Fire behaviour and firefighter safety implications associated with the Bucklands Crossing Fire burnover of 24 March 1998

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Cover Photograph: Postfire view of the ridge where the Bucklands Crossing Fire burnover incident occurred. The appliance can be seen parked on the ridgetop.

Wildfire Case Study

Fire behaviour and firefighter safety implications associated with the Bucklands Crossing Fire burnover of 24 March 1998*

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Executive Summary

On March 24, 1998, a crew of eight rural firefighters were burned over while attempting to suppress a backburning sector of the Bucklands Crossing Fire near Waikouaiti in North Otago (Figure 1). The fire occurred in very rugged terrain, comprised of a series of scrub-covered hillsides dropping steeply into the Waikouaiti River below. It burned under the influence of hot, dry nor'westerly conditions characterised by particularly strong winds, that also severely restricted aerial firefighting. The fire exhibited extreme fire behaviour in pine plantation fuels, breaching a shingle road in several places. In comparison, fire spread in grass vegetation was restricted by the low level of grass curing and this, together with the presence of many natural barriers, contained the fire to its final perimeter. Within the fire area, fire spread consisted of a series of rapid upslope runs through dense manuka scrub fuels, followed by periods of slower spread as the fire backburned down the opposite slope. The fire resulted in the loss of an area of 200 hectares that included several woodlots.

After parking their appliance on the crest of a steep ridge within the burnt area, the crew were deploying a hoseline downhill towards a fire edge that was burning slowly downslope beneath manuka scrub. Before being able to charge the hoseline, the crew were overrun by what they described as a "fireball" exploding from the gorse-filled gully beneath them. The most likely cause of the fire blow-up is a rapid re-burn back through the previously underburned scrub fuels, which is a situation reminiscent of the South Canyon Fire in Colorado where 14 firefighters were killed. The precise trigger for upslope spread and transition into the scrub canopy could not be determined, and more research is required to confirm why this fire behaviour occurred and whether it is specific to certain topographic, fuel or atmospheric conditions.

As a result of the burnover, three firefighters sustained burn injuries, one serious, and a fourth crew member received a cut to the hand whilst escaping into previously burned fuels. The driver and another crew member took shelter behind the appliance and, along with the remaining two crew members, were uninjured. The firefighters were saved from more severe injuries by the short duration of their exposure to the heat and flame, the fact that they were correctly attired in their protective clothing, and that they received immediate medical attention. Nomex coveralls maintained their integrity despite exposure to extreme heat. However, the conduction of heat through the fabric to the skin by reflective strips requires further investigation. Wearing a second layer of clothing beneath the coveralls also reduces burning from radiant heat. The integrity of the fibreglass helmet was maintained despite extreme exposure to heat, and the extra protection provided by the neck skirt and visor were instrumental in preventing more serious injuries, or even loss of life, from being sustained.

The incident has highlighted the need for increased training of firefighters in fire behaviour, and in initial attack size-up where an appreciation of the broader fire environment is required rather than just of the area in which firefighters are currently working. Firefighter training should utilise reminders such as the Common Denominators and LACES (for Lookouts, Anchor points and Awareness of fire behaviour, Communications, Escape routes and Safety zones) to reinforce potentially problematic aspects of fire behaviour and firefighter safety. The lack of a lookout that could monitor fire activity in the area beneath the crew was a serious oversight in this particular case. All training undertaken must also emphasise the correct use of protective equipment, and examples such as this incident can be used to clearly demonstrate the benefits of picking up on the lessons learned.

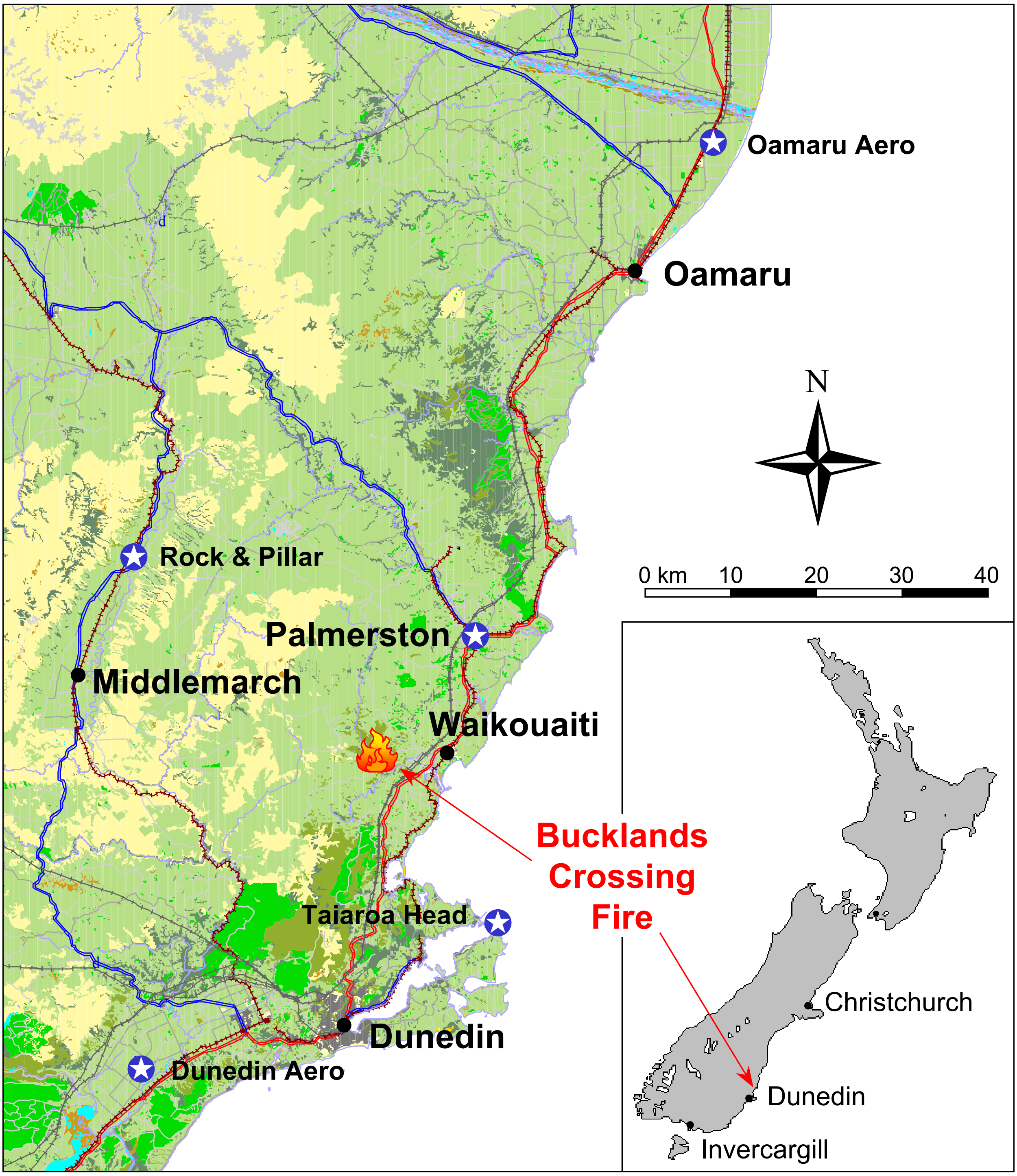


Figure 1. Map of the North Otago region showing the location of the Bucklands Crossing Fire in relation to local population centres (●) and weather stations (✪).

Introduction

While New Zealand is not recognised as having one of the worst fire climates in the world, the combination of steep slopes, highly flammable scrub fuels and a strong föhn wind effect results in many parts of the country having what could only be described as a severe fire environment. When further combined with a source of ignition, this alignment of fire environment factors contributes to relatively frequent fire occurrence[1] and, almost inevitably, extreme fire behaviour.

Such a fire outbreak occurred on March 24, 1998 at Bucklands Crossing, near Waikouaiti in North Otago (see Figure 1), when strong winds caused powerlines to ignite adjacent vegetation. The Bucklands Crossing Fire, as it became known, occurred in very difficult terrain and under the influence of dry, windy conditions. It burned an area of 200 hectares including several woodlots (Figure 2). More significantly, a crew of rural firefighters where burned over while attempting to suppress a backburning sector of the fire. One firefighter was seriously injured, receiving burns to 30% of his body, and two others were burned on the arms and shoulders by a "fireball" of hot burning gases that exploded from the scrub-filled gully below them. Two firefighters who took shelter from the fire run behind the fire appliance and the remaining two members of the crew were uninjured, while the fire engine received moderate damage.

This report describes the activities of personnel leading up to and during the incident in relation to the fire environment and fire behaviour. It presents a more detailed account of the incident described previously (Hamilton 1998a, 1998b, Pearce 1998, Pearce *et al*. 1999). Possible causes of the "blow-up" are reviewed, and observed fire behaviour compared to that predicted by available models. Aspects of firefighter safety during the incident are also discussed including the performance of protective clothing. Wildfire documentation provides valuable information for improving the knowledge and understanding of fire behaviour, and for reviewing the effectiveness of fire suppression operations (Alexander and Pearce 1992, Fogarty *et al*. 1997, Alexander and Thomas 2003). In particular, the use of lessons learned from fatality fires and near-hit incidents can act as a key method in bringing about desired changes in firefighter safety (DeGrosky 1999).

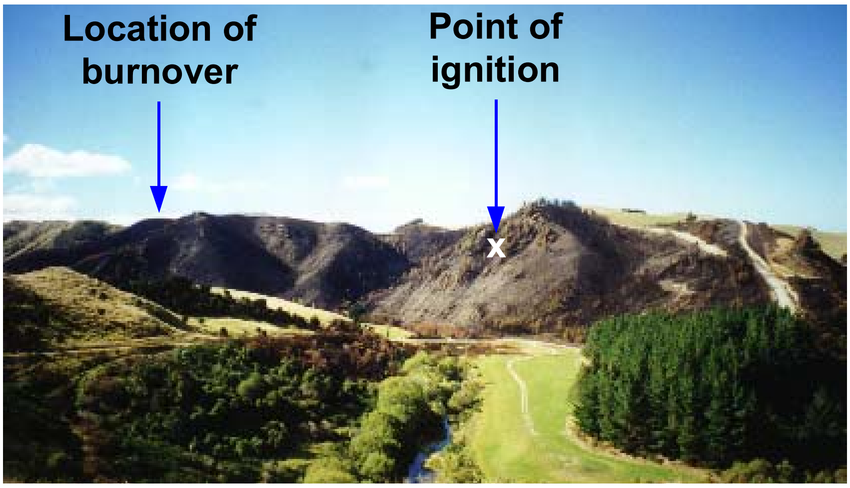


Figure 2. General view of the Bucklands Crossing Fire looking northeast.

[1] On average, New Zealand experiences around 3000 rural vegetation fires each year resulting in the loss of some 7500 ha in total (National Rural Fire Authority, Annual Return of Fires, 1993/94-2002/03).

Fire Chronology

At 0747[2] hours on Tuesday, 24 March 1998, a fire was reported via the 111 phone system by a local musterer on his way to work near Bucklands Crossing, some 30 km north of Dunedin (see Figure 1). The fire was seen burning beneath powerlines and was described as “only a few square metres in size”. The fire was most likely caused by powerlines contacting adjacent vegetation in strong winds.

New Zealand Fire Service (NZFS) volunteer fire brigades from Waikouaiti (6 km to the east) and Palmerston (17 km northeast) responded to the fire at 0753 hours, with the Waikouaiti crew arriving onsite at 0803. At that time, the fire was burning on several fronts in a stand of pine trees on a steep hillside above the Waikouaiti River (Figure 3, also see Figure 4). On the northern flank it was spreading through the pine stand and into dense manuka scrub, while on the southern flank it was reported as having jumped the Waikouaiti-Nenthorn Road (otherwise known as Ramrock Road) at 0807 hours. The fire subsequently breached Ramrock Road in several places and spread south and east through roadside rank grass into grazed pasture, scrub and several small woodlots.

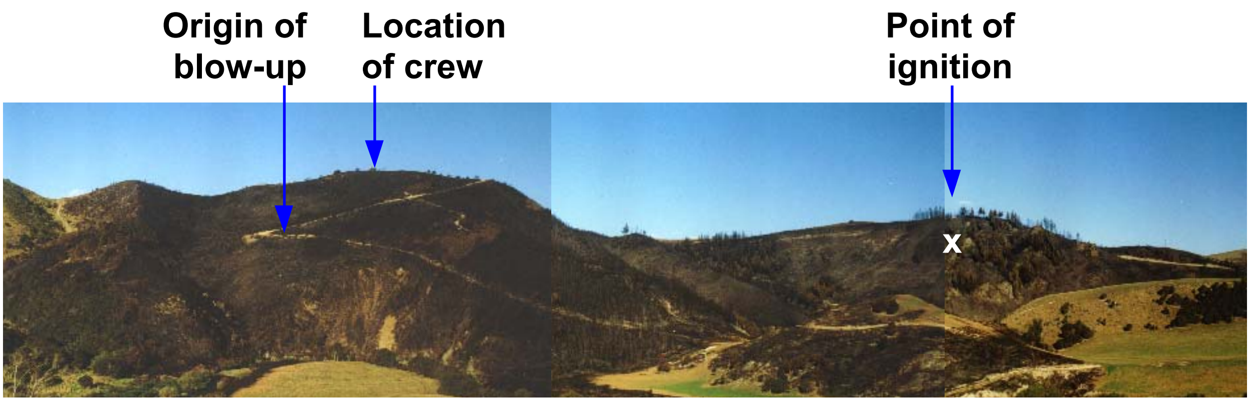


Figure 3. View of the Bucklands Crossing Fire looking east.

The Dunedin City Council’s (DCC) Principal Rural Fire Officer (PRFO) was advised of the fire at 0754 hours. He immediately tried to contact two helicopter companies and dispatched the DCC’s rural fire crews. Contact was finally made with one of the local helicopter companies at 0811, when the DCC PRFO was informed that pilots from the two companies were flying the Tranz Rail Rescue helicopter to a truck accident in North Otago. This illustrates the potential fallibility of reliance on the availability of rescue helicopter services when a fire occurs.

The DCC’s PRFO arrived at Bucklands Crossing at 0837 hours and took control of the fire. The fire had travelled some 800 m from the point of ignition and had burned an area of approximately 100 ha (Figure 4). Extreme fire behaviour was occurring, with torching and crowning in pine plantation fuels, and gale force west-nor’west winds were making it difficult for NZFS crews to mount an effective initial attack on the fire. The Waikouaiti brigade were extinguishing fire in a small forest block on the eastern side of Ramrock Road. The Palmerston crew were on the western side of Bucklands Crossing, cut off by the rapidly advancing fire front.

[2] All times used in this report are given in 24 hour format and refer to New Zealand Standard Time (NZST).

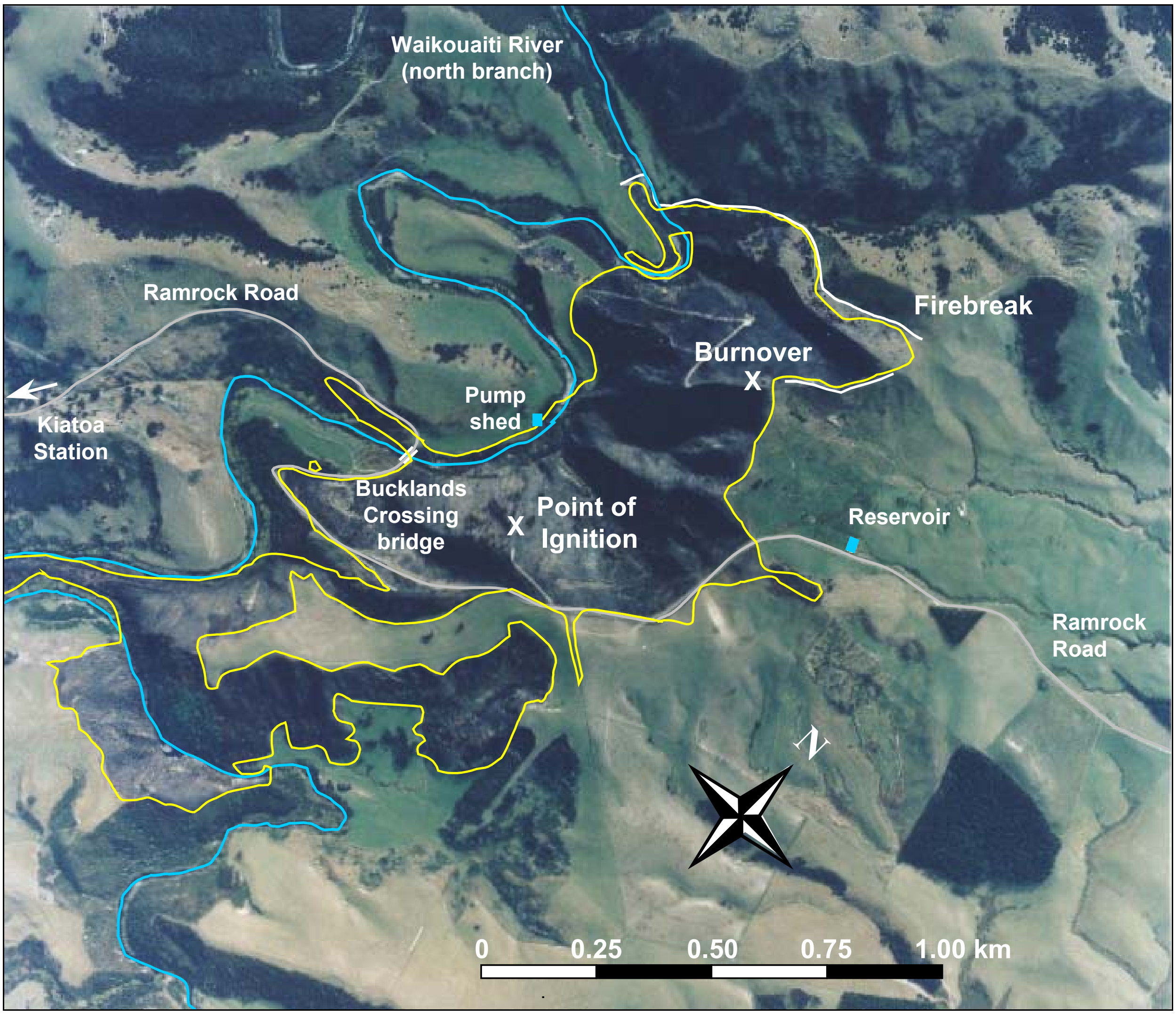


Figure 4. Fire map for the Bucklands Crossing Fire.

At 0910 hours, the DCC fire appliance and crew arrived at the scene and additional personnel were requested. An ambulance was also ordered and this arrived at 0930, whereupon it stood by on site as a safety precaution. The first helicopter, a Hughes 500C, also arrived at 0910 hours (some 75 mins. after helicopters were first called for). The Incident Controller immediately took a flight to size-up the fire and plan an attack. The flight confirmed his worst fears – the fire had spread across a wide area of steep, divided terrain and was burning on three fronts to the north, south and east.

Fire behaviour was such that it was decided to initially mount an attack using helicopters on the front spreading in a northerly direction. This front had the most potential to burn into heavier fuels and then into a large recently-planted forest block to the north. Ground crews were deployed along the edges of Ramrock Road to stop the fire getting into an unburnt forest block to the southwest and to protect the fire from spreading towards the Kiatoa Station homestead 1.5 km to the west (see Figure 4). A bulldozer was also engaged to carry out an indirect attack on the north side of the fire and to put a break around the threatened forest block. Hence, fire behaviour and resulting firefighter safety were major considerations in the deployment of all fire suppression resources.

At 0920 hours, a second helicopter arrived – a Jet Ranger. However, due to the strong, gusty winds (75-90 km/h), the pilot decided it was too rough for him to fly, and he landed in a sheltered area waiting for the wind to drop. The Hughes 500 continued to attack the fire, initially carrying loads of 500 litres with foam added. In the conditions the pilot was doing an excellent job, and the foam drops had knocked down a significant length of fireline. However, at 1030 hours, the wind strength increased and even with a reduced load of 300 litres the pilot was having difficulty dropping foam on the fire. At this point it was decided to suspend aerial operations until the wind strength abated.

Released from his role in charge of aerial operations, a senior DCC Crew Leader sought permission from the Incident Controller to scout the eastern and northern flanks of the fire. Part way through this reconnaissance, he located a lone television cameraman (on the ridge where the burnover later occurred, see Figure 4). Due to the fire activity and conditions at that time, he requested the cameraman leave the area for safety reasons. The Crew Leader continued scouting the northeastern flank before returning to the narrow ridgetop, having observed fire behaviour on this sector for some 25 to 30 minutes. At this time (1105-1110 hours), the fire had already burned up the southeastern side of the ridge through dense manuka, across the grass-covered ridgetop, and was slowly backburning down the northwest-facing slope beneath tall manuka/kanuka scrub (Figure 5a). The Crew Leader radioed the Incident Controller requesting a fire appliance and crew be sent up to him as he believed they could extinguish the fire that was backburning down the slope beneath him. The Incident Controller replied that he was unable to see the area from where he was, and that it was the Crew Leader’s call as to whether he should proceed. The Crew Leader reported that the burnt out grass area along the ridgetop and the burned manuka stand on its southeastern face provided a large enough area from which to safely deploy. However, the Incident Controller emphasised to the Crew Leader during this conversation that he should keep his crew within the burnt area.

The Crew Leader remained on the ridgetop awaiting arrival of the crew, and continued sizing up the fire situation during this time. The fire continued to backburn slowly down the hill, while a portion of the fire in the gully bottom further below would occasionally flare up, with flame

Figure 5. Fire behaviour on the ridgetop prior to the crew arriving: **(a)** fire backburning beneath manuka; and **(b)** smoke from the fire in the gully below being blown parallel with the ridgeline (source: TV3).

