is made easier by the clearing of undergrowth.
After a moderate-intensity fire in pines, loggers may be given an extra \$2-3/m^3 for these factors.

Milling problems: Extra costs for milling charred timber apply mainly to pines. With eucalypts, the bark is generally left in the bush, leaving a clean stem. 'Tight' bark on pines may result from the heat of the fire, making de-barking more difficult.

The above costs are independent of the size of the fire but certain other salvage costs are related to the total salvage volume. Small volumes that can be harvested and processed within a few weeks, simply by taking them in place of the normal green timber throughput, involve little extra cost. However, as the volume of salvage timber rises past the processing capacity of the local industry, the marginal cost increases due to one or all of the following factors:

Quality deterioration: The longer the trees are left before salvage can be completed, the greater the loss in value or volume due to degrade. With burnt pines left standing, stain may begin within weeks under wet conditions. The initial staining affects appearance rather than strength, and recent marketing suggests that the traditional consumer resistance to such wood can be overcome, so that no economic loss need result. Deterioration slows down greatly while the logs are stored awaiting milling, and overseas experience suggests that logs may still be usable after 5 years of water storage.

Storage costs: e.g. for water spray facilities at dumps to keep the logs wet, and double handling if a special dump is required.

Costs of water storage for pine in NZ were reported to be (in \$A 1975)

- construction of yard and sprinkler system \$A4.50/m^3
- first year's running costs, 28 c/m^3
- subsequent running costs, increased by 1c/m^3/yr

Costs to set up Victorian and WA storage yards were estimated at \$3/m^3 plus running costs*. The capital cost could be spread over several years on one use, and other uses (e.g. for the sprinklers) could take a share of the costs.

The unique experiment in South Australia of storing pine logs in Lake Bonney also involves considerable handling costs. Bentick reported that the average cost of transporting logs to storage is \$4/m^3, while the annual storage cost under water is around \$2/m^3 (in Healey et al 1985). This implies that the total cost of two years' storage plus transport both into and out of storage could be \$12/m^3.

Transport: The main component of FCV royalty discounts after the 1983 fires was an allowance for costs of transporting the logs to more distant mills, since the great volume of salvage necessary was beyond the processing capacity of the

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* The Logger, June-July 1983, p. 6

nearer mills. This component averaged about \$8/m^3 and ranged as high as \$17/m^3. This component was most significant for large fires in pine plantations, requiring quick salvage, with relatively small local mills e.g. capacity of only 30 000 m^3/yr in Trentham, compared with over 100 000 m^3 in Cann River or Bright. In the case of SA, additional harvesting equipment and men were brought in from other States, at additional cost.

Winter logging: If salvage cannot be completed before winter, extra costs are more likely to be incurred for logging in wet conditions, maintaining access roads, etc.

Per unit harvesting costs are increased if salvage logging has to be selective in order to take the best trees in a short time.

Additional salvage costs for the South East forests in SA were estimated to be \$12.5 million (Bentick, in Healey et al 1985, p. 141). On a salvage volume of 1.7 million m^3 (Keeves & Douglas 1983), this amounts to \$7/m^3.

Deterioration, storage or transport are basically alternatives, and costs can be distributed between them in whatever mix is appropriate to minimise total costs.

There is insufficient information in the AIRPRO model to estimate the extra costs of salvage on each fire, taking into account all the above factors. The approach taken was simply to set a constant amount (per m^3) of \$2 for eucalypt and \$3 for softwood, plus an additional amount for each 10 000 m^3 of wood salvaged of \$1, up to a maximum of \$13/m^3.

Net timber losses

Examples of the timber loss per hectare, estimated from the above formulae and data shown in Appendix 21 are given in Table 19:

Table 19. Timber losses

			Loss (\$/ha)		
			Fire Intensity class		
Forest type	Height class (m)		Low	Medium	High
Ash, HEMS	II	40-52	150	220	470
	V	0-15	160	205	340
Mixed species	III	27-40	12	25	48
	V	0-15	12	25	37
Pine	III	27-40	1050	1390	3095
	V	0-15	3110	3760	4920

The physical loss is higher for young stands than for older stands close to maturity, but the economic cost is nevertheless lower in young native forest in some cases, because the discounting period between fire and harvest is much longer.

Most forest area burnt is in the Mixed Species group. The loss per hectare is quite small, usually less than $50/ha, due to low stocking rates, low value due to defect, low mortality caused by fire, and long rotation periods which reduce the present value of future harvests. These figures are based on the current forest state and management system in Victoria, which is most relevant to this cost-benefit study.

It should be stressed, however, that if the timber value of native forests is raised in the future by rehabilitation techniques, improved silviculture or protection, then the potential losses from wildfire will accordingly be higher. This in turn could justify higher expenditures on protection, more akin to the present situation for plantations.

16. WATER

The damages sub-routine includes estimates of the economic loss or gain due to the effect of fire on water catchments. Separate calculations are made of:

- the short-term water quantity increase
- the longer term water quantity increase or decrease in Ash catchments
- the deterioration in water quality.

Sharp increase in stormflow and peakflow rates also occur after a fire, which may produce downstream flooding. The probability of economic loss resulting has not been estimated in this study which concentrates on the overall yield.

Water quantity increase

There is considerable evidence on the increase in streamflow following fire, caused by several factors:

- increased overland flow after loss of ground cover
- reduced interception of rain if canopy is burnt
- reduced transpiration following death of vegetation
- in some cases, induced increase in water repellancy of soil.

Several studies have measured aspects of these processes, usually discussing the main variables involved but often being unable to quantify them all.

The main factors are:

- soil type, e.g. depth and infiltration capacity
- slope
- vegetation type
- fire area
- pre-fire catchment moisture condition
- post-fire rainfall - amount and intensity

Although the general direction of the relationships are clear, the shape of the functional relationships are not known, and insufficient observations are available to derive them by statistical techniques. Hence the factors are combined at this stage by the simplest assumed functions.

Formula

Value of short-term increase in water quantity is given by:

W1 = Q*P
where Q = increase in volume of streamflow (ML)
= WQNI (F,L(D)) * G(I) * FA
P = value of water ($/ML of streamflow)
= CW(D) * U(D)

WQNI(F,L(D)) = Benchmark increase in water yield (ML/ha) following 'standard' fire, in forest type F in district D with land type L.
I = av. intensity of fire on one arc (kW/m)
G = function relating fire intensity to water yield
FA = fire area (ha)
CW(D) = marginal cost/value of water used in district D
U(D) = proportion of available yield used in district D.

More detail on each component is given below.

Benchmark increase in yield, WQNI

The benchmark values were derived from the better documented studies, and the calculations in Appendix 23.

For example, for Mixed Species forest in land type 1 (the main type for forested country in SE Australia), the increase in yield following a fire of 5000 kW/m intensity and heavy post-fire storms, is taken as 3.9 ML/ha. This total effect was distributed over 4 years.

It is assumed here that the increase , measured usually at streamflow recorders just below the catchment, will be fully conveyed to available water yield in reservoirs etc., without transmission losses. Another possible effect of the fire, however, is that, by causing increased soil erosion and consequent siltation of streams and channels, the flow may be retarded and the increase in yield moderated. Due to the lack of any quantitative studies on this aspect, it has not been included, and in any case is only likely to be significant in the flatter districts and those with little streamside vegetation.

Forest type

The seven forest types provided on FCV fire reports were taken as indicators of factors directly relevant to the streamflow response, such as soil type, normal rainfall and streamflow, revegetation rate and slope.

The benchmark WQNIs for Mixed Species were adjusted for different forest types according to the following considerations:

Ash and High Elevation Mixed Species (HEMS): The latest MMBW studies* of fires in Melbourne's predominantly ash catchments have not found any evidence of a short-term increase in yield.

O'Loughlin, Cheney and Burns (1982) studied a high-intensity fire in a sub-alpine catchment in the ACT with a large component of alpine ash and mountain gum, as well as peppermint and other mixed species. The increase seemed low (32 mm increase in base flow) compared with similar studies in drier eucalypt country (390 mm) (Mackay and Cornish 1982).

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*P. O'Shaughnessy, pers. comm.

Whilst the maximum change in interception and transpiration is greater for wetter denser forests, their recovery time is also quicker, and reasonable protection should be available after the second year. In low rainfall areas (500 - 750 mm/p.a.) canopy closure may take ten years or more after a severe fire (McArthur and Cheney 1965).

It is therefore assumed that the predominant factors associated with Ash and HEMS are high soil permeability and rapid revegetation, outweighing any effects of higher rainfall and slope and thicker initial vegetation, and giving a lower response to fire.

Red Gum, Box-Ironbark: No data are available, but response is expected to be much lower due to generally lower rainfall and slope.

Softwood: Softwoods are planted in a wide variety of land types, perhaps most like Mixed Species, but may show a larger response due to a greater canopy interception effect and a greater likelihood of being killed and hence ceasing transpiration.

Alpine: From McArthur's and O'Loughlin's studies, the effect is rated lower than Mixed Species due to higher soil permeability and lower transpiration effect, due in turn to lower vegetation biomass, lower temperatures and higher cloud cover. These factors seem to outweigh the effects of higher rainfall and slopes.

Mallee, Native Conifer: Effect is assumed very low due to very low rainfall and slope and low density of vegetation.

Grass, Heath, Scrub: Effect is lower than Mixed Species due to lower biomass and rapid recovery, and lower likelihood of being in an important catchment.

The values used for WQNI, the standard water quantity increase (ML/ha) for each forest type, are summarised as follows:

Ash, HEMS	1.9
Mixed Species	3.9
Red Gum, Box-Ironbark	0.5
Softwood	3.9
Alpine	1.9
Mallee, Native Conifer	0.1
Grass, Heath, Scrub	0.2

Land type

Although land and soil type and rainfall regime has already been allowed for in the forest type parameter to some extent, a further allowance was made for three different land types that may be associated with Mixed Species and Softwood in different districts.

Type 1.	Standard, used for most districts
Type 2.	Low rainfall in western Victoria
Type 3.	Very low rainfall, flat areas of N.W. Victoria

Fire intensity function, G

Runoff is hypothesised here to be positively related to fire intensity (all other things equal) by the function:

$$G(I) = \exp\left(1 - \frac{6}{(1+I)}\right)$$

where I = intensity in MW/m, G(I) has the shape shown in Figure 29.

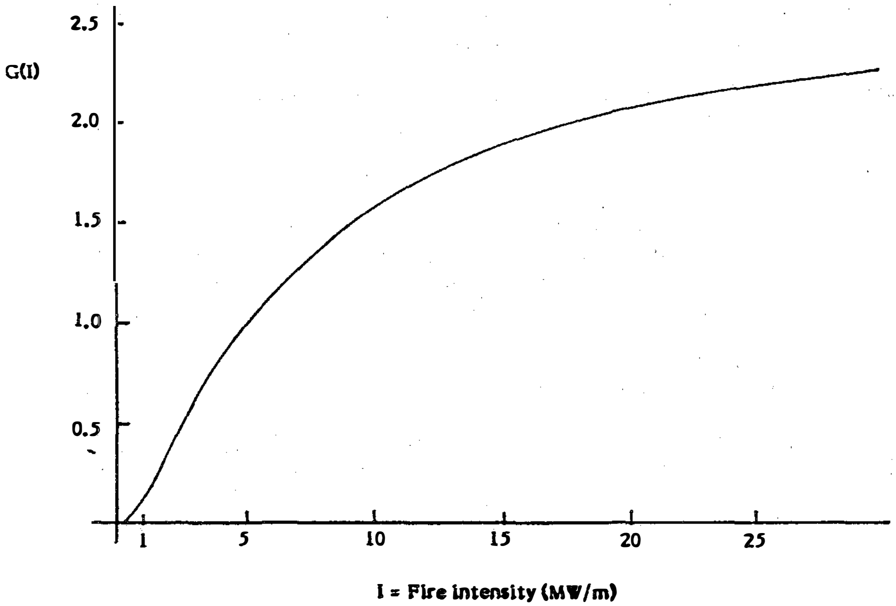

Figure 29. Relative increase in water yield/fire intensity

The relationship is generally positive because, the higher the fire intensity, the greater the proportion of vegetation cover burnt, and hence the greater the reduction in interception and transpiration, and also the greater the effect on soil properties and possible reduction in infiltration capacity.

McArthur and Cheney (1965, p.421) suggested that the effect is in direct proportion to intensity. A sigmoid shape is used here, however, to reflect the idea that effects are minimal at intensities up to about 0.2 MW/m since only surface vegetation is affected and much of the fuel is scorched rather than consumed. The effects rise sharply as flame heights rise, scorching canopy as well as burning understory. For higher intensities, above 5 MW/m, the effects tend to flatten out. When all the leaves are killed, the transpiration effect reaches a ceiling. The interception effect also tends to flatten off until it reaches a ceiling with total defoliation.

The parameters of the function (G) are set so that is passes through the origin, is 1 for the benchmark intensity level (5 MW/m) and for most fires does not exceed 2.

Rainfall intensity

The post-fire rainfall regime affects the increase in yield through:

- the amount of water input to the system
- the rate of revegetation and hence the duration of the effects on transpiration and interception.

Heavy rains on the bare catchment have a maximum erosive effect and tend to postpone recovery while light rains are more likely to protect soil stability and help re-establish vegetation.

The yield increase used for the benchmark WQNI (derived from Mackay and Cornish's study near Eden) followed some heavy downpours (e.g. 140 mm in a storm 9 weeks after the fire). Those were taken here to be somewhat more intense than average, although summer storms are quite common in the coastal areas.

A rainfall intensity index, RFI, was constructed from daily rainfalls at selected meteorological stations. The index is based on a simple model in which:

- each day's rain for 60 days after the fire contributes to the total index RFI and also to an index of soil stability
- the maximum contribution to RFI is an increasing function of daily rainfall
- the contribution to soil stability is at a maximum for rainfall of 7 mm/day
- the actual contribution to RFI is reduced according to the cumulative soil stability index, reducing to zero after five days of optimal rain.

(The formulae for RFI are given in Appendix 24).

On the basis of past meteorological patterns, the value of RFI would be less than 100 for 55 percent of days, and between 100 and 400 for a further 43 percent of days.

Because of uncertainty over the size of this rainfall effect, and because it does not capture the effect of rains more than 60 days after the fire, its effect on the yield increase is restricted through the function RFN1 (RFI) to a range of 0.25 to 2.25 times the benchmark value.

$$\text{RFN1} = 0.25 + \text{RFI}/500$$

Pre-fire rainfall is also important, through its influence on the soil moisture storage and transpiration. No attempt has been made to model this aspect here, but Mount's (1972) Soil Dryness Index (outlined in Appendix 7 in relation to the fire danger index) could provide a useful input.

Value of water

Since the physical quantities in the water equation indicate the increase in water yield from a random hectare of forest, the valuation process needs to consider both the probability that the water would be used, and its value in use. For these two factors, values were specified for each district in the State.

Figure 30 illustrates the different possibilities of how the increase in yield may affect economic values. The effect on consumer surplus is outlined in Appendix 25.

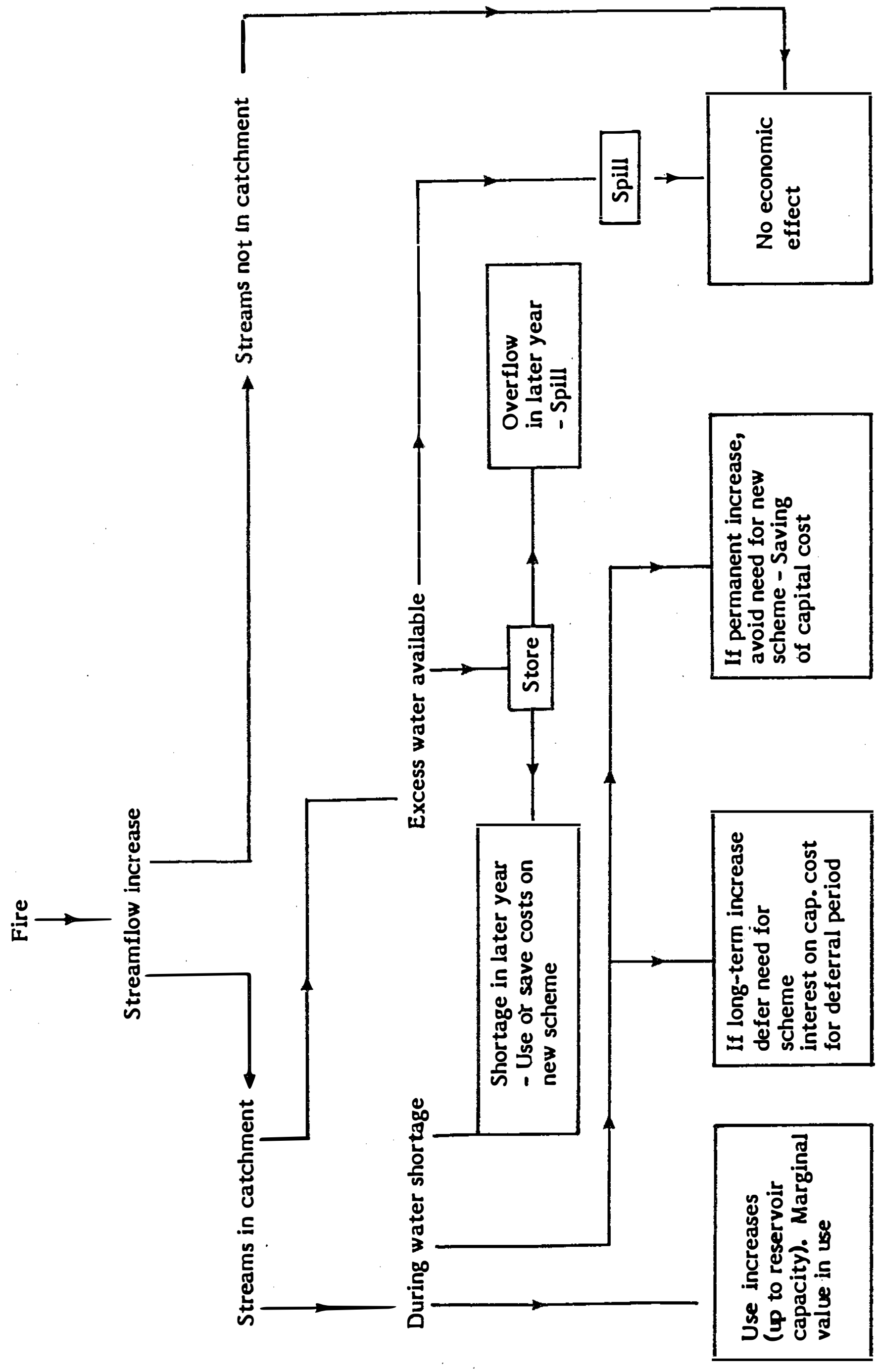

Figure 30. Alternative economic consequences of streamflow increase

Probability of use: The increase in water yield may not be used because:

- the burnt area is not in a catchment with any significant use, or
- the water is surplus to requirements and hence is spilled or stored indefinitely.

To allow for this, the proportion of streamflow utilised was estimated for each district. The data and sources are shown in Appendix 26.

Value of water per unit volume: Because of the special characteristics of water supply, the price charged (i.e. the 'water rate') is not necessarily an appropriate measure of the value to be placed on marginal changes in water supply for cost-benefit calculations. For most privately produced goods, the price approximates both the value of marginal units to consumers and the opportunity cost of producing them. Water, like many other public goods, differs in a number of ways, outlined below.

- Discontinuous cost increments:
  Given the present infrastructure it may be possible to increase consumption for years at negligible marginal cost. Eventually, however, a threshold is reached where even a small increase in consumption requires a large capital expenditure to develop the next supply extension. Prices, of course, are not set to match these short-run marginal costs, but tend to be based on average historical costs.

- Subsidisation:
  Prices charged are often less than average costs because of government subsidisation via the water authority; e.g. in Victorian country areas, a large part of the capital cost and interest has usually been subsidised.

- Price structure:
  There is generally a two-tier rating structure, with most of the revenue provided by a water rate based on some criteria other than water use (e.g. property value), with an 'excess water rate' (a true price based on use) paid on usage above a certain allowance. For the 'allowance' of typically 500 kL per consumer, the water rate charged is usually the same as, or a little less than the rate for excess water, on a per kL basis. The rate for the allowance is not a true price, however, since it must be paid for the full allowance whether used or not. Total water revenue for the MMBW comprises about 80 percent from the water rate, and 20 percent from 'water by measure'. Hence to most users, marginal water use is effectively free, so their value of marginal uses could be expected to be close to zero.

However, when there are water shortages, authorities apply rationing or restrictions (e.g. on garden watering, or through irrigation licences), and in some cases the marginal uses precluded by the restrictions could have a much higher value than the price charged for excess water. Such restrictions are common in Victorian country districts*.

The probability of the extra water not being in a catchment or being excess to requirement should be reflected for each district in the factor 'proportion of yield

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* See Vic. Ministry of Water Resources & Water Supply, Local Authorities, Annual Report 1983-84, Table W4: System Performance Indicators.

used'. Whilst a substantial proportion of streamflow is not currently exploited, often because of the high cost, most districts typically face pressures on available harnessed supplies at some time. At most points in time, a surplus may be available, but seasonal peaks in use and periodic droughts cause potential shortages, and in the longer term, secular growth in population and per capita use eventually causes demand to outstrip supply and generate pressure for a new supply scheme.

For the cases where the yield increase has an economic impact, the appropriate valuation could be based on either:

- value to users, if the increase in supply allows an increase in use, or
- cost of new supply, if the increase in yield allows avoidance or deferral of expenditure to enhance supply.

A combination of these two approaches was used in this study. The value of water in each district, CW (D), was calculated as the weighted average of the cost of supplies for town water and the value of irrigation water.

The formula used was:

$$CW(D) = (P*C*H*N + VI*PI) * PU$$

where P = Price of water in towns
C = ratio of full cost : price
H = ratio of headworks and transfer costs : full cost
N = proportion of non-irrigation use
VI = value of irrigation water
PI = proportion of irrigation in total use
PU = proportion of runoff used

Town supplies: For each district, the price was taken as a rough average of the water rates charged in the main towns of the district*.

The ratio between prices in different districts was accepted as an indicator of the ratio between costs, reflecting geographical factors, etc., assuming that a uniform degree of subsidy applied.

The ratio of cost:price was an average for all local authorities in Victoria for 1978-79, estimated by the Institute of Applied Economic and Social Research**. The cost of water for local authorities administering town water supplies was estimated to be 48 percent higher than in the MMBW area, but average bills were lower in local authorities (ibid p.150). Subsidies amounted to 37 percent of average cost of supply in local authorities, implying a cost : price ratio of 1.6 : 1.

Water from districts supplying the MMBW area is assumed to have no subsidy element.

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* Victorian Department of Water Resources and Water Supply, Local Authorities Annual Report, 1983-84.

** Institute of Applied Economic and Social Research, The Economic Impact of Public Bodies in Victoria, a report to the Public Bodies Review Committee, Parliament of Victoria, University of Melbourne, Aug. 1981.

For rural water supply (for irrigation, stock or domestic use), the price was lower and the subsidy element higher than for town supplies. The full cost : price ratio was estimated as about 2.5 : 1. (ibid p.141). The full cost, however, is assumed here to be similar for both types of supply.

Since then, there has been some reduction in the level of subsidies, but on the other hand the Institute's calculations underestimated the degree of subsidy. Whilst they took account of explicit interest and repayment subsidies on capital, they accepted the nominal level of capital and interest payments on loans on a historic cost basis rather than considering the current values.

Since a considerable degree of inflation and rises in real interest rates have taken place since many of the loans were taken out, their replacement cost of capital could be significantly higher.

Table 20. Cost of recent water supply schemes

Water supply scheme	Unit cost* ($/ML)
Melbourne	
Lower Yarra Development Stage IA and II	170
Lower Yarra Development Stage I	290
Smaller Watsons Ck Reservoir	250
(MMBW 1982)	
Country	
Lance Ck, Wonthaggi	264
Sunday Ck, Broadford	253
St Arnaud	82
Mt Cole, Ararat	181

The full cost includes both headworks and distribution costs and thereby overestimates the additional cost necessary to obtain a new water supply. For the MMBW, headworks and transfer costs are about 55 percent of total costs on a long-term average basis.

By multiplying the water price in different towns by the cost: price ratio and the headworks ratio, an estimate of cost of existing supplies was obtained, e.g. Upper Yarra $209/ML, Marysville $78/ML and Rennick $348/ML. For comparison, data on costs of new water supplies are available only for a limited number of towns, but several examples are listed in Table 20.

The cost of new schemes might be expected to be higher than for old, as more remote and expensive sources of water have to be sought, but an offsetting factor lies in technological improvements in construction methods. The cost of new schemes listed above is in fact within the range of average costs for old schemes.

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* (Based on annual allowance of 11 percent of capital cost, plus operating costs, per ML of safe annual yield increment: Rural Water Comm, 1984, pers. comm.)

In some situations, the relevant opportunity cost of water could be the cost of increasing the efficiency of use of existing supplies. The MMBW argues that increased efficiency is now the cheapest source of water, and that large gains could potentially be made in garden watering, toilet flushing, showering, clothes washing and dishwashing, as well as in the industrial and commercial sectors. The cost of water saved by a dual-flush toilet cistern, for example, is less than one third the cost of water from a headwork augmentation (MMBW 1982, pp.13-15).

Irrigation supplies: Whilst the great bulk of water supply from some districts, such as Upper Yarra, goes to towns and cities, the opposite is true for basins such as the Goulburn, over 90 percent of which is used for irrigation.

The price charged for irrigation water has usually been only a fraction of the price for town supplies, due to the large capital subsidies provided. Economic estimates (e.g. by the BAE) usually concluded that the value of water to farmers was a number of times greater than the price they paid. However, where the water is used for agricultural products which are themselves subsidised, the true value of the water in that use could well be negative if the output were valued at free trade prices (e.g. dairy products exported at a loss).

Clearly the value of irrigation water varies greatly between different activities and districts but a single value figure of $80/ML has been used for this study. This was based on a current estimate of $80/ML quoted by the NSW Water Resources Commission, and an estimate of $20-70/ML in 1976-77 for irrigation in the Kerang district of Victoria, by the Institute of Applied Economic and Social Research.

This value is likely to be lower than the replacement cost of water but it is assumed here that, in the modern political environment, shortages of water for irrigation are more likely to be reflected in a reduced level of irrigation rather than construction of new dams to meet the shortfall. Hence, value is more relevant than cost.

Cost deferral: A temporary increase in yield (for say up to 4 years) is more likely to allow a postponing of costs for supply rather than complete avoidance. The value of deferral by n years can be measured as the reduction in net present value of the capital cost, due to n years' additional discounting. In this study, the method used is to apply the cost per ML of water (which reflects annualised capital costs) to the total increase in yield, but the results should be approximately the same.

Net effects

A few examples will show the range of values of water gain per hectare generated by combining the above factors. A case in the upper range would be an area of Mixed Species forest in the Upper Yarra district, burnt by a head fire of intensity 5 MW/m, with a storm bringing 25 mm of rain shortly afterwards. The resulting gain would be $136/ha. The average gain in the same circumstances in Cann River would be only $0.4/ha.

In the case of an area burnt at low-medium intensity (1MW/m) with light rains following the fire, the gain would be $11/ha in Upper Yarra, and $0.04/ha in Cann River.

One implication is that the value of water gains following a fire in a heavily used catchment may be considerably greater than the loss of potential timber, other effects aside.

Long-term yield change

A change in water yield over the longer term (up to a whole rotation) in mountain ash-type catchments is estimated and valued in the damages sub-routine. This has been identified by the Melbourne and Metropolitan Board of Works as the most important effect of high-intensity fire in its catchments.

After the ash has been killed, the dense regrowth uses much more water than a mature forest, apparently due to a higher level of transpiration (Langford 1976). According to MMBW studies of the 1939 fires, the level of streamflow falls to a minimum around 20-40 years after the fire and then gradually increases to the long term value in a mature forest (MMBW 1982).

Kuzcera (MMBW, pers. comm., 1984) found that the following equation reasonably fitted the data following the 1939 fires:

$$R = L.K.t.\ \exp(1-Kt) \quad ; \quad t \geq 2$$

$$= O \quad ; \quad \text{otherwise}$$

where R = streamflow reduction t years after fire (mm)
L = maximum streamflow reduction (mm) = 600 for pure ash
$\frac{1}{K}$ = time from fire to maximum reduction (yr) = 30

Earlier work gave a maximum reduction of 330 mm (MMBW 1982 p.85), but subsequent work has indicated an even greater reduction of 600 mm.
The shape of the streamflow curves is shown in Figure 31(a).

L seems to increase by about 6 mm for every 1 percent of catchment converted to regrowth ash.

Stands which are not killed, such as mixed species in most cases, are believed not to experience the streamflow reduction. For example, the MMBW derived an equation which shows that the reduction in streamflow (R) increases as the percentage of ash in a mixed stand (A) increases and the percentage of Mixed Species (M) decreases:

$$R = 153 + 1.79\ A - 2.29\ M$$

The reduction of 600 mm above is based on a maximum flow of 1200 mm which is remarkably high but is typical of certain MMBW ash catchments where annual rainfall is about 1800 mm. The present average annual streamflow for Maroondah catchment is 660 mm, but this reflects the reduction due to the 1939 fires and the presence of about 30 percent by area of Mixed Species.

Whilst the regrowth effect brings a decrease in yield in all post-fire years if mature ash is burnt, there is instead an increase in yield for the first 20 years if 45-year-old ash (Height Class II) is burnt. This is because this age group is initially still near the trough of the yield curve, so that setting it back to year 1 gives a temporary increase compared with the no-fire situation. Thirty years after the fire, the regrowth is back at the minimum yield of 600 mm whereas if unburnt it would have recovered to 765 mm. Similarly, fires in Height Classes III to V give an increase before the decrease. The net change over time after a fire in Ash II is shown in Figure 31(b) and Table 21.

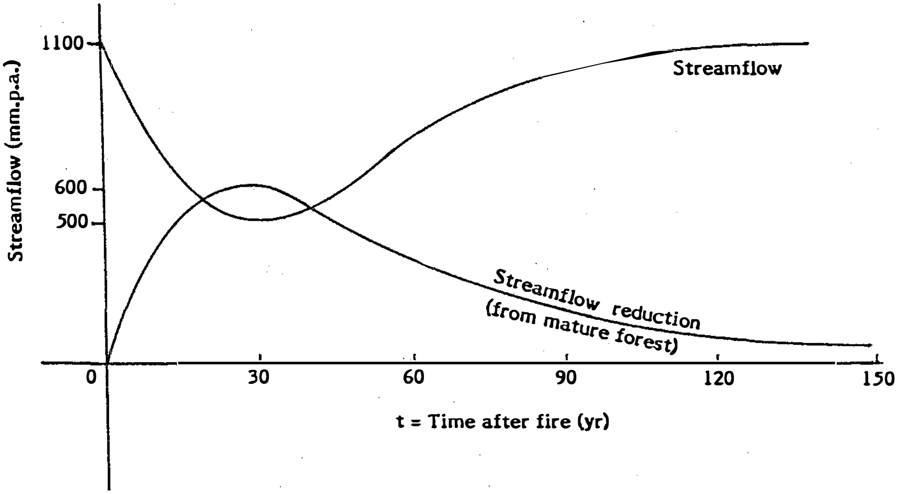

Figure 31(a). Streamflow after fire in mature mountain ash catchment

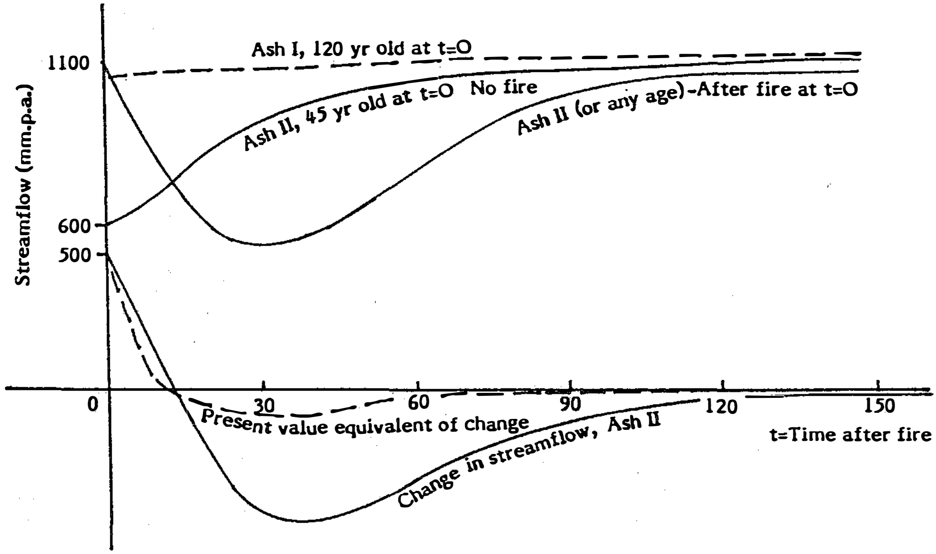

Figure 31(b). Streamflow after fire in 45-year-old mountain ash

Table 21. Streamflow after fire in mountain ash

Time since fire (years)	Streamflow from regrowth (mm)	Change in streamflow (mm)				
		Age when burnt (yr)				
		120	45	30	15	5
		Height class				
		I	II	III	IV	V
1	1147	64	487	547	458	215
2	1098	12	432	497	423	200
5	970	-125	283	362	328	159
10	810	-298	89	184	201	105
15	705	-413	-53	51	105	64
20	642	-487	-153	-45	34	32
30	600	-545	-265	-159	-54	-7
40	627	-531	-301	-204	-95	-27
50	687	-481	-296	-211	-109	-35
75	865	-318	-215	-162	-91	-32
100	1006	-186	-131	-101	-59	-22
150	1145	-53	-39	-31	-18	-7

To obtain the total present value equivalent of these changes, WQND, the changes in each of the first 150 years were discounted to the present* at 4 percent p.a. (discussed later) and summed, using the formula:

$$WQND = \sum_{T=1}^{150} \frac{[L * K(T+A) * \exp(1-K(T+A)] - L>K>T> \exp(1-KT)}{100 * (1+I)^{N}}$$

where WQND = discounted total of streamflow changes (ML/ha)

T = time since fire
A = age when burnt
I = discount rate = 0.10
1 mm = 0.01 ML/ha

Cost per unit of long-term yield reduction

The effects of a long-term yield reduction could follow (in reverse) any of the possible paths illustrated for a yield increase in Figure 30. The most relevant

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* Although quantities rather than values are discounted in this formula, each term is later to be multiplied by the current value of water, which is a constant factor.

economic situation here may be the bringing forward of future schemes, since the phenomenon occurs most importantly in Melbourne's catchments of ash forests, in a system characterised by secular growth of demand and protection against shortages.

The typical situation of supply and demand over time is shown in stylised form in Figure 32. While demand increases steadily, supply is incremented in steps every few years when a new scheme becomes operational. New schemes are constructed just in time to keep supply above demand.

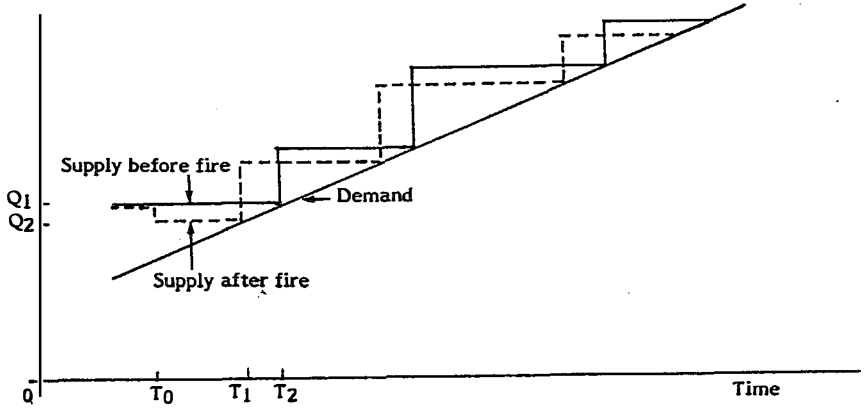

Figure 32. Water supply increments - change due to fire

A bushfire in one of the ash catchments at time T_0 causes a continuing reduction in supply of $(Q_1\text{-}Q_2)$. Consequently the next supply increment (perhaps tapping another catchment) has to be brought forward by $(T_2\text{-}T_1)$ years, equal to the reduction in yield divided by the growth rate in demand. As long as the annual reduction in yield persists, each future scheme has to brought forward similarly.

If the yield reduction increases to a maximum after 30 years and then gradually decreases, the number of years by which each scheme has to be brought forward first increases and then decreases.

The net present value of the extra cost, V, (basically higher interest) is given by:

$$V = \sum_{t=1}^{\infty} \left[\frac{C_t}{(1+i)^{t-n(t)}} - \frac{C_t}{(1+i)^{t}} \right]$$

$$= \sum_{t=1}^{\infty} C_t \frac{\left[1 - (1+i)^{n(t)} \right]}{(1+i)^{t-n(t)}}$$

where t = number of years after fire
i = opportunity cost of capital
C_t = capital cost scheduled for year t

$n(t)$ = number of years by which C_t is brought forward after fire
= $R(t)/D(t)$
$R(t)$ = reduction in yield due to fire
$D(t)$ = annual increase in demand

Operating costs are assumed to be negligible. In a simple system in which C_t and $D(t)$ are equal for all t; (i.e. each year, enough extra capacity is installed to meet the constant annual increase in demand), and $R(t)$ is the same for all t; (i.e. the reduction in yield is constant over time), the extra costs become:

$$V = C \left[1 - (1+i)^{-n} \right] (1+i)^{n} \sum_{t=1}^{\infty} \frac{1}{(1+i)^{t}}$$

$$= C\, A_{\overline{n|}\,i}\, (1+i)^{n}$$

An alternative approach to measurement could apply if there were a permanent or long-term uniform reduction in yield. This could be accommodated by investing in an entirely new scheme yielding the required amount (R) without altering the schedule of other planned schemes.

If K = capital cost per unit yield and D = constant annual increase in demand the extra cost V_2 is given by:

V_2 = RK
= nDK
V_2 = nC

The bringing forward of planned schemes is probably more likely than investment in an entirely new scheme because the planned schemes should have already been placed in order with the cheapest or most desirable first in line.

A third method, which is the one used here, is to value each future year's yield change at its unit annual cost ($ per ML safe annual yield), discount to present values, and sum.

If capital cost per unit = K = C/D as above, and L = effective life of schemes, annual cost per unit = $K\, A^{-1}_{\overline{L|}\,i}$. Present value, V_3, of cost of all years' reductions R(t) is

$$V_3 = \sum_{t=1}^{\infty} \left[\frac{K\, A^{-1}_{\overline{L|}\,i}\, R(t)}{(1+i)^{c}} \right]$$

Now $A^{-1}_{\overline{L|}\,i} = \dfrac{i}{1-(1+i)^{-L}}$ is close to i

when L is large (even L = 50 as for water supply schemes). Therefore, if R(t) are the same for all t, V_3 simplifies to V_2, since $$V_3 = \frac{C}{D}\, i\, R \sum_{t=1}^{\infty} \frac{1}{(1 + i)^t}$$

$$= nC$$

The first expression for V_3 above is the one used here to handle variation over time in R(t).

Value of yield reduction: The value of the loss, W2, is calculated as

W2 = WQND * AK * P

where AK = area of ash killed (ha)
P = cost of water ($/ML)

The discounted value of the streamflow changes is highly sensitive to the choice of discount rate, as shown in Table 22.

At a discount rate of only 2 percent, very large losses emerge for all age classes, because of the cumulative effect of water loss up to 150 years after the fire. At a discount rate of 5 percent, the losses are small due to the greater discounting of losses in later years, but are still as high as $6500/ha.

At a discount rate of 10 percent, significant losses persist for the older stands, but there are large **gains** for stands less than about 40 years of age since the increases in streamflow in the early years outweigh the heavily discounted reductions in later years. However, other adverse effects of the fire, e.g. erosion or losses in timber and conservation value, may mean that fire is not on balance desirable in young ash stands.

Table 22. Discounted value of streamflow change in mountain ash catchment ($ per hectare of ash killed, at $100/ML)

Discount rate	Age whenburnt(yr)				
(% p.a.)	120	45	30	15	5
2	-16650	-21560	-22700	-21200	-19930
5	-6510	-6390	-4480	-1870	-415
7.5	-3700	-2590	-280	+2250	+3560
10	-2350	-920	+1370	+3690	+4860

The 10 per cent rate, representing the social opportunity cost of capital, would be the most relevant to the extent that changes in streamflow affect primarily the timing of construction costs.

On the other hand, a lower rate of 5 per cent, respresenting the social time preference rate, would be more relevant if changes in consumption by future water users are involved. A compromise rate of 7½ per cent has been used in this study for long-term water effects.

Water quality

Fire may cause a deterioration in water quality from the burnt catchment when the ash and burnt debris are washed into streams and eventually travel into water supplies for human use.

Nutrients released by the fire also enter streams through overland flow and leaching. Turbidity and colour from suspended materials are likely to increase, and in some cases the dissolved nutrients may cause eutrophication or algal bloom which gives the water an unpleasant taste, odour and colour. Sediment and turbidity result also from channel scouring due to increased streamflow or flooding.

In some cases the initial pollution may have little effect on human use because the water is not in a catchment, or it is allowed to settle out or is filtered before use. Deep reservoirs or dual storage systems give the affected water time to settle out before use. If the reservoir is nearly empty after a drought, this solution is not possible.

Whilst deep reservoirs allow the sediment carried down from fire areas to settle out and thereby avoid costs at the consumer end, the additional siltation imposes costs in a different way, by reducing the capacity of the reservoir. This could bring forward the time when the next supply scheme has to be constructed to meet growing demand, so that the additional cost might be measured as the additional interest payable. The siltation problem seems to be minimal in forested catchments where streamside vegetation intercepts most of the solid matter, unless the fire is sufficiently intense to destroy even streamside vegetation.

Catchments that are already subject to other sources of pollution (e.g. from agricultural fertilisers and manure) or normal storm sediment, and which provide water for a reasonable sized population, are more likely to already have an adequate filtering and treatment system.

In unprotected catchments, fire effects may make the water unfit for drinking, blacken clothes washed in it, and clog sprays, taps and filters. An extreme case was Macedon where, over 18 months after the 1983 fires, the water was still unreliable.

Irrigation supplies are often routed separately from town supplies and are assumed here not to require expensive quality treatment as for domestic and industrial water. Nevertheless, some additional cost is likely to be imposed on irrigation use due to clogging of sprays and filters by the sediment.

A number of scientific studies have measured aspects of water quality after fire, e.g. suspended sediment, and chemical and bacterial concentrations.

For example, Brown (1972) reported that, after a severe fire in the Snowy Mountains, the suspended sediment concentration from the Wallaces Creek catchment increased from 7052 to a maximum of 143 000 parts per million and did not recover fully for 4 years. In a less severely burnt catchment at Yarrangobilly, the concentration increased from 334 to 2000 ppm.

Following a fire in the Little River Catchment near Sydney, with about 45 mm heavy rain a few weeks later, a ten-fold increase in total phosphorous concentration was recorded, from a pre-fire mean of 0.006 to 0.068 mg/L, with an increase in NH_3-N from 0.105 to 0.440 mg/L (Cullen and Smalls 1981). This can be reflected in an increase in biological activity in the water that can persist for many years. A five-fold increase in algal cell counts in Lake Burragorang (NSW) from 1969 onward for at least 4 years has been attributed to bushfires in the catchment.

Resultant algal bloom in reservoirs produces unpleasant colour, odour and taste in the water. The stimulated plant growth may be unsightly and restrict water flow, trap litter, and interfere with fishing, boating and swimming. Such effects have occurred in Sydney reservoirs at times, but are rarely experienced in the generally deeper and colder storages in Victoria.

It is difficult to value these changes in economic terms. For example, water supplies do not have price differentiation for different qualities. Their significance may be indicated by comparing the increased levels of contaminants with the minimum standards for drinking water set by health authorities. This still leaves the problem of placing a value on departures from the standard.

The costs imposed by dirty water are sometimes monetary, e.g. replacement of ruined clothes, and sometimes only discomfort, dissatisfaction and inconvenience although even these feelings might be translated into money terms if one could test consumers' willingness to pay to avoid these problems.

The approach taken here, however, was to estimate the costs in cases where communities had actually taken measures to obtain alternative supplies or treat the water to restore an acceptable quality.

The equation used to calculate water quality losses, W3, was:

$$W3 = WQLL(F,L) * WUSE(D) * RFN * G(I) * FA$$

where WQLL(F,L) = benchmark cost of water quality restoration ($/kL) following fire of high intensity and heavy rains in forest type F and land type L
WUSE(D) = water use (non-irrigation and not already treated) per hectare of forest in district D (kL/ha)
RFN = rainfall intensity function
G(I) = fire intensity function
FA = fire area

Benchmark cost to water supply WQLL

The benchmark data point was based on the experience of some towns in Victoria suffering a deterioration in water quality after the fires of February 1983 (e.g. Macedon and Lorne). Short-term responses included high-cost measures to obtain satisfactory water for the small proportion of sensitive uses, e.g. drinking, cooking, washing. The longer-term response, where necessary, was to install or upgrade treatment of the whole town supply, which is cheaper per unit, but includes even water for uses which do not require treatment (e.g. garden and toilet). Illustrative costs are given below.

Substitution of water from another supply:

Private hire of 8000 gal (ex-petrol) tanker,
including vehicle and driver = $400/day

For 50 km trip, 2 loads/day,
transport $400/(2x8000) = $25/1000 gal
+ cost of water = $ 2/1000 gal
$27/1000 gal
= $ 5.93/kL

If this is needed for only 20 percent of town water use (for drinking, cooking, washing etc.) the cost per kilolitre of total use is $1.19.

Private trip to neighbouring town to use laundry and obtain clean water:

Vehicle : 20 c x 50 km ≐ $10
Time : $5 x 2 hr = $10
$20

If trip accounts for 2 kL of water for 1 family for 1 week, or 20 percent of total use, cost is $10/kL or $2/kL of total water use.

Treatment plant After suffering the effects of fire-affected water for over 18 months, the township of Lorne had a treatment plant installed. Had the benefits of the plant been confined to the period of the fire effects, the cost may not have been considered justified. However, since the benefits extend for decades into the future, only half the capital cost has been viewed here as a charge against the fire, and the rest as a general addition to the town's welfare.

For Lorne, capital cost is $650 000 for nominal capacity of 3.5 ML/day* or average annual use of 425 ML (i.e. 1/3 x 3.5 x 365).

Capital cost = $1.5/kL
Share of capital cost attributed to fire = $0.75/kL annual use
Estimate of operating cost = $0.12/kL

If fire effects persist for 4 years,
Operating costs attributable to fire = $0.48/kL annual use
Total costs (0.75 + 0.48) = $1.2/kL

Treatment would probably be the cheaper option for long-term problems.

From the lower two of the above three figures, the benchmark cost is taken to be:

WQLL = $1.2/kL

Towns with existing treatment plants are likely to experience relatively small additional costs, e.g. of the order of $0.04/kL for chemicals and operating costs to handle the heavier sediment load.

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* Alan Strom, Capital costs of water treatment plants, Engineers Australia, June 1, 1984, p.47 Figure 2.

The benchmark cost is specific to the conditions:

Average fire intensity = 5000 kW/m
RFN = 300
Main forest type = Mixed Species

Adjustments for other conditions are outlined below:

Preventative works

Besides the costs incurred to overcome water quality problems, costs were also incurred by public authorities to try to prevent soil erosion before it created problems such as for roads and water supplies. Works costing about $170 000 were carried out by the Soil Conservation Authority, Vic. for the following purposes:

Works to hold the soil in place

- Stabilising of reservoir environs, roadside batters using aquaseeding techniques
- Contour ripping in catchment areas to protect structures
- Jute mesh covering of critical areas of reservoir batters and table drains

Works to trap moving soil/silt

- Silt-trap mesh fencing in drainage lines, particularly around water supply reservoirs
- Rock and log silt-traps placed on contour
- Road grading and track barring, in forested areas

Works to stimulate regeneration and ground cover

- Aerial fertilising of burnt foreshore reserves
- Replanting coastal vegetation
- Handseeding of disturbed areas inaccessible to machinery
- Contour sowing of pasture seed
- Refencing of fragile areas on coastal foreshore to protect revegetation areas

These costs are included in the total damage estimates where they were recorded for particular fires.

Land type, L

Soil and land type affect the amount of additional erosion due to fire as well as the normal no-fire erosion. The relevant characteristics are normal annual rainfall and run-off, slope and soil infiltration or erodibility.

Forest types have been used here as the main indicator of land type, as for water yield above. However, a land type parameter was also used to allow distinction between widely occurring forest types such as Mixed Species, Softwood and Grass in different districts.

FCV districts (pre-1984 structure) were classified into three broad classes. Most were placed in the standard category 1, the exceptions being the drier flatter areas in western Victoria.

Fire intensity function, G

The function relating water quality losses to fire intensity is here assumed to have the same shape as that for water yield. The increased transport of matter from the catchment is partly related to the increased quantity of overland flow, but other mechanisms also operate. The reduction in water quality is closely related to the loss of soil and nutrients from the burnt area by post-fire erosion. The effect of intensity on the amount of litter and vegetation destroyed is again important but in this case because of the resultant exposure of the bare soil to raindrop impact - its extent and duration - as well as its effect on interception of moving particles.

Rainfall function, RFN

As for water yield, soil erosion and water quality loss increase dramatically with rainfall intensity even in the absence of fire. The additional increase due to fire still seems to be strongly positively related to rainfall intensity, although the scientific reports have not always been able to clearly distinguish the separate contributions.

It has been estimated that while the incident energy of rainfall may have an effect on erosion of one order of magnitude, the presence of vegetation may have an effect of three orders, and soil type four orders.

The rainfall effect on quality is therefore considered to be much greater than for quantity and could also continue for several years until the vegetative cover has been restored. The effect could be near proportional to rainfall intensity while the catchment remains bare, but may flatten out eventually after most of the erodible soil has already been removed.

An index of post-fire rainfall intensity, RFI, was constructed with the formulae shown in Appendix 24. Because of the uncertainty about the effect of varying rainfall regimes and because the index with its limited tracking period could underestimate the eventual effect when rainfall in the first 60 days is low, the rainfall function was compressed to a narrower band around the benchmark. The factor RFN used to adjust the benchmark runoff is given by:

$$RFN2(RFI) = 0.25 + RFI/250$$

Thus RFN has a minimum value of 0.25, and a maximum of 4.25 for very intense storms (Max RFI = 1000 e.g. if one rainfall of 250 mm falls on a base catchment in 24 hours).

Area burnt, FA

The use of this factor implies that water quality costs are proportional to fire area. In fact, in individual cases, an increase in area burnt within a catchment may not give rise to any monetary costs until a certain threshold is reached when the quality falls to an unacceptable level. However, the costs in terms of discomfort may rise gradually as the input of contaminants rises with area burnt. The probability of the burnt area being within a catchment used for town supplies also rises with the number of hectares burnt.

Water use, WUSE

The variable WUSE (D) represents that part of the utilised water yield per hectare of forest, for each district D, that is used and may require treatment after a bushfire. It aims to exclude run-off not in catchment areas, irrigation water and supplies already subject to adequate quality treatment.

Two approaches to its measurement were tried.

- Working from catchment run-off (the preferred approach):

WUSE = Mean annual run-off in corresponding river basins (kL/ha/yr)
x Proportion of streamflow used or developed
x Proportion used for domestic and industrial (non-irrigation use)
x Proportion of non-irrigation water not already treated.

- Working from the consumption side:

WUSE = Volume of water used other than for irrigation per person (kL/yr)
x Population served per hectare
x Proportion of non-irrigation water not already treated.

The first approach was used here because it ensures greater consistency with the water yield estimates which use two of the same data items.

The 'proportion treated' factor was estimated on a district basis from the Department of Water Resources' table* showing types of treatment applied in each Victorian town (clarification, filtering and chemical treatment may all be necessary to restore fire-affected water).

The data used to calculate WUSE are shown in Appendix 26(c).

Net effects

The range of possible effects can be indicated by some examples. An above-average case would be an area of Mixed Species forest in Upper Yarra burnt at an intensity of 5 MW/m, with a 25 mm storm following, resulting in a cost of $55/ha. In Cann River the cost would be only $0.16/ha.

In the case of an area burnt at an intensity of 1 MW/m with light rains following, the cost would be reduced to $3 in Upper Yarra and $0.01 in Cann River.

The water supply costs generated usually seem to be less than the value of yield gains, although the unit cost of fully treating or obtaining temporary water supply is greater than the cost of most new supply schemes. The volume of increase in yield due to fire may be more than the pre-fire yield, and while the factor of 'proportion of yield used' is common to both situations, a large proportion of the water used is either insensitive to quality or already treated.

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* Department of Water Resources, 1984, Appendix W5.

17. NUTRIENTS

Fire has a number of complex effects on the nutrients in the soil and biomass. The heat and combustion processes release nutrients held in the soil, litter and biomass, but these may be lost from the site by:

- volatilisation (especially nitrogen) and transport in smoke and convection
- leaching with later rain
- erosion of ash, debris and top soil by rain and wind.

A portion of the transported material may come to rest in useful sites elsewhere.

The physical and chemical properties of the soil may be adversely affected by the heating but this generally occurs to more than a centimetre or two only in high-intensity fires. Organic matter desirable for soil structure and fertility is destroyed. Soil biota which are important for soil structure and nutrient cycling are reduced in numbers by fire, although their populations may quickly recover.

Shortly after the fire there may be a positive growth response (the 'ash-bed' effect) due to the mobilisation of nutrients, heating of soil, destruction of plant toxins and reductions in plant competition (Walker et al. 1983). Studies in WA jarrah and snow gum in the ACT have measured the apparent growth response.

However, any short-term effect of nutrients following fire should be captured implicitly in the data on timber losses discussed earlier. Most of the studies of Victorian timber trees in fact showed net growth losses.

Longer-term effects may follow from the depletion of the nutrient capital of the area by volatilisation, erosion by wind or water, or leaching (Raison 1980). The cost of such depletion lies in the effect on timber productivity, and the more intangible conservation values concerned with plant growth and species composition, but these effects are still uncertain.

In possibly the only direct estimate of timber losses available, Woods (1980) attributed serious declines of two or three site quality classes ($3 m^3$/ha/yr per class) in second-rotation pines in South Australian sandy soils to the loss of nitrogen and phosphorus in high-intensity slash burns. Such a loss could cost \$6750/ha at harvest time, or about \$745/ha when discounted back to the time of the fire.* The estimated cost of replacing the lost nutrients with the equivalent amounts of

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* One site class
Average loss by definition = 3 m^3/ha/yr Mean Annual Increment (definition)

= 2.5 x 3 m^3/ha/yr = 7.5 m^3/ha/yr
= 45 x 7.5 m^3/ha over full rotation
= 337.5 m^3/ha
= \$6750/ha at average royalty of \$20/m^3
Discounted loss = $\frac{\$6750}{1.05^{45}}$/ha
= \$745/ha

commercial fertiliser (which seemed to restore the health of the next rotation, in some cases), is about $400/ha. However, this technique for valuing the loss would be difficult to apply in native forest types where the effect of removing nutrients through fire could be quite different from the effects of adding them in a different form. Also, particularly if the soil is initially of high fertility, marginal losses of nutrient may have little effect on growth.

A similar loss of nutrients probably resulted from the wildfire in South Australia on 16 February 1983. However, early trials suggested that this could be correctable by sowing lupins to assist nitrogen fixation and soil stability as well as providing a grazing crop. Although the cost of treatment was about $67/ha, the policy was estimated as having a benefit-cost ratio of over 4:1, so there would appear to have been no net measurable cost to growth in that case. Nevertheless, there may be other less tangible adverse effects on soil structure and nutrient balance.

In eucalypt forests a nitrogen restoration program would be impractical and less necessary. Indeed growth of nitrogen-fixing legumes may be promoted by fire and even make nitrogen available in excess. Research in WA jarrah suggested that high-intensity fire may have the advantage of favouring leguminous species which tend to reduce the spread of the disease Phytopthora cinnamomi. Low-intensity fire on the other hand may favour Banksia species and the spread of Phytopthora. This possibility is of less significance in south-eastern Australia at present.

The loss of nutrients from wildfires (at long intervals) seems comparable with that caused by whole-crop harvesting and slash-burning. Some estimates suggest that the natural inputs to the nutrient cycle over, say, a 50 year cycle will compensate for the harvesting removals (Attiwill 1985). What is more relevant is the effect of fire on that part of the nutrient capital that is available and used, but data on this are even more deficient. Walker, Raison and Khanna (1983) maintain that there has been over-optimism that nitrogen balances can be maintained in Australian ecosystems under natural or man-made fires.

The only conclusion that could be drawn here is that there is insufficient basis for any estimate of economic losses from long-term depletion following fire.

18. BEE-KEEPING

By destroying the flowering potential of trees for many years, a severe fire can cause serious losses to bee-keepers. To take a fairly extreme example, it was estimated that a fire in Western Australia in January 1984 in a 90 000 ha area known as the Bee-keepers' Reserve resulted in \$3 500 000 loss of apicultural potentials.

When the relevant probabilities of loss are taken into account, the expected loss per hectare is quite small (compared even to the errors in other parts of the study). Nevertheless the total losses over the tens of thousands of hectares burnt on average each year are important to the industry, and the calculations may be of interest for their own sake.

The DAMAGE sub-routine calculates apicultural losses by the following equation:

$$\mathrm{BEELOS} = \mathrm{BEEV(D)} \sum_{F=1}^{7} [\mathrm{FAT(F)} * \mathrm{BYLOS(F)} * \mathrm{BSR(F)}] * \mathrm{H(I)}$$

where BEEV(D) = bee-keeping value per yield period per hectare of Mixed Species forest in district D
FAT(F) = area burnt of forest type F
BYLOS(F) = number of potential yields (harvests) lost after high-intensity fire
BSR(F) = value of forest type F relative to Mixed Species
H(I) = fire intensity factor
I = fire intensity (MW/m)

Each of these factors is discussed below:

Bee-keeping value, BEEV

Three types of loss have been included in BEEV:

Flowering potential

If the trees of understorey are killed or scorched, they may take years to recover their previous potential to supply nectar for honey and/or pollen for building hive strength.

The loss to bee-keepers is estimated here as the value of potential honey lost, less any costs saved by not harvesting that honey. In practice, in some situations bee-keepers may replace the lost honey by harvesting less preferred sites, in which case the costs could be measured as the increase in travel costs or reduction in value for lower grade honey. However, it is assumed that the cost calculated by either method would be similar at the present time when suitable bee sites are scarce.

The potential loss for honey, B1, was calculated as follows:

Wholesale price of honey*	$0.80/kg
less variable costs saved (travel, labour, etc.)**	0.25
Net value	$0.55/kg
Yield of honey per hive per harvest *** (stringybark)	50 kg
x Number of hives per hectare in exploited area (at 130 hives per licence area of 1.6 km radius, or 1000 ha)	x0.13
Yield of honey	6.5 kg/ha/harvest

Value per hectare of exploited area in Mixed Species forest per harvest
= $0.55 x 6.5
i.e. B1 = $3.58/ha/harvest

An alternative approach to calculating the value of forest land for bee-keeping is to use the rental value paid to the land manager. For example, the FCV charges in 1983 were:

Temporary licence, 3-6 months	$10/qr for 200 ha
Permanent licence	$15/p.a. for site + $0.07/ha of range, for nominal maximum of 800 ha.

Thus the total amount paid per hectare of range is only $0.05 for temporaries and $0.09 for permanent licences per year, or $0.27 over a 3 year period between yields. These payments are considerably lower than the values calculated above. However, bee range fees are not necessarily set with the objective of extracting the full surplus value from the bee-keeper.

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* ABS, Value of Agricultural Commodities Produced, and Livestock and Livestock Products. For 1983-84, Victoria, gross value of production = 3.1 million kg; quantity produced = 3.6 million kg; so unit value = $0.86/kg. Average of last 3 years was $0.80/kg.

** Suzanne Evans, The Economics of Bee-keeping: A Summary of Results from the 1980-81 Survey of Commercial Bee-keepers in Victoria, Department of Agriculture, Victoria, June 1983.

Variable costs taken were vehicle and travelling costs, hive maintenance and other production cost (including casual labour). These averaged $15 920 out of gross income of $51 160, i.e. 31 percent.

*** 'Harvesting' is generally only carried out at times of heavy flowering, which may be several years apart for some species.

As a check on the order of magnitude of the above figures, it may be noted that total honey production in Victoria averaged 3.9 million kg p.a. over the 3 years to 1983-84, and the total forested area (including woodland and high scrub) is 8 million ha, giving an average of 0.49 kg/ha/yr. This could correspond to an average of 6.5 kg/ha yield (as above), with 3 years between yields and 22 percent of the total area used.

Hives

The second type of loss, B2, refers to the boxes, bees and honey that are likely to be destroyed if present at the time of the fire.

Value of hive half-full of honey	$80
x Number of hives per hectare exploited	x0.13
x Probability of hives being present (assuming residence time of 2 months every 3 years)	x0.055
Expected loss	B2 = $0.57/ha

Pollination

Another valuable contribution by bees is the pollination of crops and orchards, with a resultant increase in yield. A bushfire could eliminate the feral bees and also the commercial honey potential, thereby removing the incentive for commercial bees to be brought in, until it recovers. During this time, the incidental value of pollination of neighbouring crops will be lost.

Some high-value crops such as apples and cherries are heavily dependent on bees for successful pollination. However, the average expectation of loss from a bushfire of this type is small because there is only a small probability that the burnt forest will be adjacent to farm land, and only a small proportion of farming land carries the type of crops assisted by bees. Estimation of the expected loss per year due to absence of bees is shown in Table 23 based on Victorian agricultural statistics for 1982-83.

A more comprehensive estimate by the Victorian Department of Agriculture suggested a total contribution by bees to Victorian production of $63 million, which is 1.8 times the above estimate. This included other crops such as safflower (50 percent reduction without bees), lucerne (19 percent), seed clover (92 percent), almonds (100 percent) and berries (50 percent).

Hence the area planted to affected crops has been adjusted upwards to 106 000 ha. Since the total area of agricultural land in Victoria is 14 255 000 ha, the probability of any random area of farm land carrying the affected crops is only 0.0074.

The probability of a fire in Mixed Species forest used by bee-keepers being within bee range of agricultural land (about 2 km) also has to be estimated, say at 0.3. For each hectare in the fire area referred to here, it is assumed that one hectare of farm land is within range.

Thus the average expected pollination loss, per year when bees are present, per hectare of forest burnt, is estimated as \$590 x 0.0074 x 0.3.

$$B3 = \$1.3/\text{ha/harvest}$$

The above three components were added to give a total value at risk.

$$B = B1 + B2 + B3 = 3.6 + 0.6 + 1.3$$
$$= \$5.5/\text{ha/harvest year}$$

District use

The factor PUB(D) tried to measure the probability that any hectare of forest would be used by bee-keepers during periods of heavy flowering.

Table 23. Effect of bee pollination on crops

Assisted crops	Loss in yield without bees (%) (1)	Area planted ('000 ha) (2)	Value (\$/ha) (2)	Total value (\$000) (2)	Reduction in value (\$000)
Lupins	18	21.0	46	918	165
Sunflower	40	14.1	106	221	884
Rape	16	4.3	84	319	51
Peaches	30	19.3	5 389	11 080	3 324
Cherries	95			1 500	1 425
Apricots	32			3 248	1 039
Pears	45			22 941	10 323
Apples	48			36 352	17 448
Total		58.7			34 659

Reduction in value per hectare of above crops = 34 659/58.7 = \$590

Sources:

(1) B.Oldroyd, Vic. Dept of Ag., and various papers such as D.E.Langridge and R. D.Goodman (Vic. Dept Ag.), A study on pollination of sunflowers, Australian Journal of Experimental Agriculture and Animal Husbandry, Vol.14, April 1974.

(2) ABS: 'Value of Agriculture Commodities Produced, Victoria', 'Crops and Pastures; Australia'

Most accessible native forest in Victoria is exploited by bee-keepers, but access depends on density of roading, and off-road terrain. The proportion used in each district was based mainly on:

- The numbers of permanent and temporary bee-range licences granted by the FCV (shown in Appendix 27), in relation to total area of district.
- The extent to which private land could be used either directly or as a base to exploit forest land without registering with FCV (partly from subjective assessment of depth of forest blocks).

The resultant estimates varied from 5 percent for Corryong to 90 percent for Maryborough and Shepparton.

The bee value at risk in each district, per yield, per hectare of Mixed Species forest, BEEV(D), was then given as

BEEV(D) = B * PUB(D)

Species value

BSR reflects differences in apicultural value between the broad tree species groups, taking into account:

- honey and nectar yield, or value for wintering and strengthening colonies
- quality, as reflected in price
- accessibility insofar as not accounted for in BEEV(D) for Mixed Species
- tree spacing

The rough averages resulting are shown in Table 24.

Yield lost

The number of yields (harvests) lost following a high-intensity fire, BYLOS, was estimated for each forest type from the number of years before recovery divided by the number of years between yields, as shown in Table 24.

Table 24. Honey yields lost after fire

Forest type	BSR Value relative to Mixed Sp.	Number of years to recovery	Number of years between yields	BYLOS Number of yields lost
Ash, HEMS	0.2	18	3	6
Mixed Species	1.0	9	3	3
Red Gum, Box-I'B	1.2	9	3	3
Softwood	0	-	-	0
Alpine	0.1	5	1	5
Mallee,Native Con.	0.3	10	2	5
Grass, Heath, Scrub	0.05	3	1	3

Eucalypts are erratic in their flowering habits and may give a good yield only once in three, four or five years. Shrubs are likely to be used annually.

Losses may be due to direct damage to buds and flowers, defoliation and set-back to growth. With higher-intensity fires or lower trees and shrubs, the vegetation may be killed and honey yields are lost until regeneration occurs. With two or more fires in quick succession, the seed source may be destroyed and the honey flora permanently eliminated.*

Fire intensity function

The extent of bee-keeping losses increases as fire intensity increases, since the trees are burnt to a greater height, recovery takes longer and there is a higher probability of trees being killed outright.