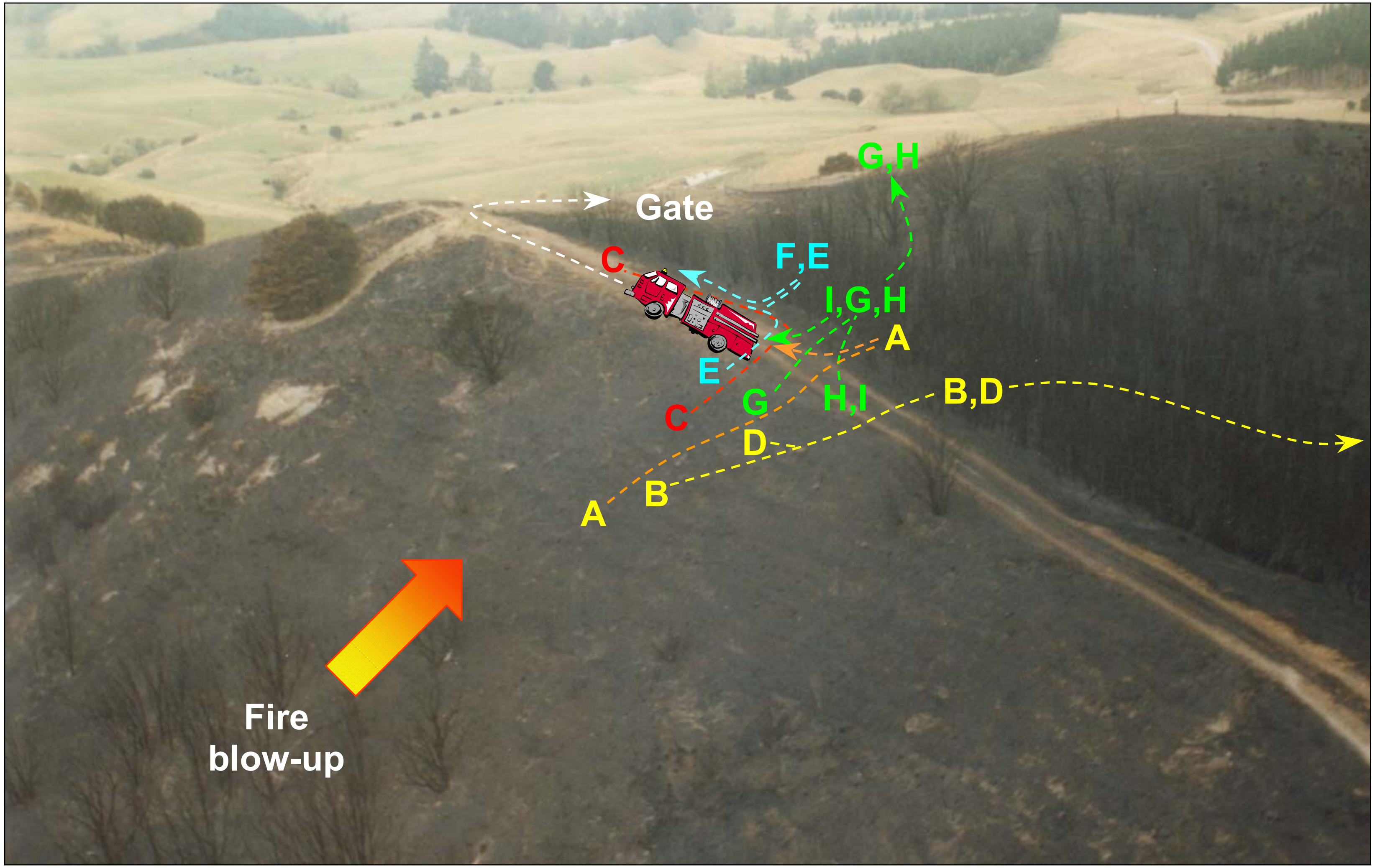


Figure 6. Locations and escape routes of fire crew members during the burnover. Symbols designate the location of important features, while letters indicate the location and escape paths taken by individual firefighters.

heights reaching 2-3 m before subsiding again. Smoke from the fire was being blown up the gully to the east roughly parallel to the ridgeline (Figure 5b), and the Crew Leader believed that if fire activity were to increase, it would spread in this direction. However, from the time the Crew Leader first entered the area until the crew arrived, a period of about 35-40 minutes, he noticed no significant change in the fire activity, although the wind was observed to drop away.

At around 1115 hours, the Crew Leader met his crew at the gate in the fenceline just to the east of the scene of the incident that was to follow and, following a short briefing, had the fire appliance reversed to a spot about 60 metres along the ridgeline track from the gate (Figure 6). It should be noted that the driver originally intended to drive forward along the track, but the Crew Leader requested that he reverse in. This indicates at least partial recognition of the risk associated with deployment in this location and identification of the track as the main escape route out of the area.

On parking the appliance, the crew began laying a hose line down the north-facing slope towards the fire which was still backing slowly downhill into the wind beneath the manuka/kanuka scrub. It must be stressed that the crew were working within an area of previously burnt grass fuels which extended about 30-35 m below the ridgeline where the appliance was located. Realising that a single hose length was not enough to reach the fire, the Crew Leader (indicated by A in Figure 6) asked for a second length to be added into the uncharged hose line. He and another crew member (B) were farthest down the hill, while a third firefighter (C) was a few metres above them along the hose line. The second length of hose was being connected into the line by a fourth crew member (D), when the Crew Leader suddenly heard the noise of the fire approaching from below. He had enough time to yell “Get out of it!” to his crew before being knocked off his feet by what the crew describe as a “fireball exploding”.

The Crew Leader (A) was the first to be hit by the fireball as he was turning uphill to retreat from it. Despite being knocked to the ground and sustaining burns to his back and shoulders, he got to his feet and ran to the ridgetop near the back of the appliance where he dived over the crest, only to be hit again by a flame rollover which burned his hands and arms. He immediately radioed the Incident Controller to alert him of the incident.

Given enough warning by the Crew Leader’s shout, Firefighter B who had been standing next to the Crew Leader managed to run to the top of the ridge, where he was hit by the blast and thrown over the crest. Avoiding injury in the first blast, he also sustained burns to the back of his hands and arms on being hit by the flame rollover. Firefighter D, who had been connecting the extra hose length into the hoseline, managed to get over the ridge crest but cut his hand on the vegetation as he dived for cover. He felt the heat of the flame rollover on his neck and shoulders but did not sustain any burns injuries. Both Firefighters B and D then headed down the lee side of the ridge through the previously burnt fuels to the other side of the gully, where they then made their way up to the fenceline and out to the ambulance.

Firefighter C, who was halfway up the hill along the hoseline (see Figure 6), ran to the top of the ridge towards the appliance, possibly sustaining burns in the first blast. From behind the appliance, he headed along the ridgeline towards the gate where he was overrun. He was found by the crew several metres in front of the fire engine, with severe burns to his back, left arm and hands, and left thigh. The nature of the injuries suggest that while he may have sustained some burns while initially running from the fire, most of the burning occurred whilst lying on the ground.

The driver (E), who was putting the appliance in gear ready for pumping, and another crew member (F) standing at the pump controls, heard the Crew Leader's shouted warning and took shelter behind the appliance as the fireball burst over, around and under it, and were protected by the rear tyres in particular. They were blown over or dived to the ground on the lee side of the ridge following the initial fire impact, but did not sustain any injuries in either this or the flame rollover that followed. Both ran some 20-30 m down the lee side of the ridge before heading up towards the fenceline and gateway. The driver (E) then ran back along the ridgeline to where he located the burned Firefighter C. After assisting him to the gateway, Driver E and other crew members loaded him into the back of a parked utility and drove him down to meet the waiting ambulance.

Two other firefighters (G and H) untangling hose behind the appliance did not hear the warning but saw the fireball coming. They were able to escape down the lee side of the ridge and were far enough away to avoid injury. Both G and H returned to the gateway, where they met the Crew Leader (A) who had driven the fire appliance out. The rear of the appliance was still on fire and had to be put out using a portable fire extinguisher.

It was later established that a ninth firefighter (I), a NZFS volunteer wearing full urban protective clothing, was also on the ridgeline at the time of the blow-up. He was not part of the DCC crew, who were not aware of his presence until after the incident. He was located some distance in front of the appliance and, after diving to the ground in the initial blast, avoided injury by evacuating along the ridgetop to the gate.

The incident occurred at approximately 1124 hours, and was of very short duration. The crew report the initial blast from the fireball lasting some 5-10 seconds, followed by a further 5-10 seconds exposure to flame rollover. After escaping in various directions, the crew regrouped and found Firefighter C lying face down on the ground in front of the fire engine. The ambulance, which had earlier been moved along the road to the track entrance only some 200-300 metres from the incident, was called and the St Johns staff treated the injured crew. Firefighter C was taken from the site to hospital by air ambulance, while the other three injured crew members were later transferred from the ambulance to the rescue helicopter while enroute to Dunedin.

Damage to the fire appliance as a result of the burnover was significant (Figure 7), with lights and decals on both the front and rear of the appliance melted along with other plastic and rubber fittings. The plastic cover over the monsoon bucket which was stored on top of the appliance was completely burned away, as was the canvas cover over the foam proportioner; the canvas cover over the pump, which was on the side farthest from the flame front, was also burned. Heavy rubber mudflaps were also deformed, thus reflecting the extreme temperatures to which both the fire appliance and crew members were exposed.

The fire continued to burn for several hours after the incident before being contained later in the day. However, mopping up of hot spots continued over the next 7 days and the fire was not declared out until April 2. At the fire's peak, some 70 firefighters were involved, including both permanent staff and volunteers from the DCC, two NZFS volunteer crews, local forestry company staff and a Civil Defence communications crew. In addition, two helicopters were used, along with four fire appliances and a bulldozer. Total suppression costs amounted to more than $60,000. The fire burned an area of around 200 ha, including two small woodlots of radiata pine totalling 20 ha; the remainder of the area was grazed pasture and manuka or gorse-covered slopes. Several kilometres of fencing was damaged and some stock were also lost.

Figure 7 (a) & (b). Damage to the DCC fire appliance, including tail lights, foam proportioner, pump cover and rubber hose fittings.

Fire Environment Factors

The fire environment concept is useful for describing "the surrounding conditions, influences, and modifying forces of topography, fuel and fire weather that determine fire behaviour" (Countryman 1972). The following section describes the fire environment factors that contributed to the burnover incident and fire behaviour during the Bucklands Crossing Fire.

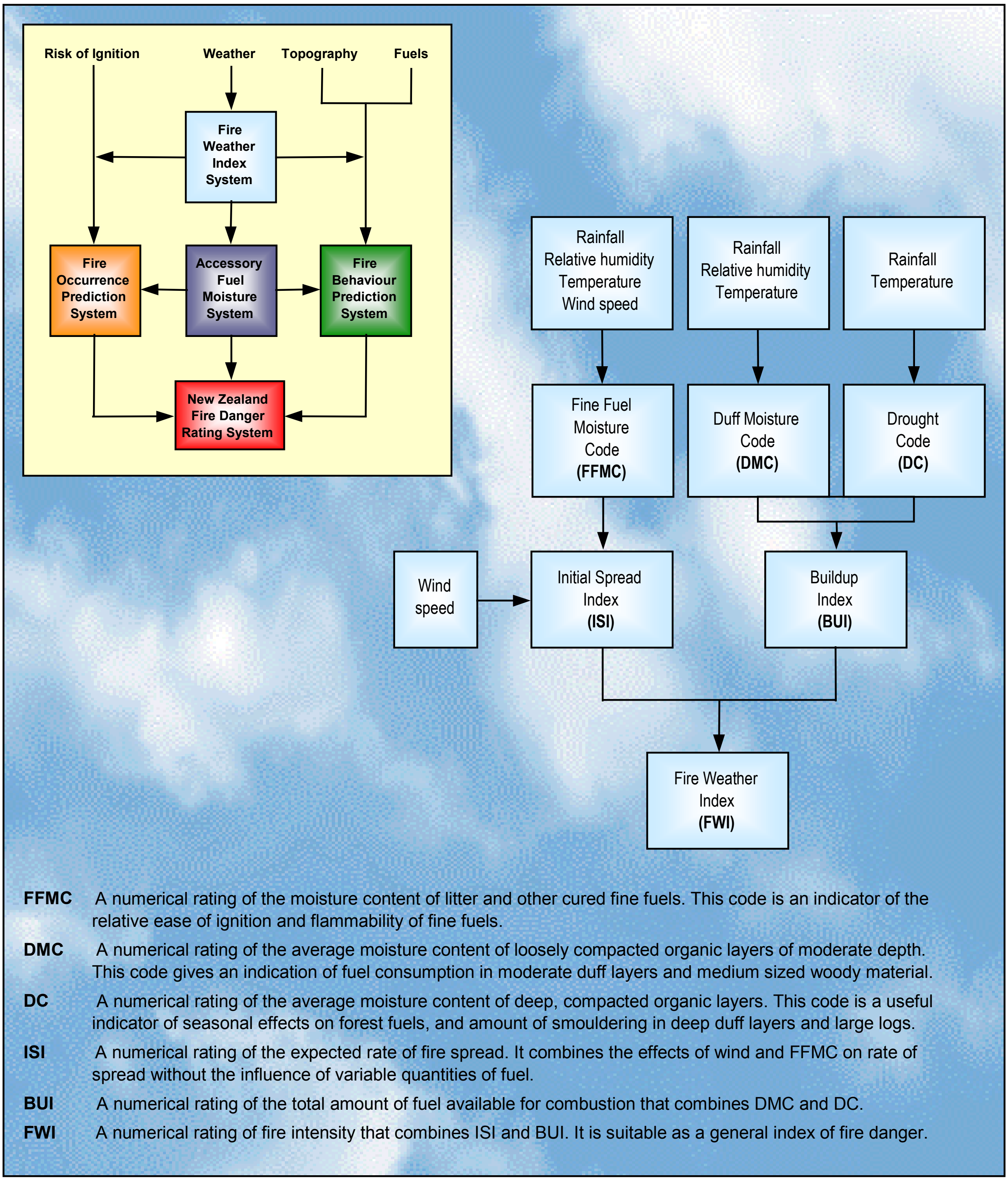


Figure 8. Structure of the New Zealand Fire Danger Rating System (adapted from CFS 1984 and Stocks *et al*. 1989).

Assessment of the fire environment factors is assisted by use of the New Zealand Fire Danger Rating System (NZFDRS) which is based on the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks *et al.* 1989, Alexander *et al*. 1996)[3]. The NZFDRS is used by New Zealand fire authorities to assess the probability of a fire starting, spreading and doing damage. Figure 8 illustrates the submodels that make up the NZFDRS; these include:

- the Fire Weather Index (FWI) System: this module produces a set of codes and indices based on current and preceding weather conditions, which indicate the relative flammability and availability of fuel and the effect that this is likely to have on the headfire rate of spread and intensity.
- the Fire Occurrence Prediction System: an incomplete module predicting the probability of fire ignition from natural and human causes relative to weather and fuel moisture conditions.
- the Accessory Fuel Moisture System: an incomplete system being developed to allow the estimation of fuel moisture content for a range of fuel types and fuel components (e.g., elevated scrub, twigs, grass, forest litter) and larger woody material. Factors taken into account include the effects of weather, time, topography, latitude and season.
- The Fire Behaviour Prediction System: this module combines the FWI spread indicators with data on fuel type and topography to make quantitative predictions of fire behaviour (e.g., head, flank and back fire rate of spread and fireline intensity).

As well as depicting the broad structure of the NZFDRS, Figure 8 also shows the components of the FWI System, values of which are used to describe the short- and long-term weather factors affecting the Bucklands Crossing Fire.

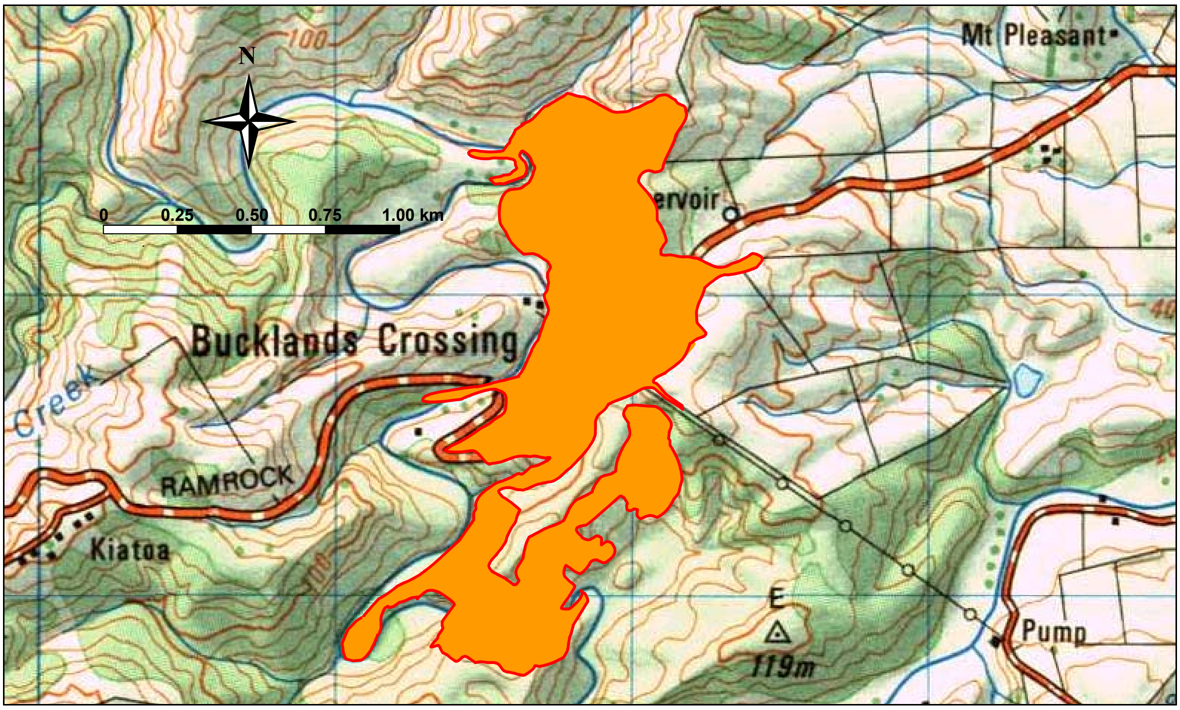


Figure 9. Map of topography in the fire area (based on NZMS 260, Sheet I43).

[3] New Zealand adopted the Canadian FWI System in 1980 as the basis for a national system of rating fire danger in exotic pine plantations (Valentine 1978). This was the precursor to the later adoption and adaptation of the CFFDRS for use throughout New Zealand (Fogarty *et al*. 1998).

Topography

The topography of the fire area is characterised by complex terrain, comprising steep slopes which drop sharply to the meandering course of the Waikouaiti River below (see Figure 9). The fire burned over a relatively narrow elevational range from about 20 to 160 m above sea level. Steep slopes of 30-40° (55-85%) are common, and many rock outcrops occur throughout the fire area. Several side gullies drain into the main river course with steep, narrow intervening ridges.

The burnover occurred on one of these ridges, which consisted of a 30º (58%) slope on the lee side (southeast aspect) which had been burned over earlier, a narrow ridge crest some 4-5 m wide, and a 25º (47%) slope on the upwind side (northwest aspect) leading down to the scrub fuels under which the fire was backburning (Figure 10a). Another significant feature of the topography in the area where the burnover occurred was a steep rock bluff, which dropped directly into the river about 250 m down the slope from the top of the ridge (Figure 10b).

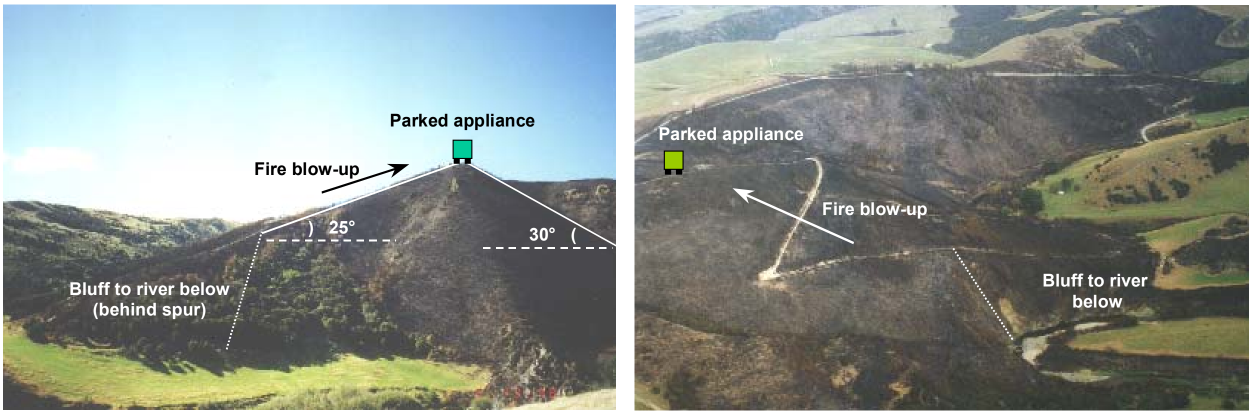


Figure 10 (a) & (b). Topography in the area of the ridge where the burnover incident occurred.

Fuels

Fuels in the broader fire area consisted of pine woodlots and manuka, kanuka and gorse scrub, together with areas of grazed pasture, including some with scattered tussock grasses (Figure 11). The fire initially burnt through a stand of pines (*Pinus radiata*), containing a mixture of older trees and newer plantings as a result of an earlier fire. It spread across the road to the east into grazed pasture (only 50-60% cured) and then into another woodlot. The fire also burned through several areas of manuka (*Leptospermum scoparium*) and kanuka (*Kunzea ericoides*) scrub, and in mixed scrub containing natives, gorse (*Ulex europaeus*) and other woody weeds beside the river. Willow trees (*Salix* spp.) along the river banks were also burned.

Dense 2-3 m tall manuka scrub, with occasional flax in the understorey, covered the lee side (southeast face) of the ridge on which the burnover incident occurred. This had been burned out earlier in a very rapid uphill fire run, as only the fine fuel had been removed and most of the woody material remained. No fuel sampling was conducted, but estimates for manuka/kanuka vegetation with similar height and cover suggest that available fuel loads were in the order of 25-30 t/ha (Fogarty and Pearce 2000).