To calculate damages in the model, the standard loss, in terms of number of yields lost, was specified for a 5 MW/m (high-intensity) fire, and a function constructed to adjust the loss for other intensities. Even at low fire intensities (e.g. prescribed burns) there may be a loss of one or two years yield from understorey plants, while loss of any hives present in the area is likely even from a surface fire. The damage rises sharply as intensity moves up to crown fire level, and then approaches a maximum.

A function with the required characteristics is illustrated in Figure 33 and the equation:

$$H(I) = 0.3 + \exp(1 - \frac{6}{(1+I)})$$

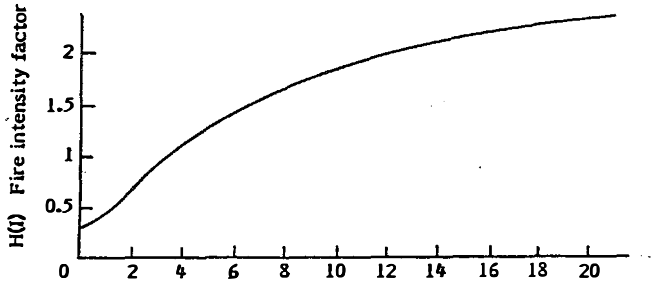

Figure 33. Function relating loss of honey yields to fire intensity

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* These tendencies in WA coastal plains and sand plains are discussed in R.C. Burking and A.C.Kessell (WA Dept Ag.), Submissions and Comments to Federal Council of Australian Apiarists Assocn on the Effects of Bushfires on Honey Production for Project Aquarius, 1983.

Out of the total fire area, 50 percent is assumed to be burnt by the head, 20 percent by each flank and 10 percent by the rear. Damage is then calculated separately for each segment according to the fire intensity on each arc.

Combining the above factors, the average loss from a moderate intensity fire (1 MW/m) in the Bendigo district, for example, would be $5.70 per ha for Mixed Species and $6.84 per ha for Box-Ironbark.

19. NATIONAL PARKS AND CONSERVATION

The damage sub-routine includes an estimate of the effect of bushfires in reducing the value of National Parks to visitors for enjoyment, recreation and study, and a component for the damage to scientific or less tangible conservation values.

The immediate effects of the fire are to destroy undergrowth and possible tree canopy, replacing attractive vegetation with black char and ash. Falling branches and tree tops can be dangerous particularly in the few days after the fire. Those visitors who normally go to enjoy the verdant scenery and diversity of plants and animals are likely to be disappointed. There may be benefits for some visitors, however, as mentioned later.

Re-vegetation begins within weeks and proceeds gradually so that after three or four years there may be sufficient greenery and diversity for the casual visitor to be unaware of the effects of fire. Complex changes in the ecology may nevertheless continue to occur for many years.

The model tries to value the losses in the following equation:

$$\mathrm{PKLOS} = \mathrm{VL(N)} * \mathrm{F} * \mathrm{VISNO(N)} + \mathrm{SCILOS(N)} * \mathrm{FA}$$

where VL(N) = loss per visitor day from 'standard' fire in park N
VISNO(N) = number of visitor days per year for park N
F = severity factor
= $1.5 * A + 0.35$ if $A > 0.1$
= $5 * A$ if $A < 0.1$
A = proportion of park's total area burnt
SCILOS = scientific loss from standard fire ($/ha)
FA = fire area (ha)

The factors are explained below.

Visitor loss survey

The estimates of visitor loss were derived from a survey undertaken in three NSW National Parks by Dr Jeff Bennett*.

Respondents surveyed in the parks were asked, through a series of hypothetical bidding questions, to estimate their willingness to pay to visit the park before and after fires of specified sizes. This aimed to measure the effect both on people who would stay after the fire but enjoy their stay less, and those who would go elsewhere at higher cost or at some sacrifice in enjoyment.

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* Full details of the theory and results are given in the report: Bennett, J.W. (1984). The cost of bushfires to National Park users. Department of Economics, University of NSW, Duntroon ACT.

The survey was conducted specially for the Project Aquarius economic study but yielded results about the value of National Parks that are of interest in themselves. The mean values estimated for the pre-fire willingness to pay to use each park (per group visit) were $4.74 for Ben Boyd, $2.15 for Morton and $8.57 for Kosciusko.

Table 25. Losses to visitors from fire in National Parks.

National Park	Fire size	Loss ($ per group visit)		Av. annual loss over 3 yr ($)	Av. no. visitors /group	Av. no. days /visit	Av. ann. loss /vis.day over 3 yr ($)	Propn. of Park burnt
		soon after fire	12 month after fire					
Ben Boyd	Small	0.32	0.93	1.42	3	5.5	0.09	0.14
	Large	0.39	0.79	1.42			0.09	0.55
Morton	Small	0.28	0.05	0.21	3.3	1	0.06	.0006
	Large	0.46	0.30	0.68			0.21	0.008
Kosciusko	Small	0.81	0.75	1.58	3.1	4.3	0.12	0.004
	Large	0.90	0.70	1.60			0.13	0.013

Individuals' estimates of loss due to the fire were mostly small and many were zero. The average loss per group visit ranged from 5c to 90c. When converted to a per visitor day basis, and extrapolated to a total over 3 years, the average loss ranged from 9c to 21c (Table 25). The losses were low apparently because activities were not dependent on the state of the vegetation in the park or they could substitute another park or else another activity with little sacrifice. Some visitors may also perceive certain benefits from the fire, e.g. enhanced display of wildflowers, or easier walking following the clearing of undergrowth, or have an interest, academic or otherwise, in the after-effects of fire.

Since the survey gave observation points for a particular set of circumstances (type of park, size and location of fire, time since fire), it was necessary to extrapolate the results to the whole range of situations possible in Victoria.

The item, average annual loss over 3 years is a notional figure, not representing the loss for any particular visitor, but being required to standardise the loss with the statistics of annual number of visitor days (by which it is multiplied). It is designed to capture the total losses of visitors after the fire before the park recovers, on the assumption that the average loss in the first year is the average of the losses soon after and 12 months after fire, and that thereafter the loss falls to zero after 3 years as the park recovers. The averages for the 3 years are then totalled.

The estimated difference between mean loss immediately after the fire and 12 months after was not statistically significant. In the case of Ben Boyd National Park, the mean loss was actually greater 12 months later, but this apparent anomaly was doubtless a reflection of the fact that the answers were obtained from two different sub-samples (to keep questioning time down) and sub-sample sizes were small.

The survey respondents were questioned about the effect of a hypothetical fire in their immediate vicinity which was one of the main focal points for visitors in each park. It was assumed that this loss would apply to all those visitors affected by the fire, while the number affected was calculated as a function of the proportion of the park burnt and total visitor usage.

The expected proportion of visitors affected would equal the proportion of the park's total area burnt only under certain extreme circumstances, namely: (i) fires strike randomly throughout the park; (ii) visitors remain in fixed sites in the park and; (iii) visitors are only affected by fires in their immediate vicinity. However, it was assumed that the proportion of visitors affected would be several times higher than the proportion of park burnt (at least for those fires affecting a minor percentage of the park) on account of two factors:

- many visitors range widely over the park (e.g. bushwalking) or can view a wide area from a look out;
- there may be a greater tendency for fires to occur near visitor focal points.

Function F which has the shape shown in Figure 34 was meant to capture this effect operating through fire size. The 'benchmark' figure of F = 1 at A = 0.43 implies that all visitors to the park are affected by a fire burning 43 percent of the Park area (based on the size of the fire in the Ben Boyd survey). Values of F greater than one are intended to capture the effect of fire intensity - presuming that larger fire areas are correlated with higher intensity and hence greater loss per person. Although this effect has not been directly measured in the survey, it could be expected that higher intensities would affect more of the vegetation and lengthen the recovery period. This would be roughly correlated with fire area insofar as higher-intensity fires are more difficult to control within a small area.

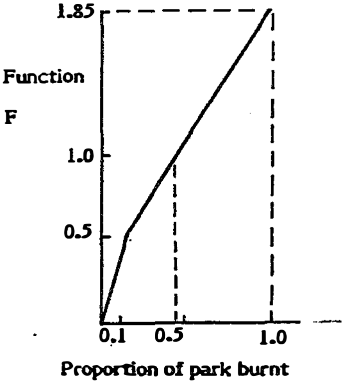

Figure 34. Function F relating number of National Park visitors affected to area burnt

The estimates of the difference in mean loss between small fires and large fires were also based on small sub-samples and were not reliable. For the Ben Boyd and Kosciusko samples, little overall differences was measured, while for Morton the mean loss per visitor day for the large fire was about three times greater than for the smaller one. It may be noted that, while the hypothetical fire sizes varied from 70 ha to 90 000 ha, the mean loss per visitor day varied by a maximum factor of only 3.

It was concluded only that the mean loss for a typical fire would be in the range of 5 to 20 cents per visitor day in the zone affected.

This range of figures from NSW parks was used as a benchmark to set visitor loss figures for each Victorian park, after adjusting for particular features of the parks likely to affect visitor sensitivity to fire. The mean losses in the survey were brought down by those visitors, for example, who went to Ben Boyd for water sports, to Morton to use the travellers' facilities or to Kosciusko for skiing. These features were also present in some of the Victorian parks (coastal, alpine and roadside), but in general visitor enjoyment in most parks seemed likely to depend more on the forest scenery, flora and fauna. Hence average losses were assumed to be higher, ranging from 12c for Gippsland Lakes to a maximum of 50c for Ferntree Gully (Appendix 28).

The results of multiplying the various factors are illustrated for the fire of 23 000 ha in Croajingalong Park in 1983, total area of which is 86 000 ha and annual visitor usage 188 600 and mean loss from fire \$0.20, A = 0.27,F = 0.75

Total visitor loss = \$0.2 * 188 600 * 0.75 = \$28 290.

Scientific loss

Fire also may have an adverse effect on environments which are being preserved by park authorities for their scientific study value, as a gene pool or for their 'existence' or future 'option' value. While periodic fires in certain environments are now thought natural and desirable by environmental managers, there are many areas of rare species or communities where wildfire is undesirable on ecological grounds at most times.

In some cases, these conservation values may also be appreciated by visitors and hence reflected in answers to the above survey. However, it is accepted that there are more esoteric values worth preserving which are at present understood mainly by scientists or specialists.

Valuing conservation areas

It is extemely difficult if not impossible to place a value on such intangible benefits but some figures of at least partial relevance are reviewed below.

Bennett (1982) tried to estimate the 'existence' value of Nadgee Nature Reserve through a direct questionnaire applied to a random sample of people. Most people claimed that they would be willing to pay some positive amount (say, as higher taxes) to maintain the reserve for its rare ecological value, even if entry to the reserve were restricted to scientists researching the area. The average amount respondents were willing to pay was \$20. With such hypothetical questions, some respondent bias (in both directions) is expected, although in this case the author argued that a checking procedure had shown the respondents to give generally honest answers on another question.

The survey suggests that the general public does accept the idea of conservation for scientific or existence value and the total amount that all taxpayers are prepared to contribute could be quite large. The figure of $20 per head for Nadgee could not be aggregated over all parks, because of the budgetary constraint amongst other reasons, but is more relevant to decisions on marginal changes in park protection.

The amounts paid by National Park services to acquire land for Parks gives an indication of the minimum conservation value placed on the area by park management. The prices paid by NPS Victoria recently have ranged from $400/ha for agricultural land to $5000/ha for land close to suburbs. Since the price is limited by the value of the land in its best alternative use, the true value as a National Park could be far above the price paid. However, part of the cost is attributable to the recreation value, already measured above. Land purchases near Melbourne tend to be at the highest price but would also include the highest component for recreational use. More relevant figures would be the amounts that agencies are willing and able to spend on preserving or restoring particular ecological communities.

For example, the cost to the Victorian NPS over the past 12 years on an intensive project to rehabilitate the natural environment of the Organ Pipes National Park is estimated at about $11 000/ha ($960 000 over 85 ha), with at least as much input of resources again from volunteers (Friends of the Organ Pipes) for collecting and growing seeds and eradicating weeds etc. In the Hattah-Kulkyne Rehabilitation Project, NPS has spent about $200 000 in a 6000 ha block since 1981 mainly on rabbit and kangaroo control ($33/ha). In the next few years expenditure will shift to revegetation.

The Organ Pipes case seems to be an exceptional one, and available funds would not permit such a heavy investment across broad areas. Nevertheless, it does indicate the high potential value placed on conservation of unique areas by interested groups.

Ecological effects of fire

The data needed for this study, however, concern not the whole value of a conservation area, but that part of the values lost because of fire. In some instances fire may destroy the protected species permanently, but generally the results will be less drastic. Burning may even be desirable in some cases to bring about regeneration of fire-dependent species.

A report on fire in the National Parks of north-west Victoria* (Wyperfeld, Little Desert, etc.) concluded that the number of plant species per unit area is much greater soon after fire, but a few species in mallee and heath are restricted to long-unburnt areas. Bird species are consistently more plentiful in long-unburnt vegetation, but some species breed best in highly productive mallee of intermediate age, 15-20 years after fire. Requirements for other areas and species may be quite different.

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* NPS Vic. Annual Report 1978-79, p.15

Rainforest, alpine vegetation, ash-type eucalypts and native conifers, for example, are particularly liable to death from fire. In the case of mountain ash (Eucalyptus regnans), trees are likely to be killed by a single medium-intensity fire, but the burnt ground provides an ideal ash-bed for regeneration from seed. A second fire within about 15 years however, could eliminate the species in that area, as it would kill the saplings before they have produced seed. Unless there is a fire every 200-400 years to provide a suitable regeneration bed, the species could also die out as the over-mature trees die and are not replaced. In some areas, rainforest is likely to take over if fire is excluded.

Studies of fauna have generally shown that individual animals may perish during or after fires, particularly high-intensity fires, but there seems to be no evidence of species being eliminated. Post-fire vegetation recovery will in fact provide a more favourable habitat to some animals than before, although the species favoured change through the successional stages of recovery.

Research by Deakin University scientists into areas burnt in the Ash Wednesday fires found that they were mostly recolonised first by different plant and animal communities. In some areas, such as near Anglesea, native species had disappeared in the first 2 years but mouse numbers had increased greatly. In other areas, native animal communities had been greatly reduced.

There may be an important interim loss if a useful or interesting species is set back by 50 years say. A permanent conservation loss is clearly more important although discounting of future values has the effect that the present value of losses to the current generation tends to exceed that of all later generations.

The frequency of fires is now several times greater than in the natural ecosystems before the advent of man, as only 10-30 percent of wildfires originate from natural causes such as lightning. The frequency of high-intensity fires is also probably greater than under aboriginal burning practices, which seemed to be more frequent and light.

Further, the NPS is increasingly carrying out deliberate burns of the appropriate timing, location and intensity when they are thought desirable on ecological or other grounds such as fuel reduction. For example, in 1980-81, a 4000 ha block of Little Desert was burnt to establish a range of ages since burning, producing a mosaic effect and increasing flora and fauna diversity (NPS Annual Report 1980-81).

In these circumstances, wildfires can generally be considered as unwanted and undesirable.

Increase in marginal loss

An important factor affecting the size of conservation losses from fire is the proportion of the available reserves of a particular species that is destroyed. Loss of 10 percent of the reserves of a species may be quite tolerable, but the marginal value of the loss for each additional percent burnt would begin to climb steeply as the percentage approached 100, and the species approaches extinction.

Conceptually it seems that the marginal loss from the burning of each additional hectare of a unique park would follow a shape like f(A) in Figure 35. The marginal loss is modest for small areas, but begins to rise rapidly after half the park is burnt ($A = 0.5$).

The total loss (T) could be described mathematically as:

$$T = \int_0^A f(A)\, dA$$

The average loss per hectare would then be T/A, which would rise less sharply than f(A).

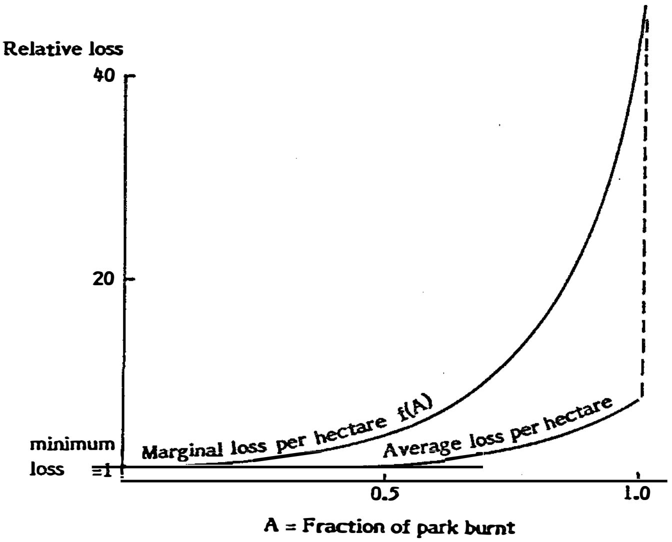

Figure 35. Function relating conservation losses to proportion of park burnt

Hence in this study, a base conservation value is set for each National Park, which represents the loss per hectare for small areas burnt, and this is multiplied by an exponential function which increases with the proportion of the park burnt. The proportion of the park's area burnt is not a particularly good indicator of the proportion of particular environments or species destroyed, but, insofar as parks are created to protect rare or representative communities, it is probably the closest indicator readily available.

The starting point S is the minimum loss per hectare for small fires. In the absence of any real data on the topic, arbitrary values for S for each park have been specified from the lower end of the scale for estimates of native timber damage, i.e. $5-20/ha. This is based on the idea that if National Parks have been judged worthy of protection for their environmental values, the values would be at least as high as that of common forest reserved for timber.

Different values within this range were given to each park on the basis of subjective assessments by park officers on the sensitivity of the park's conservation values to fire.

The following function was used for the average loss per hectare:

$$Y = S * \exp(5A - 3)$$

where A = proportion of park burnt

S = mimimum loss/ha

This function had a suitable shape and reflected the desired rate of increase in marginal loss, so that the average loss is only 1.6 times the minimum value when $A = 0.5$, but approaches a maximum of about 8 times S as A approaches 1. This corresponds to an upper limit for the average loss of $160/ha, and an upper limit for the marginal loss when nearly all of the park is burnt of around $700/ha; still less than 5 percent of the expenditure on the Organ Pipes referred to earlier.

Future values

Some comments on the significance of effects in future years are relevant here. As with timber and water losses, the environmental losses from fires can reach far into the future, e.g. rainforest could take hundreds of years to recover its original structure. When discounting of future losses is applied, however, the present value of losses in distant years becomes insignificant. For example, if fire causes a loss of $L per year forever, the present value of the infinite series of losses, discounted at 5 percent p.a., is 20L. The portion of this relating to losses after the 100th year, however, is only 0.15L.

This also means that, although it may be some consolation that the rainforest will recover its original structure in 400 years, the measured loss in economic terms will be just as great as if the loss were permanent.

Another factor, however, is the tendency for the per unit value of environmental services to increase over time, as a diminishing amount of natural environment becomes scarcer in relation to an expanding population. Increasing income and educational levels are also correlated with the increasing demand for environmental services.

Other natural resources of limited distribution, such as timber and water, could also be subject to increasing scarcity and price but such pressure can be moderated by technological improvements which increase output and reduce cost. No such solutions are possible for environmental services such as those from wilderness.

For example, Dr P. Greig estimated that demand for most forest recreation activities has been increasing at the rate of 10-20 percent p.a. (FCV Research Activity, 1973). A similar factor presumably applies to scientific values as the balance between natural environment and human civilisation shifts. As long as the rate of increase in future value is higher than the discount rate, the present value will continue to increase with each additional future year taken into account. Indeed, the aggregate will have no finite bound unless a limit to the rate of increase or the future time span is imposed.

If, for example, a 10 percent rate of increase applied each year for the next 50 years to the annual value in the above situation, and then the value stabilised, the losses would have a present value of 229L instead of 20L.

It can thus be seen that the effects of a long-term environmental loss may be greatly magnified when the increase in values over time is taken into account.

Direct costs

Direct losses of facilities, and expenditure on suppression and rehabilitation recorded by the NPS on each major fire were also input to the model. The cost of rehabilitation could be double-counted in the conservation loss where it applies to the burnt area. However, this expenditure often relates to draining, covering or replanting fire lines and bulldozer tracks, which can be classed more as a cost of suppression than as fire damage.

Conservation losses outside National Parks

Recreational and conservation losses of a similar kind could occur in forest parks and reserves and, to a lesser extent, in general bushland. Some forest parks, near Melbourne in particular, have very high visitor usage, but no data on the area of forest reserves burnt are available.

An arbitrary allowance for environmental losses in areas outside National Parks has been included, at $5/ha for most native forest types. Higher values were set for fire-sensitive forest types of more limited occurrence. For alpine areas, $100/ha was specified. For ash and high elevation mixed species, the conservation value was set at an amount sufficient to offset the gain in water supply (up to $1500/ha) after fire, on the grounds that land managers do not consider it desirable on balance to kill young ash forests for the short-term water gain.

No specific estimates for the effect of fire on animals for hunting has been made, and no discussion of it has been found in Australian literature although it is common in North American studies. It is assumed here that most game animals can either run strongly enough to escape most fires, or quickly recolonise burnt areas as the fresh green shoots favour their feeding.

20. AGGREGATION AND OUTPUT ANALYSIS

Aggregation

The value of losses on each sample fire is calculated by the methods discussed above for each suppression tactic. The benchmark loss is based on the final simulated area and intensity under ground suppression only, while the loss under other tactics is based on the area and intensity simulated under those tactics.

Ground and air costs for each tactic are calculated by the methods described earlier. Cost-plus-loss is then calculated for every tactic, and the savings for each tactic on a given fire are calculated by deducting the cost-plus-loss for each tactic from that for the benchmark. Cost-plus-loss savings may be positive or negative, but savings in area and time should always be greater than or equal to zero since additional forces are being used. When airtankers are tested, savings in ground costs and losses will always be greater than or equal to zero, but because of the additional airtanker cost, overall savings may be positive or negative.

Results by resource combination

The area, savings and other results at the end of each tactic are temporarily stored but, for any given fire, aircraft model and number, only the result for the optimal location of attack and retardant are written to the output file EVERY. At the end of each fire the result for the optimal tactic is written to another file BEST if required.

The EVERY and BEST output files have been subject to further analyses, using the SAS software package. The BEST file by itself is of limited use. It indicates which aircraft may be suitable by virtue of the number and type of fires on which they are optimal. However, the total results from BEST are of no significance unless it is feasible to have all the airtanker combinations listed available at once. In Australia's situation, assuming that a limited number of types of aircraft are initially available, the results from particular aircraft have to be studied by dissecting the EVERY file.

Appendix 36, for example, shows the total savings (in variable cost-plus-loss) achievable from a range of airtankers at particular home bases. All savings, whether positive or negative, have been aggregated, except for losses greater than $5000. The selection routine in AIRPRO has already eliminated many tactics not likely to show a surplus, but of the tactics still selected, about 30 percent result in a loss. Many such minor losses seem likely to occur in practice with a quick dispatch policy, as it is often difficult to tell at the outset of a fire whether aircraft would be a cost-effective addition to the attack.

At this stage another tactic optimisation routine has been carried out, selecting for each aircraft model and number available, that tactic with the optimal number of aircraft used on each fire (which may be less than or equal to the number available).

Weighting

The aggregate savings for the tactics retained on the sample fires run through AIRPRO are first weighted, before tabulating, to scale them from the sample size to the total number of fires expected over the long-run. Since the sample is stratified by area class and main forest type or damage class, the results (e.g. total savings) for the fires in each cell are multiplied by the ratio population number in cell:sample number in cell before all cells are added.

To indicate the effects of applying airtankers in one particular year, both sample and population numbers should refer to that year. However, since dedicated airtankers are usually purchased for an indefinite period, the more general question concerns their long-term results over the good and the bad years. Thus the results here are expressed mostly in terms of average expected savings per year.

Net savings

The variable or gross savings results are useful for comparing tactics that can be changed at will on any fire (e.g. retardant or arcs of attack). However, to compare investment decisions on acquisition of different aircraft or base configurations, it is essential to deduct the fixed costs of the number of aircraft and bases available to arrive at the net savings. This is the last step in the output analysis.

21. RESULTS

The results of simulations for Victoria indicated positive savings for several types of large and small airtankers and helicopters under certain basing and dispatch systems, and also for additional ground crews. Water-scoopers, however, gave negative results in all situations tested.

The results for different suppression resources and types of fires are discussed below, beginning with ground crews and then the large land-based airtankers. A number of features common to all types is discussed mainly in the first section on the DC6, while the discussion of other types concentrates on their special features and contrasts them with the DC6. After discussion of the results of the testing of each resource independently, consideration is given to combinations of resources.

A selection of the main tables from the output analysis programs have been included as Appendices and are referred to where appropriate in the text.

All economic results given below refer to expected average annual values in $A1983, after weighting by long-term fire frequencies. To allow for inflation up to 1985, about 10 per cent could be added to all figures. Gross savings (or losses) refer to the surplus of savings in damages and ground costs over aircraft operating costs and retardant. Net savings equal gross savings less fixed costs of the airtanker and base system - largely due to capital costs and stand-by labour.

Ground crews

Simulation of the historical fires with one additional machine crew in each of 45 forest districts yielded gross annual savings of $713 000 (Appendix 35). Given fixed costs of $13 280 per crew, net savings of $115 000 remained (Appendix 29). An important assumption underlying the estimate of fixed cost is that only 10 per cent of the labour costs and vehicle costs for the fire season need be attributed to fire suppression. Even if productive work can be found for the extra resources for most of the time when they are not fighting fires, the funds must nevertheless be found to finance their availability for the whole fire season, amounting perhaps to $80 000 per machine crew. Thus, the net savings represent a rate of return of only 2 per cent on the required annual outlay, and would be cancelled out by a small rise in the share of wage costs allocated to fire suppression.

Savings by the ground crews are posited on the same attack delays as were recorded for the suppression forces on the historical fire, and rely only on the additional line-holding ability attributed to the new crews, based on rates observed in Project Aquarius trials. However, their contribution on some fires could be over-estimated where, for example, there were special problems of initial access not encountered in the trials. Similarly, short travel times on historical fires may have been possible only for mobile hand crews or because some workers happened to be close to the origin of the fire. Bulldozers and tankers at the district base might have a substantially longer travel time. On the other hand, attack delays might often be reduced if the extra crews were dispersed from base whilst on stand-by.

Most of the savings (90 per cent) were concentrated in 16 districts (Dandenongs, Alexandra, Cann River, Nowa Nowa, Swifts Creek, Bendigo, Mansfield, Bright, Mirboo, Heyfield, Daylesford, Otways, Trentham, Rennick, Stawell and Dimboola). Limiting the investment in machine crews to these districts would increase net savings to $652 000. However, the distribution of fires and savings between districts could be significantly different over the long-term from that in the 5-year sample. In that case, additional ground crews based only in the above districts would be unable to reach fires in other districts with the speed implicit in the model, particularly with the relatively slow travel speeds of bulldozers and tankers.

Simulation with an additional hand crew in each district produced gross savings of $372 000 and net savings of $63 000 after deducting fixed costs of $6860 per crew. The rate of return on the annual outlay was 20 per cent. Limiting the strengthening of crews to the 15 districts showing positive net returns increases total net savings to $326 000. However, this would overestimate savings in a future period for the same reasons as for machine crews.

Douglas DC6B

The analysis produced positive annual net savings of $136 000 with a single DC6 stationed at Mangalore, a fairly central home base. Gross savings totalled $660 000, before deducting fixed costs of $524 000 (Appendix 29). The rate of return on the fixed annual outlay was 26 per cent, considerably higher than for the ground crews.

As for all the large aircraft, increasing the number of aircraft available increased gross savings by less than the increase in fixed costs. A second DC6 added only $69 000 to gross savings, resulting in a net loss of $297 000 for 2 aircraft (Appendix 36, 37). Similarly, 3 aircraft, whether all at the central base, or one at each of Mangalore, East Sale and Hamilton, gave rise to an even higher net loss.

Fire types

The favourable results for a single DC6 arose from large savings on a small number of fires. An average of about 8 fires per year (in frequency-weighted terms), yielding savings of more than $10 000, accounted for 94 per cent of total savings (Appendix 30, 39). Those yielding savings of more than $500 000 accounted for 70 per cent of total savings, but have an average frequency of about 1 in 7 years. The sample fires on which the greatest savings occurred included a major pine plantation fire and several forest fires over 1000 ha in historical size. Several grass fires between 20 and 1000 ha which caused property damage of many thousands of dollars also generated significant savings.

Application of the DC6 in the model reduced the areas burnt to less than 100 ha, and in some cases less than 1 ha. For a number of the large fires, the DC6 was the only one of the aircraft tested which had a dramatic impact on fire size, as the length of pattern laid was sufficient to reach the threshold necessary to hold the fire with the first load.

A further 25 fires per year give minor savings of up to $10 000 while there were about 16 fires per year on which the aircraft was dispatched on the model's criteria but returned a gross loss.

The dispatch strategy avoided attack on several hundred other fires per year. The DC6 was failed on the preliminary tests and not subject to a full simulation mainly on account of:

- maximum possible savings (if the fire were controlled immediately at detection) being less than the cost of delivery of one load, or
- ground control being achieved before the airtanker could make a drop, or
- at the other extreme, fire intensity being too high.

Of the total gross savings by the DC6, 70 per cent were on FCV fires and 30 per cent on CFA-only fires (Appendix 37). In relation to the main vegetation type, 34 per cent of total savings were in Mixed Species (dry sclerophyll forest), 41 per cent on Grass, Heath and Scrub, 16 per cent on Softwood, and 6 per cent on Ash and High Elevation Mixed Species (Appendix 45).

In relation to the seriousness of fires, 34 per cent of savings were on fires where the total cost-plus-loss was between $10 000 and $100 000, and 58 per cent between $100 000 and $1 million (Appendix 39).

The gross savings by the DC6 were larger than for other aircraft in every year although in most years none of the aircraft saved sufficient to cover fixed costs. However, the greatest advantage of the DC6 was shown in the most severe fire season 1982-83 which accounted for 52 per cent of its savings over the 5 years studied, after weighting by long-term frequencies (Appendix 42). By contrast the proportion of savings made in the severe fire year was less than a third for some of the smaller aircraft and water-scoopers (unless more than one aircraft was used).

Forty per cent of the area savings by the DC6 were on fires with an average head intensity of less than 750kW/m, whilst another 53 per cent came from fires between 750 and 3000 kW/m (Appendix 34). However, the intensity at the time the aircraft made the retardant drops was often different from the average intensity. Fires offering the greatest savings were those with a sufficiently high overall rate of spread to cause severe damage but with an intensity at the time of attack within the limits of airtanker effectiveness.

Similar considerations apply to the fire danger index. Fires where the fire danger rating (at 3pm at the nearest station) was low accounted for 11 per cent of savings, moderate for 45 per cent, high for 20 per cent, very high for 23 per cent and extreme for 0.1 per cent.

Ground attack delays were less than 1 hour on fires accounting for 58 per cent of the DC6's savings, with 16 per cent between 1 and 2 hours, and 25 per cent over 2 hours. For the latter two groups where ground delays were over 1 hour, the aircraft had the advantage of arriving first at the fire. There were nevertheless substantial savings on several fires where ground delays were less than 40 minutes. These were generally in areas with valuable resources at risk where the contribution of the DC6, even after the first ground crew's arrival, was vital to control.

Initial attack was the basis for success in most of the fires. That is, where significant dollar savings were made, the fire was generally confined to a fraction of its potential area with the use of airtankers. Once a large perimeter was established, the airtanker operating costs generally exceeded the savings made in ground costs and losses, due to the high cost per metre of line held by aircraft.

The results quoted above are based on a minimum dispatch delay of 10 minutes, combined with the assumption that, except on high fire-danger days, aircraft are not dispatched until the fire has reached at least 200 m in perimeter, with the aim of avoiding numerous wasted missions. The imposition of this constraint reduced gross savings by about 15 per cent for the DC6 relative to immediate dispatch, but the possible reduction in unnecessary mission costs has not been quantified. The extra delay criterion still left significant net savings for the DC6 although it had a more marked effect on savings for small aircraft. It might still be difficult to attain in practice the degree of discrimination in dispatch decisions assumed in the model.

Fire types not suited to air attack

Like the airtanker savings, the great bulk of actual losses from bushfires are concentrated on a small number of fires. However, the large airtanker's savings were less than 3 per cent of the maximum losses. On most of the damaging fires, in particular those of Ash Wednesday, airtankers failed in the model on account of the high intensity of the fires, the burning around of drops because of the rapid rate of arc growth, or burn-through before the ground crew arrived.

A combination of factors reflected in the model explains why the great majority of fires could not be economically attacked by airtankers and the great majority of losses could not be avoided.

In accessible terrain, machine crews are at least as effective as airtankers in holding low or medium-intensity fires, and do so at considerably less cost per unit of fire-line. Against high-intensity fires such as are responsible for most of the damage in Australia, airtankers are ineffective, as are all other means of direct attack. Most of these fires began or were detected in conditions near the daily peak fire danger and grew rapidly, leaving little opportunity for initial air attack when still at a manageable size.