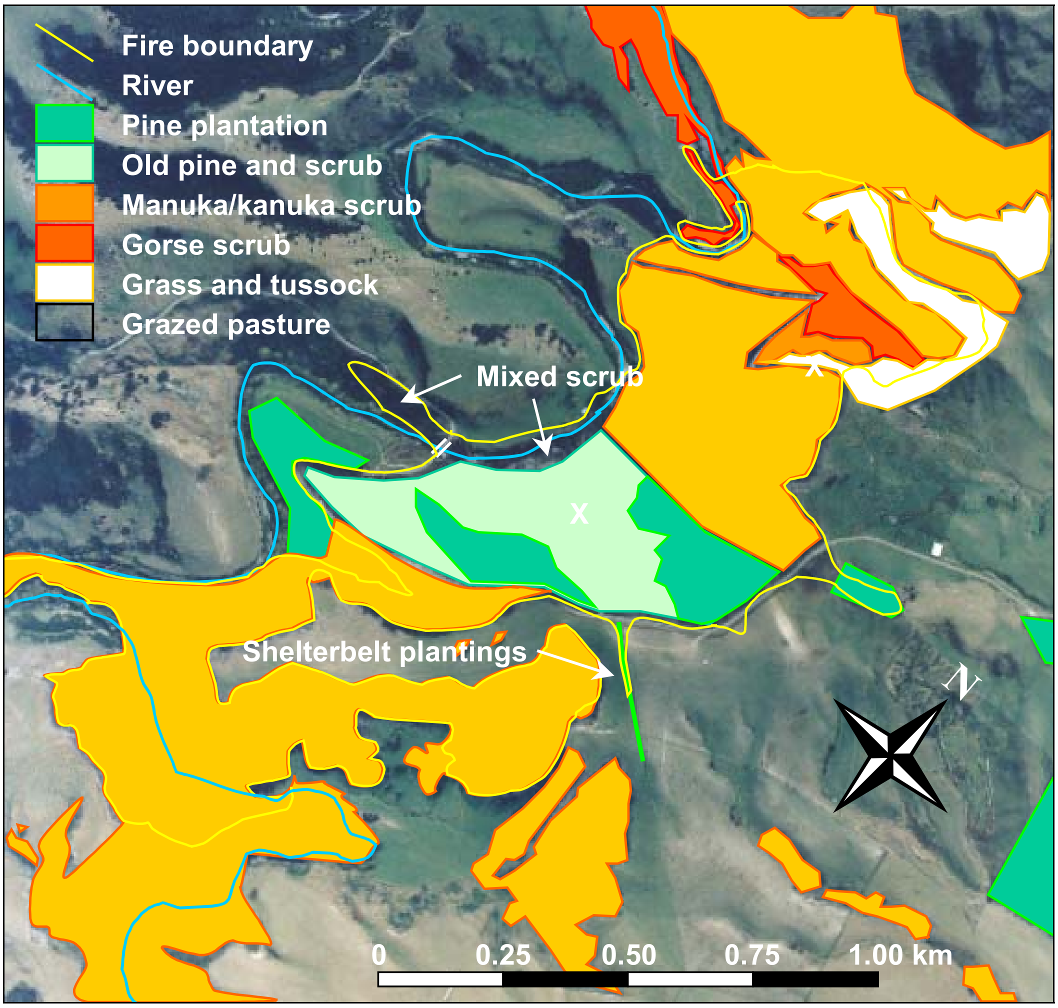


Figure 11. Fuels map for the Bucklands Crossing Fire.

Grass fuels with scattered short tussocks covered the open ridgetop where the appliance was parked, and this too had been burnt out prior to the crew arriving. Grass fuel loads of 2.0-3.0 t/ha would have been present, again based on extensive sampling in similar grass and tussock fuels (Fogarty and Pearce 2000). These grass fuels extended some 30-35 m down the upwind (northwest-facing) slope to the second manuka/kanuka stand. While this 3-4 m tall vegetation had full canopy cover, it was very open underneath with only a shallow surface fuel layer made up of litter and mosses (see Figure 12). Available fuel loads in this stand were likely to have been about 25-35 t/ha. The manuka/kanuka scrub was initially only underburnt, but burned out completely at a later time. The width of the manuka/kanuka stand was also variable, but it extended some 30-50 m to the gorse-filled gully bottom below. About 1.5-2.5 m tall, this gorse was mature and the canopy was beginning to open up and collapse. These fuels burned very intensely, as evidenced by the very clean burn with little ash or debris on the ground and minimum post-burn branch diameters up to 2-3 cm (Figure 13). Available fuels in this area, based on sampling in similar gorse fuels (Fogarty and Pearce 2000), would have been at least 25 t/ha and possibly even as high as 40 t/ha.

Figure 12. Partially burned manuka/kanuka scrub fuels on the ridge immediately to the north of where the burnover occurred.

Figure 13. Burnt gorse fuels below the location of the burnover, in the area where the blow-up is believed to have originated.

Weather and fire danger

Located in the rainshadow zone in the lee of the Southern Alps, the North Otago region commonly experiences periods of low summer rainfall and is one of the more drought-prone parts of New Zealand. This was the case prior to the Bucklands Crossing Fire, when climatic conditions over much of the North Otago region were warmer and drier than normal. Mean monthly temperatures for Palmerston[4] (17 km northeast of the fire site, see Figure 1) were around average throughout 1997, but were significantly above average in the early months of 1998 (Figure 14a). Mean monthly temperatures for January, February and March 1998 ranged from 14.7-17.1 ºC and averaged 15.9 ºC, while daily maximum temperatures varied from 13.1-32.9 ºC and averaged 21.8 ºC over the same period. Monthly rainfall totals at Palmerston tended to be either well above or well below average during 1997, but were significantly below normal for the first part of 1998 (Figure 14b). Only 67 mm was recorded in the three months prior to the fire compared to a more usual total of 160 mm and January, in particular, was especially dry with only 4.8 mm being recorded for the entire month.

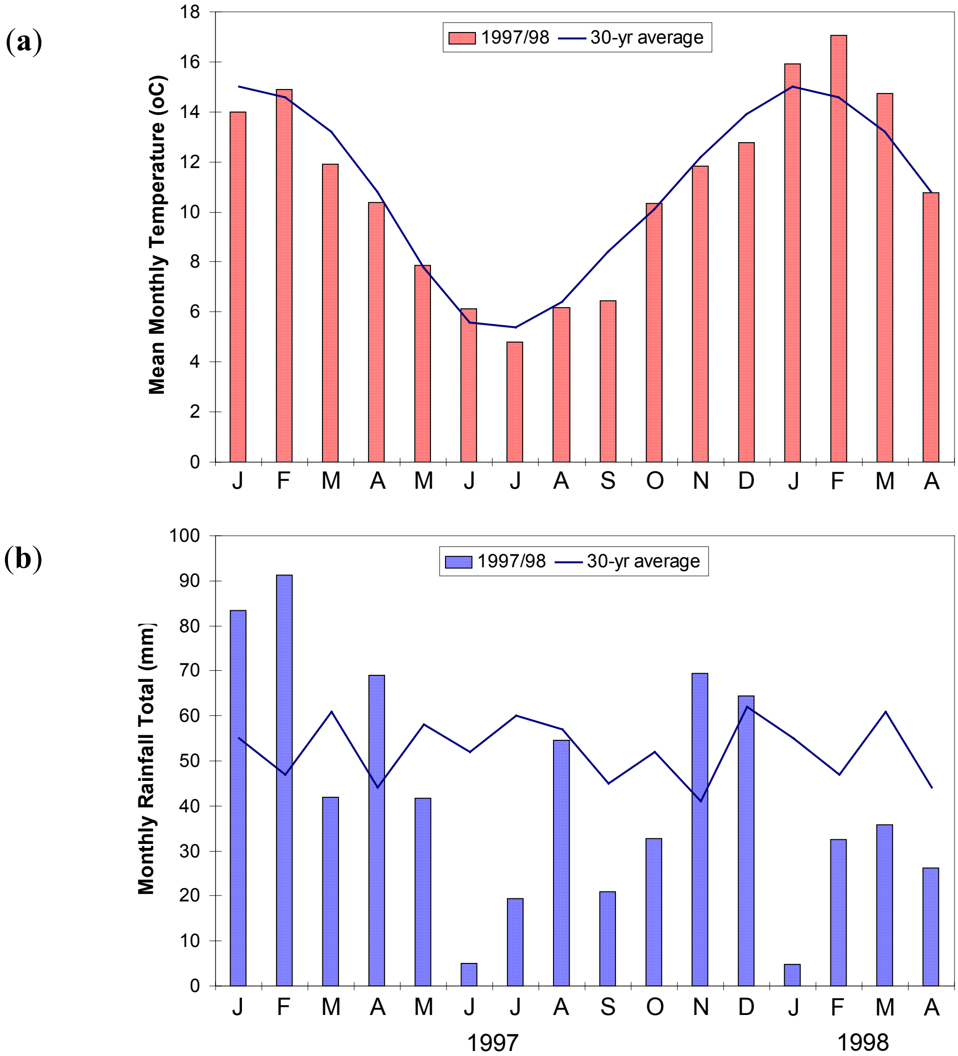


Figure 14. Comparison of monthly (**a**) mean temperatures and (**b**) rainfall totals for Palmerston in the lead up to the Bucklands Crossing Fire of 24 March 1998.

[4] Monthly values and long-term climate normals for Palmerston (station agent no. 5323) were obtained from the National Institute of Water and Atmospheric Research Ltd.'s (NIWA) National Climate Database.

The warmer and drier conditions also contributed to elevated fire danger conditions, and the seasonal trends in the Fire Weather Index (FWI) System fuel moisture codes are depicted in Figure 15. The closest remote automatic weather stations (RAWS) to the fire site recording hourly data were located at Taiaroa Head (21 km southeast), Musselburgh-Dunedin (31 km south) and Dunedin Aero (44 km south) (see Figure 1); however, the station deemed to be most representative of the fire area was located at Rock and Pillar[5], some 40 km northwest and inland of the fire site at a height of 270 m a.s.l. Rainfall data was available for a number of closer stations and observations from Palmerston (21 m a.s.l.) were used in the analyses. The Drought Code (DC) component, in particular, climbed over the summer to values in excess of 500 and, despite significant rain events throughout February and March, remained at this level for several months. The Duff Moisture Code (DMC) and Buildup Index (BUI) peaked in early February and, following rain, were climbing back to moderately high levels.

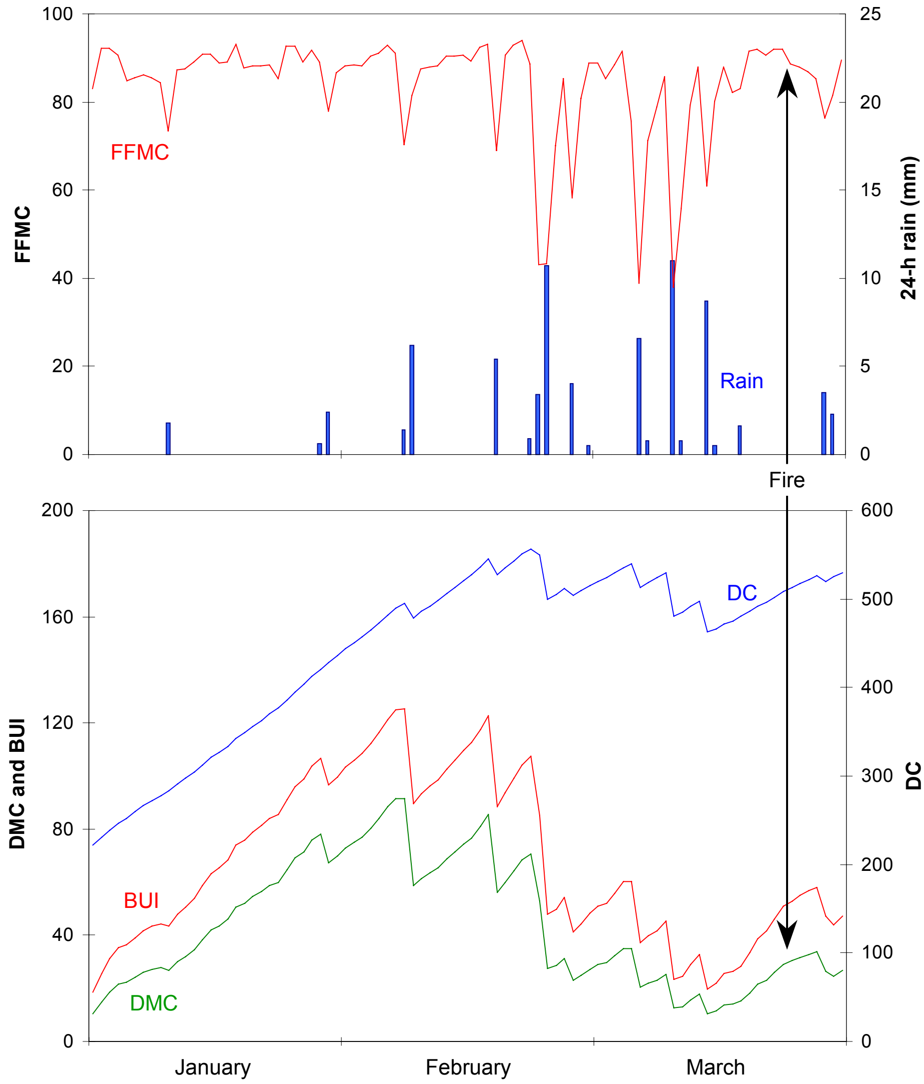


Figure 15. Wetting and drying cycles for the FWI System moisture codes leading up to ignition of the Bucklands Crossing Fire on 24 March 1998.

[5] The Rock and Pillar RAWS is part of the fire weather monitoring network maintained by the National Rural Fire Authority (NRFA).

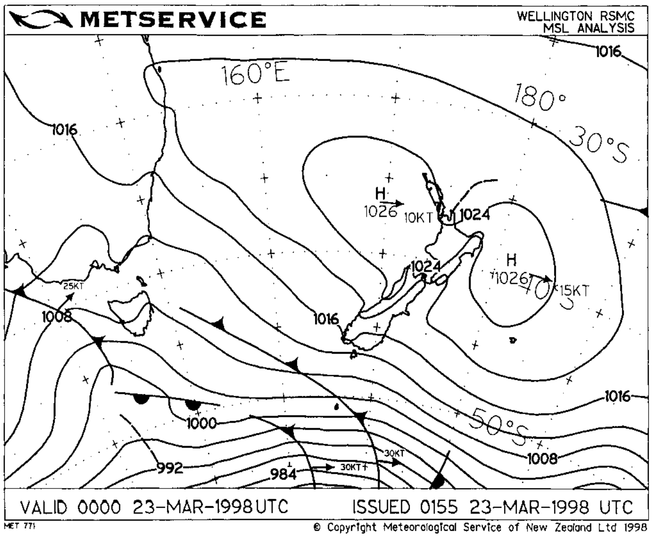
Table 1. 1200 NZST weather and FWI System values (calculated using weather data from the Rock and Pillar RAWS and Palmerston rainfall) for the day before and the day of the Bucklands Crossing Fire.

	23/3/98	24/3/98
Temperature (°C)	21.5	25.5
Relative humidity (%)	26	35
Wind speed (km/h)	23.6	16.3
Wind direction	010	010
Rain (mm)	0.0	0.0
Days since rain >0.6 mm	5	6
Fine Fuel Moisture Code (FFMC)	92.0	92.0
Duff Moisture Code (DMC)	26	29
Drought Code (DC)	502	508
Initial Spread Index (ISI)	18.6	13.0
Buildup Index (BUI)	46	51
Fire Weather Index (FWI)	32.8	26.9

The midday weather and full range of FWI System codes and indices for both the day prior to and the day of the fire are listed in Table 1. In general, DC values above 300 are considered high (Anon. 1999), and although values may exceed this relatively frequently in parts of North and Central Otago, the elevated levels existing at the time of the fire indicated very dry soil conditions and the potential for problems during fire extinguishment and mop-up. For the other codes and indices, a Fine Fuel Moisture Code (FFMC) value of 92 is considered a threshold for extreme fire behaviour and potential problems associated with spotting, while DMC and BUI values greater than 30 and 60, respectively, are considered high and indicate increased fuel availability. An Initial Spread Index (ISI) value of 10 is also considered high, with values above this indicating the potential for rapid fire spread. Values of the FWI index itself greater than 30 are also significantly high, indicating the potential for high frontal fire intensities and that any fires will be difficult to control.

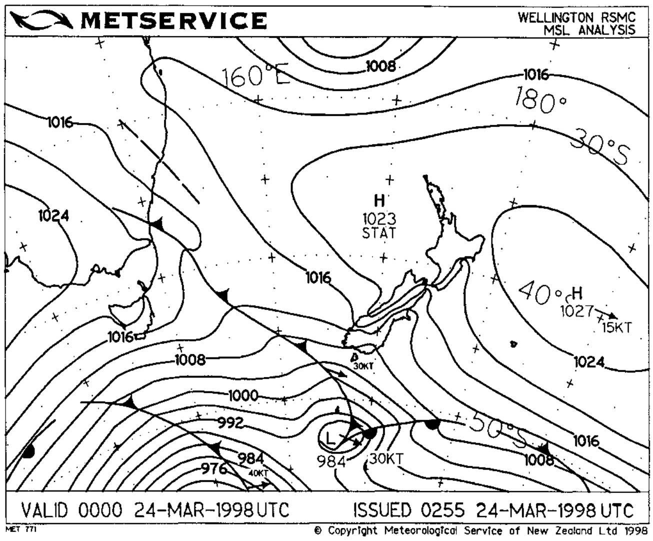
The surface weather charts and situation in the lead up to, during, and following the fire are contained in Figure 16, courtesy of the Meteorological Service of NZ Ltd. (MetService). These indicate a strong northwesterly flow across the lower South Island ahead of a cold front passage. This weather pattern – with an anticyclone to the north and a low pressure system to the southwest, and an associated cold front moving east across the country from the Tasman Sea – is one of most common weather events affecting New Zealand, particularly during spring and autumn. Called the "nor'wester", the föhn effect associated with the northwesterly flow across the mountain ranges results in strong, gusty winds and hot, dry conditions in eastern areas of both islands, and this weather pattern has contributed to many significant wildfire events (e.g., Pearce and Alexander 1994, Fogarty *et al*. 1997, Rasmussen and Fogarty 1997).

On the day prior to the Bucklands Crossing Fire (March 23), winds in the region were predominantly from the south or west, although northeasterlies were experienced near the coast. At the Rock and Pillar RAWS, winds were initially from the southerly quarter at less than 10 km/h (Figure 17). However, a change occurred at around 1100 hours when the winds turned to the north and wind speed increased to about 20 km/h, occasionally reaching 50 km/h. Later that evening, at around 2100 hours, the winds became more west-northwest averaging about



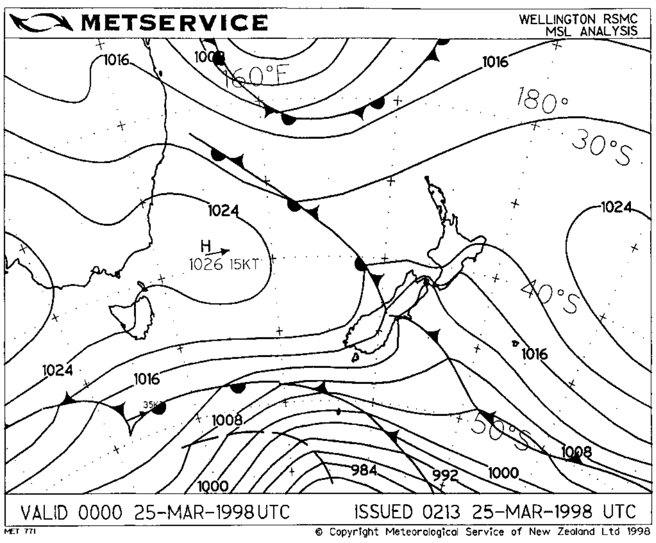
Monday, 23 March 1998 (day before the Bucklands Crossing Fire):

A ridge of high pressure is expected to continue to cover much of the North Island through to Thursday. Meanwhile, a cold front will move onto the south of the South Island late Tuesday and then move slowly north on Wednesday preceded by a northwesterly flow and followed by disturbed southwesterlies. It's likely that on Thursday the front will weaken as it moves along the east coast of the North Island while a ridge spreads over the South Island. On Friday, the ridge will cover much of the country while a depression of tropical origin moves into the north Tasman Sea.



Tuesday, 24 March 1998 (day of the Bucklands Crossing Fire):

A ridge will continue to cover much of the North Island on Wednesday while a front moves northeast over much of the South Island. It's likely that on Thursday the front will weaken as it moves up the east coast of the North Island while a ridge of high pressure spreads over the South Island. On Friday a low of tropical origin is expected to move into the north Tasman Sea and on Saturday should move southeast towards the South Island. A strengthening north to northeast flow is likely over New Zealand on Saturday ahead of the low.



Wednesday, 25 March 1998 (day after the Bucklands Crossing Fire):

A high should become established over the country over the next couple of days, with a front lying over northern New Zealand on Friday. Meanwhile, a low of tropical origin is expected to lie over the north Tasman Sea on Friday and Saturday, then deepen rapidly as it heads towards the South Island on Sunday. The low may cross the South Island overnight Sunday, with a southwest flow spreading over New Zealand on Monday in its wake.

Figure 16. Surface weather charts and situation reports in the lead up to, during, and following the Bucklands Crossing Fire (source: MetService).

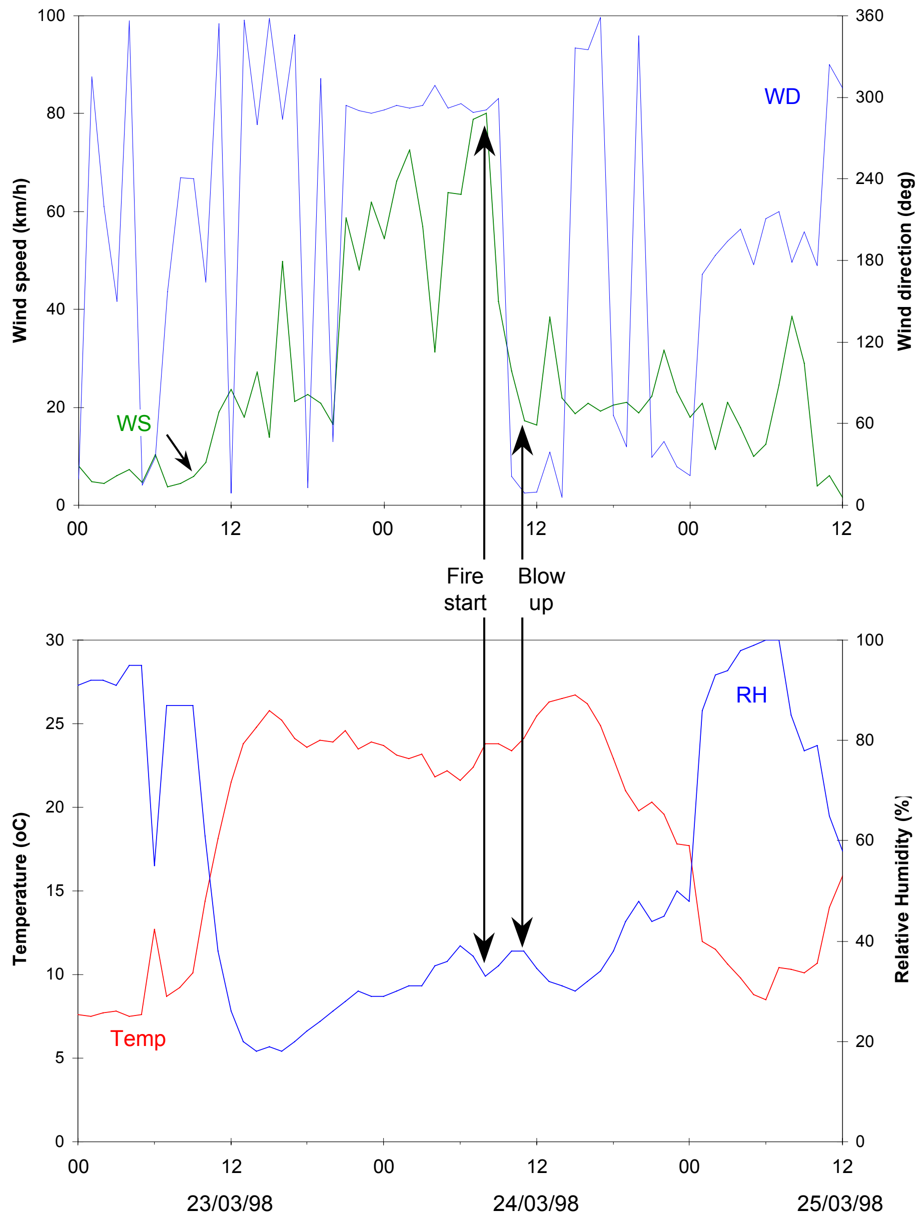


Figure 17. Diurnal weather patterns recorded at the Rock and Pillar RAWS before, during, and after the initial run of the Bucklands Crossing Fire.

50 km/h, and this wind direction remained constant through the night, with wind speed peaking at 80 km/h at 0800 hours on the morning of March 24, around the time the fire was first reported. However, soon after, the wind turned more northerly and its strength dropped significantly[6]. Wind speeds of about 20 km/h remained for the rest of the day despite a brief change to the west late in the afternoon, before turning to the south early on March 25. Observations at the fire site suggest that winds there were more variable in strength and direction, as might be expected with a gusty nor'west airflow in complex terrain, and it is likely that the drop in wind speed occurred later at the fire site than recorded at the Rock and Pillar RAWS. The first crews on the scene reported winds of 30-50 knots (55-90 km/h) and, on arriving at the fire site, helicopters were initially unable to effectively work the fire due to the strength and gustiness of the wind. These

[6] This drop in wind speed may have been a local anomaly, as winds across the region continued to blow strongly (P. Mallinson, MetService, *pers. comm.*).

gusty winds remained throughout the day of the fire although they varied significantly in both speed and direction.

As a result of the prevailing northwesterly airflow, temperatures remained unusually high (above 22 °C) and relative humidity exceptionally low (below 40%) throughout the night of March 23 at the Rock and Pillar RAWS (see Figure 17). At around 0800 hours on March 24, when the fire was first reported, the temperature had already reached 24 °C and the relative humidity 33%. Temperatures went on to peak at 27 °C later that afternoon, while the relative humidity remained below 40% well into the evening before reaching its more typical overnight maximum before dawn on March 25.

The widespread nature of the prevailing northwesterly flow can also be seen in the conditions observed elsewhere around the region on March 24. At nearby Palmerston, the daily maximum temperature reached 30 °C, the highest recorded that month. Similarly, maximum hourly temperatures recorded at Dunedin Aero and Oamaru were 29 °C and 31 °C, while minimum relative humidities were 32% and 24%, respectively. Strong northwest winds were also common, and at both Dunedin Aero and Oamaru hourly wind speeds on March 24 were consistently about 20-30 km/h with gusts exceeding 55 km/h[7]. Even stronger winds were recorded elsewhere across the region, and the National Rural Fire Authority's Daily Fire Weather Report (see Appendix 1) shows 10-minute average wind speeds at 1200 noon of 67 km/h and 77 km/h for nearby stations at Traquair and Deep Stream, and 105 km/h at Barnhill in Southland.

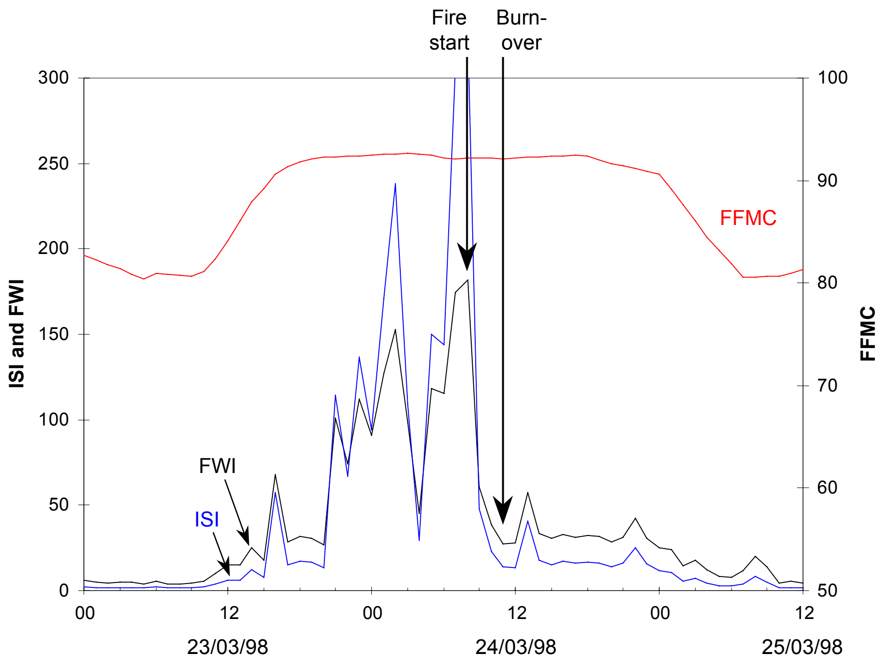


Figure 18. Hourly values of the FWI System components before, during, and after the initial run of the Bucklands Crossing Fire.

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[7] Observations of temperature, relative humidity and wind speed for Palmerston (station agent no. 5323), Dunedin Aero (7339) and Oamaru (5142) were obtained from NIWA's National Climate Database.

[8] Hourly FWI values were calculated using the equations contained in Alexander *et al.* (1984).

Table 2. Hourly weather and FWI System values for the day of the Bucklands Crossing Fire (24/03/98), using weather data from the Rock and Pillar RAWS and Palmerston rainfall.

Time (NZST)	Temp. (°C)	Relative humidity (%)	Wind direction (deg)	Wind speed (km/h)		Hourly FWI values FFMC	ISI	FWI
0000	23.7	29	291	54.5		92.5	94.3	90.7
0100	23.1	30	294	66.3		92.5	171.2	127.3
0200	22.9	31	292	72.6		92.6	238.0	152.6
0300	23.2	31	294	57.0		92.6	109.2	98.7
0400	21.8	35	309	31.4		92.5	29.8	45.1
0500	22.2	36	292	63.8		92.4	149.9	118.1
0600	21.6	39	295	63.6		92.2	143.7	115.3
0700	22.4	37	289	78.8		92.1	305.3	174.7
0800	**23.8**	**33**	**291**	**80.1**	*fire start*	**92.2**	**328.3**	**181.6**
0900	23.8	35	299	41.7		92.2	47.8	60.5
1000	23.4	38	21	27.4		92.2	23.0	38.2
1100	**24.1**	**38**	**9**	**17.2**	*burnover*	**92.1**	**13.7**	**27.1**
1200	25.5	35	10	16.3		92.2	13.2	27.6
1300	26.3	32	39	38.5		92.2	40.8	57.2
1400	26.5	31	6	21.9		92.3	17.8	33.7
1500	26.7	30	336	18.7		92.3	15.2	30.4
1600	26.2	32	335	20.8		92.4	17.1	32.8
1700	24.9	34	259	19.3		92.4	15.9	31.3
1800	22.9	38	66	20.5		92.3	16.7	32.3

Weather conditions during the fire were therefore characterised by moderately high temperatures, low relative humidity and, most importantly, strong gusty northwesterly winds. These conditions are reflected in the hourly FWI System values[8] for the day of the fire (Figure 18 and Table 2), which peaked around the time the fire started but had dropped away significantly when the burnover occurred. However, it is important to note that this drop in wind speed may have occurred later at the fire site than was recorded at the Rock and Pillar RAWS which is located 40 km northwest and inland of the fire site.

Both Table 2 and Figure 18 show that hourly FFMC values were consistently above 92 throughout March 24, which are again on the threshold for extreme fire behaviour and potential spotting problems as a result of low fine fuel moisture contents (typically less than 10%). Hourly ISI values were initially around 140 reflecting these high FFMC values and very strong wind speeds, and were in excess of 300 at the time the fire started. However, soon after this, wind speeds decreased and hourly ISI values settled around 15-20 for the remainder of the day. These values are still considered high and indicate the potential for rapid fire spread. Hourly values of the FWI index itself were also initially extremely high, exceeding 100, but settled around 30, which is still considered high, with the decrease in wind speeds which occurred just prior to the fire blow-up and burnover incident.

Atmospheric conditions

Atmospheric stability, which describes the "resistance of the atmosphere to vertical motion" (Schroeder and Buck 1970), is often an important factor in determining fire behaviour. Stable conditions produce generally settled weather and fire activity is suppressed; in contrast, unstable conditions favour gusty and turbulent winds, and increasing fire activity most commonly observed in the development of a fire's convection column. Atmospheric stability can also be a key factor in determining whether extreme fire behaviour, such as fire whirls or fire blow-ups, occur.

The closest available information on upper air conditions for the Bucklands Crossing Fire is that recorded at Invercargill Aero[9], a considerable distance (200 km) to the south of the fire area. However, the resulting temperature and wind profiles (Figure 19) are still likely to be representative of the general atmospheric conditions present at the fire site due to the widespread nature of the prevailing northwesterly airflow[10]. Observations of both temperature and wind were recorded at midnight (0000 hours) and noon (1200 hours) on the day of the fire (March 24), while an additional wind sounding was made at 0600 hours. Surface conditions for the fire, based on observations from the Rock and Pillar RAWS, are included in Figure 19 for comparison. Temperatures at both 0000 hours and 1200 hours were slightly higher than those observed at Invercargill, and dew-point temperatures (and thus, relative humidities) were lower. Surface wind speeds for the fire area were initially (i.e., at 0000 and 1200 hours) significantly higher and wind direction more westerly than at Invercargill, probably as a result of the altitude and location of the Rock and Pillar station. However, by 1200 hours, winds at the Rock and Pillar RAWS had dropped significantly and become more northerly, more closely aligned with those recorded at Invercargill.

As a measure of the ability of air to move vertically, atmospheric stability is dependent on the rate of change of air temperature with height. The ambient temperature profiles for 0000 hours and 1200 hours on March 24 both decrease at rates of around 6.4-6.5 ºC/1000 m, which is less than the dry adiabatic lapse rate (DALR) of 10 ºC/1000 m (see Figure 19) indicating a relatively stable atmosphere. An inversion (an increase in temperature with height) present at 2000 m in the 0000 profile lifted to 2500 m at 1200 hours, as did a second inversion which was initially present at 5500 m at 0000 hours but increased in height to 6000 m in the 1200 profile. These changes represent an increase in the depth of the convective boundary layer associated with surface heating during the morning, which is also reflected in increased surface temperatures.

While the ambient temperature profiles for March 24 indicate stable atmospheric conditions for both 0000 and 1200 hours, with lapse rates less than the DALR, these rates are also above the saturated adiabatic lapse rate (SALR) of 4.5 ºC/1000 m. This means that the atmosphere could be described as "conditionally unstable" (i.e., the rate of temperature decrease with height is between the DALR and SALR) (Schroeder and Buck 1970). Under these conditions, stability is dependent on the moisture status of the air. If the air is unsaturated, it cools at the DALR as it rises, and is therefore stable and inhibits vertical motion. However, if the air is saturated, it cools more slowly at the SALR, resulting in a temperature which is warmer than the surrounding air; it is therefore more likely to be buoyant, enhancing vertical motion and instability. Based on the

[9] Upper air data for Invercargill Aero (station agent no. 5814) were obtained from NIWA's National Climate Database.
[10] P. Mallinson, MetService, *pers. comm.*

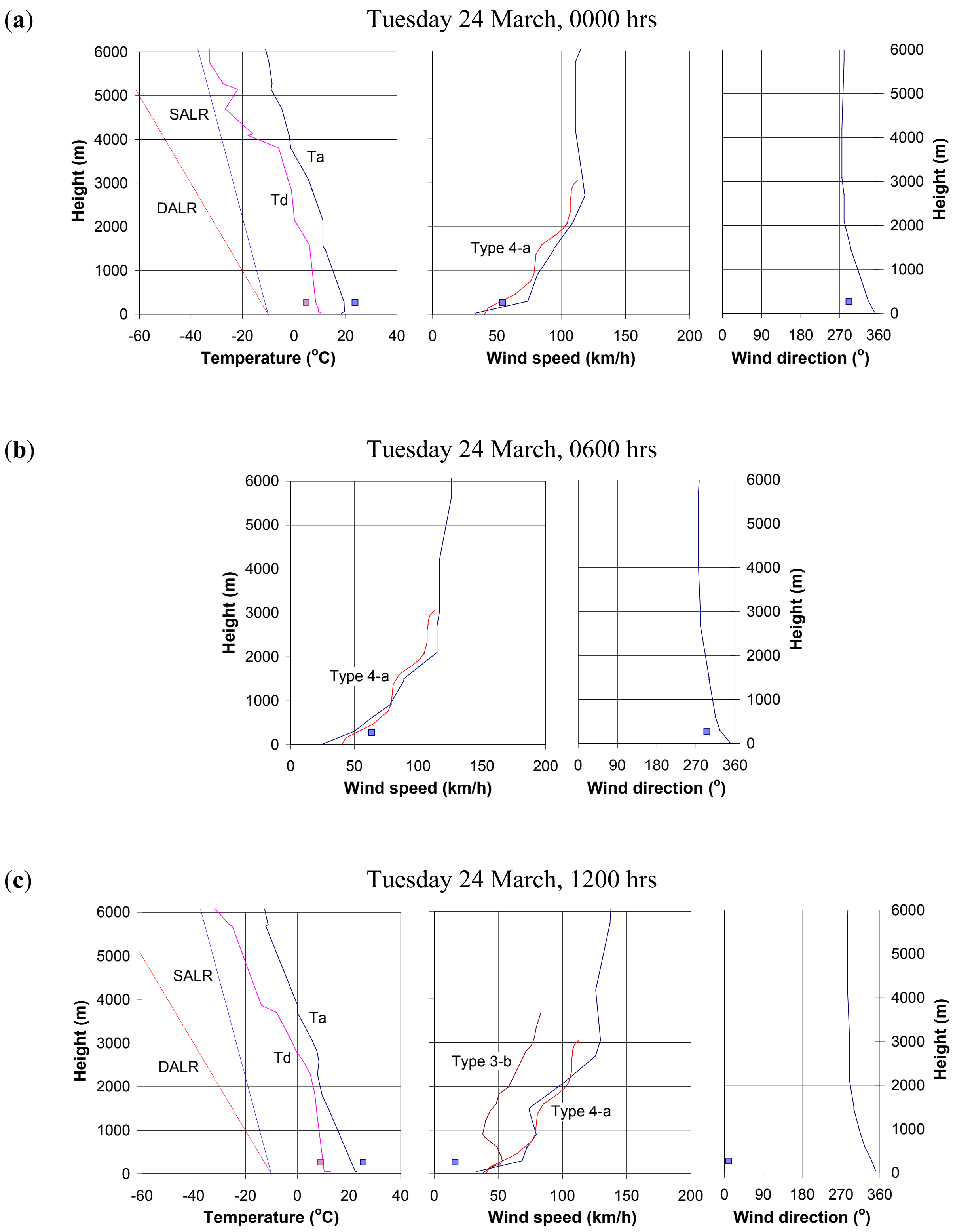

Figure 19. Upper air temperature (Ta), dew-point temperature (Td), and wind speed and direction profiles from Invercargill Aero during Tuesday, 24 March: **(a)** prior to the fire (0000 hrs); **(b)** around the time of the fire's ignition (0600 hrs); and **(c)** shortly after the burnover incident (1200 hrs). Surface observations recorded at the Rock & Pillar RAWS are included for comparison, as are the dry (DALR) and saturated (SALR) adiabatic lapse rates (and comparable Byram (1954) wind profile types[11]).

dew-point temperature profiles for the two observation times (see Figure 19), relative humidities calculated throughout the profile, although generally higher in the 1200 profile, rarely exceed 70% so that the atmosphere would be considered unsaturated. Thus, it is more likely to have been stable around the time of the Bucklands Crossing Fire blow-up and subsequent burnover, restricting mixing and vertical development.

While conditions were most likely stable at the time of the fire's blow-up, they would have become increasingly unstable throughout the afternoon of March 24 as a result of strong surface heating. This was apparent in the upper air observations recorded at 0000 hours on March 25, where the ambient temperature profile had a rate of temperature decrease much closer to the SALR, and humidities determined from the dew-point profile exceeded 95% throughout the surface layer to about 4500 m.

The wind profiles for Invercargill Aero on March 24 (see Figure 19) indicate that the strongest winds (~200 km/h) occurred at a height of around 12 000 m, although there is also some evidence of a wind speed maximum or "jet point" (~120 km/h) at 2500 m, decreasing to 2000 m at 0600 hours, and then lifting to 3000 m at noon. Like the temperature profiles, this lifting observed in the 1200 hour wind profile corresponds with an increase in the depth of the convective boundary layer due to surface heating during the day. Another maximum of about 80 km/h also developed closer to the ground surface in the 1200 hour profile, and this compares well with the reported wind speeds at both the Rock and Pillar RAWS and the fire site, particularly when the elevation of these is taken into account. The other key feature of all three wind profiles is the very consistent wind direction throughout March 24, with northerly or northwesterly winds near the surface, and west-northwest winds above.

[11] See pages 38-39 for discussion of the role of upper level winds in fire blow-up, and Byram's (1954) wind profile classification.

Fire Behaviour

Fire spread

At the time of initial attack (0803 hours), the Bucklands Crossing Fire was burning on several fronts in a stand of pine trees on a steep hillside above the north branch of the Waikouaiti River (Figure 20). The fire initially spread to the south and east, breaching Ramrock Road in several places. On the southern edge, it first jumped Ramrock Road at 0807 hours and spread through roadside rank grass into adjacent manuka scrub. To the southeast, another breach created an interesting burn pattern in grazed pasture (Figure 21) but was self-extinguishing in the light fuels and very strong winds. The fire spread more easily through heavier rank grass around young shelter plantings along a fenceline just to the south. A very narrow fire front also spread in a more easterly direction into a small woodlot, which was partially burned before being suppressed.

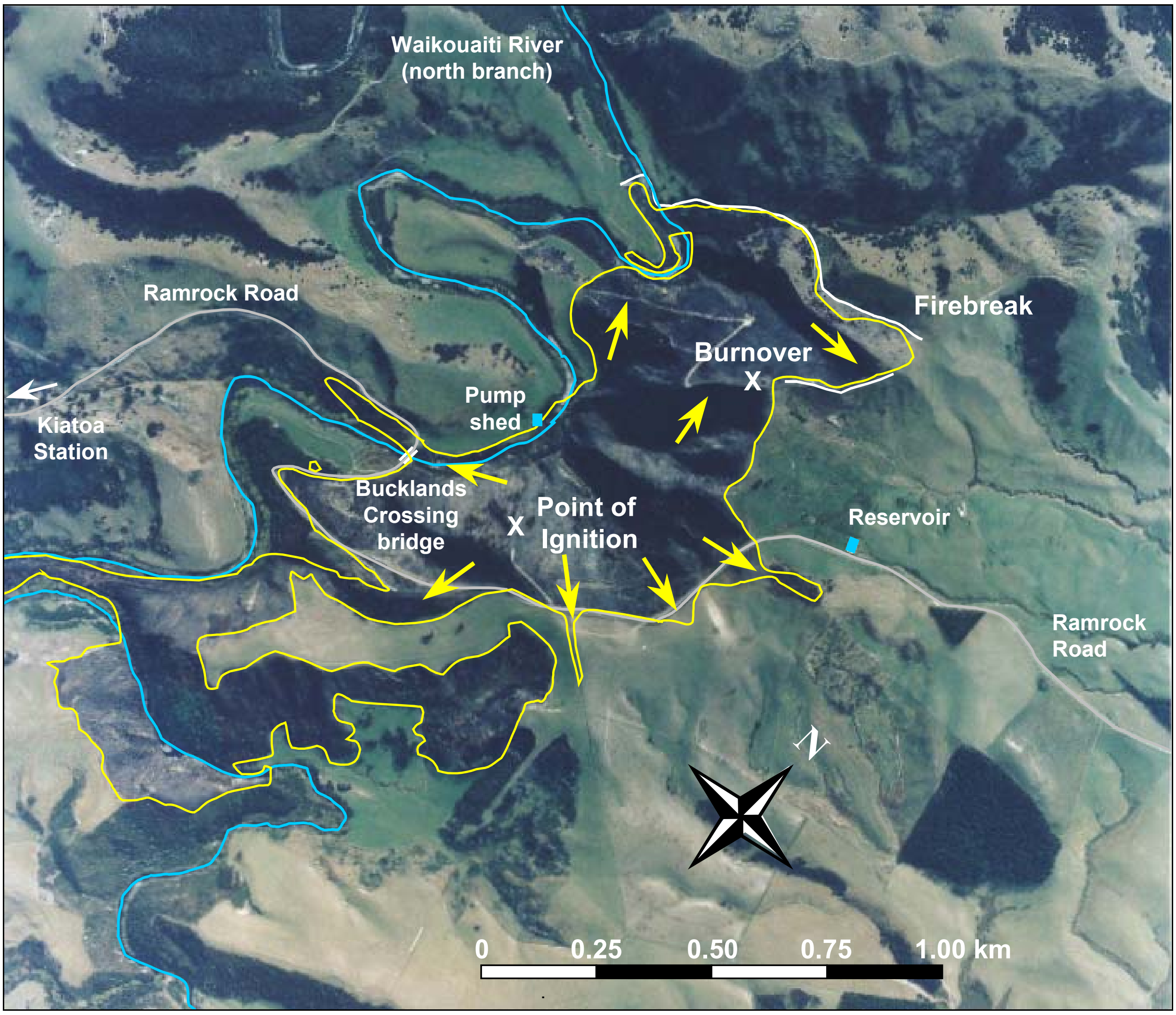

Figure 20. Map of fire spread for the Bucklands Crossing Fire.