Most of the fires which involved great property damage or loss of life began in places fairly close to settlements so that travel times for ground crews were short and did not give airtankers a particular advantage. The same applied for fires in valuable pine plantations which are generally well roaded. Ash forests are also valuable and sensitive to fire, but burn infrequently. When they are dry enough to burn, the fire intensity in the heavy fuel is generally beyond aerial attack.

The majority of fires beginning in remote locations cause little damage, due to the fire resilience of most eucalypts and the low timber values. When future harvest losses are discounted at normal rates, the estimated loss per ha is only $10 - 40 for Mixed Species in most situations. Only an average of about 7 forest fires per year grow to more than 1000 ha at which size total damages are significant. While some such fires repaid aerial attack in the model, many were too fast-spreading and intense.

The few successful attacks in the model on major historical fires occurred generally in the morning before the fires had attained their peak spread rate, and either where there was a long travel time for ground crews or a substantial delay in crew build-up to full strength.

Bases

The contribution of the three different retardant bases to gross savings by the DC6 was East Sale 85 per cent, Hamilton 10 per cent and Mangalore 5 per cent (Appendix 43). For water pick-up, Avalon was also a useful base.

Considering that the main savings were made closer to retardant bases other than the home base, it might be thought preferable to base aircraft at these airfields as well. However, the option of three DC6s - one at each of Mangalore, Hamilton and East Sale, when tested, returned gross savings only about 30 per cent higher than the one aircraft option whilst nearly trebling the fixed costs. Hence a net loss resulted with three aircraft.

The reason for this result in the Victorian model was that many of the fires on which major gains were made were nearly as close to the central base as to either of the other two, while in some other cases the large airtanker could still play a crucial role in initial attack even with an additional 30 or so minutes flying time.

The distance between fire and retardant point was less that 100 km for only 33 per cent of the area savings, with a further 62 per cent between 100 and 200 km (Appendix 38). Retardant bases are inexpensive compared to the rest of the airtanker system and a denser distribution of retardant bases for the DC6 might be thought worthwhile to increase delivery rates per hour. However, given the large size of the DC6, the possibilities for other bases are limited. The only other airfields that can accommodate the DC6, such as Avalon and Mildura, tend to be on the periphery rather than central to the main Victorian fire risk zone.

Retardant type

Long-term retardant was responsible for 69 per cent of the savings and water for 27 per cent (Appendix 46). Grass, Heath and Scrub fires accounted for 76 per cent of the savings with water, but only 24 per cent of savings with long-term retardant (Appendix 45).

These results refer, for each fire, only to the retardant providing the largest economic savings, although in some cases this may be associated with a lower area saving. In many cases the savings from less economic retardant types were only slightly below those for the optimal type.

Situations where water was found more economic in the model were generally either:

- where water could be picked up from an airfield closer to the fire than the nearest retardant base, or

- where the area savings were almost as good with water, because of the low initial intensity or size, and the extra expense of retardant was not justified by the saving in area.

In the latter situation, the early arrival of the airtanker was more crucial to success than the effectiveness of the retardant. Smaller losses due to canopy interception and longer pattern lengths at shallow depths also act in favour of water against its basic disadvantages of lower extinguishment effectiveness, higher evaporation and shorter burn-through time.

The savings with water seem high considering that in practice large land-based airtankers are generally used with chemical retardant. It is doubtless considered worthwhile to incur the extra expense of retardant to ensure a greater likelihood of holding the fire. The dispatcher cannot be certain before the mission that water will be adequate.

Short-term retardant provided only 4 per cent of the savings for the DC6 and a negligible proportion for all other aircraft. It was assumed that it could be mixed with water at any airfield, not requiring expensive mixers. While adding somewhat to the cost, its holding effectiveness was only about 25 per cent better than for water, with similar burn-through characteristics.

Costs

The fixed costs for the DC6 and other specialist airtankers are based on Canadian hire rates. While they are high relative to traditional Australian fire suppression budgets, some estimates offered to Project Aquarius suggested that costs for regular operations in Australia could be as much as 30 per cent higher than the Canadian equivalent. At that level, a net loss would result for the DC6, but it is possible that more competitive tenders could be obtained in practice.

Hercules C-130

A net loss of $372 000 emerged on the Hercules C-130 equipped with the MAFFS unit, although the tank capacity and aircraft performance are similar to the DC6 (Appendix 37). The area savings were still substantial, at 5317 ha, about three-quarters of those of the DC6 (Appendix 38). There are two main reasons for the difference in effectiveness:

- The retardant line length from the MAFFS unit is significantly shorter at higher depths (above 1 mm) than the DC6, and hence the limit of effectiveness is reached at lower fire intensities. This results from the fact that the MAFFS ejects the retardant under pressure through large nozzles, so that it falls like a fine rain, rather than being dumped vertically through large doors.

- The 12 compartments of the DC6 tank allow greater flexibility in allocating the load according to the requirements of different segments of the fire. MAFFS units have variously from 1 to 5 compartments.

The economic results for the Hercules are relatively worse than the physical results, as the hire rates charged by the Defence Department are apparently higher than for the specialist large airtankers in Canada, and the MAFFS is an additional cost. The Defence Department charges rates designed to recover full costs and indeed is constrained not to compete unfairly with private operators by means of subsidised rates for civilian work.

The economic loss for the Hercules tends to agree with the experience of the FCV in their operational use of the Hercules-MAFFS in 1981-82 and 1982-83. The FCV concluded that the contribution of the MAFFS was quite limited, and not sufficient to justify the costs which absorbed a large proportion of the total fire suppression budget (Rawson and Rees 1984).

Nevertheless, the area savings by the Hercules indicated by the AIRPRO model are more substantial than those apparently achieved in practice in Victoria, and there are several possible explanations for this:

- The model assumed the aircraft would be on standby in Victoria from 1 November to 28 February, whereas in practice it was not brought into use till January, and in the early period, had to fly from Richmond NSW when first called to a fire. Some substantial savings in the model arose from fires in November.
- Attack delays and circuit times for airtankers are assumed in the model to be shorter than those experienced in the MAFFS operation. It is assumed that the airtankers can be dispatched with only 10 minutes delay whereas in practice the MAFFS was sometimes not called the fire had been burning for several hours and had clearly become too difficult for the ground crews to control. The circuit times in the model are also shorter because because faster mixing and loading, and shorter times over the drop zone are assumed.
- The standard deduction from line length to allow for inaccuracy or misplacement is probably less than wastage that occurred in practice. A significant proportion of MAFFS drops had no effect because they were inappropriately placed (e.g. one drop was made on an FCV back-burn), and this generally stemmed in turn from poor communication between aircraft and ground crew or fire boss.

Operational times and accuracy in the model were based more on North American experience than on the limited Australian trials, as it seems reasonable to assume that the efficiency of Australian operations would increase steadily with experience if they became a regular part of fire control operations.

Neptune P2V-7

The Neptune, a land-based aircraft of 8000 litre capacity, returned net losses in all tests. Its costs, based on the depreciated aircraft currently used in the USA were relatively low. However, it failed to achieve some of the major savings made by the DC6, and even the DC4, due mainly to lower pattern length.

Douglas DC4

The DC4, with retardant capacity about two-thirds of that of the DC6, gave a net gain of $8000, with gross savings of $344 000 and fixed costs of $336 000 (Appendix 29). Area savings were 4109 ha, only 30 per cent more than for the Tracker despite twice the tank capacity (Appendix 38). Increasing the number of available aircraft led to net losses.

Since DC4 airtankers are used only in the USA, cost data had to be obtained from that source but were adjusted upward in line with the generally higher Canadian rates. If fixed costs for an Australian operation were just 3 per cent higher than the level estimated here, the gain would be turned into a loss.

Grumman Tracker S2

With a single Tracker at the home base of Mangalore, a net loss of $74 000 resulted, from gross savings of $227 000 and fixed costs of $301 000. Increasing the number available at the central base to 2, 3 or 4 increased gross savings by $113 000, $139 000 and $116 000 respectively, but in each case this fell well short of the increase in fixed costs, resulting in increasing net losses (Appendix 36). Although marginal savings ultimately fall with increasing numbers of aircraft, there are occasional discontinuities when, as in this case, large gains on several fires required a threshold capacity of 3 rather than 2 trackers.

Similarly, with one Tracker at each of 3 home bases in Victoria (Mangalore, Hamilton and Bairnsdale) substantial net losses resulted. These tests included the fixed costs of aircraft at all bases but only allowed for the use on any fire of the aircraft from the nearest base. The use of reinforcements from another base was not modelled, but an upper limit to the possible savings can be found from the results from an extreme situation - where up to 3 aircraft are used on any fire and fixed costs are calculated for 3 aircraft, but they are all assumed to come from whichever of 3 possible home bases is nearest to the fire, i.e. the delay in borrowing from more distant bases is ignored. A net loss of about $200 000 was still indicated.

Gross savings were not sufficently increased over the alternative of 3 aircraft at one central base. Having a home base closer to fires in the eastern or western districts makes the time of first drop earlier, but has no effect on subsequent circuit times from the nearest retardant base.

Although the Tracker appeared promising as a medium-sized compromise between the small and large airtankers, it did not live up to these expectations under the model's assumptions. Its capacity is about 30 per cent of the DC6's and twice that of the Thrush Commander. Partly because their uses are largely restricted to firebombing, the overall costs for Trackers per unit capacity are high relative to those of agricultural aircraft.

The Tracker can use 31 aerodromes compared with 9 for the DC6 but there are none suitable for either in an extensive area of the eastern highlands where, however, there are several strategic airfields for light aircraft (Appendix 14). The Tracker's savings were slightly increased by the assumption that it could operate with a mobile retardant mixer from any suitable aerodrome. The difference due to the mobile was not dramatic since the transport and set-up delay often prevented the advantage of rapid turn-around time being exploited during initial attack.

Of the total area savings of 3149 ha, 33 per cent were achieved with a fire-to-retardant distance of less than 40 km and 88 per cent with less than 80 km (Appendix 38).

Long-term retardant was the optimal type for 92 per cent of the Tracker's gross savings, and 32 per cent of savings with long-term retardant were achieved in Mixed Species forest types, 42 per cent on Grass, Heath or Scrub, 17 per cent on Ash, and 4 per cent on Softwood (Appendix 45, 46).

Thrush Commander

The optimal economic result was obtained with 2 available aircraft at each of 3 home bases (Moorabbin, Benambra and Stawell), with stand-by restricted to days of very high fire danger. Net savings were $76 000, from gross savings of $236 000 and fixed costs of $160 000 (Appendix 29). Although net savings were lower than for the DC6, the rate of return over the regular annual fixed costs was higher, at 48 per cent.

Given only one Thrush Commander at each base, gross savings were $151 000 and net savings $26 000. Increasing the number available at each base to 2, 3 or 4 changed net savings to $77 000, $71 000 and $72 000 respectively (Appendix 37).

The main distinguishing feature of the agricultural aircraft was the shorter distances between fire and retardant base. Distances of less than 20 km were associated with 58 per cent of gross savings with long-term retardant, distances between 20 and 40 km for 35 per cent of savings, and between 40 and 60 km for 6 per cent (Appendix 38). By contrast, only 25 per cent of gross savings by the DC6 were based on distances of less than 100 km. The final combination tested provided for 14 fixed retardant bases for the agricultural aircraft, most of which are already established, and 84 airfields suitable for use with a mobile retardant mixer or water. Many other locations would be available in practice in the flatter districts.

The relative strength of the agricultural aircraft, in comparison with the DC6, was on fires in remote areas. Fires with ground attack delays longer than 1 hour accounted for 71 per cent of the small aircraft's savings, and delays longer than 2 hours for 51 per cent (Appendix 48).

With a single agricultural aircraft, an average of only 3 fires per year gave savings of more than $10 000, compared with 8 for the DC6, although the number increased to 5 with 6 agricultural aircraft (Appendix 30).

As the number of aircraft available increased, the distribution of savings in other respects also changed to resemble more closely that of a DC6 (e.g. the proportion of savings with water increased and the proportion with short ground travel times increased). The absolute level of savings remained smaller than the DC6 in almost all categories.

On about two-thirds of the fires where the DC6 made substantial savings, a fleet of up to 6 agricultural aircraft made similar savings. Some of the exceptions were a major pine plantation fire and some fast-spreading grass fires in rural areas distant from the small aircraft's home bases.

About 77 per cent of the savings by the Thrush Commanders involved the use of long-term retardant (Appendix 46). The main forest type was Mixed Species for 71 per cent of these savings with long-term retardant, Ash and HEMS for 19 per cent, and Grass, Heath and Scrub for 9 per cent. Grass fires accounted for 90 per cent of savings where water was used (Appendix 45). Water and short-term retardant were ineffective or less economic in most cases on forest fires. This is explained by the low pattern depths available from the small aircraft, together with the high evaporation losses, limited effectiveness of water as a retardant, and shorter burn-through times. Further, water has less advantage in relation to distance to fire since any airfield where the aircraft could pick up water could also be used for a mobile retardant base.

There were no positive savings in Softwood for the agricultural aircraft, partly because of the high canopy interception relative to the pattern depth available.

Fires on days of very high fire danger (FDI over 24 at 3 pm at nearest station), when the aircraft were on stand-by, contributed only 18 per cent of gross savings (Appendix 48). Fixed costs were based on an average of 8 such days per season. On other days the aircraft were assumed to be on one hour's call but still achieved 6 per cent of the gross savings on days of low or moderate fire danger (FDI less than 12), and 16 per cent on days with FDI between 12 and 24. While the state of availability was based on the FDI at 3 pm at the nearest station, conditions during the fire were not necessarily exactly related to that index.

In another option tested, agricultural aircraft were on stand-by on days of high fire danger rating (FDI over 12), an average of 30 per season. However, the increase in gross savings was only $12 000, considerably less than the increase in stand-by costs for aircraft and base, so that lower net savings resulted.

A set of 6 home bases (the existing bases for agricultural aircraft in Victoria) was initially tested but those at Leongatha, Ballarat and Bairnsdale did not produce enough savings for the years tested to cover fixed costs. The final results were obtained with 2 aircraft at each of 3 home bases of which Benambra in the eastern highlands contributed 65 per cent of the savings, Moorabbin 30 per cent and Stawell 5 per cent. However, it seems likely that a similar or better result could be obtained by redistributing the 6 aircraft to 1 at each of 6 home bases, and borrowing aircraft from more distant bases when required for a large fire. The latter concept is not presently provided for in the model.

Of the 14 locations tested for small fixed retardant bases the best were Noorinbee (Cann River), Snowy Range, Grampians, Benambra, Ballarat and Gelantipy, while those at Bairnsdale, Matlock, Mt Beauty, Tallangatta and Dartmoor did not save sufficient to cover their fixed costs (Appendix 43).

However the success of different bases is heavily dependent on the geographic distribution of fires in the five-year period sampled. Whilst the frequency of fires is reasonably uniform on a State-wide basis between five-year periods, the distribution between localities can vary widely. Indeed, a district experiencing large fires in one year is less likely to suffer the same fate in the next 5 years, due to the reduction in fuel loads and perhaps temporarily increased awareness of fire risk. Hence to draw conclusions on optimal base locations would ideally require a sample fire distribution based on a considerably longer time period.

The use of mobile retardant mixers gave an adequate return at a limited number of locations. Given mobiles at 7 key forest depots around the State, gross savings were $23 000 on fires where the mobile was used, (Appendix 49) for an increase in fixed costs of $15 000 per year. Most of the returns derived from the mobile bases at Fiskville, Orbost and Rennick. Those tested at Beaufort, Beechworth, Bendigo, Benalla, Heyfield, Mildura, St. Arnaud and Wail returned losses or did not cover costs. Even where an airfield suitable for a mobile base was closer to the fire than the nearest fixed retardant base, the availability of the mobile base did not greatly increase savings in many cases due to the delay for travel and set-up time. Major savings were usually based on the contribution of the aircraft in the early stages of the fire (up to 3 hours after detection) before the mobile base was ready, during which time the nearest fixed retardant base was used.

The positive economic results for the light aircraft, despite their smaller capacity, stems from several features:

- The number of aircraft used can be readily incremented in accordance with the requirements of any fire.
- Their ability to use any airfield allows a better distribution of fixed retardant bases thereby reducing time between drops. Similarly even shorter circuit times were achieved by the use of mobile retardant mixers at any airfield.
- Times for loading, take-off, landing and dropping are lower for the smaller aircraft. Thus, taking into account also the generally shorter flying distances, a typical time between drops is 30 minutes compared with 65 minutes for the DC6.
- Accuracy is higher for the smaller aircraft.
- The cost per flying hour for the small aircraft is substantially less. The variable cost per metre of line resulting is similar to the DC6, if the smaller aircraft deliver twice as many loads per hour.
- The fixed cost for a fire season is very much less for the agricultural aircraft, because it is not necessary to incur costs for stand-by on most days.

Helicopters

The 206B, a small helicopter with 340 litre capacity produced net savings of $28 000 given the availability of 2 helicopters at each of 2 home bases, Melbourne and Latrobe Valley. Gross savings were $232 000 and fixed costs $204 000 (Appendix 29). Net savings did not vary much with increases in the number available at each base, being $15 000 for 1, $28 000 for 2, and $14 000 for 3, and $16 000 for 4 (Appendix 37).

The best results were based on fixed costs for a total of 4 helicopters (2 at each of 2 bases) although the models provides for only those from the nearest base to be used on any fire. As for the agricultural aircraft, better results would probably be obtained in practice with the borrowing of aircraft from more distant bases.

The physical effectiveness of the helicopters largely reflects the assumptions of an average distance of 6 km between water point (or ground tanker) and fire, and 10 km between mobile retardant mixer and fire, combined with shorter circuit times for loading and taking off etc., and high accuracy. Rates of line construction, after the first drop, were therefore sometimes better than for the DC6 or agricultural aircraft, for example at 6 drops per hour using long-term retardant, and 240 m of line at 0.5 mm per hour per helicopter.

About 62 per cent of the savings derived from the use of water, and 38 per cent from long-term retardant (Appendix 46).

Grass fires accounted for 77 per cent of the helicopter's savings with water. With long-term retardant, Mixed Species accounted for 89 per cent of savings, and Ash for 9 per cent (Appendix 45).

The base at Latrobe Valley accounted for 60 per cent of the gross savings and Moorabbin for 40 per cent (Appendix 41). Several other home bases (Bright, Stawell, Fiskville) were also tested but did not return sufficient additional gross savings to cover the fixed costs, which include ferry costs from the normal base to that nominated for fire availability.

As for the agricultural aircraft, the helicopters were assumed to be all on stand-by for fire-bombing on days of very high fire danger only and available at 1 hour's call on other days. However, it would often be more difficult to divert commercial helicopters from their other work in the event of a fire call, than it is to divert aircraft from agricultural work. Some allowance for this was made by setting the availability cost at 50 per cent of the full stand-by rate, in contrast to 14 per cent for agricultural aircraft.

The Bell 212 a medium-sized helicopter with tank capacity of 1300 litres, produced the second-best results after the DC6. With 2 available at one base only (Latrobe Valley), net savings were $78 000, from gross savings of $306 000 and fixed costs of $228 000 (Appendix 29). Net savings for other numbers available were not much different, being $65 000 for 1, $52 000 for 3 and $53 000 for 4 (Appendix 37).

The general reasons for the cost-effectiveness of the helicopters are similar to those for the agricultural aircraft and indeed are more pronounced:

- flexibility of using the most appropriate number on each fire;
- short turn-around times;
- long pattern-length (at depths up to 1.5 mm in the open) per litre of capacity;
- high accuracy; and
- low fixed costs attributable to fire-bombing.

However, the accuracy parameters assumed in this study have not been validated in Australian field trials and arguably could overestimate the performance of helicopters in drop placement with optimal overlap, especially with its narrow drop width.

Canadair CL-215

The CL-215 returned a loss in all circumstances tested. With a single aircraft at Mangalore, gross savings were $233 000 compared with fixed costs of $511 000, giving a net loss of $278 000 (Appendix 29). A second aircraft at Mangalore added only $84 000 to gross savings, far below the amount required to cover the extra fixed cost. Similarly, with one aircraft at each of 3 home bases, net losses increased to $1 million.

Water was responsible for 74 per cent of the CL-215's savings and long-term retardant for the other 26 per cent (Appendix 46). Water-scooping from lakes frequently made possible better rates of line holding per hour than were possible with retardant from a land base. However, the difference was usually minor, and other land-based aircraft using long-term retardant were usually able to obtain savings of similar or greater magnitude.

Out of total area savings of 1286 ha using water, 66 per cent were achieved using lakes less than 20 km from the fire, and a further 25 per cent between

20 and 40 km. The positive savings derived from an average of 31 fires per year within 40 km of a lake, and of these 30 were within 10 km (Appendix 33). On the great majority of fires the distance to water was too great for the CL-215 to be able to exploit its main advantage.

The CL-215 has a tank capacity of 5500 litres, compared with 3500 litres for the Tracker. However, when tested with long-term retardant alone, the CL-215's gross savings were somewhat lower than those for the Tracker, due to a combination of factors - slightly higher flying cost, slower speed and fewer available aerodromes - 16 for the CL-215 compared with 31 for the Tracker.

The main vegetation type was Grass, Heath and Scrub for 48 per cent of the total savings (Appendix 45). These were generally on fires which significant property damage or high CFA turnouts, but were well short in intensity of those experienced on Ash Wednesday. Gross savings by the CL-215 on fires with average head intensity less than 750 kW/m were 45 per cent of those by the DC6, but this percentage fell to 21 per cent on intensities between 750 and 3000 kW/m (Appendix 40).

Canso PBY5A

The Canso gave a net loss of $63 000 considerably smaller than the CL-215 (Appendix 29). Gross savings were $126 000, 54 per cent of the CL-215's, while fixed costs were only $189 000. Water was used for 93 per cent of the Canso's gross savings, although it has the advantage of being able to use water or land bases as required (Appendix 46).

The tank capacity of the Canso and its ability to use a range of aerodromes are similar to the Tracker's but its gross savings were only 56 per cent of those of the Tracker (Appendix 41). The Canso's relative disadvantages lie in slower speed, lower manoeuvrability and less flexibility in tank releases.

Twin Otter DHC-6

Given one Twin Otter at each of 2 home bases, operating only as a water-scooper, a net loss of $85 000 resulted. Gross savings were $187 000 but fixed costs for stand-by throughout the season were $273 000 (Appendix 29).

Out of 62 fires per year that the the Twin Otter was selected to fight, savings were negative on 31, between 0 and $10 000 on 27 and exceeded $10 000 on only 4 (Appendix 30).

The Twin Otter was economically optimal on more individual fires than any other aircraft model; out of 180 sample fires on which aircraft were optimal, the Twin Otter was best on 84. However, these were mostly small fires and the Twin Otter gave the best savings due to its low operating costs. Most of its economic savings were achieved on a small number of fires less than 10 km from a suitable waterbody, but in general waterbodies in Victoria do not seem to be sufficiently well distributed to make water-scoopers an economic proposition.

When tested on land-based operations, the Twin Otter also made savings approaching those of the Thrush Commander but these have been excluded here as Twin Otters are operated either in water-based or land-based mode in America but are not interchangeable. If it were possible to convert such small aircraft to an amphibian design at reasonable cost, so that it could use either a water or land-based operation as appropriate on each fire (like the CL-215), it could be one of the most economic airtankers.

Combinations of resources

The model itself tests each type of resource independently, rather than comparing different combinations of resources, either working together on a fire or in the fleet available for dispatch to any fire.

Those aircraft with negative net savings may be eliminated from further consideration but the question remains as to what combinations of those resources with positive savings would maximise total savings. Further analysis of the distributiion of savings on different fires can indicate the extent to which different resources are complementary rather than competing.

Whilst the DC6, DC4, Thrush Commander and helicopters all gave positive savings when tested independently, a large proportion of the savings proved to be on the same fires, so that use of any one of the models (with the optimal number at each base) would pre-empt the need for the others.

This approach is in fact similar to that which has become increasingly common in Victoria in recent years. The potential savings indicated by the model, however, are based on criteria for availability and early dispatch which are more automatic and simplistic than those applied in practice.

The savings by ground crews produced by the model would also be largely pre-empted by the aircraft. There were several districts where ground crews made substantial savings not matched by helicopters (Alexandera, Mirboo, Trentham and Rennick for machine crews), but these would not necessarily be the districts showing the greatest savings over the long-term.

However, there would be further gains not accounted for in the model by combining helicopters with a small number of additional hand crews in key districts. The helicopters can be used to transport fire-fighters for initial attack (e.g. as for smoke-jumpers in North America) as well as other fire work. This extends the effective range of the hand crews and improves their time of first attack.

Qualifications

In developing the model, the intention was to incorporate as far as possible some quantitative allowance for all the major considerations thought to affect the viability of fire-bombing. Nevertheless, there remain a number of considerations not presently addressed in the model, in the light of which the results should be qualified or adjusted.

One consideration is that of simultaneous fires. Savings would be over-estimated to the extent that they include savings on two or more fires which were burning concurrently. The allocation problem is particularly acute on those infrequent days of severe fire danger when over 50 fires may be burning in the State.

However, a check of the results indicated that a time overlap applied to a relatively minor part of the savings. In operations it would in any case ideally be possible to select the fire offering the highest savings from aerial attack and, if necessary, divert the aircraft in mid-air to the more important fire. Further, rather than remaining on one fire, the aircraft could share its time in an optimal way between fires burning concurrently.

A similar problem concerns whether fires suitable for air attack could be identified as accurately as assumed in the model, which relies to a certain extent on hindsight as to the size the historical fire reached without air attack. A policy of liberal and immediate dispatch would ensure that the major savings are captured but could be accompanied by a higher number of costly unnecessary missions. On the other hand, a more cautious dispatch system could minimise wasted missions but forgo some savings. An attempt to allow for this in the model has been made by assuming that, except on days of high fire danger, aircraft are not dispatched until a fire has reached a 200 m perimeter.

A factor which underestimates savings for the smaller aircraft is the assumption that only the aircraft from the nearest base fight any fire. Allowing for the borrowing of aircraft from more distant bases would increase gross savings for no additional fixed cost, although the gross savings would clearly be less than if the aircraft had all been available at the nearest base. However, this is unlikely to affect the balance of whether net savings are positive or negative.

ABBREVIATIONS

BAE	Bureau of Agricultural Economics
CFA	Country Fire Authority of Victoria
FCV	Forests Commission of Victoria
FDI	Fire Danger Index (McArthur's)
HEMS	High elevation mixed species
MAFFS	Modular Airborne Fire Fighting System
MMBW	Melbourne and Metropolitan Board of Works
RLC	Rate of line construction
ROS	Rate of spread
SCA	Soil Conservation Authority of Victoria

Note

References to proprietary brands or companies in this report are as examples only and do not imply endorsement of these products by CSIRO or the National Bushfire Research Unit.

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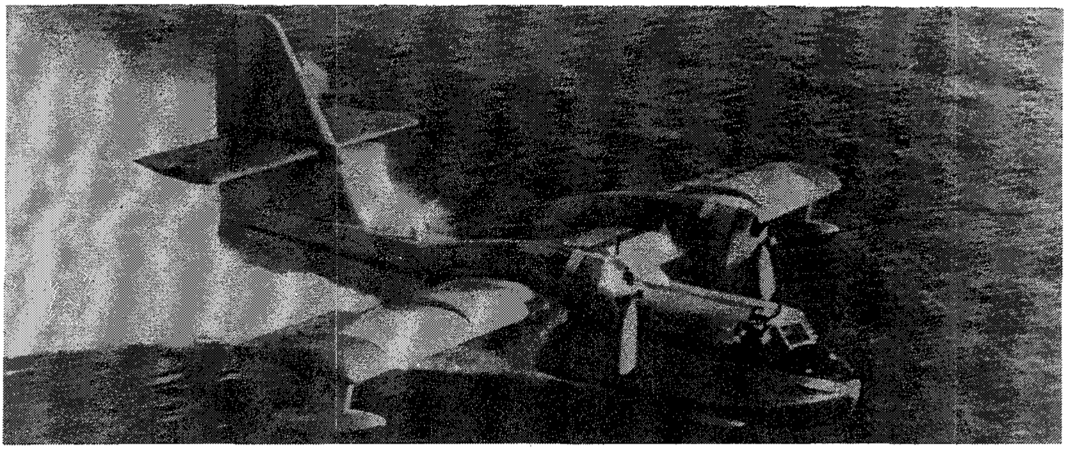
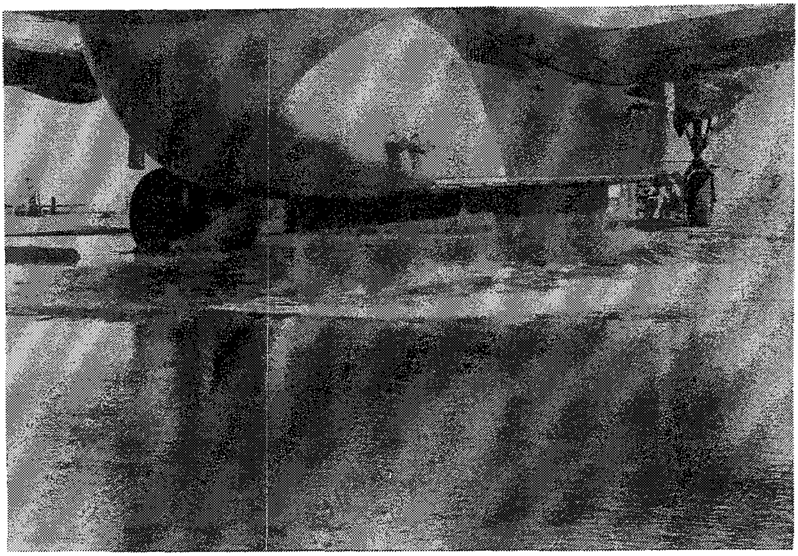
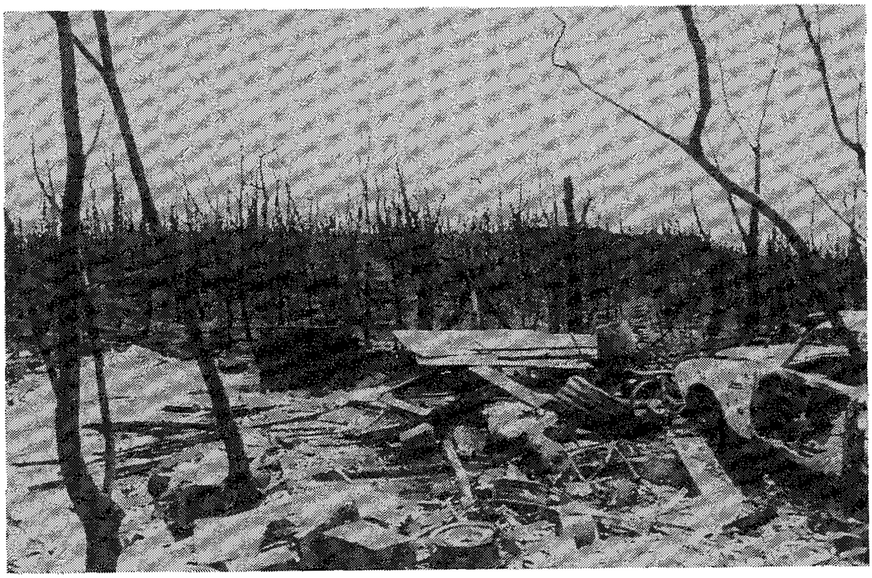


Canadair CL-215 scooping load of water
(Photo: Canadair)



Undercarriage of DC-6 showing retardant tank
(Photo: P. Hay)

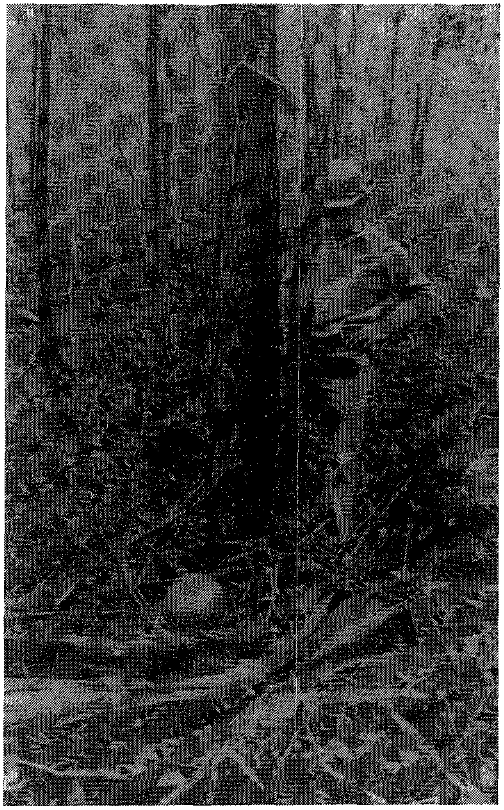


Remains of house destroyed by bushfire,
Blue Mountains, NSW 1977

(Photo: CSIRO)

Defoliation and denudation of soil cover
following severe fire

(Photo: CSIRO)



A dominant stem in a stand of Eucalyptus sieberi burnt by wild fire eight years previously. The internal damage is shown in the following photograph

(Photo: FCV)

Sections cut at 0.5 m intervals from the stem shown in the previous photograph. The original stem contained white rot, and wood laid down since the fire contains gum veins and brown staining.

(Photo: FCV)

APPENDICES

APPENDIX 1

COST OF FIRE-LINE PER METRE

(a) AERIAL SUPPRESSION

		Retardant type and aircraft type						
		Phoscheck					Water	
Conditions assumed	Units	DC-6	Hercules MAFFS	Grumman Tracker	Thrush Commander	Bell 212	Bell 206	CL-215
<u>TIME</u>								
Fire-to-retardant	km	150	150	75	25	10	6	25
Cruising speed	km/hr	402	459	325	204	185	214	258
Flying time 2-way base to fire	min.	45	39	28	15	7	4	12
<u>CIRCUIT TIME</u>								
Take-off	min.	6.4	6.2	4.5	2.9	0.5		
Climb	min.	2	2	2	2	2	2	2
Drop	min.	7.7	7.5	5.5	3.5	4.9	2.5	4
Landing	min.	5.1	5	3.6	2.3	0.5	0.5	
Retardant tank								
Volume	litres	11 365	11 355	3 545	1 500	1 362	340	5 455
Loading rate	L/min.	5.9	5.9	1.8	3	2.7	1	1
Total time Between loads	min.	72.1	65.6	45.4	28.7	17.6	10.5	19
Total cost per load	$	7 565	10 016	2 381	525	806	87	1 195
Total cost	$/hr	6 295	9 161	3 147	1 098	2 748	499	3 773

		Retardant type and aircraft type						
		Phoscheck					Water	
Conditions assumed	Units	DC-6	Hercules MAFFS	Grumman Tracker	Thrush Commander	Bell 212	Bell 206	CL-215
<u>LINE BUILDING</u>								
Retardant required on ground to check 500kW/m fire	mm	0.15	0.15	0.15	0.15	0.15	0.35	0.35
With throughfall of 60%, depth required from aircraft	mm	0.25	0.25	0.25	0.25	0.25	0.6	0.6
Length of line available from one load	m	503	473	252	174	221	73	145
Accuracy deduction	m	13	13	11	8	4	2	10
Net length of line per load	m	490	460	241	166	217	71	135
Rate of line construction	m/hr	408	420	318	347	740	405	426
<u>Cost per metre</u>	$/m	15.4	21.8	9.9	3.2	3.7	1.2	8.8

Notes:

- cost includes aircraft, base and retardant, including allocation of fixed cost, but excludes any bird-dog cost.
- Based only on fire to nearest retardant base ignoring time to arrive from home base.
- Includes costs for only one base although shorter fire-to-retardant distances for smaller aircraft implies a more extensive network of bases.

(b) GROUND SUPPRESSION

For consistency with airtanker cost, ground costs include travel from base to fire, as well as work constructing a line to check fire, but exclude mop-up.

Hourly rates (1983 FCV) for various classifications are first established:

Labour	Weekly wage ($) (38 hr)	Hourly wage ($)	Hourly cost ($) (wage + 35% on-cost *)
Overseer	271.80	7.15	9.65
Dozer operator	300.10	7.90	10.67
Dozer offsider (labourer)	253.10	6.66	8.99
Water tanker driver	284.80	7.50	10.13
Water tanker offsider	253.10	6.66	8.99
Light support units			
- pump operator	272.60	7.18	9.69
- labourer	253.10	6.66	8.99

* On-costs allow for leave, superannuation, workers compensation, personnel administration etc.

Bulldozer, D6- working	$58.40/hr
Prime mover for dozer plus low-boy	$46.60/hr

Vehicles - FCV charging rates per kilometre (including allowance for capital as direct costs), are converted here to hourly rates by assuming certain speeds for both (i) travel to fire (ii) work on fire-line, the proportion of hours spent on each, and that cost per km is twice as high on fire-line as on road, due to greater fuel consumption, wear and tear etc.

Water-tanker, 4WD, 400 litre (Class 5C): Standard charging rate = $1.98/km. If rate for road use is $x/km, and on fire-line is 2x, with 50% of distance covered on each

$$0.5x + 0.5(2x) = 1.98$$
$$x = 1.32$$

Road $1.32/km at 70km/hr = $92.4/hr
Off-road $2.64/km at 30km/hr = $79.2/hr

Dozer operator's vehicle (Class F2): $0.25/km

As above $0.8x + 0.2(2x) = 0.25$

Road $0.21/km at 80km/hr = $16.7/hr
Off-road $0.42/km at 15 km/hr = $6.3/hr

2 x Light support units, utility, Class F2 - as for dozer operator's vehicle

Overseer's vehicle, Class F5
$0.8x + 0.2\,(2x) = 0.18$

Road $0.15/km at 80 km/hr = $12/hr
Off-road $0.30/km at 15km/hr = $4.5/hr

Passenger bus, Class B5 $0.22/km
$0.8x + 0.2\,(2x) = 0.22$
$x = 0.18$

Road $0.18/km at 80km/hr = $14.60/hr
Off-road $0.36/km at 15km/hr = $5.40/hr

Given the composition of the crews used in Project Aquarius trials at Nowa Nowa, **hourly costs** for crews would be as follows:

Machine crew			Hand crew		
Labour: 9 people		$	6 people		$
Overseer		9.65	Leader		9.52
Dozer operator		10.67	Labourers	5 x	8.99
Tanker driver		10.13			
L.S.U. pump operators	2 x	9.69			
Labourers	4 x	8.99			
		85.9			54.47

Vehicles		Road	Fire-line		Road	Fire-line
Bulldozer			58.4	Passenger bus	14.6	5.4
Prime mover for dozer		46.6		Leader's vehicle	16.7	6.3
Tanker		92.4	79.2			
Light support units	2 x	16.7	6.3			
Personnel vehicles	2 x	12.0	4.5			
		196.4	159.2		31.3	11.7

To distribute travel cost over fire-line construction time, assume travel time, all at road rate) is 1 hour each way, for 6 hours work on fire-line.

Travel cost per hour on fire-line: 2x (85.79 + 196.4)/6 = 94.1 — 2x (54.47 + 31.3)/6 = 28.6

Capital cost* ($)

Equipment	Machine crew		Hand crew	
Pumps, tanks & hoses for light support units	2 x	1500		-
Radios	4 x	600	1 x	600
Chainsaws	1 x	650	1 x	650
Knapsack pumps	2 x	80	1 x	80
Drip torches	2 x	63.5	1 x	63.5
Axes	2 x	32	1 x	32
Rake-hoes	4 x	19	8 x	19
Slashers	2 x	16.5	2 x	16.5
Shovels	2 x	16.5	1 x	16.5
Miscellaneous		400		200
TOTAL		6943		1827

At 4-year life expectancy with 10% p.a. interest, 10% salvage value, 10% extra costs for fuel, repairs and maintenance,

Annual equivalent cost =	$2168	$571
If used for 375 hr. /year (as CFA units), hourly cost =	5.8	1.45

Other fixed costs

Administration (fire protection)**

- av. expenditure per year over 1977-78 to 81-82 at 1983 constant prices = $557 726.
30% share attributed to ground suppression,
(remainder to prevention, aircraft etc.)
Assume cost proportional to number of personnel used on fire protection, at 40 per district X 45 districts.
Administration cost per person per year = $93

Expenditure on fire equipment (includes mobile camps)	$
- average per year	557 694
x 30% / (40x45)	
Cost per person per year	93

Expenditure on fire prevention (includes training)	
- average per year	2 141 000
x 10% / (40x45)	119

---

* B. Marsden, FCV, pers. comm.

** FCV, 'Fire protection and fuel reduction burning', 1982, Table 1.

Expenditure on special-purpose equipment (fire protection), including radios

	$	$
- average per year	218 074	
x 30%/(40 x 45) =		
S.P.E. cost per person per year	36	
Total other fixed costs		
$/yr/crew	3 069	2046
$/hour	8.2	5.5
Stand-by or unproductive labour time		
at 10% of wages for 4 months,		
- cost per crew per year	7 711	4 822
- cost per crew per hour of fire fighting	20.5	12.8
	Machine	Hand
Total hourly cost	85.9 + 159.2 + 94.1 + 5.8 + 8.2 + 20.5 = 374	54.5 + 11.7 + 28.6 + 1.5 + 5 + 12.8 = 115
Rate of line construction against 500 kw/m fire* (m/hour)	1 000	350
Cost per metre of fire-line	$0.37	$0.33

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* Based on rates observed at Nowa Nowa trials. They actually relate to line built and held, which is a stricter standard than that applied to the retardant drops, thus slightly over-estimating the equivalent cost/m for ground crews.

APPENDIX 2

FIREIN FORMAT

(a) FCV RECORD

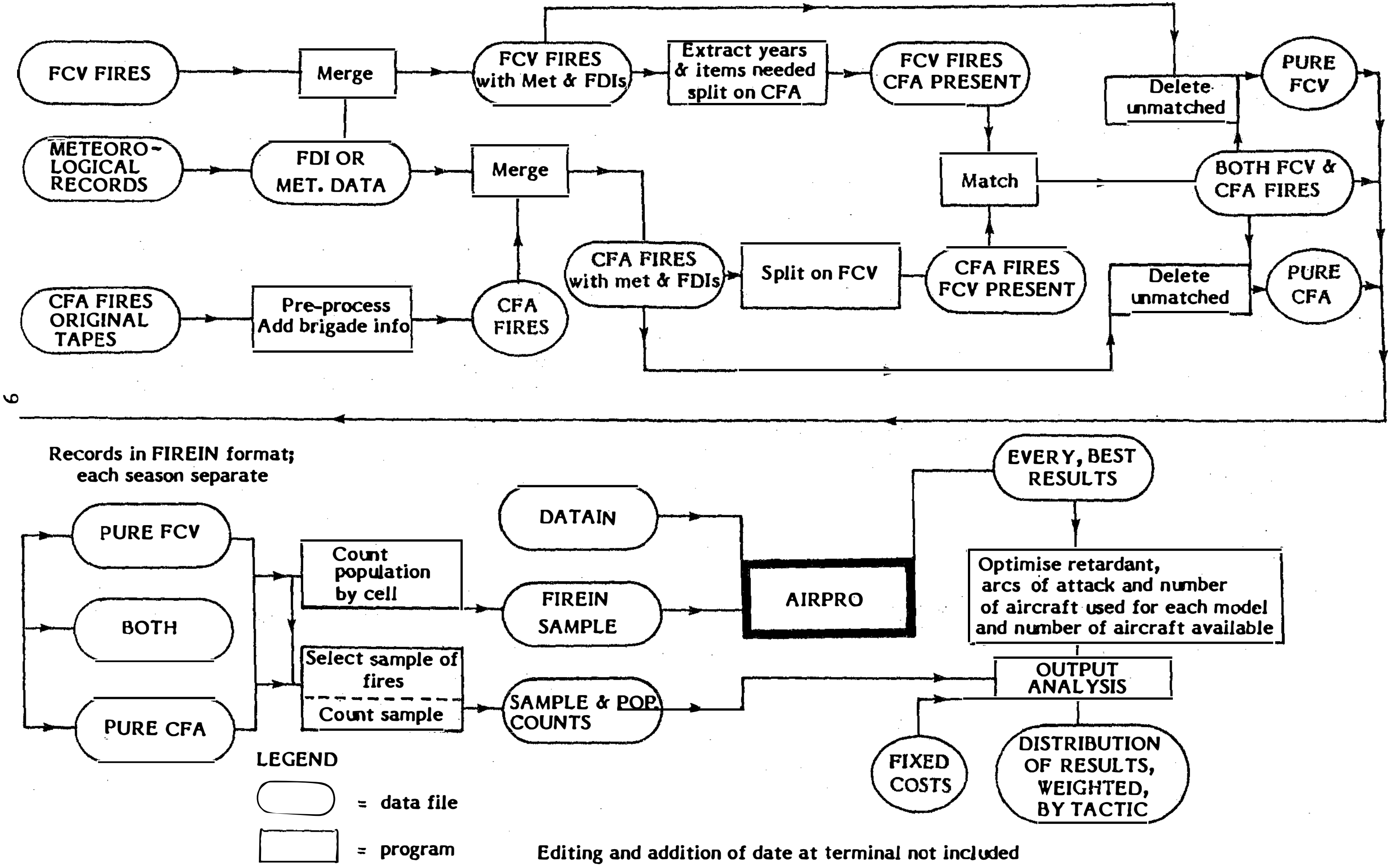
Format	Field	Description		
	<u>Card 1</u>			
I2	IDIST	FCV District number		
I4	IFIRE	Fire report number		
I2	IDAY	Day of month fire detected		
I2	MO	Month		
I2	IYR	Year		
I4	MAP	Map (1:250 000) number	OR	Latitude - degrees Latitude - minutes Longitude - degrees Longitude - minutes
I3	IEAST	Map easting		
I3	INORTH	Map northing		
F5.1	AATT	Fire area at first attack (ha)		
I2	IHDET	Time fire detected - hour		
I2	IMDET	Time fire detected - minutes		
I2	IDARR	Time crew arrived - days since detection		
I2	IHARR	Time crew arrived - hour		
I2	IMARR	Time crew arrived - minutes		
I2	IDCNT	Time checked - days since detection		
I2	IHCNT	Time checked - hour		
I2	IMCNT	Time checked - minutes		
F8.0	RFA	Fire area at control (ha)		
F9.0	DAMGE	Property damage ($)		
I2	NPNO	National Park number		
F5.0	ABNP	Area burnt in National Park (ha)		
	<u>Card 2</u>			
23I2	PBURN(23)	Per cent of area burnt in each forest type		
I1	MFTY	Main forest type		
I1	MFHT	Main forest height		
F8.0	TLOSS	Timber losses ($)		
F3.0	FDI3	Fire Danger Index at 3 pm - first day		
F3.0	FDIT	Fire Danger Index at 3 pm - second day		
F3.0	WS	Wind speed (km/hr)		
F3.0	RFI	Rainfall intensity index		
I1	FFR	First FCV response		
F3.0	VRD	Volume of retardant dropped (hundreds litres)		

(b) CFA RECORD

Format	Field	Description
	<u>Card 1</u>	
I2	IDAY	Day of month of fire
I2	IMO	Month of fire
I2	IYR	Year of fire
I5	IBRIG	Brigade number
I2	IREG	CFA region number
I4	INCID	Incident number
I4	ITOUT	Time of turnout (hhmm)
I4	IRETN	Time of return (hhmm)
I2	IBDIST	Fire base distance (km)
I3	IMEN	Number of men turned out
I2	IAPP(12)	Number of appliances used
I3	ICAUSE	Cause of fire
I4	IDETN	Time of call
I4	IDURN	Duration of fire (hhmm)
I1	IFCVA	Did FCV attend (1=Yes, 0=No)
I3	IBRIGS	Number of supporting brigades
	<u>Card 2</u>	
I2	ICMIN	Minor casualties
I2	ICMAJ	Major casualties
I2	ICFAT	Fatalities
I6	IRFA	Fire area (ha)
I4	ISECP	Number of SEC poles burnt
I3	IWTFD	Water to fire distance (km)
I9	ILOSS	Total value of losses ($)
I1	IMFTC	Major fuel type
I1	IMFQC	Major fuel quantity
I2	IFDI	Fire danger rating (McArthur)
I3	IELEV	Elevation (m)
I1	ISLOPE	Slope
I1	IASPCT	Aspect
I1	IACCS	Accessibility
I2	IFRS	Forward rate of spread (km/hr)
I3	ICONT	Time to contain fire (hours)
I3	ISAFE	Time to make fire safe (hours)
I2	IWS	Wind speed (km/hr)
F6.2	ALAT	Latitude of brigade (degrees)
F6.2	ALONG	Longitude of brigade (degrees)
I3	IDIST	FCV district number
	<u>Card 3</u>	
I4	ITT	Travel time (hand coded)
I5	IRPG	Rate of perimeter growth (hand coded)
I2	IWSM	Wind speed (met.)
I3	IFDIM	Fire danger index at 3 pm (met.)
I3	IFDIT	Fire danger index next day (met.)
F3.0	RFALL	Rainfall index (met.)

APPENDIX 3

FLOW-CHART OF COMPUTER PROCESSING OF FIRES



Editing and addition of date at terminal not included

APPENDIX 4

LOSSES IN BUSHFIRE DISASTERS, VICTORIA, 1918-1985

The following table compares damages from bushfires of disaster magnitude in recent years with those over the last 67 years. Published estimates of the dollar value of damages were used where available but, where not, any other available information on lives or buildings lost was used to impute a figure for losses in a common monetary unit.

Year	Damage reported $ million 1983	Buildings lost	Lives lost	Total damage imputed $ million 1983
1919	n.a.	n.a.	3	10
1925-26	n.a.	n.a.	60	192
1931-32	n.a.	n.a.	20	64
1938-39	n.a.	1300	71	227
1943-44	110	700	49	121
1951-52	88	n.a.	10	90
1961-62	21	454	14	24
1964-65	6	n.a.	7	8
1968-69	46	264	23	51
1976-77	28	455	5	29
1982-83	235	1511	46	244
1984-85	20	150	3	21
				1081

n.a. = not available

Sources:

1. FCV (1980). Fire Protection and Recreation - Conservation. Submission to Grants Commission. 29 February.
2. Foster, Ted (1976). Bushfire - History, Prevention, Control. Reed: Terry Hills.
3. Cheney, N P (1976). Bushfire disasters in Australia 1945-75. Australian Forestry, vol.39, pp.245-68.
4. Luke, R H & McArthur, A G (1978). Bushfires in Australia. AGPS: Canberra.
5. McArthur, A G , Cheney, N P & Barber, J (1982). The Fires of 12 February 1977 in the Western District of Victoria. CSIRO & CFA.
6. CFA (1983). The Major Fires Originating 16 February 1983.
7. Treasurer of Victoria. Media Release. 9 November 1983.
8. The Age, Melbourne, 16 January 1985.

Imputation method

1. Reported value of damages where available, updated by Melbourne Consumer Price Index.

2. Where only number of buildings lost reported, total damages imputed at $90 000 per building, as in 1982-83.

3. Where only number of fatalities reported, total damages imputed at $3 million per fatality, as in 1982-83.

4. Allowance for value of life added of $200 000 per fatality, each year.

Averages

Average imputed losses over 70 years from 1915 to 1985 = $15.4 million per annum.
Average losses over 11 years from 1972-73 to 1982-83 = $24.8 m.p.a.
Average losses over 5 years from 1978-79 to 1982-83 = $48.8 m.p.a.

Average period between disasters above = 6 years
Average loss = $90 million per event

Ash Wednesday 1983 is exceeded only by the 1939 fires in the apparent magnitude of losses.

These estimates indicate that the 5 years sampled for the cost-benefit study, by including Ash Wednesday, over-represent disaster fires. Over the long term, average annual losses from such fires have been only 50 per cent of those in the sample period, and about 62 per cent of losses over the 11-year period from which the stratified population numbers were obtained.

APPENDIX 5

AVERAGE ANNUAL NUMBER OF FIRES

(a) FCV FIRES

by area class and main forest type, (November-February, 1972-73 to 1982-83)

Main forest type	Area class (ha) 0-1	1-10	10-100	100-1000	>1000	Total
Ash, HEMS, >27m	7.0	2.7	1.4	0.7	0	11.8
Ash, HEMS, <27m	2.5	0.5	0.7	0.2	0	3.4
Mixed sp., >27m	28.4	12.4	4.1	3.3	1.4	49.7
Mixed sp., <27m	50.1	17.5	13.4	5.4	2.6	89.7
Redgum, Box, I'B, >27m	4.4	3.2	1.2	0	0	8.9
Redgum, Box, I'B, <27m	23.5	9.2	4.6	1.0	0.3	38.5
Softwood, >27m	2.1	0.6	0.4	0	0	3.1
Softwood, <27m	8.3	2.6	0	0.2	0	10.9
Alpine	1.6	0.8	0.5	0.2	0	3.1
Mallee, Native Conifer	0.7	1.1	1.4	0.5	2.5	6.5
Grass, Heath, Scrub	51.9	15.1	9.4	4.4	1.2	81.7
Total	181.0	66.0	37.0	16.0	8.0	307.0

Note: For 47% of these reported fires, forest type was not reported. They have been allocated to forest types in the above averages in the same proportion as for the fires on which forest type was reported in each area class.

(b) CFA FIRES

by area and damage class, November to February.

Damage class ($)	Area class (ha) 1-10	10-100	100-1000	>1000	Total
1:1-1000	10	51	1	0	62
2:1000-10 000	7	80	9	0	96
3:10 000-100 000	1.7	12	9	0.7	23.4
4:100 000-1 000 0000	0.7	0.7	1.7	0.3	3.4
5: over 1 000 000	0	0	0	0.2	0.2
Total	19.4	143.7	20.7	1.2	185.0

Note: The averages are based on the 3 yr period 1979-80 to 1981-82 except for damage class 5 for which a long-term estimate is used. Fires of less than 10 ha with no property damage are excluded.

APPENDIX 6

BUSHFIRE REPORT DATA - AUSTRALIAN AGENCIES

Item	Agency														
	NSW FC	NSW BFC	NSW NPWS		VIC FC	VIC CFA	QLD FD	QLD RFB	SA WFD	SA CFS	WA FD	WA BFB	TAS FC	TAS FS	ACT BFC
			Old	New											
Computerised	Y	N	N	N	Y	Y	N	N	N	Y	N	N	Y	N	N
FIRE DETAILS															
District no.	N	N	N	N	Y	Y	N	N	N	N	N	N	Y	Y	N
Fire no.	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	N	N	Y
Location															
- perm. map	Y	N	Y	Y	N	N	Y	N	Y	N	Y	N	Y	Y	Y
- map no.	Y	N	N	N	Y	N	N	N	N	N	Y	N	N	Y	N
- grid ref. no.	Y	N	N	N	Y	N	N	N	N	N	N	N	Y	Y	N
Date started	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Time started	N	N	Y	N	N	N	Y	N	N	N	N	N	N	N	N
Time detected	Y	Y	N	N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y
Time controlled	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	N	Y	Y
Time mopped up	Y	Y	N	N	Y	Y	Y	N	Y	Y	N	N	Y	N	Y
Land tenure at start	N	Y	Y	Y	N	N	Y	N	N	Y	Y	Y	N	Y	N
Fuel load	N	N	N	N	N	Y	Y	N	N	N	N	N	Y	N	N
F.D.I	Y	N	Y	Y	N	Y	Y	N	Y	N	Y	N	Y	N	Y
Drought Index	Y	N	Y	Y	N	N	Y	Y	Y	N	N	N	Y	N	Y
Temperature	N	N	Y	Y	N	Y	Y	N	Y	Y	N	N	Y	N	Y
R.H.	N	N	Y	Y	N	Y	Y	N	Y	N	N	N	Y	N	Y
Wind speed	N	N	Y	Y	N	Y	Y	Y	Y	Y	N	N	Y	N	Y
Wind direction	N	N	Y	Y	N	Y	Y	Y	Y	Y	N	N	Y	N	Y
Rate of spread	N	N	N	N	N	Y	Y	N	N	N	N	N	Y	N	Y
Flame height	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	Y
Intensity	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	Y
Factors aiding/ inhibiting	Y	N	N	N	N	Y	N	N	N	N	N	N	N	N	Y
Spotting distance	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	N

Item	Agency														
	NSW FC	NSW BFC	NSW NPWS Old	NSW NPWS New	VIC FC	VIC CFA	QLD FD	QLD RFB	SA WFD	SA CFS	WA FD	WA BFB	TAS FC	TAS FS	ACT BFC
<u>SUPPRESSION</u>															
Agency in charge	Y	Y	N	N	Y	Y	N	N	N	N	N	N	N	Y	N
Other brigades	N	N	N	N	N	Y	N	N	N	Y	N	N	N	Y	N
No. men - own	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
- other	Y	N	Y	Y	N	N	N	N	N	N	Y	N	N	Y	Y
No. units equipt															
- own	Y	N	N	N	Y	Y	N	N	Y	Y	Y	N	Y	Y	Y
- other	Y	N	N	N	Y	N	N	N	N	N	Y	N	N	N	Y
Time despatched	Y	N	N	N	Y	Y	N	N	N	N	N	N	N	N	Y
Time arrived	N	N	N	N	Y	N	Y	N	Y	N	N	N	N	N	Y
Time began attack	Y	N	N	N	N	N	N	Y	N	N	N	N	N	N	Y
Time finished	Y	Y	Y	Y	Y	Y	N	Y	N	N	N	N	N	N	Y
Time left	Y	N	N	N	Y	Y	N	N	Y	N	N	N	N	N	Y
Method of attack	Y	N	Y	Y	Y	Y	N	Y	N	N	N	N	Y	Y	N
Amount water used	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Amount retardant used	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N
Cost suppression	Y	N	N	Y	Y	N	Y	N	Y	N	Y	N	N	N	N
<u>RESULTS</u>															
Area at attack	N	N	N	N	Y	N	Y	N	Y	N	N	N	Y	N	N
Area burnt - total	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
- by tenure	Y	N	Y	Y	Y	N	Y	N	Y	N	Y	N	Y	N	N
- by forest type	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
- by stand condition	Y	N	N	N	Y	N	Y	N	N	N	N	N	N	N	N
- by severity	Y	Y	N	N	N	N	N	N	N	N	N	N	Y	N	N
Quantities lost	N	Y	N	N	N	Y	N	Y	N	Y	N	Y	Y	N	N
Salvage	N	N	N	N	N	N	Y	N	N	N	N	N	Y	N	N
Casualties	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N
Estimated value losses	N	N	N	N	N	Y	N	Y	N	Y	N	Y	Y	N	N
Line construction rate	N	N	N	N	N	N	N	N	N	N	Y	Y	N	N	N
Remedial costs	N	N	Y	Y	N	N	N	N	N	N	N	N	N	N	N

APPENDIX 7

FORMULAE FOR METEOROLOGICAL VARIABLES

(a) MOUNT'S SOIL DRYNESS INDEX

Data given for each met-station:

DC = Date of commencement for SDI calculations
(date selected just after heavy rainfall mostly Aug. 1978)
INT = Interception as proportion of rainfall
KWET = Wet day evaporation) FCV data used
MAXC = Max. rain held by canopy)

NET (IVAP) = Evapo-transpiration for Melbourne, IVAP = 1 to 115, one value for each
of 5 SDI categories x 23 temperature categories.

Meteorological observations at 3 pm for each day at each station

KT = Dry bulb temperatures
RAIN = rainfall since previous day

SDI is started at 0 on a selected date, DC, when soil is saturated.

Basic equation is

SDIN = SDIO + RAIN-CANINT + NET
where SDIN = new SDI
SDIO = old SDI

CANINT = min (RAIN*INT, MAXC-KRCN) where rain left in canopy, KRCN = KRCO + CANINT-KWET where KRCO = rain left in canopy yesterday. If SDI is calculated to be negative, it is set equal to 0. The only apparent difference between this simplified routine and the original is that this ignores flash run-off.

Sources: Mount (1972); R. Rawson, FCV (pers.comm.)

(b) RELATIVE HUMIDITY

Formula 1
If dry bulb temperature, $T^{(^\circ C)}$, and dewpoint, $DEWPT^{(^\circ C)}$, are available (as for most Card 7 meteorological records),

$$RH\,(\%) = 100 * 10^{P}$$

$$\text{where } P = \frac{7.5 * DEWPT}{273.15 + DEWPT} - \frac{7.5 * T}{273.15 + T}$$

Source: Greg Broszczyk, Project Aquarius meteorologist.

Formula 2

If dry bulb temperature (T), wet bulb temperature (W) and pressure (PRES in mb) are available, as on most Card 18 records,

$$T1 = 1 - \frac{373.15}{T + 273.15}$$

$$T2 = 1 - \frac{373.15}{W + 273.15}$$

$$\begin{aligned}
ESD &= 1013.25 * e^{A} \\
ESW &= 1013.25 * e^{B} \\
\text{where } A &= 13.3185 * T1 - 1.976 * (T1)^{2} - 0.6445 * (T1)^{3} - 0.1299 * (T1)^{4} \\
B &= 13.3185 * T2 - 1.976 * (T2)^{2} - 0.6445 * (T2)^{3} - 0.1299 * (T2)^{4} \\
EA &= ESW - 0.000799 * PRES * (T-W) \\
RH &= 100 * \frac{EA}{ESD}
\end{aligned}$$

Source: Crane (1982) p.93-4.

(c) GRASS CURING PERCENTAGE

Final equation is:

$$C = 10 + 10*MSO + ASDI/10 - SRAIN$$

where MSO = month since October, with following values:
Jan 3, Feb 4, Mar 5, Apr 6, May 7, June 8
July 0, Aug 0, Sep 0, Oct 0, Nov 1, Dec 2.

ASDI = average of last 15 days' SDI (mm)

SRAIN = sum of rainfall (mm) for 3 weeks up to 4 days ago

The first 3 terms (10+10*MSO+ASDI/10) are constrained to an upper limit of 100, and C is constrained to a lower limit of 0.

(d) DROUGHT FACTOR

Equation used is:

$$DF = \frac{0.191 * (SDI + 104) * (NDSR + 1)^{1.5}}{3.52 * (NDSR + 1)^{1.5} + ALR - 1}$$

where DF = drought factor, constrained to range 0 to 10.
SDI = Mount's Soil Dryness Index (mm).
NDSR = number of days since rain
ALR = amount of last rain (mm)

Source: Noble, Bary & Gill (1980) with Mount's SDI (mm) substituted for Keetch-Byram Drought Index (points)

(e) McARTHUR FIRE DANGER INDEX

Forest FDI, Mark 5 = $2 * e^{X}$
where $X = -0.45 + 0.987 * \ln(DF) - 0.0345 * RH + 0.0338 * T + 0.0234 * V$

Grass FDI, Mark 3 = $2 * e^{Y}$
where $Y = -23.6 + 5.01 \ln(CI) - 0.226 * SQRT(RH) + 0.0281 * T + 0.633 * SQRT(V)$

where DF = drought factor
RH = relative humidity (%)
T = temperature (°C)
V = wind velocity (km/hr)
CI = curing percentage

For 3-hourly Forest FDI, RH was lagged 2 hours

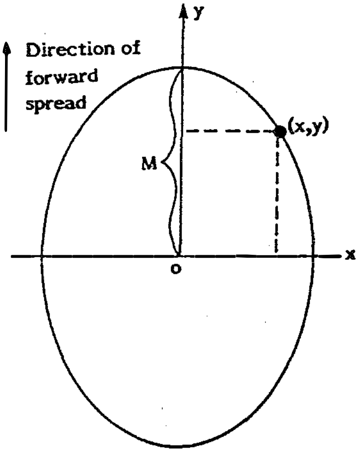
Source: Noble, Bary & Gill (1980).

APPENDIX 8

GROWTH RATIOS IN FIRE ELLIPSE

The following series of equations*, based on the geometry of the ellipse, are used in AIRPRO to convert the perimeter growth rate to the forward rate of spread, or vice versa.

Notation: V = wind speed (km/hr)
R = length: width ratio of ellipse



Intersection point between head and flank is where tangent to ellipse has slope equal to length: width ratio.

x and y coordinates are defined in space shown in diagram.

All lengths are defined relative to length of semi-major axis, M.

Equations

Width: length ratio: $W = \exp(-0.0162 * V^{1.2})$

Length: width ratio: $R = 1/W$

x coord. of intersection between head and flank:

$$X = W/\sqrt{2}$$

$$C = 1.171 * R^2$$

$$D = X * C$$

$$G = \sqrt{D^2 + 1}$$

Length of head: $H = X * G + \log(D + G)/C$

$$C1 = 1.71 * W$$

y coord. of intersection between head and flank:

$$Y = 1/\sqrt{2}$$

$$G = \sqrt{0.5 * C * C + 1}$$

---

* Deviation from Simard and Young, 1978, p.65-66 and 185-191.

Length of flank: $A = Y * G + \log(Y * C + G)/C$

$S = 2 * (H + A)$

Rear to forward ROS ratio: $R1 = \exp(-0.047 * V)$

$Q = S * (R1 + 1)/2$

If perimeter length = P

Forward ROS is: $F = P/Q$

Values of Q for wind speeds in the typical range are as follows:

V	5	10	20	30	50
Q	5.3	4.5	3.5	2.8	2.3

APPENDIX 9

CFA APPLIANCE COSTS - DERIVATION OF HOURLY RATES

Selected example:

Small town tanker: 3000 litres, 4WD

Capital cost (1983): C = \$46 500

Effective life: n = 17 years

Residual value as proportion of original cost: s = 0.1

Average annual usage: V = 1740 km

Proportion of depreciation due to usage: u = 0.8

Interest rate = 5%
$i = 0.05$

Use and Cost summary, from CFA sample of 140 tankers:

1. Annual repair cost = \$552/tanker
2. Annual petrol and oil cost = \$507/tanker
3. Comprehensive insurance = \$195 per vehicle
4. Average usage per year = 1738 km
5. Average speed travel 25 km/hr

Fixed Cost

Fixed capital charge p.a.*

$$= C\left[1 - \frac{s_1 + u\,(1 - s_1)}{(1 + i)^n}\right] A^{-1}_{\overline{n}|\,i}$$

$$= 46\ 500\left[1 - \frac{0.1 + 0.8(0.9)}{(1.10)^{17}}\right](0.1247)$$

= \$4858/yr or \$2.79/km

Insurance cost = \$195/yr or \$0.11/km

Total fixed cost = \$5053/yr or \$2.90/km

---

* Derivation of formulae shown in Appendix 10.