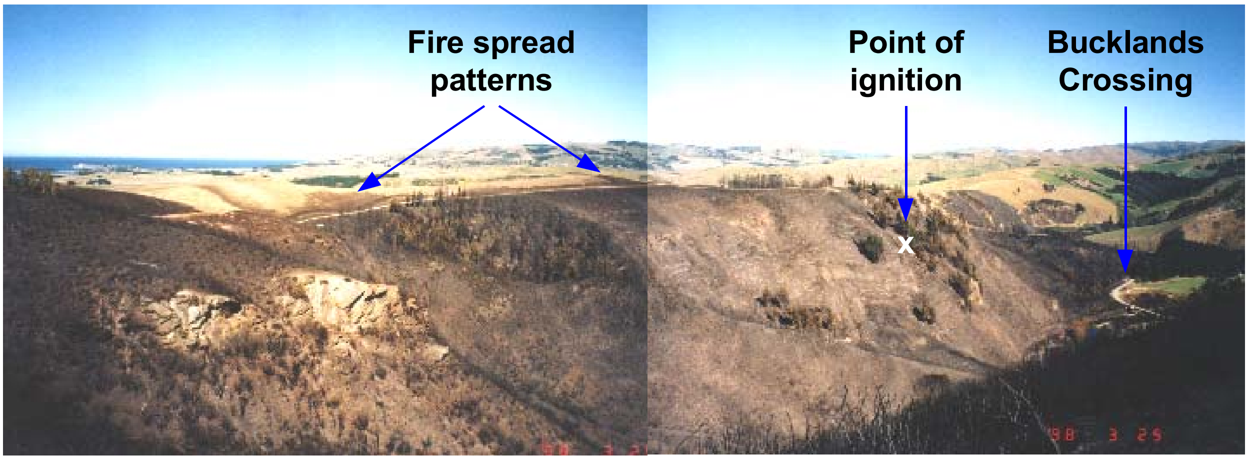

Figure 21. View from the ridge on which the burnover occurred looking south towards the point of ignition.

From the point of ignition, the fire also continued to backburn down the slope to the river and spread around the ridge to the southwest threatening another pine stand, and again breaching Ramrock Road between the initial breach and the Bucklands Crossing bridge. This flank burned to the south, spreading through dense scrub on the slopes alongside the river, eventually joining with another front above the river to the east which had been ignited by firebrands thrown from scrub along the roadside across the narrow, intervening grass-covered ridgetop. This flank to the south also breached the river, most likely via spotting, and made several rapid upslope runs on the southern bank which were quickly knocked down by helicopter bucket drops.

To the north of the ignition point, the fire continued to spread through the pine stand and into dense manuka scrub clothing the southern face of the first of a series of ridges that drop to the river. The fire also spread to the north along the eastern bank of the river, jumping the river in at least one location into willows and damaging a pump shed. On the western side, the fire spread slowly through the riverside willows and exotic weeds, eventually reaching a narrow strip of gorse scrub which threatened to provide a link to more continuous scrub fuels further to the north. However, this was quickly headed off by a bulldozer working on a firebreak ahead of the northern flank.

As a result of the complex terrain associated with the series of spurs leading from the plateau down to the river below, fire spread to the north of the fire's origin was via a succession of rapid uphill runs. These were interspersed with periods of slower spread as the fire backed down the opposite slopes into the intervening gullies. The fire reached its northernmost extent just beyond the last of these spurs, where fire spread was contained by a combination of fire environment factors including more mature manuka/kanuka fuels, presumably with more moist surface fuels associated with the denser canopy, and sheltering from the prevailing wind by the more dominant ridges leading off Mt. Watkin.

Alternating rapid upslope fire spread followed by slower downslope spread was also the case for the ridge on which the burnover incident occurred, which had been burned out well before the crew arrived. The dense stand of young manuka/kanuka on the southern face was almost completely burned out with little or no residual burning and only the standing stick material remained. Similarly, the grass fuels and scattered tussocks on the ridgetop itself were almost

Figure 22. View of the ridgetop on which the burnover occurred. The fire originally burned up the slope from the right, and was backburning down the slope to the left at the time the crew arrived and began deploying a hoseline. The utility is parked in the same position as the burned-over appliance, which was hit by a "fireball" travelling up the left-hand slope.

entirely consumed. The fire was observed to be about midway downslope, backburning slowly in the litter layer beneath the manuka/kanuka stand with flames about half a metre high. The wind was blowing smoke up the gully to the east roughly parallel to the ridgeline which, together with the tall scrub fuels and steep terrain, obscured views into the bottom of the gully. Fire activity was seen in the gully below, where flame heights would reach 1-2 m as the fire occasionally flared up in gorse fuels, but this was not observed to change during the 35-40 minute period the Crew Leader spent reconnoitering this sector of the fire.

As the crew were in the process of laying a hoseline downhill, the Crew Leader suddenly heard the noise of the fire approaching from below. Several of the crew report being knocked to the ground by a shock wave or by a "fireball exploding", and two crew members describe being blown over a second time after getting to their feet to run to the ridgetop (Figure 22).

Fire danger rating and fire behaviour prediction

Few observations of the location of the fire front or of other aspects of fire behaviour were made during the Bucklands Crossing Fire. This, combined with the complex nature of the fuels and topography, means that it is difficult to make meaningful comparisons with fire behaviour predicted using available models. However, some comparisons can be made with predicted rates of fire spread and intensity using the fuel models contained within the New Zealand Fire Danger Rating System (NZFDRS). In particular, the NZFDRS contains fire danger class criteria (FDCC) for Forest and Grassland (after Alexander 1994), and a newly developed Scrubland FDCC (Anon. 2000, Majorhazi 2000).

The distance from the point of ignition to the point where the fire first breached Ramrock Road was later measured at 500 m, and the fire was observed to cover this distance in around 14 minutes (at a rate of 2140 m/h). Similarly, when the Principal Rural Fire Officer arrived and took control of the fire, it had travelled some 800 m from the point of origin in 50 minutes (a rate of spread of 960 m/h) and had burned approximately 100 ha of land (see Figure 20). Apart from the final perimeter, these were the only observations made of the location of the fire front at specific times.

The Forest FDCC contained within the NZFDRS (see Figure 8) is derived from the Pine Plantation (C-6) fuel model in the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). It utilises the ISI and BUI components of the FWI System to determine rate of fire spread and amount of available fuel, and hence fire intensity and resulting fire danger class (Alexander 1994). This Forest FDCC has been successfully evaluated against general fire behaviour exhibited by several major New Zealand plantation wildfires by Pearce and Alexander (1994) and Fogarty *et al*. (1997). Based on the noon conditions (see Table 1), the models on which the Forest FDCC is based predict a rate of fire spread of 470 m/h and available fuel load of 10.5 t/ha, resulting in a likely head fire intensity (after Byram 1959a) of 2450 kW/m and the fire danger for Forest being classified as VERY HIGH; under these conditions, head fire attack would be very difficult and restricted to use of aircraft. In contrast, using the conditions prevailing at the time of ignition (Table 3) results in a head fire rate of spread of 1710 m/h and intensity of 8950 kW/m; i.e., an EXTREME fire danger class, where direct head fire attack would be extremely difficult, if not impossible. Neither of these predictions allow for any effect of slope, which would increase the predicted rates of spread and intensity. Taking this into consideration, the predictions made using the Forest models compare relatively well with fire behaviour observations made soon after the fire's ignition (see Table 3).

The Grassland FDCC also included within the NZFDRS is derived from the Natural/Standing Grass (O-1b) fuel model from the Canadian FBP System (Forestry Canada Fire Danger Group 1992), and utilises the ISI and degree of curing[12] to determine rate of fire spread. A grass fuel

Table 3. Comparison of observed and predicted rates of fire spread (ROS) for the Bucklands Crossing Fire based on fire behaviour models contained within the NZFDRS.

Fire run (time)	Fuel type	Observed ROS (m/h)	Adjusted[a] ISI	Predicted ROS (m/h)[b] Forest[c]	Grass[c]	Scrub
Ignition to Ramrock Rd (0753-0807)	Pine	**2140**	69.1	**1710**	2560	4910
Ignition to PRFO arrival (0753-0837)	Pine/ Grass	**960**	65.6[d]	**1700**	2500	4910
Burnover (1100)	Scrub		13.8	370	590	3190
1200 noon			13.0[e]	470	540	3050

[a] Hourly ISI values for fire behaviour prediction have been calculated using the modified wind function for the ISI as recommended in the Canadian FBP System (Forestry Canada Fire Danger Group 1992, p. 32), and therefore differ from those quoted elsewhere in the report.
[b] All predicted ROS values are for flat ground (i.e., 0° slope), whereas observed ROS values include slope effects.
[c] Predicted ROS for Forest were calculated using the daily BUI value of 51, while Grass ROS were calculated using a degree of curing of 60%.
[d] Based on average wind speed and FFMC values for 0800 and 0900 hours (see Table 2).
[e] Based on the standard daily ISI (see Table 1).

load of 3.5 t/ha is assumed in computing the resulting fire intensity and fire danger class (Alexander 1994). The Grassland FDCC and its underlying rate of spread model has been tested successfully against fire behaviour observed during several significant grassfires (Rasmussen and Fogarty 1997, Anderson 2003b, Pearce and Baxter *in prep.*). Grasses at the time of the Bucklands Crossing Fire were generally only about 50%-60% cured, and fire spread only occurred where there was sufficient rank or seeding grass to carry the fire under the influence of strong winds, such as along fencelines and roadsides. In most cases, fire spread into areas of grazed pasture was self-extinguishing. Using a degree of curing of 60% and the noon conditions, the model on which the Grassland FDCC is based predicts a head fire rate of spread of 540 m/h and intensity of 950 kW/m; this corresponds with a HIGH Grassland fire danger class where fire control, although difficult, could be readily achieved using heavy machinery and/or water under pressure. Based on conditions at the time of ignition, the predicted rate of spread and intensity in grass fuels are 2560 m/h and 4500 kW/m respectively; i.e., an EXTREME fire danger class, where control is extremely difficult if not impossible. These values are halved if a degree of curing of only 55% is used. The predictions again do not include a slope effect, which would increase predicted rate of fire spread and intensity further, so that the difference between these predicted values and observed fire behaviour (see Table 3) would be greater. In general, the Natural/Standing Grass model overpredicts the rate of spread and intensity, most likely as a result of overestimation of onsite wind speed (and ISI), variability in grass curing and lower fuel loads encountered in grazed pasture.

The newly-developed Scrubland FDCC is based on fire behaviour information collected from 32 experimental burns and 3 wildfires in manuka/kanuka and gorse scrub and heathland fuels[13]. It combines a model for rate of fire spread based on ISI with another model for available fuel load from scrub height to estimate frontal fire intensity and hence fire danger class. For the purposes of fire danger rating, a standard fuel load of 20 t/ha (roughly equivalent to 1.5 m tall scrub; see Fogarty and Pearce 2000) has been proposed, so that fire danger class can effectively be determined from FFMC and wind speed (see Figure 23). Using the noon conditions, the models underlying the Scrubland FDCC predict a head fire rate of spread of 3050 m/h and intensity of 30 500 kW/m, and results in an EXTREME Scrubland fire danger class for the day of the fire where suppression of the headfire would be impossible using conventional means. Using conditions that existed at the time of ignition, the predicted rate of spread on flat ground in scrub fuels is 4910 m/h and the head fire intensity 49 000 kW/m. Similarly, at the time the burnover occurred, a rate of spread of 3190 m/h and intensity of 32 000 kW/m are predicted using the Scrubland FDCC. However, if the fuel load was increased to reflect the height of the 3 m tall manuka stand from which the blow-up came (i.e., around 28 t/ha, after Fogarty and Pearce 2000), the predicted intensity is about 44 000 kW/m.

Once again, it should be stressed that these predictions are for flat terrain and do not include a slope effect. The burnover incident involved the fire running back up a 30º slope, so that the rate of spread would be expected to increase significantly, up to as much as 6 times based on the Slope Correction Factor used in the FBP System (Forestry Canada Fire Danger Group 1992). This would result in a slope-corrected rate of spread of almost 20 km/h (20 000 m/h), so that the Bucklands Crossing Fire blow-up would have taken less than a second to travel from the base of the slope to the appliance and crew above, a distance of approximately 200 m. However, limited

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[12] The *degree of curing* is "the proportion of cured and/or dead material in a grassland fuel complex expressed as a percentage of the total" (Alexander 1994).

[13] NZ Fire Research (2000). Scrubland fire danger rating. Unpublished paper prepared for the National Rural Fire Authority's (NRFA) Principal Rural Fire Officer (PRFO) Course, 17-21 July 2000, Upper Hutt. 3 p.

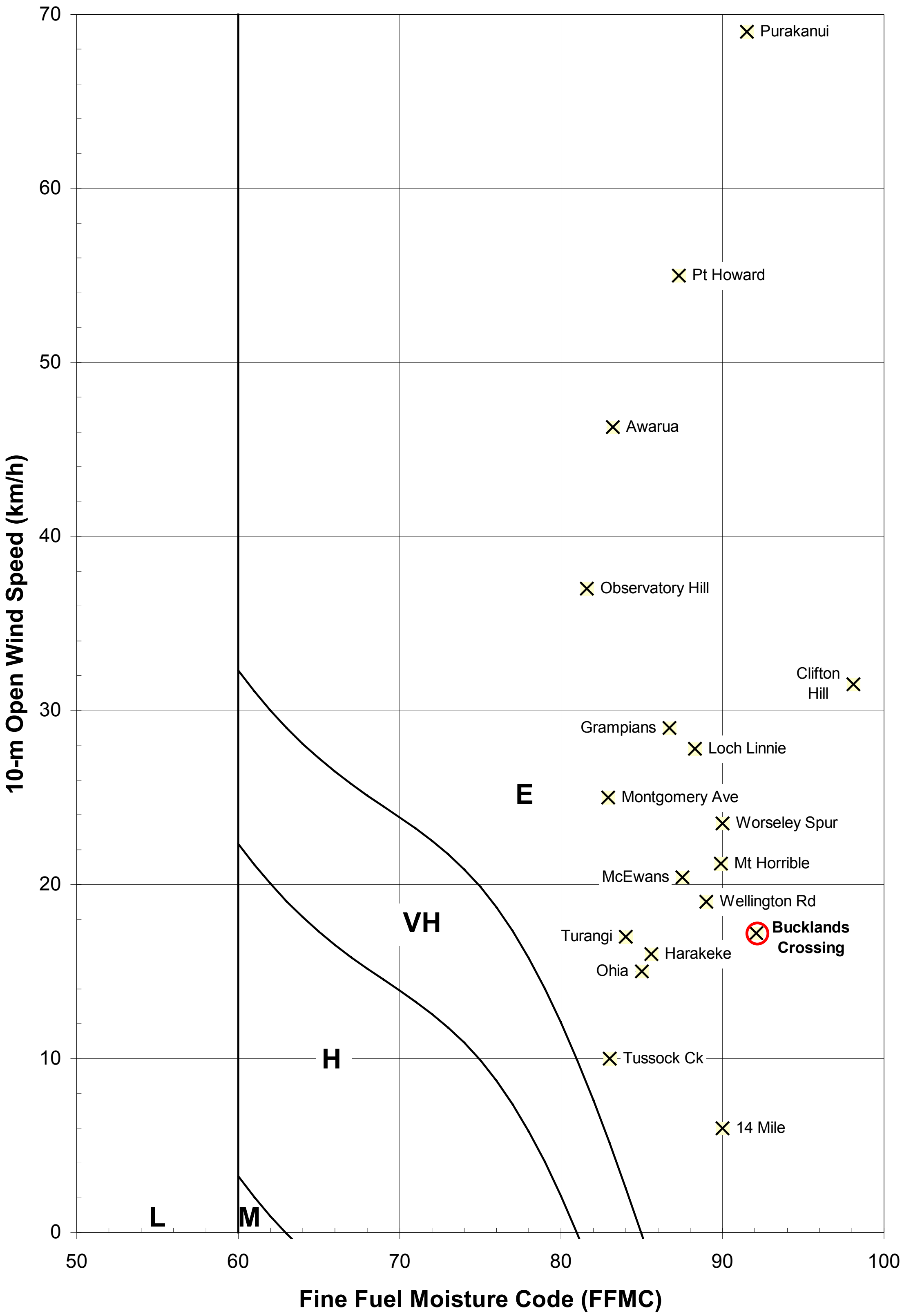

Figure 23. Fire danger conditions associated with the Bucklands Crossing Fire burnover (1100 hourly values) and other major scrub fires as documented by Fogarty *et al*. (1998), based on the Scrubland Fire Danger Class Criteria graph.

studies of the effect of slope in New Zealand scrub fuels[14] have hinted that the effect of slope may not be as dramatic in scrub fuels as in other vegetation types such as forests and grasslands (Van Wagner 1977, Cheney 1981). Even at the rate of spread predicted for scrub fuels on flat terrain, the fire would have taken less than 4 seconds to reach the ridgetop, so that the crew had little time to react to the blow-up once it was underway.

Fire blow-up mechanisms

The fire "blow up" and subsequent burnover as occurred during the Bucklands Crossing wildfire is a situation reminiscent of the 1994 South Canyon Fire[15] in Colorado, USA, where 14 firefighters were killed. Numerous reports and articles have been written on this South Canyon incident (e.g., Anon. 1994a, 1994b, 1995, Butler *et al*. 1998, 2001, Campbell and Campbell 1994, Gleason 1994, Putnam 1995a, 1995b). As well as the obvious burnover incident itself, where firefighters were overrun by a fire from below and thrown to the ground, there are many other similarities including steep slope, desiccated scrub fuels and high air temperatures. However, the South Canyon Fire was larger in scale than the Bucklands Crossing Fire, and also involved numerous fatalities whereas thankfully the Bucklands Crossing Fire did not. In many respects, the Bucklands Crossing Fire burnover is also similar to another incident that occurred during the 1993 Anerley Fire in Sakatchewan, Canada (Alexander 1998, Alexander 2002). This involved three firefighters charging a hoseline from a fire appliance parked above a seemingly innocuous grassfire. Two firefighters sought the shelter of the vehicle, while a third was severely burned and later died, when the fire rapidly spread up the short slope and overran them. An overview and review of contributing factors for both the South Canyon and Anerley fire burnovers are included as part of the *Wildland Fire – Safety on the Fireline* CD-ROM training package (ETC and CIFFC 2000).

Such a fire "blow-up" as described by the crew burned over during the Bucklands Crossing Fire is analogous with a ***flashover***, where the explosion results from the ignition of trapped, unburned gases which are given off by fuels as they are preheated. Flashovers usually occur in poorly ventilated areas and, as such, are normally associated with structural or urban fires. Although rare, the flashover phenomenon can occur in vegetation fires when gases are trapped in topographic pockets or accumulate over a broad area when there is a temporary lull in air movement (Chandler *et al*. 1983, Merrill and Alexander 1987). Although disputed, such a fuel-air explosion has been suggested as the possible cause of the blow-up responsible for many of the 14 deaths on the South Canyon Fire (Putnam 1995a), where it appears victims may have been overtaken by a blast of superheated air which exploded just before the fire front arrived. Putnam (1995a) notes that hot gases containing unburned, vaporised fuels sometimes move uphill ahead of a flame front. This gas movement would not be highly visible and would be detected more as a noise from below or as an odour. This concurs with observations made by the Crew Leader at the Bucklands Crossing Fire who described hearing an explosion then the roar of the fire just moments before being struck by the heat. Such an effect would be required to knock firefighters to the ground as occurred at South Canyon and during this Bucklands Crossing Fire.

[14] NZ Fire Research (1998). *Fire Research Update*. Newsletter of the Forest and Rural Fire Research Programme, New Zealand Forest Research Institute, Rotorua. May 1998: 5-6.

[15] Also known as Storm King Mountain.

Figure 24. View to the northwest from the ridgetop on which the burnover occurred, illustrating the steepness of the slope in the direction from which the flame front came.

Flashovers tend to blow out in a horizontal direction, following the direction of air movement and terrain. However, the resulting flames generally only travel short distances and are short-lived, ending when either the gas is consumed or dissipated. Thus, flashovers in rural fire situations are extremely rare, as wind in particular tends to dissipate gases preventing their accumulation. Butler *et al*. (1998) dispute the fuel-air explosion theory proposed for the South Canyon Fire by Putnam (1995a) on this basis, concluding that the strong winds and turbulence, general instability, and topography would have prevented combustible gases accumulating in sufficient concentrations to support an explosion, and the same reasoning could also be applied to the Bucklands Crossing blow-up.

Fireballs, which are again more typically associated with structural or industrial firefighting, are the explosion of burning gases contained within a ball of swirling air. The explosion blows out in all directions creating a ball effect. The resulting flames are largely contained within the ball, and therefore travel only short distances. They tend to rise vertically very quickly and are also short-lived, finishing when all the gas is consumed (Cheney and Sullivan 1997). Despite this, several international examples of the fireball phenomena from vegetation fires have been reported[16]. Fireballs in vegetation fires are typically separate envelopes of burning gases which detach from surface flames. They often have a rolling appearance associated with the movement of air produced by convection. The gas is produced by combustion of surface fuels and, once detached, these envelopes burn up rapidly and usually do not roll significant distances ahead of the flame front (Cheney and Sullivan 1997). Cheney and Sullivan (1997) further note that the fireball impression can be accentuated through poor visibility, when smoke and darkness (even

[16] For example, the 2001 Fridley Fire near Livingston, Montana, USA (see http://www.montanafires.com/gallery/820fireball_large.php).

during daytime), can reflect the light from flames and produce red rolling billows of smoke giving the impression of balls of flame high up in the convection column.