Variable Cost

$$\text{Variable capital charge p.a. at normal use} = C\left[\frac{u\,(1 - s\,)}{(1 + i\,)^{n}}\right] A^{-1}_{\overline{n|}\,i}$$

$$= 46\ 500\left[\frac{0.8(0.9)}{(1.10)^{17}}\right] 0.1247$$

$$= 826$$

Variable capital charge p.a. $\frac{826}{1740} = \$0.47/\text{km}$

Fuel (petrol + oil) $\frac{507}{1740} = \$0.29/\text{km}$

Repairs + maintenance $\frac{552}{1740} = \$0.32/\text{km}$

Insurance $\frac{195}{1740} = \$0.11/\text{km}$

Total variable cost $= 0.47 + 0.29 + 0.32$

$= \$1.19/\text{km}$

Calculation of hourly rate

Assume 50% of distance travelled is on-road and 50% on fire-line, and variable cost per km on road (x) is half that on fire-line (2x).

Weighted average cost (\$/km): $0.5x + 0.5(2x) = 1.19$

$\therefore x = 0.79$

Variable cost on road at average 55 km/hr $= \$0.79/\text{km} \times 55\ \text{km/hr}$

$= \$43/\text{hour}$

Variable cost on fire-line at av.15 km/hr $= \$1.58/\text{km} \times 15\ \text{km/hr}$

$= \$24/\text{hour}$

(Use on fire-line includes fire suppression, patrolling and chasing breakaways and travelling off-road to refill water tank.)

APPENDIX 10

CAPITAL COSTS - FIXED AND VARIABLE

In calculating the cost-benefit results for a project with a range of different levels of usage or output, it is desirable to separate the capital costs into a purely fixed component and a component that varies with the level of use.

Suppose the machine has an initial cost of C, and an effective life of n years, at a normal usage rate of V per year, after which time its salvage value is s_1C. If it receives only minimal use, however, its value after n years is still s_2C, where the reduction $(1 - s_2)\,C$ represents depreciation with the passage of time (e.g. due to corrosion or obsolescence). The amount $(s_2 - s_1)\,C$ represents depreciation of the 'wear and tear' variety, proportional to use. (If use were higher than V, the effective life would be shorter than n).

Discounting future sums at i, the social opportunity cost of capital.
Net present value of capital costs, at minimal use

$$= C - \left[\frac{s_2C}{(1+i)^n}\right]$$

$$= C\left[1 - \frac{s_2}{(1+i)^n}\right]$$

$$\text{NPV of capital costs at usage V} = C - \left[\frac{s_1C}{(1+i)^n}\right]$$

$$= C\left[1 - \frac{s_1}{(1+i)^n}\right]$$

$$\therefore \text{ Increase in NPV capital costs due to usage V} = C\left[\frac{s_2 - s_1}{(1+i)^n}\right]$$

(i.e. variable component)

If costs and benefits are expressed as equal annual equivalents rather than NPV's, including interest at i,

$$\text{fixed capital charge per annum} = C\left[1 - \frac{s_2}{(1+i)^n}\right] A^{-1}_{\overline{n}|\,i}$$

$$\text{and variable capital cost per unit use} = \frac{C\,(s_2 - s_1)\,A^{-1}_{\overline{n}|\,i}}{(1+i)^n\ V}$$

where $A^{-1}_{\overline{n}|\,i}$ = constant annual amount required to repay a sum of

1 over n payments with interest at i per payment

$$= \frac{i\,(1 + i)^n}{(1 + i)^n - 1}$$

The formulae can be rewritten in the following terms:
Given parameters: C = capital cost
u = proportion of depreciation related to use

$$u = \frac{(s_2 - s_1)}{(1 - s_1)}$$

s_1 = salvage value
n = effective life (years)
i = interest rate
V = normal usage per annum

Fixed charge per annum $= C \left[1 - \dfrac{s_1 + u\,(1 - s_1)}{(1 + i)^n} \right] A^{-1}_{\overline{n}|\,i}$

Variable cost per unit use $= C \left[\dfrac{u(1 - s_1)}{(1 + i)^n} \right] \dfrac{A^{-1}_{\overline{n}|\,i}}{V}$

Combined cost per annum $= C \left[1 - \dfrac{s_1}{(1 + i)^n} \right] A^{-1}_{\overline{n}|\,i}$

There is an implicit interest component in the above costs which may bear no relation to the actual interest paid on the funds used to buy the machine. The latter is irrelevant in a social cost-benefit study, as it will vary according to whether the machine is financed by internal finance or external debt, whether any loan is subsidised, and what the terms of repayment are.

The interest rate used in the cost-benefit study is the social opportunity cost of capital (here assumed to be 10% p.a.). The interest component in the above charge can be viewed as the annual return on capital that could have been obtained had the capital instead been invested by a private enterprise.

It may be noted that, by the above formulae, the fixed cost element in capital charges predominates, even though the majority of depreciation may be related to use. For example, if $u = 0.8$ and $s_1 = 0.2$, the variable cost per annum is only 27% of the combined charge. This is basically explained by the fact that the capital is tied up for the life of the asset, regardless of the extent of use.

APPENDIX 11

AIRTANKER DATA

(a) PERFORMANCE

Model	Cruising speed (km/hr)	Rate of climb (m/min)	Endurance (hr)	No. of tanks	Retardant tank capacity (litres)	Manoevr-ability	Accuracy (m)
Hercules C-130	459	488	7	2	11 355	0.67	13
Canadair CL-215	258	269	5	2	5 455	1.38	10
DC6 B	402	274	9	12	11 365	0.56	13
Neptune P2V-7	346	636	5	4	9 092	0.60	13
Canso PBY5A	185	152	11	2	3 637	0.95	10
Grumman Tracker S2	325	457	3	4	3 545	1.20	11
Thrush Commander	204	274	3	1	1 500	2.40	8
Bell 206	214	384	4	1	340	3.00	2
Twin Otter DHC-6	266	396	4	2	1 818	1.52	8
Bell 212	185	402	2	2	1 362	3.00	4
DC4	315	250	8	8	7 570	0.60	12

(b) CHARACTERISTICS FOR USE OF AERODROMES

Model	Weight (kg)	Take-off run (m)	Tyre pressure (kPa)	ACN*			
				A	B	C	D
Hercules C -130	70 300	1 158	620	20	25	31	37
Canadair CL-215	19 620	944	531	11	13	15	16
DC6 B	44 000	1 370	689	17	20	23	27
Neptune P2V-7	32 650	762	758	24	26	27	28
Canso PBY5A	13 835	1 097	345	6	8	11	12
Grumman Tracker S2	11 680	975	517	6	8	9	10
DC4	32 440	700	534	10	12	15	18

* ACN = Aircraft Classification Number

APPENDIX 12

SELECTED BASE COMBINATIONS

The following table lists the bases tested on various AIRPRO runs for each aircraft. Those marked * indicate the preferred base combinations used in the final run.

Aircraft	Home Bases	Fixed retardant facilities
Hercules & Neptune	Mangalore*, East Sale, Tullamarine, Portland	East Sale*, Mangalore*, Portland*, Tullamarine, Avalon, Mildura
Canadair CL-215 & DC4	Mangalore*, East Sale, Hamilton	East Sale*, Mangalore*, Hamilton*, Benalla, Bacchus Marsh, Avalon
DC6 B	Mangalore*, East Sale, Hamilton	East Sale*, Mangalore*,Hamilton*, Avalon, Portland
Canso PBY5A	Mangalore*, East Sale, Hamilton	East Sale*, Mangalore*, Hamilton*, Avalon, Ballarat, Bendigo, Mildura
Grumman Tracker S2	Mangalore*, Hamilton, Bairnsdale, Benalla, Bacchus Marsh, Maryborough	Bairnsdale*, Hamilton*, Benalla*, Mangalore*, Maryborough, Mildura, Bacchus Marsh, East Sale, Ballarat, Bendigo
Thrush Commander	Bairnsdale*, Stawell*, Benambra*, Moorabbin*, Leongatha*, Ballarat*,	Bairnsdale*, Ballarat*, Benambra*, Leongatha*, Noorinbee*, Dartmoor* Mt Beauty*, Snowy Range*, Bright*, Stawell*, Gelantipy*, Matlock*, Victoria Valley*, Tallangatta*, Mangalore
Bell 206 & Bell 212	Latrobe Valley*, Moorabbin*, Bright, Ballarat, Hamilton, Orbost, Fiskville	As for Thrush Commander
Twin Otter DHC-6	Moorabbin*, Benambra*, Bairnsdale, Fiskville, Lilydale, Mansfield, Stawell, Colac	——

APPENDIX 13

AIRFIELD LOCATIONS AND CHARACTERISTICS

BASE	LATITUDE (deg min)	LONGITUDE (deg min)	PCN	SSS	MTP	RLEN	ELEV
ARARAT	-37 19	142 59	12	B	500	1239	995
AVALON	-38 02	144 28	43	B	1400	3048	35
BACCHUS MARSH	-37 44	144 25	10	B	450	1553	520
BAIRNSDALE	-37 53	147 34	5	A	400	1101	165
BALLARAT	-37 31	143 48	6	B	450	1265	1433
BENALLA	-36 33	146 00	10	B	450	1043	569
BENDIGO	-36 44	144 20	8	A	450	1135	705
BIRCHIP	-36 00	142 55	0	D	450	1043	340
CORRYONG	-36 11	147 53	5	A	450	1401	963
DONALD	-36 22	143 00	0	D	0	1160	377
EAST SALE	-38 06	147 07	50	B	1400	3000	15
ECHUCA	-36 10	144 46	9	A	800	1102	323
HAMILTON	-37 39	142 04	10	B	600	1404	803
HOPETOUN	-35 43	142 22	0	D	450	1110	256
HORSHAM	-36 40	142 10	6	B	580	1322	445
KERANG	-35 45	143 56	0	D	400	1067	254
LATROBE VALLEY	-38 13	146 28	0	D	450	930	182
LAVERTON	-37 52	144 46	50	B	1400	3000	15
MALLACOOTA	-37 36	149 43	5	B	500	1028	102
MANGALORE	-36 53	145 11	17	C	850	2027	467
MARYBOROUGH	-37 02	143 42	6	A	450	1040	766
MELBOURNE(TULLAMARINE)	-37 40	144 51	73	C	1400	3657	434
MELBOURNE(MOORABBIN)	-37 59	145 06	0	D	0	1123	50
MILDURA	-34 14	142 05	32	A	750	1479	166
NHILL	-36 19	141 39	0	D	450	1102	454
ORBOST	-37 48	148 37	0	D	0	1140	92
PORTLAND	-38 19	141 28	14	B	850	1417	265
ROBINVALE	-34 39	142 47	8	A	450	1140	284
SALE	-38 06	146 58	12	B	600	1527	93
SEA LAKE	-35 32	142 53	0	D	0	1040	184
SHEPPARTON	-36 26	145 23	0	D	450	1147	374
ST ARNAUD	-36 39	143 11	0	D	450	999	639
STAWELL	-37 04	142 44	0	D	450	1403	807
SWAN HILL	-35 23	143 32	6	B	600	1492	71
WARRACKNABEAL	-36 19	142 25	6	B	600	1372	121
WARRNAMBOOL	-38 18	142 27	6	B	500	1372	74
WYCHEPROOF	-36 04	143 14	0	D	0	1042	107
YARRAM	-38 34	146 45	0	D	0	914	15
APOLLO BAY	-38 46	143 40	0	D	0	0	9
BEAUFORT	-37 28	143 14	0	D	0	0	305
BEECHWORTH	-36 25	146 38	0	D	0	0	610
BENAMBRA I	-36 58	147 42	0	D	0	0	671
BONANG	-37 11	148 44	0	D	0	0	701
BRIGHT	-36 44	146 52	0	D	0	0	285
BUCHAN	-37 30	148 11	0	D	0	0	213

CANN RIVER (NOORINBEE)	-37 31	149 10	0	D	0	0	122
CASTERTON	-37 36	141 24	0	D	0	0	152
CASTLEMAINE	-37 04	141 13	0	D	0	0	290
COLAC	-38 17	143 41	0	D	0	0	137
CRESSY (HIRTH)	-38 02	143 38	0	D	0	0	128
DIMBOOLA	-36 28	142 03	0	D	0	0	122
DUNDONNELL II	-37 53	142 59	0	D	0	0	244
EILDON	-37 13	145 52	0	D	0	0	190
EUROA	-36 45	145 35	0	D	0	0	114
FISKVILLE	-37 30	144 14	0	D	0	0	442
GEELONG (GROVEDALE)	-38 18	144 20	0	D	0	0	37
GELANTIPY	-37 12	148 14	0	D	0	0	763
GLENLOFTY	-37 08	143 11	0	D	0	0	305
GRAMPIANS (VIC VALLEY)	-37 10	142 20	0	D	0	0	220
HEYFIELD I (MCINNES)	-37 59	146 47	0	D	0	0	46
KYABRAM	-36 20	144 58	0	D	0	0	104
KYNETON	-37 14	144 27	0	D	0	0	503
LAKES ENTRANCE	-37 53	148 00	0	D	0	0	79
LEONGATHA	-38 29	145 58	0	D	0	0	69
LICOLA	-37 38	146 37	0	D	0	0	213
LILYDALE	-37 42	145 22	0	D	0	0	76
LONGWARRY	-38 06	145 47	0	D	0	0	46
MANSFIELD III (BARRAGUNDA)	-37 02	146 10	0	D	0	0	610
MATLOCK (JESSOP)	-37 37	146 10	0	D	0	0	1219
MOUNT BEAUTY	-36 45	147 10	0	D	0	0	335
MUNRO	-37 50	147 9	0	D	0	0	30
ORBOST (SIMPSONS CK)	-37 43	148 38	0	D	0	0	30
OUYEN	-35 04	142 19	0	D	0	0	30
PAKENHAM	-38 06	145 29	0	D	0	0	91
DARTMOOR	-37 55	141 16	0	D	0	0	30
SNOWY RANGE	-37 21	146 46	0	D	0	0	1585
SWIFTS CK	-37 16	147 45	0	D	0	0	366
TALLANGATTA B (SHELLEY)	-36 12	147 10	0	D	0	0	786
VICTORIA VALLEY	-37 32	142 20	0	D	0	0	229
WANGARATTA	-36 22	146 19	0	D	0	0	149
WHITTLESEA	-37 32	145 5	0	D	0	0	201
WOODFIELD	-37 02	145 48	0	D	0	0	305
YARRAWONGA	-36 03	146 03	0	D	0	0	129
YEA	-37 13	145 18	0	D	0	0	190

ABBREVIATIONS:

PCN= pavement classification number
SSS= sub-surface strength
MTP= maximum tyre pressure (kpa)
RLEN= runway length (m)
ELEV= elevation above sea level (m)

APPENDIX 14

AIRCRAFT-AIRFIELD SUITABILITY MATRIX
AIRTANKER MODEL

AERODROME	1	2	3	4	5	6	7	8	9	10	11
ARARAT	101	111	010	100	111	111	111	111	111	111	111
AVALON	111	111	111	111	111	111	111	111	111	111	111
BACCHUS MARSH	100	111	110	100	111	111	111	111	111	111	111
BAIRNSDALE	000	100	000	100	111	111	111	111	111	111	110
BALLARAT	100	101	000	100	111	111	111	111	111	111	101
BENALLA	000	111	010	100	011	111	111	111	111	111	111
BIRCHIP	000	111	000	100	111	111	111	111	111	111	111
CORRYONG	000	100	000	100	011	111	111	111	111	111	100
DONALD	100	101	100	100	111	111	111	111	111	111	111
EAST SALE	100	100	000	100	100	100	111	111	111	111	100
ECHUCA	111	111	111	111	111	111	111	111	111	111	111
HAMILTON	001	111	011	101	111	111	111	111	111	111	111
HOPETOUN	101	111	111	101	111	111	111	111	111	111	111
KERANG	000	100	000	100	111	111	111	111	111	111	100
LATROBE VALLEY	101	101	001	100	111	111	111	111	111	111	101
LAVERTON	000	100	000	100	011	111	111	111	111	111	100
MALLACOOTA	000	000	000	100	011	011	111	111	111	111	100
MANGALORE	111	111	111	111	111	111	111	111	111	111	111
MARYBOROUGH	001	101	000	100	011	111	111	111	111	111	101
MELBOURNE(TULL)	111	111	111	111	111	111	111	111	111	111	111
MELBOURNE(MOOR)	000	111	000	100	011	111	111	111	111	111	111
MILDURA	111	111	111	111	111	111	111	111	111	111	111
NHILL	000	100	000	100	100	100	111	111	111	111	100
ORBOST	111	111	111	111	111	111	111	111	111	111	111
PORTLAND	000	100	000	100	111	111	111	111	111	111	100
ROBINVALE	000	100	000	100	100	100	111	111	111	111	100
SALE	111	111	111	111	111	111	111	111	111	111	111
SEA LAKE	000	111	000	100	111	111	111	111	111	111	111
SHEPPARTON	101	111	111	101	111	111	111	111	111	111	111
ST. ARNAUD	000	100	000	100	000	100	111	111	111	111	100
STAWELL	000	100	000	100	111	111	111	111	111	111	100
SWAN HILL	000	100	000	100	011	111	111	111	111	111	100
WARRACKNABEAL	100	100	100	100	111	111	111	111	111	111	100
WARRNAMBOOL	101	101	101	101	111	111	111	111	111	111	101
WYCHEPROOF	101	101	101	101	111	111	111	111	111	111	101
YARRAM	101	101	100	100	111	111	111	111	111	111	101

AIRTANKER MODEL:
1= HERCULES
2= CL-215
3= DC-6
4= NEPTUNE
5= CANSO
6= TRACKER
7= THRUSH
8= BELL 206
9= TWIN OTTER
10= BELL 212
11= DC-4

LEGEND: FOR ANY PARTICULAR BASE AND MODEL.
1 for the first digit model passes runway lenght test
1 for the second digit model passes ANC-PNC test
1 for the third digit model passes tyre pressure test
EG. 111= model can use base
000= model cannot use base

APPENDIX 15

LOCATIONS AND SUITABILITY FOR WATER SCOOPING

LAKES	LATITUDE (deg min)	LONGITUDE (deg min)	LENGTH (km)	SUITABILITY FOR WATER SCOOPING	CONTROLLING AUTHORITY IF NOT DEPT. WATER RESOURCES
ACHERON L	-37 14	145 43	4.0	?	
APOLLO B	-38 45	143 41	10.0		
BANIMBOOLA L	-36 32	147 28	1.5		
BARKERS CK R	-36 58	144 17	1.2		
BARWON R	-38 33	143 42	3.0	?	GWB
BELLFIELD L	-37 12	142 33	4.0		
BOGA L	-35 27	143 39	4.0		
BOLAC L	-37 44	142 51	5.0		
BONG BONG L	-38 08	141 11	1.2	?	
BUFFALO L	-36 44	146 39	3.0		
BURRUMBEET L	-37 30	143 39	7.0		
CAIRN CURRAN R	-37 01	143 58	7.0		
CARDINIA CK R	-37 58	145 25	6.0		MMBW
COLAC L	-38 18	143 36	7.0		
COLONGULAC L	-38 10	143 10	7.0	?	
CONNEWARRE L	-38 14	144 27	5.0		
COOPER L	-36 30	144 48	5.0		
COORONA L	-35 44	142 24	2.0	?	
CORANGAMITE L	-38 11	143 25	26.0		
CORANGAMITE L2	-38 20	143 25	4.0		
CORINGLE L	-37 47	148 29	3.0	?	
CORNER INLET	-38 43	146 15	5.0		
CULLULLERAINE L	-34 16	141 34	1.2	?	
CURDIES I	-38 36	142 53	3.0	?	
DARTMOUTH R	-36 34	147 32	6.0		
EILDON L	-37 12	145 55	13.0		
EILDON L 2	-37 15	145 58	2.0		
ELINGHAMITE L	-38 21	143 01	2.0	?	
EPPALOCK L	-36 53	144 36	10.0		
FAIRY P	-38 22	142 22	10.0		
FYANS L	-37 08	142 37	3.0		
GELLIE L	-37 49	143 03	3.0	?	
GLENMAGGIE L	-37 55	146 47	8.0		
GOLDSMITH L	-37 33	143 21	4.0	?	
GOULBURN W	-36 44	145 11	5.0		
GREENVALE R	-37 38	144 54	2.0		MMBW
HAWTHORN L	-34 12	142 06	2.0	?	
HAZELWOOD CP	-38 18	146 22	4.0		SECV
HEARD L	-36 51	141 50	1.2		
HINDMARSH	-36 04	141 55	15.0		

HUME L	-36 11	147 04	15.0		
HUME L2	-36 02	147 21	4.0		
JACK SMITH L	-38 30	147 02	6.0	?	
KANGAROO L	-35 35	143 46	6.0		
KARNAK L	-36 50	141 31	1.2	?	
KEILAMBETE L	-38 13	142 53	2.0	?	
KIMBOLTON L	-36 28	143 02	2.0		
KORWEINGUBOORA R	-37 30	144 09	1.5		
LAL LAL R	-37 40	144 04	1.5		
LALBURT L	-35 40	143 20	3.0	?	
LEARMONTH L	-37 26	143 43	3.0		
LINLITHGOW L	-37 45	142 11	4.0	?	
LOCKIE L	-35 45	142 20	5.0	?	
LOGAN L	-37 55	143 11	3.0	?	
LONSDALE L	-37 01	142 37	7.0		
MALLACOOTA I	-37 30	149 43	4.0		P&H
MALMSBURY R	-37 13	144 22	2.5		
MAROONDAH R	-37 38	145 34	3.0		MMBW
MEERING L	-35 53	143 48	2.0	?	
MELTON R	-37 44	144 34	3.0		
MERRIMU R	-37 38	144 29	2.0		
MODEWARE L	-38 15	144 06	3.0	?	
MOKOAN L	-36 27	146 05	15.0		
MOONDARRAHN L	-38 05	146 22	4.0		MMBW
MOORA MOORA R	-37 14	142 25	2.5		
MOORABOOL R	-37 30	144 05	2.0		GWB
MUIRHEAD L	-37 29	142 36	3.0	?	
MULWALA L	-36 01	146 07	10.0		
MURDEDUKE L	-38 11	143 54	5.0	?	
MURRAY R1	-36 04	144 55	6.0		RMC
MURRAY R2	-36 03	146 22	1.2		RMC
MURRAY R3	-36 03	146 45	2.0		RMC
NEWLYN R	-37 25	144 00	1.2		
NILLAHCOOTIE L	-36 53	146 00	7.0		
PHILLIP P	-38 08	144 50	40.0		P&H
PINE LAKE	-36 47	142 21	5.0		
PORTLAND B	-38 18	141 50	25.0		
PURRUMBETE L	-38 17	144 13	2.5		
PYKES CK R	-37 36	144 18	1.5		
ROCKLANDS R	-37 14	142 05	13.0		
ROCKY VALLEY S	-36 53	147 18	3.0		SECV
ROSSLYNNE R	-37 29	144 34	4.0		
SAND HILLS L	-35 43	143 40	1.2	?	
SILVAN R	-37 51	145 25	4.0		MMBW
SPRING GULLY R	-36 48	144 17	1.2		
SYDENHAM R	-37 46	148 59	5.0	?	
TAMBOON I	-37 45	149 08	4.0	?	
TARAGO R	-38 00	145 55	2.5		
TAYLOR L	-36 47	142 23	6.0		
THOMSON L	-37 47	146 21	7.0		MMBW
TIMBORAN L	-35 19	143 03	7.0	?	
TOOLIOROOK L	-37 59	143 16	3.0	?	
TOOLOONDO R	-37 01	141 57	5.0		
TULLAROO R	-37 07	143 52	5.0		
TYERS L	-37 50	148 06	6.0	?	

UPPER COLIBAN R	-37 17	144 24	4.0		
UPPER YARRA R	-37 42	145 55	7.0		MMBW
VICTORIA L	-38 03	147 45	16.0		P&H
VOLLNEY C	-38 46	143 19	4.0		
WALLACE L	-37 01	141 17	2.0	?	
WALLAWALLA L	-34 11	141 11	2.0	?	
WARANGA R	-36 33	145 06	10.0		
WARTOOK R	-37 04	142 27	6.0		
WELLINGTON	-38 05	147 20	18.0		
WESTERNPORT B	-38 18	145 17	10.0		P&H
WHITE SWAN R	-37 31	143 55	2.0		BWT
WILLIAM HOVELL L	-36 55	146 24	4.0		
WINGAN I	-37 44	149 30	3.0	?	
WINNEKE RES	-37 40	145 18	5.0		MMBW
WNY WYN L	-36 40	141 54	3.0	?	
YAMBUK L	-38 20	142 03	2.0	?	

Abbreviations for Authorities:

BWT	Ballarat Water Trust
RMC	River Murray Commission
SECV	State Electricity Commission of Victoria
P&H	Ports and Harbours Divisions, Public Works Dept.
MMBW	Melbourne and Metropolitan Board of Works
GWB	Geelong Waterworks Board

APPENDIX 16

FREQUENCY OF HIGH FIRE DANGER DAYS

(East Sale, Victoria, 1978-79 to 1982-83)

	Number of days with Forest FDI over 12												
Period	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	Total Nov-Feb
1978-79	0	0	0	1	2	1	5	6	4	1	0	2	14
1979-80	2	3	4	2	7	16	10	11	10	7	1	0	44
1980-81	0	5	11	5	2	4	6	7	1	11	1	0	19
1981-82	0	0	1	0	0	4	10	7	4	0	1	0	21
1982-83	0	5	5	7	14	12	13	12	7	0	0	0	51
5yr total	2	13	21	15	25	37	44	43	26	19	3	2	149
5yr av.	0.4	2.6	4.2	3.0	5.0	7.4	8.8	8.6	5.2	3.8	0.6	0.4	29.8

APPENDIX 17

FREQUENCY OF FIRES BY MONTH AND AREA CLASS

(FCV, 1972-73 to 1982-83)

Month	Area class (ha)					Total	Annual
	0-1	1-10	10-100	100-1000	1000+	(11 years)	average
July	8	1	2	0	0	11	1
August	37	34	27	12	2	112	10
September	49	69	73	53	24	268	24
October	129	95	80	52	16	372	34
November	266	120	72	40	18	516	47
December	556	210	120	51	23	960	87
January	705	239	139	44	27	1154	105
February	469	157	71	37	21	755	69
March	397	137	74	20	9	637	58
April	172	79	65	20	8	344	31
May	15	25	8	6	0	54	5
June	5	0	0	0	0	5	0.5
All months	2808	1166	731	335	148	5188	472

APPENDIX 18

RETARDANT BASE DATA

(a) OPERATING LEVELS

			Fixed		
Type		Mobile	Small	Medium	Large
Aircraft retardant tank capacity	(L)	0-3000	0-2000	2000-5000	5000+
Maximum number aircraft		3×1500	4×1500	3×3500 or 2×5500	2×11500
Aircraft cycle time	(min)	40	40	50	50
Batch size	(L)	1600	3000	4000	2×4000
Storage tank capacity	(L)	4000	10000	15000	30000
Mixing rate	(L/hr)	12000	18000	24000	2×24000
Time to mix batch	(min)	10	10	10	10
Loading rate	(L/min)	300	500	1900	1900
Time to load	(min)	5	5	5	10
Amount premixed for maximum number	(L)	0	10000	15000	20000
Crew	(no. men)	2	3	3	3 5(for more than one aircraft)

Other assumptions: Mixing and loading are not done simultaneously.

(b) BASE COSTS PER UNIT

				Fixed		
			Mobile	Small	Medium	Large
C	Capital cost	($)	14 000	35 000	40 000	45 000
n	Effective life at usage rate of:	(years)	10	10	10	10
t	number of airtanker loads per annum		300	400	300	150
l	load size	(L)	1200	1200	4000	10 000
V	volume per annum	(kL)	360	480	1200	1500
u	% of depreciation variable with use		50	50	50	50
i	At 10% interest rate	(i=0.10)				
D	Present value of depreciation(1) variable with use		2700	6747	7708	8672
E	Annual equivalent including(2) interest at 10% per annum		439	1098	1254	1411
K	Capital cost/kilolitre(3)	($/kL)	1.22	2.29	1.05	0.94
R	Remaining capital cost(4) annual equivalent	($)	1839	4598	5256	5912
M1	Preventative maintenance	($/yr)	200	300	350	400
M2	Variable repairs and maintenance	($/year)	200	300	350	400
M3	Variable repairs and maintenance	($/kL)	0.55	0.62	0.30	0.27
	Minimum stand-by labour - number men		0	2	2	2
S	@ 9 hr/day @ $10/hr	($/day)	0	180	180	180
	Additional labour during fires - number men		2	1	1	1:1 a/c 2:2 or more a/c
A	cost @ $10 per hour	($/hour)	20	10	10	10

			Mobile	Fixed		
				Small	Medium	Large
<u>Fuel</u>						
F	Amount used/batch	(L)	4.5			
	Cost	($/litre fuel)	0.50			
	Batch size	(L)	1600			
	Cost	($/kL retardant)	1.42	1.20	1.00	1.00
<u>Totals</u>						
R+M1	Fixed costs	($/year)	2039	4898	5606	6312
S	Stand by cost	($/day)	0	180	180	180
A	Additional Labour	($/hour)	20	10	10	10
K+M3+F	Operating	($/kL)	3.2	4.1	2.35	2.2

Notes:

(1) $$D = \frac{uC}{(1+i)^n}$$

(2) $$E = D\ A^{-1}_{\overline{n}|\,i}$$

where $$A^{-1}_{\overline{n}|\,i} = A^{-1}_{\overline{10}|\,0.1} = 0.163$$

(3) $$K = E/V$$

(4) $$R = (C - D)\ A^{-1}_{\overline{n}|\,i}$$

APPENDIX 19

PROPERTY LOSSES ON MAJOR FIRES, VICTORIA, 1983

(a) LOSSES BY ITEM AND FIRE

		Number of units lost						
		Fire location						
Selected items	Average value /unit ($)	Belgrave Heights	Cockatoo	Otways	E.Trentham-Macedon	Warburton	Cudgee	Mount Macedon
Houses	30 000-62 500	238	300	729	628	27	71	22
Other buildings	5 000-100 000		7	53	5	30	353	2
Fencing (per km)	1 000	650		1 000	50+	10	7 000	
Pasture (per ha)	40	1 090		5 000	3 000	162	45 000	600
Hay (per bale)	4			25 000	10 350	300	1 000 000	1 000
Cattle (per head)	300	462		159	149		7 800	30
Sheep (per head)	15	566		2 624	3 631		11 500	
Total estimated losses ($ million)*		27	21	67	40	2.3	23	2.4
Fatalities		21	6	3	7	0	9	0

* including items not specified above

Sources: Country Fire Authority; Department of Agriculture; Department of Management and Budget.

(b) SOURCES OF FINANCE

	$ million
Natural Disaster Relief Account	
- Victorian Government	21
- Commonwealth	23
Other costs of Victorian agencies	3
Insurance payments	138
Bushfire Appeal Trust Fund	23
Private losses not covered by Government or insurance, including other Appeals	27
	235

Source: Treasurer of Victoria, Media Release, 9 November 1983.

APPENDIX 20

TOTAL AREA BURNT IN EACH FOREST TYPE BY FCV DIVISION
(HECTARES 1972-73 to 1982-83)

	Central	Eastern	Northern	North East	Southern	South West	Western	State
ASH,HEMS								
I	1	5		1		1309		1316
II	942	2392		543	346	4		4227
III	5544	2063		1065	132	167		8971
IV	1	41		1331	187	122		1682
V	890	47		225	86	1		1249
MIXED SPECIES								
I		48				2060		2108
II	5	10116	223	1584	284	4165	19	16396
III	47179	237161	1345	8427	13032	18238	1770	327152
IV	21706	145299	1352	20073	10725	40410	5277	244842
V	6384	36435	58	1480	4699	16217	19466	84739
RG,BOX,IRON-BK								
I			79					79
II			193				2	195
III		1302	190	9	100		12	1613
IV	15	2909	8685	13	3093	320	2705	17740
V	5	3926	5682	82	204	238	3495	13632
SOFTWOOD								
I						3		3
II				99				99
III				98		2320	2	2420
IV				31	3	35	16	85
V		2	46	256	27	1778	29	2138
ALPINE		2348		197	275	63		2883
MALLEE			132				323014	323146
GRASS, SCRUB	304	38239	2059	2314	1170	14658	42671	101415
TOTAL	82976	482333	20044	37828	34363	102108	398478	1158130

APPENDIX 21

TIMBER DATA

(a) TIMBER RESOURCES

(i) Current stands

Forest type & height class	Number of years to harvest	Current salvageable volume (m^3/ha)	Current annual increment (m^3/ha)	Royalty (\$/m^3)	Fraction salvaged of those killed or severly damaged (%)
ASH, HEMS					
I (>52 m)	5	500	0	15	60
II (40-52 m)	20	400	7	14	60
III (27-40 m)	35	300	7	8	50
IV (15-27 m)	65	100	10	6	25
V (0-15 m)	75	20	5	6	5
MIXED SPECIES					
I	5	100	0	9	5
II	15	100	0	9	5
III	20	100	0.2	8	5
IV	30	80	0.2	8	10
V	60	20	1	4	0
RG, BOX-IRONBK					
I	5	20	0	15	60
II	10	20	0	14	60
III	15	20	0.5	8	50
IV	20	10	0.3	6	25
V	60	0	0.3	6	5
SOFTWOOD					
I	5	600	0	27	90
II	5	600	10	26	90
III	5	550	20	24	90
IV	15	400	25	17	40
V	25	10	15	8	5

(ii) Expected at next harvest

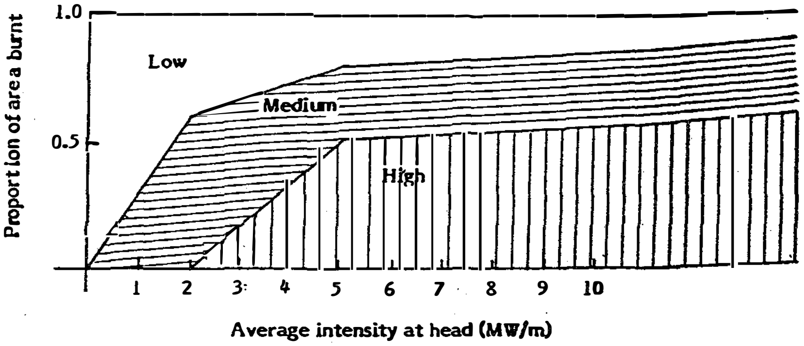
Forest type & height class	Merch. vol. (m^3/ha)	CAI (m^3/ha)	Royalty (\$/m^3)	Annual rate price increase (%)
ASH, HEMS	500	3	15	1
MIXED SPECIES	100	0	9	0.5
RG, BOX-IRONBK	20	0.3	15	1
SOFTWOOD	600	15	30	0

(b) FIRE DAMAGE

				Timber left to harvest at maturity					
Forest type	% killed or severely damaged			Growth loss (Number of years CAI)			Additional defect (% of merch. vol. at harvest)		
				Fire intensity*					
Height class	Low	Med	High	Low	Med	High	Low	Med	High
ASH, HEMS									
I–III (>27 m)	0	20	80	0	0.5	2	2	10	20
IV (15-27 m)	15	40	90	0	1	3	3	20	30
V (0-15 m)	25	60	100	0	2	4	5	40	50
MIXED SPECIES									
I–III	0	0	10	0	0.3	1.5	1	5	10
IV	0	5	20	0	0.7	2	1	10	20
V	5	15	50	0	1.5	3	2	30	40
RG, BOX-IRONBK									
I–III	0	10	30	0	0.5	2	2	7	15
IV	5	15	40	0	1	3	3	15	25
V	10	30	70	0	2	4	4	35	50
SOFTWOOD									
I–III	5	40	100	0	0.5	2	5	10	20
IV	20	70	100	0	1	3	7	20	30
V	40	100	100	0	2	4	10	40	60

* Fire intensity classes:

Low = 0-750 kW/m;
Medium = 750-3000 kW/m;
High = over 3000 kW/m.



Proportion of area burnt at different intensities

APPENDIX 22

COMPARISON OF THREE METHODS OF VALUING TIMBER LOSSES

This note demonstrates the equivalence of three methods of valuing timber losses under certain assumptions, the methods being:

A: discounted harvest value
B: accumulated past costs
C: regeneration costs and interim growth loss.

Notation:

a = age when burnt
h = harvest age
C_j = cost of regeneration in j^{th} year (per hectare), $j = 1$ to h
G = growth rate in royalty value due to increment in volume and unit value
V = value at harvest

Assume total destruction by fire with no salvage:
Method A:

L_1 = loss = discounted present value of harvest lost, less future costs saved

$$L_1 = \frac{V}{(1+I)^{h-a}} - \sum_{j=a+1}^{h} \frac{C_j}{(1+I)^{j-a}}$$

Method B:

L_2 = accumulated amount of sunk costs

$$L_2 = \sum_{j=1}^{a} \left[C_j \, (1 + I)^{a-j} \right]$$

$$= (1 + I)^{a} \sum_{j=1}^{a} \frac{C_j}{(1+I)^{j}}$$

$$= (1+I)^{a} \left[\sum_{j=1}^{h} \frac{C_j}{(1+I)^{j}} - \sum_{j=a+1}^{h} \frac{C_j}{(1+I)^{j}} \right]$$

$$= \left[(1+I)^{a} \sum_{j=1}^{h} \frac{C_j}{(1+I)^{j}} \right] - \sum_{j=a+1}^{h} \frac{C_j}{(1+I)^{j-a}}$$

Defining expected net present value of plantation at time of establishment as N:

$$N = \frac{V}{(1+I)^h} - \sum_{j=1}^{h} \frac{C_j}{(1+I)^j}$$

$$\text{Then } L_2 = (1+I)^a \left[\frac{V}{(1+I)^h} - N \right] - \sum_{j=a+1}^{h} \frac{C_j}{(1+I)^{j-a}}$$

$$= \frac{V}{(1+I)^{h-a}} - \sum_{j=a+1}^{h} \frac{C_j}{(1+I)^{j-a}} - (1 + I)^a \quad N$$

$$= L_1 - (1 + I)^a \quad N$$

If the plantation is economically marginal, $N = 0$, and $L_2 = L_1$

Method C:

L_3 = discounted value of regeneration costs after fire, less costs saved, plus interim compounded growth loss

$$L_3 = \sum_{j=1}^{h} \frac{C_j}{(1+I)^j} - \sum_{j=a+1}^{h} \frac{C_j}{(1+I)^{j-a}} + \frac{V[(1+G)^a - 1]}{(1 + I)^h}$$

$$= \sum_{j=1}^{h} \frac{C_j}{(1+I)^j} - (1+I)^a \sum_{j=a+1}^{h} \frac{C_j}{(1+I)^j} +$$

$$\left[(1+I)^a - 1 \right] \left[N + \sum_{j=1}^{h} \frac{C_j}{(1+I)^j} \right]$$

assuming annual rate of increment equals interest rate, $G = I$; i.e. rotation age is financial optimum.

$$L_3 = \left[\sum_{j=1}^{h} \frac{C_j}{(1+I)^j} \left[1 + (1+I)^a - 1 \right] \right] - (1+I)^a \sum_{j=a+I}^{h} \frac{C_j}{(1+I)^j} + \left[(1+I)^a - 1 \right] N$$

$$= (1 + I)^a \sum_{j=1}^{a} \frac{C_j}{(1+I)^j} + \left[(1 + I)^a - 1 \right] N$$

$$= \sum_{j=1}^{a} C_j (1+I)^{a-j} + \left[(1 + I)^a - 1 \right] N$$

$$= L_2 + \left[(1 + I)^a - 1 \right] N$$

If the plantation is economically marginal ($N = 0$), and if costs for first a years of plantation life in the past are the same as in the future;

$$L_3 = L_2$$

Thus the three methods are equivalent if forest management is in economic equilibrium.

APPENDIX 23

CALCULATIONS FOR STANDARD INCREASE IN WATER YIELD FOLLOWING FIRE

		1977	1978	1979	1980	Total
A	Rainfall (mm)	457 (Apr-Dec)	1,514	530	509	
	Catchment 1 (C.1) (unburnt)					
B	Runoff as % of rainfall	18	37	5	3	
C	Runoff (mm)	-	560	27	16	
	Catchment 3 (burnt Jan. 1979)					
B	Runoff as % of rainfall	10	39	15	7	
C	Runoff (mm)		-	590	80	37
D	Difference in runoff to C.1 (% of rainfall)	-8	+2	+10	+4	
E	Increase in runoff in 1979 and 1980 from level expected - % of rfl			18	12	
F	- mm			95	61	156
	Catchment 5 (logged 1978, burnt Jan 1979)					
B	Runoff as % of rainfall	10	44	32	21	
C	Runoff (mm)	-	666	170	111	
D	Difference in runoff to C.1 (% of rainfall)	-8	+7	+27	+18	
E	Increase in runoff in 1979, and 1980 from level expected - % of rfl			35	26	
F	- mm			185	138	323
	Catchment 6 (burnt Jan 1979, logged 1979-80)					
B	Runoff as % of rainfall	18	47	34	22	
C	Runoff (mm)	-	712	180	117	
D	Diff in runoff to C.1 (% of rfl)	0	+10	+29	+19	
	Increase in runoff in 1979 and 1980 from level expected at 1977 rate					
E	- % of rfl			29	19	
F	- mm			154	97	251

Source:

A and B	McKay & Cornish (1982), p.112 & 113 (Fig.2)
C =	A * B
D =	B for each catchment (3,5 & 6) - B for Catchment 1
E =	(D for 1979 & 1980 - D for 1977) for each catchment
F =	E * A

The calculations above attempt to isolate the effects of fire on runoff from other influences such as rainfall, soil and land type, logging, etc.

The figure calculated in row E is assumed to be the increase in runoff due to fire and logging, excluding change due to rainfall. The large changes in runoff in Catchment 3, for example, between 1977 and 1979 are clearly due predominantly to changes in annual rainfall. Nor should the difference in runoff in 1979 or 1980 between Catchment 1 (unburnt) and Catchment 3 (burnt) be attributed solely to fire because the behaviour of Catchment 1 may normally be different from Catchment 3, perhaps due to different soil type.

Taking as a benchmark 1977 (April-December) which was also a period of fairly low runoff rates and presumably rainfall, when all catchments were still unburnt, the runoff percentage in Catchments 3 and 5 was 8 percentage points below, and in Catchment 6 was equal to, that in Catchment 1. This percentage difference was assumed to be what would have prevailed in 1979 and 1980 if all had been undisturbed so that the difference in percentage runoff between Catchment 1 and the burnt ones in 1979 and 1980, less the 'normal' difference in 1977, was attributed to disturbance. It was applied to the actual rainfall in 1979 and 1980 to give the increase in mm.

After a total increase over 2 yr of 156 mm, Catchment 3 apparently recovered to normal flow. However, the logged Catchments 5 and 6 were still showing storm runoffs 3 to 4 times those expected after a 168 mm storm in May 1981. If it is assumed that the increase in annual yield gradually diminished to zero after 4 yr , the total increases in Catchments 5 and 6 over 4 yr could be extrapolated as 440 and 340 mm respectively.

The higher runoff in Catchments 5 and Catchments 6 than in Catchments 3 after the fire is partly due to the higher fire intensity and partly to the logging.

The differences in Catchment 5 between 1977 and 1978, and in Catchment 6 between 1979 and 1980, possibly due to logging*, seem to be only a few percentage points, but the logging affected only part of the area and part of the second year.

The bulk of the difference between Catchment 3 and the logged ones is therefore more likely attributable to the difference in fire severity.

The actual increases in runoff can be viewed as area-weighted averages of effects of different fire severities, e.g. in Catchment 1, 20 per cent was burnt at high severity, and 60 percent at low, and in Catchment 6, 80 percent at high and 20 percent at low. This indicates that the total increase in runoff on lightly burned areas (L) was a rate of 130 mm and on severely burnt areas (S) 390 mm**.

---

* MacKay and Cornish warn against attributing the small difference in 1978 to logging (p.112), but it seems to be one feasible explanation.

** obtained by solving $0.2\,S + 0.6\,L = 156$

$$0.8\,S + 0.2\,L = 340$$

The increases in runoff derived from McKay and Cornish's Eden data seem consistent with those from McArthur and Cheney (shown in the table below) bearing in mind that the historical increases in Cotter streamflow probably resulted from fires in only part of the catchment area.

Streamflow following widespread fires in Cotter catchment

Year	A Calculated flow from monthly rainfall ('000 ac ft)	B Actual flow ('000 ac ft)	C Percentage increase	D Calculated flow (mm)	E Increase in flow attribd. to fire (mm)
1917	146	260	78	374	292
1918	40	134	235	102	241
1923	64	133	108	164	177
1926	56	157	180	143	257
1939	115	164	43	295	127

Source: A,B,C from McArthur and Cheney (1965).
Catchment area = 119 000 ac; 1 foot = 304.8 mm
D = (1000 * A/119 000) * 304.8
$E = \frac{C}{100} * D$

The Eden data, however, suggest increases several times greater than those found by O'Loughlin et al. in the Cotter; namely 32 mm increase in base-flow mainly due to reduced transpiration in the first summer following the fire.

The main apparent explanations for this are:

- the greater permeability of soils in the Cotter which is in a higher altitude zone with a higher component of alpine and moist forest types.
- the low intensity of rainfall in the first 3 months in the Cotter

The severity of the Eden fire may have been slightly greater (e.g. 5MW compared with 3 MW), given that most of the riparian vegetation was destroyed. Although the annual post-fire rainfall in the Eden study was only half that in the Cotter the few storm events were more intense, which would have a disproportionate impact.

APPENDIX 24

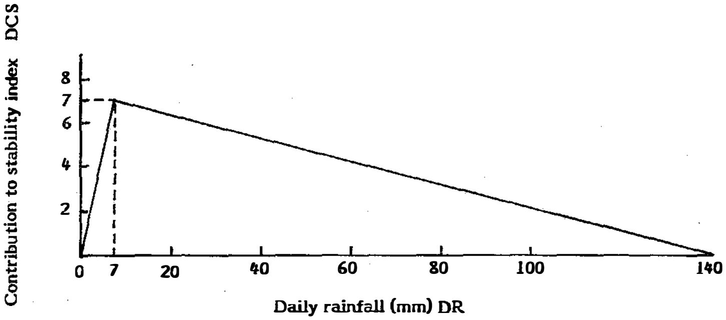
RAINFALL INTENSITY INDEX

RFI is an index calculated for each day at each representative meteorological station to indicate the extent of water run-off and erosion hazard following a fire on the given day, based on the rainfall pattern for the following 60 days.

It is calculated by the following steps:

DR(I) = daily rainfall (mm) on Ith day after fire
DCS(I) = daily contribution to vegetation regrowth and soil stability on Ith day after fire
DCS(I) = DR(I) if DR ≤ 7
7 - 0.05*DR(I) if DR > 7
with minimum of 0.

DCS has the following shape, reflecting the assumption that daily rainfall of 7 mm, given normal summer evaporation, would be about optimal for regrowth.

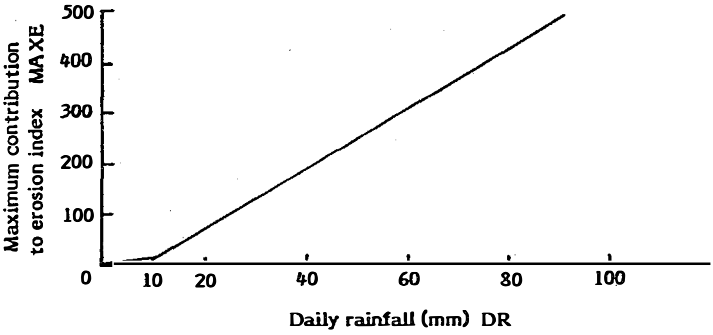


STAB(I) = cumulative stability of soil, based on previous rainfall up to 7 days earlier
= 0 if I = 1 to 7
= DCS(1) + DCS(2) + ... + DCS(I-7)
if I = 8 to 60

This reflects the idea that it takes about a week before accumulated rainfall has any practical effect on revegetation and soil stability.

MAXE (I) = maximum erosion index on day I, relevant only to bare catchment with STAB = 0
= DR(I) if DR < 10
10 + 6 * (DR(I)-10) if DR > 10

The shape of MAXE reflects the idea that the run-off and erosive effect increases sharply after a certain amount of rainfall, set here at 10 mm/day, after the infiltration capacity of the soil is exceeded.



MINE (I) = minimum erosion index

= MAXE (I) /60

DER (I) = daily contribution to erosion index

= $\text{MAXE (I)} * (1 - \frac{\text{STAB(I)}}{35})$

with minimum of MINE and maximum of MAXE.

This reflects the idea that, for a given rainfall intensity, erosion hazard decreases as stability increases until it reaches the minimum amount when STAB reaches 35, which could be achieved quickest, for example, after 5 days each of 7 mm rainfall.

RFI, the final index, is the sum of daily contributions to erosion hazard accumulated for 60 days.

RFI (I) = DER (1) + DER (2) + ... + DER (60).

Compressed functions of RFI are used in the DAMAGE routine as a factor to adjust both short-term water yield increase and water quality reduction.

Processing limitations

1. Daily rainfall data does not always capture the variations in rainfall intensity during the day. However, rainfall data for shorter intervals were not readily available for the stations required.

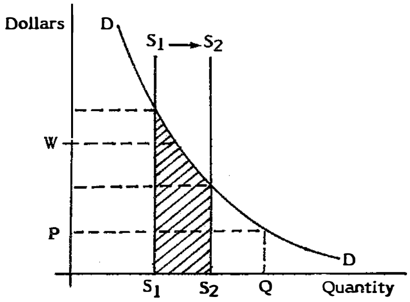
2. The period of 60 days is not always long enough to capture the effects of a fire on a catchment. After a dry period of 60 days, the calculated index RFI would still be low but the soil would still be vulnerable to erosion from later down-pours. However, the arbitrary cut-off point was set to limit computer processing costs.

APPENDIX 25

VALUATION OF CHANGES IN WATER SUPPLY

The appropriate method of valuing changes in water-supply for cost-benefit analysis could be either (i) value or (ii) cost, depending on whether the change effects usage of system costs.

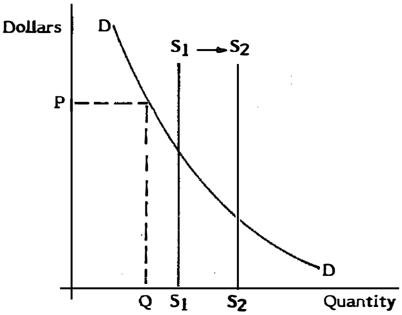
Where the increase in yield has no effect on system cost, the increase in actual usage may be valued at the user's marginal willingness to pay measured from their demand curve. This will not necessarily be the price charged. The following situations could apply:



(a) Usage is constrained by supply restrictions to a level below the quantity Q is desired at the price charged, P. Increase in yield from S_1 to S_2 is fully reflected in increase in use, S_2-S_1, at an average value of W, which is above price charged.

Figure (a). Supply restrictions

The increase in value (consumer + producer surplus) is represented by the shaded area, or approximated by W (S_2-S_1).



(b) Usage is rationed only by price, to Q which is below available yield S_1. The increase in yield to S_2 (whether store or not), has no effect on actual use. Marginal value = 0.

Figure (b). Excess supplies

The extra supply is not used immediately - short-term surplus situation as in (b) - but is stored and eventually used in a dry year when the situation is as in (a). This is quite common in that many Victorian towns have some degree of water restrictions in most years. The present value of the increased yield is the sum of probabilities of use in each future year times the discounted value W.

APPENDIX 26

WATER DATA

(a) WATER RESOURCES, VICTORIA

Drainage basin	Av. annual runoff (mm x 10) (kL/ha) (1)	Proportion used or developed (2)	Proportion of use for non-irrigation (3)	Non-irrigation use (kL/ha) (4)
South-East Coast				
221 East Gippsland	990	0.002	0.19	0.4
222 Snowy	1520	0.46	0.03	21
223 Tambo	890	0.015	0.29	4
224 Mitchell	1830	0.018	0.12	4
225 Thomson	2030	0.42	0.70	597
226 Latrobe	2130	0.47	0.82	821
227 South Gippsland	1870	0.026	0.46	22
228 Bunyip	1340	0.14	0.9	169
229 Yarra	2930	0.402	0.9	1060
230 Maribyrnong	740	0.09	0.9	60
231 Werribee	600	0.49	0.9	265
232 Moorabool	470	0.36	0.95	161
233 Barwon	800	0.093	0.82	61
234 Lake Corangamite	520	0.006	0.52	1.6
235 Otway	2090	0.024	0.70	35
236 Hopkins	450	0.022	0.35	3.5
237 Portland	930	0.008	0.54	4
238 Glenelg	660	0.110	0.35	25
Murray-Darling				
401 Upper Murray	2350	0.55	0.05	65
402 Kiewa	3530	0.014	0.36	18
403 Ovens	2140	0.062	0.19	25
404 Broken	440	0.308	0.02	3
405 Goulburn	1289	0.586	0.03	33
406 Campaspe	660	0.393	0.02	5
407 Loddon	190	0.398	0.02	1.5
408 Avoca	70	0.059	0.91	4
414 Mallee	0	0	0.11	0
415 Wimmera-Avon	100	0.13	0.70	9

Sources

(1) Dept National Resources, 'Review of Australia's Water Resources 1975', AGPS, Canberra, 1976, Tables IIa, IVa.

(2) Australian Water Resources Council, 'Review 85: Water Resources and Water Use', preliminary data, 1985.

(3) Dept National Development and Energy, 'The first national survey of water use in Australia', AGPS, Canberra, 1981, Appendix 2.

(4) = (1) x (2) x (3).

(b) WATER COSTS AND VALUES, VICTORIA

FCV district	Water rate (1)	Proportion of use for non-irrigtion (2)	Proportion of use for runoff (3)	P (4)
Dandenongs	380	0.9	0.27	53
Alexandra	150	0.03	0.58	48
Toolangi	380	0.9	0.40	78
Upper Yarra	380	0.9	0.40	78
Broadford	300	0.9	0.09	22
Marysville	90	0.03	0.59	45
Bruthen	220	0.12	0.02	2
Cann Valley	360	0.19	0.002	0.25
Nowa Nowa	440	0.16	0.23	29
Orbost	250	0.03	0.46	39
Swifts Creek	100	0.17	0.20	16
Barmah	230	0.02	0	0
Bendigo	140	0.02	0.39	31
Castlemaine	140	0.02	0.39	31
Cohuna	150	0.46	0	0
Heathcote	140	0.02	0.40	32
Maryborough	300	0.02	0.40	33
Shepparton	140	0.02	0.50	40
St Arnaud	400	0.70	0.10	27
Beechworth	120	0.25	0.05	4
Mansfield	250	0.05	0.45	40
Tallangatta	160	0.05	0.55	46
Myrtleford	150	0.19	0.06	5
Bright	300	0.25	0.05	6
Benalla	350	0.08	0.30	29
Corryong	170	0.05	0.55	46
Maffra	260	0.41	0.21	29
Erica	200	0.70	0.42	61
Mirboo	280	0.86	0.30	66
Meerim	330	0.82	0.47	117
Yarram	300	0.46	0.03	5
Heyfield	270	0.7	0.42	79
Ballarat	230	0.43	0.014	2
Beaufort	220	0.35	0.02	2
Daylesford	250	0.92	0.40	82
Geelong	340	0.9	0.30	82
Otways	300	0.5	0.02	3
Gellibrand	300	0.7	0.024	5
Creswick	250	0.82	0.09	17
Trentham	280	0.95	0.36	85
Macedon	300	0.9	0.49	119
Casterton	200	0.35	0.11	12
Heywood	200	0.54	0.008	1
Rennick	400	0.35	0.11	19
Mildura	150	0.11	0	0
Stawell	250	0.35	0.11	14
Dimboola	250	0.70	0	0

Sources

(1) Average rate for main towns from Victorian Department Water Resources and Water Supply, Local Authorities, Annual Report 1983-83. Appendix W3, Water Supply Rates and Charges ($/ML).

(2) DNDE 'First national survey of water use in Australia', Tables IIa, IVa (As in Appendix 25a).

(3) AWRC, 'Review 85' (As in Appendix 25a).

(4) ((1) x A x B x (2) + 80 x (1-A)) x (3),
where A = full cost: price ratio = 1 for Dandenong, Toolangi and Upper Yarra (MMBW) and 1.58 for all other districts
B = ratio of headworks or transfer costs to full cost = 0.55
80 = average value of irrigation water ($/ML)

(c) WATER USE, VICTORIA

FCV district	Basin number	River basins (1)	Water use for non-irrigation (kL/ha) (2)	Proportion not treated (3)	WUSE water use requiring treatment (kL/ha) (4)
Dandenongs	229	Yarra,228 Bunyip	614	0.1	61
Alexandra	405	Goulburn	33	0.8	26
Toolangi	229	Yarra	1060	0.2	212
Upper Yarra	229	Yarra	1060	0.1	106
Broadford	230	Maribyrnong	60	0.7	42
Marysville	405	Goulburn	33	1.0	33
Bruthen	224	Mitchell	4	0.9	4
Cann Valley	221	East Gippsland	0.4	0.8	0.3
Nowa Nowa	222	Snowy,223 Tambo	12	0.8	10
Orbost	222	Snowy	21	0.8	17
Swifts Creek	223	Tambo,401 Upper Murray	10	0.8	8
Barmah	404	Broken	3	0.8	0
Bendigo	406	Campaspe,407 Loddon	4	0.8	3
Castlemaine	406	Campaspe,407 Loddon	4	0.8	3
Cohuna	407	Loddon,408 Avoca	3	0.8	0
Heathcote	407	Loddon	1.5	0.8	1.2
Maryborough	407	Loddon	1.5	0.5	0.7
Shepparton	404	Broken,405 Goulburn, 406 Campaspe	25	0.1	2.5
St Arnaud	15	Wimmera-Avon,8 Avoca, 7 Loddon	3	0.8	2.4
Beechworth	3	Kiewa,3 Ovens	22	0.2	4.4
Mansfield	5	Goulburn,4 Broken, 3 Ovens	30	0.8	24
Tallangatta	1	Upper Murray	65	0.8	52
Myrtleford	3	Ovens	25	0.8	20
Bright	3	Ovens,2 Kiewa	22	0.8	18

FCV district	Basin number	River basins (1)	Water use for non-irrigation (kL/ha) (2)	Proportion not treated (3)	WUSE water use requiring treatment (kL/ha) (4)
Benalla	4 3 5	Broken, Ovens, Goulburn	20	0.8	16
Corryong	1	Upper Murray	65	0.8	52
Maffra	5 24	Thomson, Mitchell	300	0.1	30
Erica	25	Thomson	597	0.1	60
Mirboo	28 26	Bunyip, Latrobe	420	0.1	42
Meerim	26	Latrobe	821	0.2	164
Yarram	27	South Gippsland	22	0.8	18
Heyfield	25	Thomson	597	0.1	60
Ballarat	34 36	Lake Corangamite, Hopkins	2.5	0.8	2
Beaufort	236	Hopkins	3.5	0.8	2.8
Daylesford	231 232	Werribee, Moorabool	210	0.8	168
Geelong	231 232 233	Werribee, Moorabool Barwon	160	0.8	128
Otways	234 235 236	Lake Corangamite, Otway, Hopkins	13	0.4	5
Gellibrand	235	Otway	35	0.8	28
Creswick	233	Barwon	61	0.8	49
Trentham	232	Moorabool	161	0.4	64
Macedon	231	Werribee	265	0.8	212
Casterton	238	Glenelg	25	0.7	18
Heywood	237	Portland	4	0.8	3
Rennick	238	Glenelg	25	0.8	20
Mildura	414	Mallee	0	0.8	0
Stawell	238	Glenelg	25	0.8	20
Dimboola	415	Wimmera-Avon River	9	0.8	0

Sources

(1) Matching of districts and basins based on FCV district map, and Department National Development and Energy, 'The first national survey of water use in Australia', AGPS 1981, Figs 9 & 11.

(2) From Appendix 25a, col (4).

(3) 'Guestimates' based on types of treatment applied in main towns of district (from Victorian Dept Water Resources, Local Authorities, Annual Report 1982-83, Appendix W35). Clarification, sedimentation and/or filtering assumed to be required to avoid fire effects on water quality. Non-urban supplies assumed untreated.

(4) = (2) x (3).

APPENDIX 27

BEE-KEEPING DATA

District number	FCV district	Number of permanent FCV licences 1983	Number of temporary FCV licences Av. 1980-83	Estimate of percentage of forest area used
10	DANDENONGS	0	3	10
20	ALEXANDRA	0	5	25
30	TOOLANGI	0	6	25
40	UPPER YARRA	0	6	25
50	BROADFORD	6	9	40
60	MARYSVILLE	0	6	25
100	BRUTHEN	3	72	20
110	CANN VALLEY	0	12	10
120	NOWA NOWA	5	65	20
130	ORBOST	0	9	10
140	SWIFTS CREEK	0	7	10
200	BARMAH	34	79	80
210	BENDIGO	68	138	80
220	CASTLEMAINE	22	109	80
240	COHUNA	24	34	60
250	HEATHCOTE	–	–	70
260	MARYBOROUGH	80	182	90
280	SHEPPARTON	27	169	90
290	ST ARNAUD	77	172	70
300	BEECHWORTH	24	12	60
310	MANSFIELD	16	10	40
320	TALLANGATTA	0	0	10
330	MYRTLEFORD	0	5	40
350	BRIGHT	0	7	40
360	BENALLA	45	24	85
370	CORRYONG	0	0	2
400	MAFFRA	12	37	30
410	ERICA	0	1	12
420	MIRBOO	0	–	40
430	NEERIM	0	1	10
440	YARRAM	0	16	50
450	HEYFIELD	3	21	15
500	BALLARAT	0	15	80
510	BEAUFORT	12	61	75
520	DAYLESFORD	1	70	60
540	GEELONG	3	16	80
550	OTWAYS	0	3	30
560	GELLIBRAND	–	–	30
570	CRESWICK	1	6	75
580	TRENTHAM	1	48	65
590	MACEDON	0	15	80
610	CASTERTON	0	–	5
620	HEYWOOD	0	40	80
630	RENNICK	0	–	85
640	MILDURA	21	43	50
670	STAWELL	71	55	40
690	DIMBOOLA	20	11	50

APPENDIX 28

NATIONAL PARK DATA

No.	NAME	AREA (ha)	ANNUAL NUMBER OF VISITOR days	LOSS FROM FIRE PER VISITOR DAY ($)	MINIMUM CONSERVATION LOSS ($/ha)
1	ALFRED	2300.	25000.	0.18	20.
2	BAW BAW	13300.	31500.	0.20	10.
3	BEECHWORTH	1130.	25900.	0.12	5.
4	BOGONG	81000.	23900.	0.20	10.
5	BRISBANE RANGES	7485.	101500.	0.20	10.
6	COOPRACAMBRA	14500.	900.	0.18	15.
7	CROAJINGALONG	86000.	188600.	0.12	10.
8	DISCOVERY BAY	8530.	108700.	0.15	10.
9	FERNTREE GULLY	466.	419200.	0.50	5.
10	GIPPSLAND LAKES	16100.	155100.	0.12	20.
11	HOLEY PLAINS	10450.	4100.	0.15	5.
12	KINGLAKE	11290.	134600.	0.30	10.
13	LANGWARRIN	206.	2000.	0.20	20.
14	LITTLE DESERT	35300.	20900.	0.20	15.
15	LOWER GLENELG	27300.	96500.	0.18	10.
16	LYSTERFIELD	1150.	800.	0.15	5.
17	MORWELL	283.	13200.	0.18	10.
18	MT.BUFFALO	31000.	203200.	0.20	20.
19	MT.ECCLES	400.	18300.	0.15	10.
20	OTWAY	12750.	128400.	0.30	20.
21	PINK LAKES	50700.	6300.	0.15	5.
22	PORT CAMPBELL	1750.	319700.	0.15	10.
23	SNOWY	26200.	12000.	0.20	15.
24	WABONGA	21200.	21900.	0.15	10.
25	WARBY	3320.	9600.	0.20	5.
26	WILSONS PROM	49000.	395400.	0.30	20.
27	WONNANGATTA	107000.	58700.	0.20	15.
28	WYPERFELD	100000.	33400.	0.20	20.
29	BURROWA-PINE MTN	17300.	6000.	0.40	20.
30	CATHEDRAL RANGE	3570.	15900.	0.15	15.
31	ORGAN PIPES	85.	107600.	0.20	20.

APPENDIX 29

SUMMARY OF AVERAGE ANNUAL SAVINGS BY RESOURCE TYPE AND OPTIMAL NUMBER OF AIRCRAFT

Resource type	Number of home bases	Optimal number of aircraft at each base	Area savings (ha)	Gross savings ($'000)	Fixed savings ($'000)	Net savings ($'000)
<u>Airtankers</u>						
DC6 B	1	1	6 907	660	524	136
Bell 212	1	2	4 544	306	228	78
Thrush Commander	3	2	3 445	237	160	77
Bell 206	2	2	3 269	232	204	28
DC4	1	1	4 109	344	336	8
Canso PBY5A	1	1	1 102	126	189	- 63
Grumman Tracker S2	1	1	3 149	227	301	- 74
Twin Otter DHC6	1	2	1 914	187	273	- 85
Canadair CL 215	1	1	2 576	233	511	-278
Hercules	1	1	5 317	415	788	-373
	Number of districts					
<u>Ground crew</u>						
Machine	45		8 947	713	598	115
Hand	45		3 531	372	309	63

Notes: The results are based (unless otherwise specified) on

- the number of available aircraft indicated above
- utilisation on any fire of the number of aircraft providing the best savings, up to a maximum of the number available at nearest base
- fixed costs for the number at each base times the number of bases
- the base locations listed in Appendix 12
- exclusive use of each model in turn, ie. no combinations of different model
- use of whichever retardant type provided the best savings on each fire
- costs and losses are on a common level, June 1983, using CPI for Melbourne.