The "fireball" described by the crew involved in the Bucklands Crossing burnover appears to have originated from a patch of heavier gorse fuels in the gully some 200 m (slope distance) below the crew (see Figure 24), with the unburnt gases contained within it "exploding" when it neared the ridgetop. Due to the distance, it is therefore unlikely that the burnover resulted from a fireball as previously described. However, fireballs were observed by pilots at other stages of the Bucklands Crossing Fire, and similar gas explosions have been reported during other New Zealand fires in steep terrain[17].

Although the firefighters involved in the Bucklands Crossing Fire burnover believe this was not the case, the observed "fireball" may also have been the result of direct flame contact, ***flame extension*** or "rollover" associated with an uphill run and re-burn through the preheated scrub canopy. The effects of wind and slope driving the flame front uphill combined with the collapse of the fire front as it reached the end of the scrub stand would produce increased flame lengths and tend to push flames along the ground.

In itself, slope steepness has a decided effect on fire behaviour – in particular, rate of fire spread and intensity, but also flame length. In fires spreading upslope (as opposed to downslope), flames lean uphill toward the slope surface, even in the absence of wind (Van Wagner 1977a). This reduces the distance between the flame and fuels ahead of the flame front, resulting in more efficient preheating of fuels through radiation and also convection. The steeper the slope, the more preheating occurs through both radiation and convection, and the greater the rate of fire spread and fire intensity, and subsequently, flame length. The combined effect of wind and slope is to further reduce the flame angle, flattening and lengthening the flames so that they "attach themselves" to the slope (Albini 1976, Rothermel 1985) (Figure 25). Once slope exceeds 15-20º (27-36%), the flame front is "virtually a sheet of flame moving upslope, and the flame propagation process is almost one of direct flame contact" (Luke and McArthur 1978). Above 30-35º (60-70%), flames tend to bathe the slope directly, fire behaviour becomes very intense

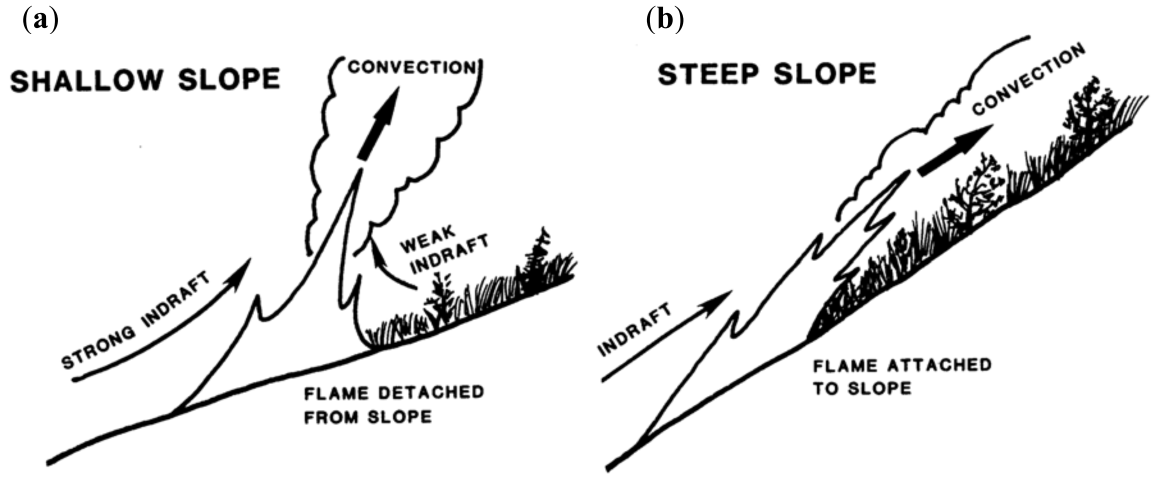

Figure 25. Effect of slope steepness on degree of flame attachment for:
(**a**) shallow slopes, and (**b**) steep slopes (after Rothermel 1985).

[17] For example, the 1996 Bergin's Point Fire in Northland (A. Gamble, Thames Valley Rural Fire District, *pers. comm.*).

and unstable, and exceptionally high rates of spread can occur (Van Wagner 1977a). Cheney and Sullivan (1997) also note that a fire starting at the bottom of a slope can create a strong driving in-draft wind that increases the fire's rate of spread and intensity. Under very strong winds, the convection column will not lift away from the surface of a steep slope. Flames are therefore blown directly into unburnt fuels resulting in a very high rate of fire spread (Cheney and Sullivan 1997). In the absence of fuels, the flames and associated convective gases will be blown upslope ahead of the fire, and may extend a considerable distance.

Flames are also subject to normal variations in size associated with "flame flashes" that detach themselves from the main flame front. Flames are the result of flammable gases emitted from the fuel bed by pre-heating combining with oxygen in the surrounding air. The convective forces of the bouyant combustion gases and the wind establish a dynamic balance that results in flames of an average length (Cheney and Sullivan 1997). However, fluctuations in wind velocity, turbulent mixing and fuel variation cause wide fluctuations around this mean length. Billows of burning gas may also become detached from the flames and burn as they are carried aloft. The result is pulses or surges in flame height and length (i.e., flame extension) that occur quite naturally as part of the combustion process. These brief flashes of flame can extend considerably higher than normal flame lengths. In high intensity grassfires, flames are typically less than 5 m high but may occasionally reach 10 m or more for short periods. Flames in forest fires can be two to three times the height of the tree canopy, but have been reported as high as 200-300 m (Sutton 1984, Cheney and Sullivan 1997). In comparison, flame lengths in scrub fuels are usually in the range of 5-10 m, but may occasionally reach 15-20 m or more in very high intensity fires (Catchpole *et al*. 1998) (Figure 26). These towering flames are short-lived, and result from the concentration of unburnt gases caused by very high rates of combustion (Cheney and Sullivan 1997).

Figure 26. Examples of flame length variation in New Zealand manuka/kanuka and gorse scrub fuels, illustrating the leaning flame front, flame detachment or "flashes", and flame front collapse typically encountered in these vegetation types.

Flame extension can also occur as a result of the collapse of flames as they run out of fuel. This may be associated with a change in fuel type (e.g., Fig. 3 in Van Wagner 1977b) or a fire reaching a firebreak (e.g., Fig. 8.6 in Cheney and Sullivan 1997). The reduction in the amount of convection supporting the flames and increased winds behaind the flame front cause the flames to lean over almost parallel to the ground, and to increased amounts of radiative and convective heat being transferred ahead of the collapsing flame front. Fogarty (1996) describes flame extension or "roll over" associated with flame front collapse in New Zealand scrub fuels similar to those involved in the Bucklands Crossing Fire, with flame lengths in the order of 10-20 m and as high as 30-40 m for high intensity fires (see Figure 26). Both Fogarty (1996) and Cheney and Sullivan (1997) highlight the dangers to firefighters working on breaks or in open areas ahead of the fire as a result of this phenomenon. Together with the pulsing of the flame front as volatile gases are burned, this flame front collapse would create an effect similar to that of a fireball or flashover observed by the firefighters burned over during the Bucklands Crossing Fire, and is certainly capable of producing the extreme flame lengths required to reach 30-50 m from the standing scrub to the ridge where the fire appliance was parked (see Figures 22, 24 and 28).

Such an upslope fire run, through a mix of unburned and previously underburnt vegetation, has been suggested as the likely cause of the South Canyon Fire blow-up (Butler *et al*. 1998). They presented two possible mechanisms for upslope spread, as either a line of fire or, as they concluded was most likely, as a U-shaped fire front. In the case of general upslope spread, the blast of hot air reported could have been associated with the expansion of air in front of the fire as it quickly spread upslope. For a U-shaped fire front, the shape results from faster spread on the fire's flanks associated with slope and/or fuel type differences. Such a fire front is inherently unstable (Butler *et al*. 1998), as the unburned area within the concave front receives heat from three sides rather than one, increasing the amount of energy transferred to the vegetation and causing more rapid preheating, ignition and fire spread. On steep slopes, convective heating also contributes to fire spread. The movement of air in front of the fire as it ignites a large area and accelerates upslope could therefore provide the source of the blast of hot air felt at both the South Canyon and Bucklands Crossing fires, which was of sufficient force to knock firefighters to the ground. In the case of the Bucklands Crossing Fire, it is possible the fire backburned all the way down the slope or around the base of the hill prior to the firefighters deploying on the ridge. Although less likely due to the prevailing wind direction being upslope, it may even have spotted into the gully bottom. Whatever the mechanism, the fire possibly built up over a period of time before running upslope through the tops of the previously underburnt manuka/kanuka scrub under the influence of both slope and the prevailing wind.

While an upslope fire run involving flame extension is the most likely of the mechanisms described to have caused the Bucklands Crossing Fire burnover, there are also several other possible explanations. These include the collapse of a fire whirl and the possibility of a carbon dust explosion.

A ***fire whirl*** is "a spinning, moving column of hot air and gases rising up from a fire and carrying aloft smoke, debris, flame, and firebrands" (Merrill and Alexander 1987). Fire whirls can range in size from less than one metre to several hundred metres in diameter. They result in greatly increased rates of burning and flame heights, and may involve the entire fire area or only hotspots within or outside the fire perimeter (Countryman 1964). Fire whirls increase in frequency and size as fire activity increases; however, the largest fire whirls often develop after the fuel has practically all been consumed. The conditions most conducive to fire whirl development are

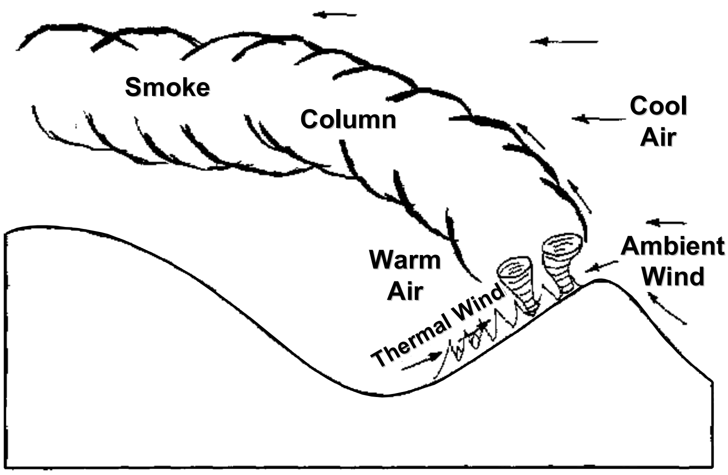

Figure 27. Diagrammatic depiction of the formation of fire whirls on lee slopes (after Countryman 1964).

unstable air, a large heat source, circular motion in the ambient air, and flat to rolling topography (Countryman 1964, 1971).

A favoured location for fire whirl development is on the lee side of a ridge (Figure 27), where an airflow eddy is created by the topography (Countryman 1964) and/or the lower pressure caused by the airflow across the ridge (Graham 1957). The air within the gully is also heated by the fire, creating upslope thermal winds; these warmer winds meet the cooler downslope ambient wind, creating an unstable condition on the upper part of the slope. This instability enhances upward movement of air which is already rotating as a result of the eddying, and a less intense heat source is required to start a fire whirl in this area.

In the case of the Bucklands Crossing Fire burnover, a fire whirl could therefore have developed on the face opposite or in the gully below the fire crew and, as a result of either a drop in fire activity or a change in wind conditions, collapsed or been pushed over the crew as they were deploying. A surfacing smoke column, similar to a collapsing fire whirl, was also proposed as a possible cause of the South Canyon Fire blow-up by Butler *et al.* (1998). It is possible that a turbulent gust associated with the strong prevailing winds pushed the column of smoke and burning gases from the fire against the slope around the firefighters as they were escaping above it. Embers and hot air would have enhanced preheating, as well as impaired the breathing and vision of firefighters leading to their incapacitation.

A ***carbon dust explosion*** is a chain reaction explosion where combustion is sustained by the burning of small particles of carbon left on vegetation and the ground after an initial burn[18]. Such explosions are normally associated with confined spaces but are longer lived than other explosions, depending on the amount of carbon dust present. The combustion of the suspended dust provides a mechanism whereby a fire can travel considerable distances across a previously burned area, although it would tend to hug the ground where carbon particles are concentrated. A carbon dust explosion would result in a blast strong enough to knock people over and, if the carbon dust were to be dislodged into the air by air movement, could also explain the longer than expected flame propagation observed during the Bucklands Crossing burnover.

[18] G. Wallace, Wainuiomata Bushfire Force and Institute of Geological and Nuclear Sciences, *pers. comm.*

Effect of atmospheric stability and upper level winds

As noted previously, atmospheric stability can be an important factor in determining fire behaviour, with unstable conditions in particular often contributing to problem fire behaviour. Upper atmospheric conditions indicate that a stable or conditionally unstable state existed at the time of the Bucklands Crossing Fire and associated burnover. These conditions would tend to support a “flare-up” and reburn as the most likely mechanism of blow-up. Firewhirls are usually more likely in unstable conditions, while the naturally strong, gusty nor’west winds prevailing at the time of the “blow-up” would inhibit the build-up of volatile gases or carbon particles required to sustain a flashover, fireball or carbon dust explosion. Under stable conditions, wind flow tends to follow the terrain (*cf.* unstable conditions where it continues to rise), and this would also aid in keeping flames low and blowing flames upslope along the ground.

In a study of atmospheric conditions related to blow-up fires, Byram (1954) found that wind speed profiles above significant fires could be classified into 4 major groups, based on whether they exhibited a decrease in wind speed with height (Type 1), included specific wind speed maximum at a height above the surface (Types 2 and 3), or followed the more typical increase in wind speed with height (Type 4). Profiles exhibiting a decrease in wind speed with height are considered the most dangerous, as the lower wind speeds aloft allow a fire to develop a convection column which can suddenly lead to erratic and unpredictable fire behaviour.

In the case of the profiles existing at the time of the Bucklands Crossing Fire, the 0000 and 0600 hour profiles observed prior to the fire’s ignition very closely resemble Byram’s (1954) Type 4-a (see Figure 19). Type 4-a is the most common of the profiles, reflecting the decrease in wind speed close to the surface associated with friction effects, although wind speeds throughout the profile are usually considerably less than either those observed at Invercargill or illustrated in Byram’s (1954) example which corresponds to a particularly bad fire day in 1950 in South Carolina. While generally intense and fast spreading, wind-driven fires exhibiting the Type 4-a profile are not considered dangerous to experienced crews because the spread direction is predictable and the rapid increase of wind speed with height prevents an active convection column from forming (Byram 1954).

The 1200 hour profile could also be classified as Type 4-a, but it also resembles Byram’s (1954) Type 3 profiles. These consist of a wind speed maximum near the surface and stronger winds at high levels, with a marked decrease in wind speed for several hundred metres above the jet point. In contrast to the wind-driven Type 4 profiles, profiles of Type 3 clearly show the “battling” between the power of the wind and the power of the fire (Byram 1959b). Wind speeds at the jet point close to the surface (>45 km/h at about 300 m in the case of Type 3-b), favour wind-driven fire spread and restrict formation of a convection column. However, the decrease in wind speed with height above the jet point increases the tendency for a column to form. So while the 1200 hour profile for Invercargill could be described as a Type 3-b, wind speeds throughout the profile are generally stronger and the jet point is higher above the surface (i.e., 80 km/h at the jet point at a height of 900 m) than in Byram’s models (see Figure 19). In addition, the decrease in wind speed above the jet point is not as marked.

The Bucklands Crossing Fire would therefore be described as a wind-driven fire where the “power of the wind” was much greater than the “power of the fire” (Byram 1959b, Nelson 1993). In fact, in many regards, it would be more accurate to describe the “blow-up” as a situation where the “power of the slope” was greater than the “power of the wind” (Campbell

1991), although the effects of wind and slope were likely to have been cumulative as opposed to "battling" as described by Byram (1954). Atmospheric conditions at the fire site were stable around the time of the fire's ignition, but would have become increasingly unstable as surface heating and lifting began to occur during the day. Despite this, atmospheric stability was unlikely to have been a major factor contributing to the fire's blow-up and subsequent burnover.

Transition from surface to crown fire

If a reburn involving an upslope fire run through the preheated scrub canopy is accepted as the most likely cause of the Bucklands Crossing Fire blow-up, the transition from a low-intensity, backburning fire in surface fuels to a high-intensity crown fire run is a critical phase that warrants further investigation. Butler *et al*. (1998) state that, in general, the spread of fire into the vegetation canopy follows an increase in the amount of energy entering the canopy, or a decrease in the amount necessary to ignite the aerial fuels, or both.

While fire spread from the surface into the vegetation canopy often occurs rapidly, the factors leading up to the transition may develop relatively slowly (Butler *et al*. 1998). For example, fires often burn downslope slowly, but when a backing fire reaches a position where an upslope run is possible, the transition from backing to a fast-moving upslope fire may happen suddenly. Cheney *et al*. (2001), in describing their "Dead-man Zone" concept, report that an aspect reversal associated with fire crossing a valley bottom, and transition from down-slope to up-slope fire spread, can lead to a 40-50 times increase in rate of fire spread (and intensity) (e.g., 1983 Grays Point Fire, after Cheney *et al*. 2001). A change in wind speed and/or wind direction is another means by which a transition can occur. Cheney *et al*. (2001) note that a 20-40º change in wind direction is sufficient to change a flank fire into a head fire (e.g., 1983 Grays Point Fire, after Cheney *et al*. 2001). A fire may also burn from an area where it is sheltered from the wind into a location where it is more exposed to the wind, with an increase of as little as 5 km/h producing a dramatic increase in fire behaviour. At low wind speeds, fires in scrub fuels can be particularly responsive, with Fogarty (1996) reporting a 30 times increase in rate of spread (and intensity) for scrub fuels for an increase in wind speed from 0 to 10 km/h, compared with a three times increase for forest fuels. Whatever the mechanism, increased wind exposure can lead to a sudden change in fire behaviour with little or no apparent change in the environment. In all of the above cases, the fire burns from one area to another where an abrupt change in slope and/or wind exposure results in an increase in fire intensity, and more energy to aid fire spread into the canopy.

Changes in fuel characteristics can also aid fire spread into the canopy, by both increasing the amount of energy available and decreasing the amount needed to ignite crown fuels. Lower fuel moisture contents reduce the amount of energy needed for ignition, and elevated dead fine fuels play a major role; however, live fuel moisture can also be important (Butler *et al*. 1998). Lower fuel moistures can result from increased exposure to solar heating or to the drying effect of wind through aspect or slope position, or from a change in weather conditions such as a drop in relative humidity. The transition from surface to crown fuels can also occur as a result of changes in the structural characteristics of fuels. Ladder fuels provide vertical continuity between surface fuels and crown fuels, reducing the distance between burning and unburned fuels so that a fire with the same intensity can spread more readily into the canopy. Alternatively, an increase in fuel load, especially the amount of fine, elevated dead fuels, increases the fire intensity so that more energy is available to aid spread into the crowns.

The transition of the Bucklands Crossing Fire from a backburning flank to an uphill fire run could therefore have been brought about by the fire in the gully bottom reaching the base of the slope, and the resulting increase in rate of spread and intensity associated with upslope spread enabling it to jump into the canopy. Spread into the crowns could also have occurred through the low-intensity backing fire burning into an area where it was exposed to a subtle change in wind direction, wind speed, or both, that provided the impetus to push the fire into the canopy and run upslope. Alternatively, the transition could have been due to a change in fuel characteristics or even vegetation type. The spread of the fire from beneath a dense manuka/kanuka stand with full canopy closure into older, more open gorse vegetation exposed to the drying effects of sun and wind could have meant that it encountered lower fuel moisture contents. However, manuka/kanuka vegetation is considered sclerophyllous[19] and the moisture contents of live foliage are lower (e.g., 100-120%) than found in many other species (e.g., 200-300% in gorse) (NZ Forest and Rural Fire Research, unpublished data). In addition, the manuka/kanuka foliage was likely to have been preheated by the fire backburning downslope beneath and this, in combination with the effect of slope, would have readily enabled fire spread into the canopy. The increased vertical fuel continuity associated with a change in vegetation type from discontinuous manuka/kanuka with well-separated litter and crown fuel layers to more continuous gorse scrub with increased dead or ladder fuels could also have aided spread into the crowns. Gorse, especially "old-man" gorse, is also likely to have had higher fuel loads, which would have increased the fire intensity and the amount of energy available to aid spread from the surface fuels into the canopy. Whatever the mechanism for the transition, once the canopy was ignited the increase in energy release rates would have contributed to continued crowning (Butler *et al.* 1998) and, in the case of the Bucklands Crossing blow-up, sustained fire spread would also have been aided by the steep slope and preheated canopy.

Alignment of factors

While there were no obvious individual indicators that alerted crew members to an imminent change in fire behaviour, it is possible that the combined influences of a number of fire environment factors may have contributed to the Bucklands Crossing fire blow-up. The concept of "alignment of factors" within the fire environment that combine to produce an escalation in fire activity has been formalised within the Campbell Prediction System (CPS) (after Campbell 1991[20]).

Through the fire environment factors of weather, topography and fuel, the CPS identifies the primary causative forces present which influence the variations in rate of spread and intensity of a wildland fire. In particular, the CPS emphasises the effects of wind, slope, and fuel temperature variations. As the fire burns over the topography, the forces controlling fire behaviour change independently. Each force can aid or retard fire spread, and can work together or cancel each other's effects out. Observations of how these forces vary in the path of the fire are the first step in predicting changes in the fire behavior potential (Campbell 1991).

Alignment of factors may involve simple combination of the effects of a few elements, such as wind direction and slope. This combination has been found to have a dramatic impact on fire

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[19] The term *sclerophyll* refers to hard-leaved plants, resistant to drought through having thickened cell walls and reduced intercellular spaces (Kenneth 1972).

[20] Also see www.dougsfire.com

behaviour, and rate of spread in particular (e.g., 1998 Johnstones Creek Fire, after Cheney *et al.* 2001). In the case of the Bucklands Crossing Fire blow-up, the combined influences of wind direction, slope and aspect (via solar radiation and time of day), potentially also with a change in atmospheric stability (from stable to unstable conditions with surface heating), may have resulted in a more complex alignment of a greater number of fire environment factors. In addition, the changes in many of these factors may have been subtle, taking place over a period of time, so that they went unnoticed. Unless being measured frequently, minor increases in temperature (1-2 ºC) and associated decreases in relative humidity (5-10%), possibly also with slight increases in wind speed (3-5 km/h) and/or change in wind direction (15-30 degrees), can combine to produce a dramatic escalation in fire behaviour sufficient to more than double the rate of fire spread and intensity. The effect of a change in spread direction on slope (i.e., from downslope to upslope spread) or aspect (i.e., from a fire backing slowly downslope to one running up the opposite slope) can be even more dramatic, where it can result in up to a 40 times increase in fire intensity for slopes up to 25-30º (Cheney *et al.* 2001).