APPENDIX 30

AVERAGE ANNUAL NUMBER OF FIRES
BY AIRTANKER MODEL AND SAVINGS CLASS
STATE OF VICTORIA 1978-79 TO 1982-83

	SAVINGS CLASS					
	$<0	$0-1000	$1000- 10 000	$10 000- 100 000	$100 000 1M	TOTAL
	#	#	#	#	#	#
AIRTANKER MODEL						
C-130 HERCULES	13.2	4.9	8.1	6.0	1.2	33.4
CANADAIR CL-215	27.9	9.5	11.4	4.8	0.5	54.2
DC-6	15.7	6.7	19.2	6.7	1.5	49.8
DC-4	8.8	5.0	8.4	4.6	0.9	27.6
PBY5A CANSO	3.3	3.8	6.5	2.6	0.3	16.6
S2F TRACKER	34.1	8.4	10.2	4.2	0.7	57.5
THRUSH COMMAND.	40.3	6.5	6.7	4.3	0.7	58.6
BELL 206B	42.1	9.2	11.0	3.5	0.7	66.5
DHC6 TWIN OTTER	30.5	17.0	10.8	3.5	0.3	62.2
BELL 212	24.4	4.0	7.9	4.4	0.9	41.6

APPENDIX 31

AVERAGE ANNUAL NUMBER OF FIRES
BY TRAVEL TIME CLASS AND SAVINGS CLASS
2 THRUSH COMMANDERS AT EACH BASE
STATE OF VICTORIA 1978-79 TO 1982-83

	SAVINGS CLASS					
	$<0	$0-1000	$1000- 10 000	$10 000- 100 000	$100 000 1M	TOTAL
	#	#	#	#	#	#
TRAVEL TIME CLASS (MIN)						
0-20	8.7	1.0	1.6	1.0	0.5	12.9
21-40	6.5	0.7	.	.	.	7.2
41-60	4.6	.	0.6	.	.	5.1
61-120	9.8	2.4	0.9	1.3	0.1	14.4
121-180	2.1	1.0	0.6	.	0.1	3.8
181+	8.5	1.5	3.0	2.0	.	15.1
TOTAL	40.3	6.5	6.7	4.3	0.7	58.6

APPENDIX 32

AVERAGE ANNUAL NUMBER OF FIRES BY 20 KM DISTANCE CLASS FROM RETARDANT BASE TO FIRE AND SAVINGSCLASS

2 THRUSH COMMANDERS AT EACH BASE

STATE OF VICTORIA 1978-79 TO 1982-83

	SAVINGS CLASS					
	$<0	$0-1000	$1000- 10 000	$10 000- 100 000	$100 000 1M	TOTAL
	#	#	#	#	#	#
20 KM CLASSES						
1	18.5	1.9	2.5	2.4	0.7	26.1
2	20.0	4.0	3.2	1.4	0.1	28.6
3	1.5	0.6	1.0	0.5	.	3.5
6	0.3	.	.	.	.	0.3
TOTAL	40.3	6.5	6.7	4.3	0.7	58.6

APPENDIX 33

AVERAGE ANNUAL NUMBER OF FIRES BY 10 KM DISTANCE CLASS FROM LAKE TO FIRE AND SAVINGS CLASS

STATE OF VICTORIA 1978-79 TO 1982-83

AIRTANKER MODEL CANADAIR CL-215

	SAVINGS CLASS					
	$<0	$0-1000	$1000- 10 000	$10 000- 100 000	$100 000 1M	TOTAL
	#	#	#	#	#	#
10 KM CLASSES						
1	12.8	6.7	7.5	3.4	0.3	30.7
2	8.4	1.4	2.0	0.3	.	12.2
3	4.1	0.3	0.8	.	.	5.1
4	1.6	0.8	0.2	.	.	2.6
5	0.4	.	.	.	.	0.4
TOTAL	27.2	9.1	10.5	3.7	0.3	50.9

APPENDIX 34
AVERAGE ANNUAL AREA SAVINGS (HECTARES) BY AVERAGE INTENSITY OF HEAD FIRE AND ADDITIONAL SUPPRESSION RESOURCE
STATE OF VICTORIA 1978-79 TO 1982-83

	ADDITIONAL RESOURCE						
	DC-6	S2F TRACKER	THRUSH COMMAND.	BELL 206B	BELL 212	HAND CREW	MACHINE CREW
	---HA---	---HA---	---HA---	---HA---	---HA---	---HA---	---HA---
INTENSITY CLASS (KW/M)							
0-750	2805	1561	1425	1790	1783	2470	4232
750-1500	1526	358	317	645	1899	971	3084
1500-3000	2164	987	1382	539	497	72	811
3000-10000	411	238	316	290	309	17	711
10 000 +	.	5	5	5	56	0	110
TOTAL	6907	3149	3445	3269	4544	3531	8947

APPENDIX 35

AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY FOREST DISTRICT AND ADDITIONAL SUPPRESSION RESOURCE STATE OF VICTORIA 1978-79 TO 1982-83

	ADDITIONAL RESOURCE						
	DC-6	S2F TRACKER	THRUSH COMMAND.	BELL 206B	BELL 212	HAND CREW	MACHINE CREW
	$'000	$'000	$'000	$'000	$'000	$'000	$'000
FCV DISTRICT							
DANDENONGS	25	9	6	12	19	12	15
ALEXANDRA	47	16	8	14	9	48	58
TOOLANGI	-0	.	.	.	.	0	-0
UPPER YARRA	-0	-1	-1	-1	-0	0	0
BROADFORD	1	2	-0	-0	.	0	9
MARYSVILLE	.	-0	-0	-0	.	0	-0
BRUTHEN	1	2	4	3	3	3	2
CANN VALLEY	115	50	73	38	28	15	36
NOWA NOWA	9	1	4	4	5	10	20
ORBOST	18	13	13	10	11	12	-4
SWIFTS CREEK	54	5	13	35	48	7	36
BARMAH	2	0	-2	.	-1	0	0
BENDIGO	21	14	-2	1	-1	16	21
CASTLEMAINE	.	-1	.	.	.	-0	0
COHUNA	2	1	0	-1	.	5	7
MARYBOROUGH	.	.	.	.	.	0	-0
SHEPPARTON	1	-0	-1	-1	-1	2	3
ST. ARNAUD	-1	-1	0	-1	-1	2	1
BEECHWORTH	1	0	.	.	.	2	3
MANSFIELD	25	17	16	19	17	21	29
TALLANGATTA	1	-2	0	0	-1	-0	2

(CONTINUED)

APPENDIX 35

AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY FOREST DISTRICT AND ADDITIONAL SUPPRESSION RESOURCE STATE OF VICTORIA 1978-79 TO 1982-83

	ADDITIONAL RESOURCE						
	DC-6	S2F TRACKER	THRUSH COMMAND.	BELL 206B	BELL 212	HAND CREW	MACHINE CREW
	$'000	$'000	$'000	$'000	$'000	$'000	$'000
FCV DISTRICT							
MYRTLEFORD	3	-0	-1	-0	0	0	3
BRIGHT	100	7	-0	-1	32	3	103
BENALLA	0	-0	-1	-0	-1	-0	-1
CORRYONG	-1	-0	-0	-1	-1	-0	-2
MAFFRA	1	0	-1	1	2	2	1
ERICA	.	.	.	-0	.	0	-0
MIRBOO	52	-1	4	23	31	42	61
NEERIM	2	-0	-1	0	3	1	1
YARRAM	0	-1	-0	2	2	2	4
HEYFIELD	34	32	30	5	34	32	30
BALLARAT	.	-1	.	.	.	-0	4
BEAUFORT	.	.	.	.	.	-0	2
DAYLESFORD	4	0	-2	-1	3	7	29
GEELONG	1	-1	-1	-1	-2	3	7
OTWAYS	37	9	17	19	16	5	19
GELLIBRAND	.	.	.	.	.	-0	-0
CRESWICK	1	-0	-1	-0	.	2	3
TRENTHAM	61	44	42	44	34	62	73
MACEDON	.	.	.	.	.	-0	1
CASTERTON	2	3	4	4	0	5	5
HEYWOOD	3	4	2	4	1	8	13

(CONTINUED)

APPENDIX 35
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY FOREST DISTRICT AND ADDITIONAL SUPPRESSION RESOURCE
STATE OF VICTORIA 1978-79 TO 1982-83

	ADDITIONAL RESOURCE						
	DC-6	S2F TRACKER	THRUSH COMMAND.	BELL 206B	BELL 212	HAND CREW	MACHINE CREW
	$'000	$'000	$'000	$'000	$'000	$'000	$'000
FCV DISTRICT							
RENNICK	1	1	3	1	-2	6	55
MILDURA	1	-1	-1	-1	.	-0	-3
STAWELL	20	9	13	2	-2	11	31
DIMBOOLA	13	-2	-2	1	20	23	36
STATE	660	227	237	231	306	372	713

APPENDIX 36
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY AIRTANKER MODEL AND NUMBER OF AIRCRAFT OF EACH TYPE AVAILABLE AT HOME BASE
STATE OF VICTORIA 1978-79 TO 1982-83

	NUMBER AVAILABLE AT EACH HOME BASE			
	1	2	3	4
	$'000	$'000	$'000	$'000
AIRTANKER MODEL				
C-130 HERCULES	415	590	610	616
CANADAIR CL-215	233	317	358	389
DC-6	660	729	745	749
DC-4	344	567	600	632
PBY5A CANSO	126	255	286	308
S2F TRACKER	227	340	479	595
THRUSH COMMAND.	154	237	263	297
BELL 206B	164	231	273	329
DHC6 TWIN OTTER	187	305	381	395
BELL 212	225	306	348	417

APPENDIX 37

NET SAVINGS BY AIRTANKER MODEL
STATE OF VICTORIA 1978-79 TO 1982-83
NUMBER AVAILABLE AT EACH HOME BASE=1

AIRTANKER MODEL	FCV GROSS SAVINGS $'000	CFA GROSS SAVINGS $'000	FIXED COST $'000	NET SAVINGS $'000
C-130 HERCULES	253	162	788	-373
CANADAIR CL-215	121	112	511	-278
DC-6	451	209	524	136
DC-4	251	93	336	8
PBY5A CANSO	70	56	189	-63
S2F TRACKER	139	87	301	-74
THRUSH COMMAND.	106	48	128	26
BELL 206B	93	72	149	15
DHC6 TWIN OTTER	90	97	273	-85
BELL 212	159	66	160	65

APPENDIX 37

NET SAVINGS BY AIRTANKER MODEL
STATE OF VICTORIA 1978-79 TO 1982-83
NUMBER AVAILABLE AT EACH HOME BASE=2

AIRTANKER MODEL	FCV GROSS SAVINGS $'000	CFA GROSS SAVINGS $'000	FIXED COST $'000	NET SAVINGS $'000
C-130 HERCULES	406	184	1554	-964
CANADAIR CL-215	164	153	999	-682
DC-6	496	234	1026	-297
DC-4	400	167	649	-83
PBY5A CANSO	133	122	358	-103
S2F TRACKER	208	131	559	-220
THRUSH COMMAND.	171	66	160	77
BELL 206B	138	94	204	28
DHC6 TWIN OTTER	153	152	537	-232
BELL 212	228	78	228	78

APPENDIX 37
NET SAVINGS BY AIRTANKER MODEL
STATE OF VICTORIA 1978-79 TO 1982-83
NUMBER AVAILABLE AT EACH HOME BASE=3

AIRTANKER MODEL	FCV GROSS SAVINGS $'000	CFA GROSS SAVINGS $'000	FIXED COST $'000	NET SAVINGS $'000
C-130 HERCULES	422	187	2319	-1710
CANADAIR CL-215	195	163	1488	-1130
DC-6	510	235	1527	-782
DC-4	427	173	963	-363
PBY5A CANSO	148	138	527	-241
S2F TRACKER	300	179	818	-339
THRUSH COMMAND.	191	72	192	71
BELL 206B	171	102	259	14
DHC6 TWIN OTTER	198	183	801	-420
BELL 212	265	83	296	52

APPENDIX 37
NET SAVINGS BY AIRTANKER MODEL
STATE OF VICTORIA 1978-79 TO 1982-83
NUMBER AVAILABLE AT EACH HOME BASE=4

AIRTANKER MODEL	FCV GROSS SAVINGS $'000	CFA GROSS SAVINGS $'000	FIXED COST $'000	NET SAVINGS $'000
C-130 HERCULES	429	187	3085	-2469
CANADAIR CL-215	219	170	1976	-1587
DC-6	514	235	2029	-1280
DC-4	449	183	1276	-645
PBY5A CANSO	163	145	696	-388
S2F TRACKER	400	195	1077	-482
THRUSH COMMAND.	224	73	224	72
BELL 206B	225	104	313	16
DHC6 TWIN OTTER	204	191	1065	-670
BELL 212	332	85	364	53

APPENDIX 38

AVERAGE ANNUAL AREA SAVINGS (HECTARES) BY AIRTANKER MODEL AND 20 KM DISTANCE CLASS FROM RETARDANT BASE TO FIRE

STATE OF VICTORIA 1978-79 TO 1982-83

20 KM CLASSES

AIRTANKER MODEL	1	2	3	4	5	6	7	8	9	10	11
	---HA---	---HA---	---HA---	---HA---	---HA---	---HA---	---HA---	---HA---	---HA---	---HA---	---HA---
C-130 HERCULES	67	306	235	428	288	371	219	170	708	1288	1043
CANADAIR CL-215	1286	525	197	250	123	2	50	.	87	56	.
DC-6	47	467	697	541	539	324	248	1099	857	1732	121
DC-4	33	362	236	405	604	84	109	71	306	1604	102
PBY5A CANSO	432	593	42	42	.	2	.	.	70	.	.
S2F TRACKER	298	741	523	1207	377	2	.	.	.	.	.
THRUSH COMMAND.	2010	1210	224	.	.	1	.	.	.	.	.
BELL 206B	3269	0	.	.	.	.	.	.	.	.	.
DHC6 TWIN OTTER	1210	506	118	69	12	.	.	.	.	.	.
BELL 212	4544	.	.	.	.	.	.	.	.	.	.

APPENDIX 38

AVERAGE ANNUAL AREA SAVINGS (HECTARES) BY AIRTANKER MODEL AND 20 KM DISTANCE CLASS FROM RETARDANT BASE TO FIRE STATE OF VICTORIA 1978-79 TO 1982-83

	20 KM CLASSES			
	12	13	19	TOTAL
	---HA---	---HA---	---HA---	---HA---
AIRTANKER MODEL				
C-130 HERCULES	191	4	.	5317
CANADAIR CL-215	.	.	.	2576
DC-6	233	2	2	6907
DC-4	190	2	.	4109
PBY5A CANSO	.	.	.	1182
S2F TRACKER	.	.	.	3149
THRUSH COMMAND.	.	.	.	3445
BELL 206B	.	.	.	3269
DHC6 TWIN OTTER	.	.	.	1914
BELL 212	.	.	.	4544

APPENDIX 39

AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY AIRTANKER MODEL AND SAVINGS CLASS STATE OF VICTORIA 1978-79 TO 1982-83

	SAVINGS CLASS					
	$<0	$0-1000	$1000- 10 000	$10 000- 100 000	$100 000 1M	TOTAL
	$' 000	$' 000	$' 000	$' 000	$' 000	$' 000
AIRTANKER MODEL						
C-130 HERCULES	-16	2	31	195	203	415
CANADAIR CL-215	-33	4	42	153	68	233
DC-6	-22	3	66	227	386	660
DC-4	-9	2	30	134	187	344
PBY5A CANSO	-1	2	23	66	36	126
S2F TRACKER	-42	4	38	116	111	227
THRUSH COMMAND.	-46	2	27	114	139	237
BELL 206B	-39	3	47	126	95	231
DHC6 TWIN OTTER	-17	7	41	112	44	187
BELL 212	-43	2	30	178	139	306

APPENDIX 40

AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY AIRTANKER MODEL AND AVERAGE INTENSITY OF HEAD FIRE CLASS STATE OF VICTORIA 1978-79 TO 1982-83

	INTENSITY CLASS (KW/M)					
	0-750	750-1500	1500-3000	3000-10000	10 000 +	TOTAL
	$'000	$'000	$'000	$'000	$'000	$'000
AIRTANKER MODEL						
C-130 HERCULES	225	69	104	18	.	415
CANADAIR CL-215	149	26	39	19	0	233
DC-6	333	154	153	19	.	660
DC-4	153	62	110	19	.	344
PBY5A CANSO	94	4	21	6	0	126
S2F TRACKER	118	35	63	10	0	227
THRUSH COMMAND.	111	25	81	19	0	237
BELL 206B	174	2	37	18	1	231
DHC6 TWIN OTTER	138	4	25	19	1	187
BELL 212	166	81	35	17	6	306

APPENDIX 41
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY AIRTANKER MODEL AND HOME BASE STATE OF VICTORIA 1978-79 TO 1982-83

	AIRTANKER MODEL						
	C-130 HERCULES	CANADAIR CL-215	DC-6	DC-4	PBY5A CANSO	S2F TRACKER	THRUSH COMMAND.
	$'000	$'000	$'000	$'000	$'000	$'000	$'000
HOME BASE FOR AIRTANKER							
LATROBE VY	.	.	.	.	.	.	.
MANGALORE	415	233	660	344	126	227	.
MOORABBIN	.	.	.	.	.	.	70
STAWELL	.	.	.	.	.	.	16
BENAMBRA I	.	.	.	.	.	.	151
TOTAL	415	233	660	344	126	227	237

APPENDIX 41
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY AIRTANKER MODEL AND HOME BASE STATE OF VICTORIA 1978-79 TO 1982-83

	AIRTANKER MODEL		
	BELL 206B	DHC6 TWIN OTTER	BELL 212
	$'000	$'000	$'000
HOME BASE FOR AIRTANKER			
LATROBE VY	139	.	306
MANGALORE	.	.	.
MOORABBIN	93	116	.
STAWELL	.	.	.
BENAMBRA I	.	72	.
TOTAL	231	187	306

APPENDIX 42
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY AIRTANKER MODEL AND FIRE SEASON STATE OF VICTORIA 1978-79 TO 1982-83

	FIRE SEASON					
	1978-79	1979-80	1980-81	1981-82	1982-83	TOTAL
	$'000	$'000	$'000	$'000	$'000	$'000
AIRTANKER MODEL						
C-130 HERCULES	5	97	29	109	175	415
CANADAIR CL-215	7	81	25	64	56	233
DC-6	12	111	47	145	345	660
DC-4	6	90	17	42	190	344
PBY5A CANSO	10	50	23	20	23	126
S2F TRACKER	3	80	21	27	95	227
THRUSH COMMAND.	2	81	18	16	120	237
BELL 206B	8	84	23	43	73	231
DHC6 TWIN OTTER	8	98	28	27	26	187
BELL 212	8	74	32	50	141	306

APPENDIX 43
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY AIRTANKER MODEL AND NEAREST FIXED RETARDANT BASE STATE OF VICTORIA 1978-79 TO 1982-83

	AIRTANKER MODEL						
	C-130 HERCULES	CANADAIR CL-215	DC-6	DC-4	PBY5A CANSO	S2F TRACKER	THRUSH COMMAND.
	$'000	$'000	$'000	$'000	$'000	$'000	$'000
FIXED RETARDANT BASE							
BAIRNSDALE	.	.	.	.	.	103	2
BALLARAT	.	.	.	.	.	.	15
BENALLA	.	.	.	.	.	6	.
EAST SALE	218	55	387	189	6	.	.
HAMILTON	.	5	44	14	2	14	.
MANGALORE	54	0	22	86	1	86	.
PORTLAND	30	.	.	.	.	.	.
STAWELL	.	.	.	.	.	.	-2
BENAMBRA I	.	.	.	.	.	.	24
BRIGHT	.	.	.	.	.	.	-3
CANN RIVER	.	.	.	.	.	.	75
GELANTIPY	.	.	.	.	.	.	10
GRAMPIANS	.	.	.	.	.	.	13
LEONGATHA	.	.	.	.	.	.	3
MATLOCK	.	.	.	.	.	.	-3
MOUNT BEAUTY	.	.	.	.	.	.	-1
DARTMOOR	.	.	.	.	.	.	3
SNOWY RANGE	.	.	.	.	.	.	47
TALLANGATTA	.	.	.	.	.	.	-0
TOTAL	303	61	453	290	9	209	184

APPENDIX 43
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY AIRTANKER MODEL AND NEAREST FIXED RETARDANT BASE STATE OF VICTORIA 1978-79 TO 1982-83

	AIRTANKER MODEL	
	BELL 206B	BELL 212
	$'000	$'000
FIXED RETARDANT BASE		
BAIRNSDALE	0	-0
BALLARAT	13	1
BENALLA	•	•
EAST SALE	•	•
HAMILTON	•	•
MANGALORE	•	•
PORTLAND	•	•
STAWELL	-1	•
BENAMBRA I	7	7
BRIGHT	•	32
CANN RIVER	31	22
GELANTIPY	33	39
GRAMPIANS	3	20
LEONGATHA	-1	-1
MATLOCK	-2	-2
MOUNT BEAUTY	-0	•
DARTMOOR	•	•
SNOWY RANGE	5	29
TALLANGATTA	•	•
TOTAL	88	148

APPENDIX 44
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY MODEL AND 20 KM DISTANCE CLASS FROM RETARDANT BASE TO FIRE
LONG-TERM RETARDANT
STATE OF VICTORIA 1978-79 TO 1982-83

20 KM CLASSES

AIRTANKER MODEL	1 $'000	2 $'000	3 $'000	4 $'000	5 $'000	6 $'000	7 $'000	8 $'000	9 $'000	10 $'000	11 $'000	12 $'000	13 $'000	19 $'000	TOTAL $'000
C-130 HERCULES	2	21	11	74	0	19	6	24	53	74	12	5	2	.	303
CANADAIR CL-215	.	-1	2	26	5	14	5	.	5	5	.	.	.	.	61
DC-6	.	5	5	87	16	20	11	119	79	100	.	9	1	1	453
DC-4	.	4	-0	33	73	19	7	25	26	94	5	6	-1	.	290
PBY5A CANSO	.	3	.	1	.	.	.	.	5	.	.	.	.	.	9
S2F TRACKER	8	65	34	76	26	.	.	.	.	.	.	.	.	.	209
THRUSH COMMAND.	113	57	14	.	.	-0	.	.	.	.	.	.	.	.	184
BELL 206B	88	.	.	.	.	.	.	.	.	.	.	.	.	.	88
BELL 212	148	.	.	.	.	.	.	.	.	.	.	.	.	.	148

APPENDIX 45

AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY RETARDANT TYPE , MODEL AND MAIN FOREST TYPE

STATE OF VICTORIA 1978-79 TO 1982-83

RETARDANT TYPE WATER

	MAIN FOREST TYPE								
	ASH,HEMS (>27M)	ASH,HEMS (<27M)	MIXED SPECIES (>27M)	MIXED SPECIES (<27M)	BOX,I-BARK (>27M)	BOX,I-BARK (<27M)	SOFTWOOD (>27M)	SOFTWOOD (<27M)	ALPINE
	$'000	$'000	$'000	$'000	$'000	$'000	$'000	$'000	$'000
AIRTANKER MODEL									
C-130 HERCULES	-0	0	4	27	4	.	.	-0	.
CANADAIR CL-215	-0	1	10	42	3	-1	1	1	-1
DC-6	0	1	6	26	2	-2	.	2	7
DC-4	7	1	1	24	.	.	.	0	.
PBY5A CANSO	0	2	17	37	3	0	.	-0	.
S2F TRACKER	-2	1	3	-6	-1	-2	.	0	-1
THRUSH COMMAND.	-1	1	-4	5	.	-1	.	.	0
BELL 206B	-0	1	6	29	.	-1	.	.	-1
DHC6 TWIN OTTER	0	3	22	50	4	-1	.	1	5
BELL 212	10	1	4	49	1	-1	.	.	.

APPENDIX 45
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY RETARDANT TYPE , MODEL AND MAIN FOREST TYPE STATE OF VICTORIA 1978-79 TO 1982-83

RETARDANT TYPE WATER

	MAIN FOREST TYPE	
	GRASS, SCRUB	++ TOTAL++
	$'000	$'000
AIRTANKER MODEL		
C-130 HERCULES	79	113
CANADAIR CL-215	116	172
DC-6	139	182
DC-4	15	47
PBY5A CANSO	59	117
S2F TRACKER	10	2
THRUSH COMMAND.	53	53
BELL 206B	111	144
DHC6 TWIN OTTER	105	187
BELL 212	94	158

APPENDIX 45
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS
BY RETARDANT TYPE , MODEL AND MAIN FOREST TYPE
STATE OF VICTORIA 1978-79 TO 1982-83

RETARDANT TYPE SHORT-TERM

	MAIN FOREST TYPE								
	ASH,HEMS (>27M)	ASH,HEMS (<27M)	MIXED SPECIES (>27M)	MIXED SPECIES (<27M)	BOX,I-BARK (>27M)	BOX,I-BARK (<27M)	SOFTWOOD (>27M)	SOFTWOOD (<27M)	ALPINE
	$'000	$'000	$'000	$'000	$'000	$'000	$'000	$'000	$'000
AIRTANKER MODEL									
DC-6	.	.	2	-1	2	.	.	.	.
DC-4	.	.	-1	-0	.	.	.	-1	.
S2F TRACKER	-0	.	.	16	.	.	.	.	.
THRUSH COMMAND.	-0	.	0	.	.	.	.	.	.
BELL 206B	.	.	-0	.	.	.	.	.	.

APPENDIX 45
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS
BY RETARDANT TYPE , MODEL AND MAIN FOREST TYPE
STATE OF VICTORIA 1978-79 TO 1982-83

RETARDANT TYPE SHORT-TERM

	MAIN FOREST TYPE	
	GRASS, SCRUB	++ TOTAL++
	$'000	$'000
AIRTANKER MODEL		
DC-6	22	26
DC-4	8	7
S2F TRACKER	-0	15
THRUSH COMMAND.	-0	-0
BELL 206B	-0	-0

APPENDIX 45
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY RETARDANT TYPE , MODEL AND MAIN FOREST TYPE
STATE OF VICTORIA 1978-79 TO 1982-83

RETARDANT TYPE LONG-TERM

	MAIN FOREST TYPE								
	ASH,HEMS (>27M)	ASH,HEMS (<27M)	MIXED SPECIES (>27M)	MIXED SPECIES (<27M)	BOX,I-BARK (>27M)	BOX,I-BARK (<27M)	SOFTWOOD (>27M)	SOFTWOOD (<27M)	ALPINE
	$'000	$'000	$'000	$'000	$'000	$'000	$'000	$'000	$'000
AIRTANKER MODEL									
C-130 HERCULES	39	.	83	29	-1	-1	2	17	5
CANADAIR CL-215	31	.	5	6	.	.	.	.	5
DC-6	41	.	160	35	1	0	4	102	.
DC-4	32	.	105	36	2	-0	2	23	7
PBY5A CANSO	.	.	.	1	.	.	.	.	5
S2F TRACKER	35	1	42	26	4	-0	.	8	6
THRUSH COMMAND.	34	1	81	49	-2	-2	.	-1	7
BELL 206B	7	1	59	20	1	-1	.	-0	7
BELL 212	29	.	61	5	.	.	-2	32	8

APPENDIX 45
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY RETARDANT TYPE , MODEL AND MAIN FOREST TYPE
STATE OF VICTORIA 1978-79 TO 1982-83

RETARDANT TYPE LONG-TERM

	MAIN FOREST TYPE GRASS, SCRUB $'000	++ TOTAL++ $'000
AIRTANKER MODEL		
C-130 HERCULES	128	303
CANADAIR CL-215	14	61
DC-6	110	453
DC-4	84	290
PBY5A CANSO	3	9
S2F TRACKER	88	209
THRUSH COMMAND.	17	184
BELL 206B	-7	88
BELL 212	15	148

APPENDIX 45

AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY RETARDANT TYPE , MODEL AND MAIN FOREST TYPE

STATE OF VICTORIA 1978-79 TO 1982-83

ALL RET. TYPES

	MAIN FOREST TYPE								
	ASH,HEMS (>27M)	ASH,HEMS (<27M)	MIXED SPECIES (>27M)	MIXED SPECIES (<27M)	BOX,I-BARK (>27M)	BOX,I-BARK (<27M)	SOFTWOOD (>27M)	SOFTWOOD (<27M)	ALPINE
	$'000	$'000	$'000	$'000	$'000	$'000	$'000	$'000	$'000
AIRTANKER MODEL									
C-130 HERCULES	39	0	87	56	3	-1	2	17	5
CANADAIR CL-215	30	1	15	48	3	-1	1	1	4
DC-6	41	1	168	60	5	-2	4	104	7
DC-4	39	1	105	59	2	-0	2	23	7
PBY5A CANSO	0	2	17	38	3	0	.	-0	5
S2F TRACKER	33	1	45	36	4	-2	.	8	5
THRUSH COMMAND.	33	2	77	54	-2	-3	.	-1	7
BELL 206B	7	2	65	49	1	-2	.	-0	7
DHC6 TWIN OTTER	0	3	22	50	4	-1	.	1	5
BELL 212	39	1	65	53	1	-1	-2	32	8

APPENDIX 45
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY RETARDANT TYPE , MODEL AND MAIN FOREST TYPE
STATE OF VICTORIA 1978-79 TO 1982-83

ALL RET. TYPES

	MAIN FOREST TYPE	
	GRASS, SCRUB	++ TOTAL++
	$'000	$'000
AIRTANKER MODEL		
C-130 HERCULES	207	415
CANADAIR CL-215	130	233
DC-6	271	660
DC-4	107	344
PBY5A CANSO	62	126
S2F TRACKER	97	227
THRUSH COMMAND.	70	237
BELL 206B	104	231
DHC6 TWIN OTTER	105	187
BELL 212	109	306

APPENDIX 46
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY MODEL AND RETARDANT TYPE
STATE OF VICTORIA 1978-79 TO 1982-83

	RETARDANT TYPE			
	WATER	SHORT-TERM	LONG-TERM	TOTAL
	$'000	$'000	$'000	$'000
AIRTANKER MODEL				
C-130 HERCULES	113	.	303	415
CANADAIR CL-215	172	.	61	233
DC-6	182	26	453	660
DC-4	47	7	290	344
PBY5A CANSO	117	.	9	126
S2F TRACKER	2	15	209	227
THRUSH COMMAND.	53	-0	184	237
BELL 206B	144	-0	88	231
DHC6 TWIN OTTER	187	.	.	187
BELL 212	158	.	148	306

APPENDIX 47

AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS
BY DAMAGE CLASS AND AREA CLASS
2 BELL 206'S AT EACH OF 2 BASES
STATE OF VICTORIA 1978-79 TO 1982-83

	AREA CLASS (HA)				
	1-10	10-100	100-1000	1000+	TOTAL
	$'000	$'000	$'000	$'000	$'000
DAMAGE CLASSES ($)					
$0-1000	.	-0	.	.	-0
$1000- 10 000	-9	-6	-0	.	-15
$10 000-100 000	12	37	59	.	108
$100 000-1M	.	68	.	71	139
TOTAL	4	98	58	71	231

APPENDIX 48

AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS
FIRE DANGER RATING (3PM) AND TRAVEL TIME CLASS
2 THRUSH COMMANDERS AT EACH OF 3 BASES
STATE OF VICTORIA 1978-79 TO 1982-83

	TRAVEL TIME CLASS (MIN)						
	0-20	21-40	41-60	61-120	121-180	181+	TOTAL
	$'000	$'000	$'000	$'000	$'000	$'000	$'000
RATING							
LOW	-1	-3	-0	6	0	31	32
MODERATE	27	-2	-1	25	62	15	125
HIGH	9	-2	-1	16	0	14	37
VERY HIGH	45	-2	-1	0	-3	3	43
EXTREME	.	-0	.	-0	.	.	-1
TOTAL	80	-9	-3	47	60	62	237

APPENDIX 49
AVERAGE ANNUAL GROSS SAVINGS IN COST-PLUS-LOSS BY MOBILE BASE AND HOME BASE
2 THRUSH COMMANDERS AT EACH OF 3 BASES
STATE OF VICTORIA 1978-79 TO 1982-83

MOBILE BASE USED

	HOME BASE FOR AIRTANKER			
	MOORABBIN	STAWELL	BENAMBRA I	TOTAL
	$'000	$'000	$'000	$'000
MOBILE BASE NO.				
BEAUFORT	-1	1	.	-0
BENDIGO	-2	-3	.	-5
FISKVILLE	15	.	.	15
HEYFIELD	3	.	2	5
MANSFIELD	-2	.	-1	-3
ORBOST	.	.	7	7
RENNICK	.	5	.	5
TOTAL	13	2	8	23

High-intensity fire, around 10,000 kW/m
(Photo: CSIRO)

Preparing a bulldozer fire-line
(Photo: CSIRO)

Retardant drop from DC-6, with sequential tank release (Photo: CSIRO)

Retardant mixing base at East Sale – loading mixer with powdered retardant (Photo: CSIRO)

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