Common denominators

Despite the lack of obvious indicators to alert the firefighters to the potential for extreme fire behaviour during the Bucklands Crossing Fire blow-up, this incident like so many others, including the South Canyon Fire, can be summed up by four[21] of the Common Denominators that have been found to contribute to fire behaviour on fatal and "near-hit" fires (Wilson 1977, NWCG 1996, Millman 1993, 2000):

- most incidents occur on small fires or on isolated sectors of larger fires;
- flare-ups generally occur in light, flashy fuels;
- most fires are innocent in appearance before unexpected changes in wind speed and/or direction result in flare-ups. Sometimes, incidents occur in the mop-up stage;
- fires respond to topography, running rapidly uphill on steep slopes.

The Bucklands Crossing Fire burnover occurred on a sector of the fire which was deemed to be relatively quiet, where fire behaviour had remained unchanged for a considerable period of time prior to the blow-up. The fire was burning in gorse and manuka/kanuka scrub fuels which, with large amounts of fine, elevated dead fuels, respond extremely rapidly to relatively small changes in wind speed such as might be caused by a slight change in wind direction as a result of upslope channeling. As well as this possible indirect effect on wind direction (and speed), topography[22] also had a direct effect on the fire, causing it to run very rapidly up the steep slope immediately below where the crew were working (Figure 28). Firefighters should therefore be aware that where any of these common denominators are present (either individually or in combination), there is the potential for a problem to occur.

[21] A fifth Common Denominator has been identified since Wilson's (1977) original study: "Helicopters or air tankers can adversely affect fire behaviour in certain situations. The blasts of air from low-flying aircraft have been known to cause flare-ups" (NWCG 1996). However, this was not a factor in the Bucklands Crossing Fire blow-up.

[22] The topography in the burnover area also had a secondary impact, with several of the firefighters describing being struck by another blast of heat and flame once they had crossed the ridge crest and started down the lee side. Two of the firefighters received burns to their hands and forearms from this second blast. This was most likely due to lee slope eddying resulting from turbulence as the flame burst over the steep ridge crest and curled back on itself (see Figure 30).

Figure 28. View looking up the ridge in the direction from which the blow-up came, depicting both the steepness of the slope and distance between the vegetation and the site where the fire appliance was parked (as indicated by the utility).

Similarities between the Bucklands Crossing and South Canyon fires extend beyond the possible cause of the blow-ups to the broader impact of the fire environment on fire behaviour. During earlier stages of the South Canyon Fire, general fire activity also consisted of low intensity downslope spread interspersed with intermittent flare-ups and short duration upslope runs in the fire's interior. The report on fire behaviour associated with the South Canyon Fire (Butler *et al*. 1998) identified a number of points which build on the Common Denominators, and can also all be applied just as readily to the Bucklands Crossing Fire. These include:

- *the longer a fire burns and the larger it gets, the greater the likelihood of high-intensity fire behaviour at some location around the perimeter* – a fire is not always ignited in a location for high-intensity burning; however, given sufficient time, a low-intensity fire will often reach a position where fuel, weather and topography combine to produce high-intensity fire behaviour.

- *the transition from a slow-spreading, low-intensity fire to a fast-moving, high-intensity fire often occurs rapidly* – transitions often occur as a result of significant changes in weather, topography or fuel conditions; however, they can also occur as a result of subtle changes that take place over longer time periods so that they go unnoticed.

- *topography can dramatically influence local wind patterns* – surface winds in complex terrain are highly variable, and areas of light winds or even calm conditions can exist while other areas experience dramatically different wind direction, wind speed, or both. These conditions can change without visible warning, for example, as a result of very subtle differences in wind direction. The change from westerly to a more nor'westerly wind direction during the Bucklands Crossing Fire could have caused up-gully winds to become cross-gully and up-side slope winds. A change in wind direction could also have reduced any sheltering effect of Mt Watkin, the major topographical feature upwind of the fire area, exposing the ridge on which the crew were deploying to the true prevailing wind strength.

- *current and past fire behaviour often does not indicate the potential fire behaviour that could occur* – estimates of potential fire behaviour should be based on actual (present and future) fuel, weather and topographic conditions, and compared to maximum possible spread rates and fire intensity. At no time during earlier stages of the Bucklands Crossing Fire, including during the size-up undertaken by the Crew Leader, did it exhibit periods of fire behaviour similar to that which occurred during the blow-up.

- *vegetation and topography can reduce a firefighter's ability to see a fire or other influencing factors* – complex topography and tall or dense vegetation can restrict the ability of firefighters to sense, visually or otherwise, changes in wind, fire behaviour and fire location. In this instance, it would have been very difficult for the crew to see into the bottom of the gully where fire activity was occurring.

- *smoke can significantly reduce the firefighter's abilities to sense changes in fire behaviour* – the lack of a clear view of the fire commonly prevents firefighters from noticing any increase in fire activity, and this could also have been a contributing factor in the crew not foreseeing the blow-up of the Bucklands Crossing Fire.

In their "Dead-man Zone" concept, Cheney *et al*. (2001) also highlighted problems associated with recognising changes in fire activity. A common tendency to overestimate distances in a vegetated environment, due to presence of objects (trees, etc.) within the field of view, can often mean there is little warning and insufficient time to escape, even via pre-determined escape routes. Similarly, the virtually instantaneous increase in rate of fire spread from an established line of fire (versus a point ignition), but delay in the increase in convection and observable increase in flame size, can also mean critical time is lost before increased fire activity is noticed. This delay may be further accentuated on steep slopes and under strong winds (Cheney *et al*. 2001).

Firefighter Safety

Protective clothing

The firefighters burned over during the Bucklands Crossing Fire were saved from more severe injuries by the short duration of their exposure to heat and flame, the fact that they were correctly attired in their protective clothing, and that they received immediate attention from onsite medical services. The correct use of protective clothing had been emphasised to the crew during their fire training, although it is interesting to note that they also discussed this on arrival at the scene prior to the burnover.

The crew were all wearing standard Nomex *3A* coveralls as recommended by the National Rural Fire Authority (NRFA), the Crew Leader having orange coveralls and other firefighters yellow. All had these buttoned up over the top half of the body and around the neck, and the sleeves rolled down (not rolled up or tied around the waist as they had been earlier during the fire). Burns to the lower arms and hands appear to be the result of sleeves being pulled back or dragged up in diving to the ground or in placing hands over the head, a reflex action which is commonly observed in extreme situations. Despite being exposed to high temperatures – the brown discoloration and change to a brittle card-like texture indicate exposure to temperatures greater than 400 ºC – the Nomex *3A* fabric maintained its integrity, and most of the damage to the coveralls was done in cutting them off to give medical treatment (Figure 27). Other materials such as the NRFA shoulder badges melted, but did not contribute to the burn injuries. Conduction of heat through the fabric to the skin under reflective strips requires further investigation, as burned stripes were observed on the back and arms of one firefighter. These

Figure 29. Damage to personal protective clothing from Firefighter C (who received the most serious burn injuries), including Nomex coveralls, cotton T-shirt and fibreglass helmet.

strips may hold heat longer resulting in more severe burning. The worst burns occurred where clothing was pulled tight against the skin. However, the most important observation was that the wearing of a second layer of clothing beneath the coveralls can significantly reduce the amount of burning. A cotton T-shirt with short sleeves provided better protection than a singlet, which resulted in additional burns to the shoulder areas. Cotton rugby shorts also provided extra protection to the hip and buttocks area.

All the firefighters were also wearing fibreglass helmets of the latest type recommended by the NRFA. These were correctly attached with the chin strap done up and the neck skirt down. The integrity of the fibreglass helmet was maintained despite extreme exposure to heat, and the discolouration/degradation of one of the firefighters' helmets provides ample evidence of this (see Figure 27). Standard plastic forestry-type hard hats would almost certainly have melted under similar conditions (Mangan 1997, Anderson 2003a). The additional protection provided by the neck skirt or shroud and, to a lesser extent, the visor, has almost certainly also prevented several of the firefighters from sustaining more serious burn injuries.

An interesting feature of the burnover incident was the lack of burn injuries to the feet, particularly as the positioning of the burned crew members was such that they were lying with the soles of their feet facing in the direction of maximum heat exposure. Several footwear failures have been reported previously in Australia[23], particularly regarding footwear with non heat-resistant soles. In this case, all crew members were wearing standard issue calf-length leather boots with heat-resistant soles, and these performed well and very likely contributed to the lack of foot injuries.

Many of the injuries sustained during this incident were to the hands (in the form of both burn and cut wounds), and firefighters initially expressed a view that they should have been provided with protective gloves. However, on later reflection, they changed this stance suggesting that covering of exposed skin would reduce heat sensitivity and therefore recognition that conditions might be too extreme, so that firefighters would stay where it might be better to get out. Obviously, provision of gloves would reduce the number of hand injuries, but these gloves would have to be suitable to enable firefighters to undertake the wide variety of tasks involved in fire suppression. Hence, light-weight leather work gloves or similar that can be worn during specific tasks may be a better option than the heavier-type protective gloves used by urban firefighters.

The burn injuries to the hands could also be attributed to the instinctive reaction of firefighters to place the hands over their heads when sheltering from fire by lying face-down on the ground. This results in the backs of the hands being directly exposed to radiant heat and possibly even flame contact. Firefighter safety training should therefore reinforce, through repetitive rehearsals, the correct survival position to be assumed in the event of being overrun by fire. This is lying face down on the ground (with the feet pointing toward the oncoming fire if caught in the open), with the forehead resting on the arms which are crossed at the wrists or forearms. In this position, the hands are protected by the head and upper arms. More importantly, this position also helps to protect the airway, as cooler air is found nearest the ground and the shielding from the arms acts to create a pocket of clearer air that reduces inhalation of smoke, dust and heated air. Anderson (2003a) provides a good description of "sheltering in place" during a burnover, and of the importance of realistic training so that actions become second nature during an actual incident.

[23] R. Donarski, Australasian Fire Authorities Council, East Melbourne, Victoria. *pers. comm.*

These findings from the Bucklands Crossing Fire burnover agree with those found in other published studies (e.g., Mangan 1993, 1994, Putnam 1995a), including those of Project Aquarius which included a major investigation of the effects of job demands, personal factors and clothing on firefighter stress, strain and productivity (Budd *et al*. 1997a). Light weight multi-layer clothing is considered preferable to wearing a single heavier garment, as loose fitting, lightweight layers provide better ventilation and protection from metabolic heat build-up and more comfortable, flexible workwear while still providing a similar level of protection from radiant heat (Budd *et al*. 1997b, 1997c). Mangan (1993) also reported that loose-fitting clothing was often just as important as the flame-resistance of materials in preventing serious burn injuries. Undergarments enhance the thermal protective performance by providing an additional layer of fabric and air between the radiant heat source and the skin, and can reduce the extent of burn injury by 15% (Mangan 1993, 1994). They also have the capacity to absorb moisture and transport it away from the body to enhance evaporative cooling during periods of heavy work. The Project Aquarius study noted that while the benefits of heavier or encapsulating clothing were not considered worthwhile in wildland fire suppression due to the increase in serious heat stress, they are acceptable for short periods for structural firefighting (Budd *et al*. 1997c).

The Project Aquarius study also reported that firefighters over-run in the open by fires with intensities greater than 6000 kW/m would certainly perish, regardless of the clothing they were wearing (Budd *et al*. 1997c). New Zealand (and Australian) rural fire authorities have therefore considered it impractical to provide clothing that gives protection from high intensity fires, preferring instead to demand safe work practices to avoid entrapment (Cheney 1998). Initial evaluation of the performance of protective clothing worn during the Bucklands Crossing Fire burnover by the NRFA Rural Fire Equipment Working Group indicates that, considering the exposure to extreme temperatures and the injuries received, the protective clothing performed to expectations and no major deficiencies in design were found. However, the Group is reviewing current standards for protective clothing for vegetation firefighting, including development of a joint Australia/New Zealand standard.

Medical attention

A major positive during the incident was the provision of onsite professional medical support as part of the incident management support services. The prompt attention from these onsite paramedics, providing a higher level of treatment than would otherwise have been available through basic first aid, was a key factor in minimising the extent of the injuries experienced during the incident.

At incidents of significant size or fire behaviour, and involving large numbers of personnel, consideration should be given to having professional medical support (e.g., St Johns or Red Cross) onsite. As a minimum, a member of all fire crews (such as the Crew Leader) should be trained in basic outdoor first aid, including the treatment of burn injuries.

Safety rules and reminders

In addition to the Common Denominators already described, there are a number of firefighter safety guides and prompts available internationally that are promoted in firefighter training. These include the 10 Standard Fire Fighting Orders (Fire Orders) and 18 Watchout Situations

(Gleason 1994) and the LCES concept (Gleason 1991). Recent fatality fire reviews have resulted in further proliferation of these rules, on top of departmental operational procedures and Health and Safety requirements. Several authors (e.g., Campbell and Campbell 1994, Gleason 1994, Cook 1995, Putnam 1995b, Chamberlin 2000) have expressed concerns that there are too many rules, and that firefighters have difficulty in recalling all these rules on the fireline. It has been suggested that a typical individual can only readily recall 3-5 key points when working in demanding situations, and that the array of safety rules and reminders needs to be simplified into one encapsulating concept or acronym.

The LCES concept was developed in the U.S. as a direct response to loss of life in wildland fires (Chamberlin 2000), and a concern for the overload of rules and procedures that firefighters are expected to remember at any one time (Thorburn and Alexander 2001). LCES stands for Lookout(s), Communication(s), Escape routes and Safety zone(s) (Gleason 1991). These four aspects of fireline safety can dramatically reduce the probability of an entrapment or burnover. Together, the elements of LCES form a safety system that firefighters use to protect themselves. It is a procedure that is put in place before fighting the fire, and is built around two basic premises (after Thorburn and Alexander 2001):

- (i) each firefighter must know how the LCES system will be implemented on a given incident; and
- (ii) the LCES system must be re-evaluated continuously as the fire environment changes.

The LCES concept has been adopted by many firefighting agencies worldwide and, in some cases, extended to LACES where "A" stands for "Anchor points" (Thorburn and Alexander 2001). However, there are a number of alternatives including "Awareness" (Teie 1994) or even "Attitude" (after Thorburn and Alexander 2001). Many agencies have considered and support the concept of "LACES" as opposed to "LCES", but currently it has not been formally adopted or standardised on a international scale, although it has been adopted in New Zealand since this incident (NRFA 2002).

Thorburn and Alexander (2001) believe that the acronym LACES fits more easily into the firefighter's vocabulary and is therefore easier to remember or recall than LCES, given that one periodically looks down and checks their boot laces. This analogy should serve as a reminder to firefighting personnel to address and re-address the situation with regard to LACES as required. On the fireground, the Common Denominators can then be used to provide an awareness of dangerous fire environment situations, which should be coupled with LACES principles to reinforce firefighter safety issues.

In simplifying existing safety rules and reminders for recall on the fireground, the Fire Orders, Watchouts and other rules must not be overlooked in terms of their value, and these should continue to be used in training to illustrate the wide array of factors that need to be taken into account regarding firefighter safety. In fact, use of the examples contained within the Watchouts, Fire Orders, and Health and Safety requirements provides the underpinning understanding of the numerous factors encapsulated within LACES.

As an example, one of the most basic safety rules recognised by firefighters around the world is to never place oneself uphill on a slope above unburned fuels with a fire burning beneath you. This encapsulates Watchout Situations 9 – "building fireline downhill with fire below", and 11 – "unburned fuel between you and the fire" (NWCG 2004). In deploying where he did, the Crew Leader during the Bucklands Crossing Fire burnover broke this basic rule and immediately placed himself and his crew in a potentially dangerous situation. While the Crew Leader did recognise the potential for the fire to "flare-up", he believed that the fire would spread up-gully under the influence of the local windflow. With the benefit of hindsight, he should probably have recognised the potential that existed for a rapid upslope run towards the crew, due to the combined influences of the slope steeness, partially burned scrub fuels and prevailing wind direction. Downhill fireline construction from above a fire has been identified as a particularly dangerous tactic, so much so that it has its own checklist of guidelines surrounding its use (NWCG 2004). In addition to the potential for a rapid uphill run of fire, the inherent dangers in use of this tactic also include the inability to establish a safe anchor point and that a safe escape route from a fire travelling uphill cannot be assumed (ETC and CIFFC 2000), all concepts encapsulated within the broader LACES framework.

While issues relating to the Common Denominators for the Bucklands Crossing Fire incident have been discussed earlier, a number of the specific safety considerations covered by the LACES concept deserve further consideration. These include:

- Lookout(s) – use of one or more lookouts to observe current and potential fire activity within the local and broader fire environment may have provided an earlier warning of the fire blow-up. However, given the rapidity with which the incident developed, it is debatable as to how useful such lookouts would have been. While the crew had considered the local area, they had most likely underestimated the effects of the broader fire environment on potential fire behaviour. In hindsight, the deployment of an observer with a good overview of the fire area (for example, on the opposite side of the river looking up into the area) may have provided insight on the potential for an escalation in fire activity which might have altered the Crew Leader's deployment tactics or provided earlier warning. To be most effective, it is essential that the person given this lookout role has a good understanding of fire behaviour in order to anticipate potentially hazardous situations, including escalation in fire activity.

- Anchor points – in the size-up of the situation, the Crew Leader had identified the burnt out ridge (the "black") as the anchor point from which to start their suppression activities. While this provided an adequate local anchor point within the area in which the crew were working, in broken terrain with areas of partially burned or unburned fuels, it may also be necessary to take into account the wider fire area in determining a safe anchor point from which to base operations.

- Awareness – in conducting size-up, it could be debated that the Crew Leader reacted to observed fire activity as opposed to potential fire behaviour based on fire environment factors. While his size-up had considered a "flare-up" in the gully below, it was expected that this would run up the gully parallel to the ridge on which the crew deployed and not upslope through the partially burned fuels to where they were located. As noted previously, only subtle changes in conditions (either singly or in combination) may be required to bring about a dramatic escalation in fire activity that could impact on fire suppression operations. As such, it is necessary to be aware of the broader fire environment rather than just of the area in which firefighters are currently working. This should include appreciation of the effects of changes in the fire environment on potential fire behaviour, including possible alignment of various factors. It is also necessary to be aware and communicate what is happening on adjacent sectors of the fire where they may impact on local sector operations. In this regard, use of a lookout that can observe a wider area of the fire could facilitate broader awareness and appreciation of current and potential fire behaviour.

Awareness of fire behaviour potential also extends beyond size-up during the initial attack phase to the concept of situational awareness throughout the entire fire incident, including the mop-up phase (Beaver 2001). Situational awareness refers to "the understanding of what the fire is doing and what you are doing in relation to the fire and your goals. It involves an awareness of fire behaviour and terrain and the ability to predict where the fire and you will be in the future" (Putnam 1995c). As such, situational awareness implies the use of both current and anticipated fire behaviour (based on assessment of the fire environment factors) in the development and implementation of appropriate fire suppression strategies and tactics. Weick (1998) states that "knowledge of a fire should be used not just to fight it, but also to decide how and when to walk away from it".

- Communications – in general, the communications function during the Bucklands Crossing Fire was well established and performed well. There was a clear chain of command, good use of briefings throughout the incident, excellent radio communications which (unlike many other New Zealand rural fires) did not experience any technical problems, and effective use of a mobile command vehicle. In particular, the Crew Leader maintained constant dialogue with the Incident Controller. There was also effective communication between the Crew Leader and his crew, and crew members were well briefed on the tactics to be employed and safety procedures. However, Gleason (1991) highlights that the communications system needs to include the link between the lookout(s) and firefighters, so that warnings of an approaching threat can be passed on promptly and clearly and, as was the case following occurrence of the "blow-up" during the Bucklands Crossing Fire, subsequently passed on to each firefighter by word of mouth. Gleason (1991) stresses that it is paramount that every firefighter receives the correct message in a timely manner.

- Escape routes and Safety zones – these were emphasised immediately prior to deployment during a crew briefing. This included the clear identification of the previously burned-out area along the top of the ridge as the initial fall-back zone and, if necessary, the ridgetop track as the escape route to the adjacent open pasture area to the east as the safety zone. Clear recognition of the pre-determined escape route is illustrated by the fact that all crew members followed very similar escape paths following the burnover. However, the lack of warning and insufficient time to escape when the blow-up occurred meant that not all crew members were able to safely evacuate via this pre-determined escape route to the safety zone. Time is critical during an escape (Beighley 1995, Anderson 2003a), and escape routes and safety zones should be scouted out, and travel times to safely reach safety zones along these escape routes measured and compared with potential rates of fire spread (Beighley 1995). However, when retreating upslope, escape routes may not really be viable, as foot travel is slow and rate of spread is fast so that fire typically overtakes retreating firefighters (e.g., 1949 Mann Gulch (Rothermel 1993), 1994 South Canyon (Butler et al. 1998)). Due to flame attachment, convective heat also flows readily upslope ahead of the flame front, so that firefighters may be overcome even before the fire reaches them. Therefore, wherever, possible, firefighters should have more than one (i.e., two or even three) alternative escape routes identified (Gleason 1991, Beighley 1995).

  The Crew Leader's impression of what constitutes a safety zone is also interesting. Anderson (2003a) states that a previously burned area can be a safe refuge providing there are no fuels left to reburn, including large fuels that prolong burning and high heat levels. Differences in what constitutes a good safety zone or escape route varies between individuals based on their training, experience and frame of reference (Mangan 1997). Individuals also have different risk thresholds so that they may be willing to accept quite different levels of risk, both prior

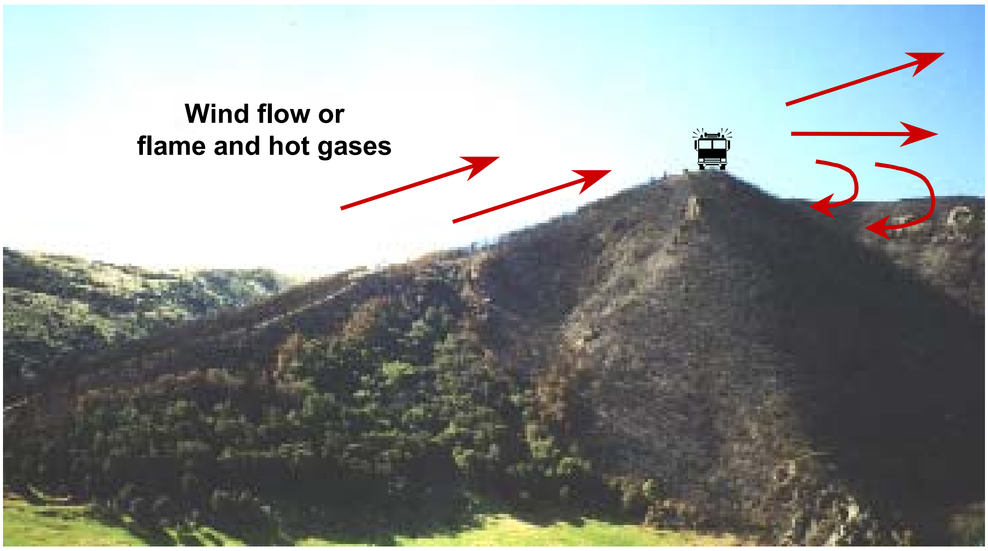

Figure 30. Separation of the flow of wind or flame and hot gases from a fire over a ridge forming a lee slope eddy (adapted from Cheney and Sullivan 1997, Anderson 2003a).

to and during an escape (Beighley 1995). In regards previously burned vegetation, Butler *et al*. (1998) found that this was significant in that it did not provide a safety zone for firefighters during the South Canyon Fire entrapment, where the amount of unburned fuels in previously burnt scrub areas together with their pre-heated condition precluded them from providing an adequate safety zone. Topography (i.e., slope) and weather (i.e., wind) also need to be considered in conjunction with fuels in deciding on safe work areas and fallback positions (Gleason 1991, Anderson 2003a). During the Bucklands Crossing Fire burnover, the previously burned-out open grass area between the scrub vegetation and the ridgetop was not a sufficient safety zone due to the high fire intensity and extreme flame lengths produced by the fire's upslope run. The retreating firefighters also used the lee slope as a refuge, and this can provide an effective safety zone as flames and hot gases can usually be expected to rise above the ridge (Anderson 2003a). However, in addition to the possibility of firebrands igniting spot fires on the lee slope below, wind and slope conditions may cause a lee slope eddy to develop resulting in the fire burning back on itself (Figure 30), as was reported by the firefighters who sought refuge in this area during the Bucklands Crossing Fire burnover.

Alternative escape options

Fire shelters – personal emergency tents made of reflective material (Anderson 2003a) – are not used in New Zealand, so their use was not an option available to firefighters in this situation. However, it is unlikely that crew members would have had sufficient time to deploy shelters due to the rapid approach of the fire. It is also likely that, as a result of the blast of air preceding the fire front and extreme fire intensities encountered, shelters would not have been able to be deployed or have provided adequate protection even if they had been. If firefighters had attempted to deploy shelters where they stood, it is highly likely that these would have been blown away, damaged or not deployed correctly in the strong, gusty wind conditions. In these circumstances, the firefighting crew would have been more vulnerable and potentially exposed to more serious injury than they were as a result of escaping to and over the ridgetop.

Another option potentially available to the firefighters was to use the vehicle as a refuge during the burnover. This could have included sheltering in the cab of the appliance in addition to sheltering behind it, as several of the crew did. In the latter case, this was more a result of good luck than design, as these appliance blocked the view (and noise) of the oncoming fire and these crew members did not have as much time to respond to the blow-up as other members. In this instance, sheltering behind the vehicle (and in particular, standing against the wheels) shielded these firefighters from the radiant heat, and from flame contact extending over and beneath the vehicle.

Safety inside vehicles is dependent on the level of fire intensity and duration of exposure. Where exposure to the flame front is of short duration, occupants need shelter in their vehicles for only a few seconds (Luke and McArthur 1978). There has been considerable research undertaken on the safety of vehicles during wildfires (Mangan 1997) and on additional equipment and protective design features (Paix 1999a, 1999b), including considerable debate on their effectiveness during high intensity burnovers (Leonard *et al*. 2001). However, none of these additional vehicle protection systems are included on New Zealand rural fire appliances. Even if these had been available, there was insufficient time for crew members to shelter in the vehicle, let alone deploy such systems. It is likely that had crew members had more time to enter the vehicle, they would have survived unscathed as the cab of the appliance was undamaged by the burnover.

Training and competency

The crew involved in the burnover incident included a mix of permanent Dunedin City Council employees and volunteer firefighters. They had an average of three to five years experience in vegetation firefighting and, by New Zealand standards, had attended a large number of fires including several major incidents (e.g., the 1994 Purakanui and 1995 Berwick Forest fires). All had undertaken training[24] in accordance with the national standard course on the "Fundamentals of Forest and Rural Firefighting" and had been assessed accordingly. Two of the crew had undertaken and attained the national standard "Crew Boss" course certificate, and the Crew Leader had recently attended the "Initial Attack Fire Boss" course. The application of the knowledge gained by the crew from this training was also instrumental in preventing more serious injuries.

For example, the crew were well versed in the need for and correct use of all their protective clothing. In addition, the Crew Leader undertook a prolonged size-up of the area prior to calling for the crew, and carefully considered safety and potential fire behaviour in this size-up. He also briefed the crew prior to deploying, paying particular attention to escape routes and insisting that the driver back the appliance in. Crew members had been exposed to safety rules including the Fire Orders and Watchout Situations during their previous training, but the acronyms LCES/LACES to encapsulate the numerous safety concepts had not been part of their formal training at that time. While it may have been used informally, LCES/LACES has only formally been incorporated into firefighter safety training since this event. A possible weakness, therefore, was that the Crew Leader's size-up only focussed on the immediate area in which the crew was working, so that there was a lack of appreciation of fire behaviour potential in the broader fire

[24] Since this incident, there has been a change in national fire training with a move towards a structured series of training unit standards within a national qualifications framework. Despite these changes, the knowledge and training gained by the crew at that time generally equates to current qualifications.

environment (i.e., Awareness). The lack of a lookout in a location where they could observe fire activity also meant that no earlier warning of escalating fire behaviour could be given.

The Bucklands Crossing Fire incident is a further example that illustrates that the training of fireline personnel in New Zealand (and overseas) must have increased emphasis on fire behaviour and firefighter safety. The aim should be to instil a "passion for safety" (Fogarty *et al.* 1997). A thorough understanding of the fire environment and fire behaviour (both current and anticipated) and how this relates to safety should underpin all suppression actions. Suppression strategies should not be rushed into but should be selected on the basis of terrain, current and expected weather and fire behaviour, whether the fire is still accelerating, fuel types involved, access to safety zones, and the knowledge and skills of the firefighters (Cheney 1994, Rasmussen and Fogarty 1997). The continued failure of incident managers and fireline personnel to recognise suppression strategies and tactics that involve unacceptable risks suggests that, despite the greater emphasis on fire behaviour training since 1992, many New Zealand fire authorities require further substantial investment in training to ensure that firefighters are able to work safely and effectively (Rasmussen and Fogarty 1997). Training for size-up and initial attack should also give consideration to the "stand off" approach of not undertaking direct suppression action until fire conditions are more favourable (Fogarty 1996).

Operational procedures

This incident highlighted a number of issues relating to operational procedures undertaken by New Zealand fire services. It illustrates once again that fire management needs to go beyond fire suppression resource use and allocation to include consideration of fire behaviour (Alexander 1999, 2000). In providing competency assessment for all levels of the fire management structure, this need to emphasise the understanding of fire behaviour and its relationship with firefighter safety cannot be overstated. This idea could be further extended to include the issue of resource effectiveness. It is essential that resource commitment be based on fire behaviour, otherwise fire intensity may exceed the capability level of the resources being utilised, and therefore place firefighters and/or equipment operators at unnecessary risk.

Other aspects and operational procedures employed during the Bucklands Crossing Fire worthy of note include:

- <u>preplanning</u> – the use of medical support (e.g., onsite ambulance), an incident management structure (i.e., identified roles) and use of a mobile command vehicle proved to be beneficial at this incident. It is essential that these activities be considered prior to an incident occurring.

- <u>command and control</u> – it is essential that fireline and incident management personnel focus on their allocated roles and are not tempted to become "hands on" by getting involved in operational activities. While there are benefits in providing guidance or mentoring, this can often inadvertently lead to taking over a subordinate role to the detriment of the primary role.

- <u>incident management</u> – all personnel at an incident require an understanding of their roles and responsibilities in relation to others within a clearly identified incident management structure appropriate to the size of the nature of the incident; for example, the New Zealand Coordinated Incident Management System (CIMS). It is essential that the management structure is reviewed throughout the incident to ensure that any changes in situation are taken into account through addition (or removal) of subsidiary roles (e.g., safety officer, lookout(s)).

- role competency – historically when identifying appropriate competencies for positions in incident management, the focus has been on firefighter training and experience. For example, assuming a skilled firefighter will make a good crew leader, or a very capable crew leader will make a good incident manager. However, determining whether a person is competent to fulfil a higher role should also consider an individual's capabilities in areas such as supervisory skills, problem solving, teamwork, and their attitude towards the responsibilities of the role.

- incident size-up/situational awareness – the importance of size-up during initial attack and ongoing suppression activities cannot be overstated. A clear understanding of fire behaviour potential and the ability to predict changes in that potential in a timely manner is essential in the development of appropriate suppression strategies and tactics. This size-up must include consideration of adjacent areas that may impinge on the immediate work environment. In addition, the principles of size-up need to be extended beyond the initial attack phase to situational awareness (Putnam 1995c, Beaver 2001) during all stages of an incident, including mop-up.

- fire suppression strategies – often there is a tendency to commit resources to fire suppression irrespective of fire behaviour, and this can lead to ineffective or inappropriate resource use. This includes committing resources at fire intensity levels beyond their capabilities, as well as consideration of the need for suppression versus a "let burn" policy where values are not being threatened. Too often, little is gained through intervention other than a slight reduction in burnt area (Leuschen 1999, Leuschen and Frederick 1999). The perceived need for firefighters to be "doing something", through being unwilling to just stand back due to either their own attitudes or pressures from property owners for the fire to "put it out", must be balanced against safety considerations and/or fire behaviour. For example, the South Canyon fire (where 14 firefighters were killed) was initially classified as a low priority fire and actioned only after public concerns were expressed (Beaver 2002). Beaver (1997, 2001, 2002, 2003) provides an excellent overview of the "risk versus reward" relationship.

  Downhill fireline construction, as was being attempted prior to the Bucklands Crossing Fire blow-up, is a particularly hazardous practice, especially when one considers what was to be gained (i.e., protection of an unburned island within the fire perimeter). NWCG (2004) stress that it should not be attempted unless there is no tactical alternative. Even then, careful consideration should be given to wind direction, escape routes and safety zones, slope steepness, terrain factors and, perhaps most importantly, expected fire behaviour (ETC and CIFFC 2000). In similar situations in future, for operations where it is necessary to work or move downhill with fire below, consideration should be given to having the hoseline charged before proceeding, and to approaching from the side(s) as opposed to proceeding directly downhill in the centre of the line of fire. Where possible, escape routes might also consider cross-slope escape options rather than attempting to retreat upslope.

- reporting of near hits – "there is a hairline difference between a situation that leads to a fatality and many other situations where movement from the fireline to a safe area means that the same fire behaviour passes without incident or comment" (Cheney 1994). Successful results involving unnecessary risks or survival from occasional near-hit events can lead to the adoption of unsafe actions as standard procedures, and this becomes more likely through repeated occurrences. It is therefore essential that all near-hit incidents are recognised, and that a culture of reporting and analysing these near-hits is developed and encouraged. This should form a key part in a process of on-going education in lessons learned, and as a basis for remedial action (Rasmussen and Fogarty 1997).

Recommendations

The Bucklands Crossing fire burnover incident highlighted a number of positive aspects of both national and local fire management and suppression. These included: correct use of protective clothing (including the value of an extra layer of clothing); adequate training (competency-based); onsite medical support; use of the Coordinated Incident Management System (CIMS); established communications (radio and briefings); and identified escape routes. On the other hand, several negative aspects were also identified, including: incomplete size-up (of the broader environment) and lack of a lookout; and commitment to a suppression strategy without consideration of the value of this strategy.

As a result, a number of points have been identified that are worthy of further consideration:

<u>Fire behaviour</u>

- More research be conducted to investigate the "fireball" phenomenon, including clarification of the mechanisms involved and determination of whether they are specific to certain topographic, fuel or atmospheric conditions.
- More research be undertaken into the triggers for upslope spread and crown fire transition in scrub fuels.
- More effort should be made to document fire behaviour during wildfire events, for use in testing and development of fire behaviour models.
- Encouragement of production of case studies of wildfire behaviour, for use in training and dissemination of information relating to lessons learned.

<u>Protective clothing</u>

- It is essential that appropriate basic protective clothing is provided; this includes loose fitting coveralls, additional cotton T-shirt and shorts/undershorts, fibreglass (as opposed to plastic) helmets complete with neck skirt, and leather boots. In addition, other accessories (e.g., eye, hearing, respiratory and hand protection) may be warranted for specific tasks or conditions.
- Correct use of all items of personal protective equipment (PPE) must be reinforced during both training and operational activities (e.g., prescribed burning, firefighting).

In light of this incident and following recent international developments, the NRFA Rural Fire Equipment Working Group is reviewing current standards for protective clothing for vegetation firefighting. The initial evaluation of the performance of protective clothing worn during the Bucklands Crossing burnover indicates that, considering the exposure to extreme temperatures and the injuries received, the protective clothing performed to expectations and no major deficiencies in design or material used were found. However, four specific recommendations have resulted from this initial evaluation:

- In selecting the size of coveralls, an individual should increase this by one size from a firm fitting. Looser fitting coveralls assist with wearer comfort and protection from heat by improving metabolic heat release, and minimising the area of body contact and direct heat transfer to the skin.
- The wearing of lightweight, loose-fitting 100% cotton undergarments is also preferable, and a short-sleeved T-shirt and boxer shorts are considered adequate. Long-sleeved garments may contribute to metabolic heat build-up during normal operations, while the shoulders,

back and buttocks are the most important areas of the torso requiring additional protection from exposure to radiant heat during burnover conditions.

- That New Zealand continue involvement with Australian counterparts in development of new standards (ISO and joint AS/SNZ) for firefighter protective clothing, and the NRFA Rural Fire Equipment Working Group be tasked with developing a range of protective clothing to meet the requirements of these new standards.
- Due to the nature of the injuries received to the hands, that further consideration be given to hand protection during extreme fire conditions. While providing protection from abrasion and burn injuries, wearing of gloves removes an early warning sensor of increasing radiant heat exposure. Future firefighter training should also reinforce hand placement in the survival position.

Training

- Training of fire managers and firefighters should have increased emphasis on fire behaviour and firefighter safety; the aim should be to instil a "passion for safety".
- Training should emphasise consideration of the broader fire environment, fire behaviour potential and possible safety implications during size-up.
- All fire training (and operational activities) should reinforce the correct use of all items of personal protective equipment (PPE).
- Fire training should continue to use the Standard Fire Orders and Watchout Situations to highlight safety considerations, but should emphasise use of the acronym LACES (Lookout(s), Anchor points and Awareness, Communications, Escape routes and Safety zones) to promote recall of safety issues.
- Training should also utilise the Common Denominators to encourage awareness of fire behaviour potential, and promote consideration of dangerous fire environment factors that may contribute to fire blow-up.
- Fire training should also utilise case studies to illustrate lessons learned.

Operational procedures

- Use of onsite medical support must be considered, based on the size (number of personnel) and nature (hazards) of the incident, and likely response time of specialist medical support (incident remoteness).
- As a minimum, at least one crew member within each crew should be trained in outdoor first aid (including treatment of burn injuries), given the likely isolation of incidents.
- Size-up must be undertaken for all fires, and should be continually reviewed throughout the incident through situational awareness. Size-up and situational awareness should use checklists such as LACES, and include consideration of the safety implications and fire behaviour potential within the context of the broader fire environment.
- Suppression strategies and tactics should give consideration to values-at-risk/potential losses versus the need for suppression (i.e., "risk versus reward" relationships).
- Incident management principles (i.e., CIMS) must be applied at all rural fires, big or small.
- All near-hit incidents must be reported as soon as possible after the event, and analysed as part of a process of on-going education in lessons learned, and as a basis for remedial action.

Conclusion

The Bucklands Crossing Fire is another example where the factors typical of the New Zealand fire environment – steep slopes, highly flammable scrub fuels and a strong föhn wind effect – combined to produce extreme fire behaviour. But unlike past fires where firefighters may have experienced near-hit situations but escaped uninjured, the crew burned over during the Bucklands Crossing Fire were not so lucky. They were hit by a blow-up that was most likely caused by a rapid re-burn through previously underburned scrub fuels, a situation not unlike the South Canyon Fire in Colorado where 14 firefighters were killed. The exact trigger for upslope spread and transition to a crown fire could not be definitively identified; however, it was most likely the result of strong winds and localised turbulence, combining with steep topography and highly flammable, pre-heated scrub fuels. Although few observations of fire behaviour were made during this incident, available fire behaviour models including the newly-developed Scrubland fire danger class criteria accurately predicted the extreme fire behaviour potential.

The firefighters burned over during the Bucklands Crossing Fire were saved from more severe injuries by the short duration of their exposure to heat and flame, the fact that they were correctly attired in their protective clothing, and that they received immediate attention from onsite medical services. However, while these were positive outcomes, there were also a number of other safety issues that, had they been considered, might have indicated that the crew were undertaking suppression in a potentially dangerous situation. In particular, the crew were approaching the fire from above, on a steep slope with partially burned fuels between them and the fire in the gully below (i.e., downhill fireline construction). Firefighters must have an understanding in the subjects of personal safety and vegetation fire behaviour, and must apply this knowledge at all times during size-up and ongoing fire suppression. Importantly, they must also have an appreciation of potential fire behaviour in the broader fire environment rather than just of the immediate area in which they are working (i.e., situational awareness). In addition, firefighter training should utilise reminders such as the Common Denominators and LACES (Lookout(s), Anchor points and Awareness, Communications, Escape routes and Safety zones) to reinforce potentially problematic aspects of fire behaviour and firefighter safety. All training undertaken must also emphasise the correct use of protective equipment, and examples such as this incident can be used to clearly demonstrate the benefits of picking up on the lessons learned.

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Appendix 1. NRFA Daily Fire Weather Report for 24 March 1998 for stations in the lower South Island.

Stn	Station Name	Temp	RH	Dir	Wsp	Rn24	FFMC	DMC	DC	ISI	BUI	FWI	GC%	Forest	Grass	Stat
Canterbury RRFC																
HAN	Hanmer	30.0	18	221	10	0.0	94.8	33	402	13.7	55	29	75	V	V	Aut
BML	Balmoral	33.0	19	276	13	0.0	95.5	61	720	17.5	101	46	100	E	E	Aut
ASY	Ashley	31.0	18	38	14	0.0	95.2	29	419	17.8	49	33	85	V	E	Aut
BTL	Bottle Lake	33.8	20	77	4	0.0	94.9	50	760	10.6	86	30	95	V	V	Aut
SDN	Snowdon	24.4	37	318	52	0.0	90.2	15	281	60.1	26	54	60	H	E	Aut
CHA	Christchurh Aero	33.0	19	20	7	0.0	95.1	40	631	12.6	69	31	95	V	E	Met
FPL	Darfield	31.6	23	322	26	0.0	94.3	30	494	28.9	52	46	95	E	E	Aut
BUR	Burnham	30.9	19	270	0	0.0	93.6	28	504	7.1	49	17	95	H	H	Aut
LBX	Le Bons Bay	24.0	26	360	20	0.0	91.8	49	562	15.2	80	37	70	E	V	Met
ASH	Ashburton Plains	32.9	25	338	10	0.0	93.9	32	410	12.3	54	27	90	V	V	Aut
South Canterbury RRFC																
TUA	Timaru Aero	31.0	22	290	33	0.0	94.5	29	477	42.4	50	58	90	E	E	Met
CAN	Cannington	29.1	32	287	8	0.0	91.8	26	487	8.2	46	18	85	H	H	Aut
THE	Tara Hills	23.0	39	360	42	0.0	89.8	32	586	34.8	56	53	95	E	E	Met
OUA	Oamaru Aero	29.0	26	230	33	0.0	93.2	22	351	35.5	38	46	80	E	E	Met
Otago RRFC																
WFA	Wanaka	23.0	39	360	42	0.0	89.8	23	336	34.8	39	46	80	E	E	Met
DNP	Dansey Pass	26.5	26	335	27	0.0	92.8	34	476	25.5	58	45	85	E	E	Aut
LAE	Lauder	23.8	38	349	38	0.0	90.1	21	377	29.2	37	40	85	V	E	Aut
QNA	Queenstown Aero	23.0	39	250	18	0.0	90.0	20	267	10.7	34	19	75	H	H	Met
RNP	Rock & Pillar	25.4	35	10	16	0.0	92.0	31	475	13.0	53	28	90	V	V	Aut
TRQ	Traquair	21.6	46	322	67	0.0	88.3	9	265	98.3	16	61	60	H	E	Aut
DNA	Dunedin Aero	26.0	38	340	26	0.0	89.3	9	258	14.4	16	17	60	M	H	Met
TPN	Tapanui	24.9	56	352	28	0.0	85.5	5	143	9.1	10	9	65	M	H	Aut
CYB	Glenledi	26.6	44	302	32	0.0	89.0	7	278	18.6	14	19	55	M	H	Aut
CLY	Clyde	25.3	42	343	5	0.0	89.8	34	603	5.3	59	15	80	M	H	Aut
DPS	Deep Stream	20.6	47	282	77	0.0							75			Aut
Southland RRFC																
MOA	Manapouri Aero	22.0	56	350	29	0.0	84.6	4	14	8.6	5	6	40	L	L	Met
MOS	Barn Hill	19.7	51	347	105	0.0	86.8	7	35	540.6	9	136	65	M	E	Aut
LUX	Lumsden	24.0	65	320	26	4.0	73.9	3	16	2.7	4	1	40	L	L	Met
BMT	Blackmount	21.8	60	357	41	0.0	85.5	5	31	17.6	8	14	65	M	V	Sub2
WRY	Wreys Bush	21.8	60	357	41	0.0	85.5	5	96	17.6	9	15	60	M	H	Aut
GCE	Gore	24.0	65	320	26	0.0	83.9	4	49	6.8	6	6	40	L	L	Met
TUT	Tuatapere	22.9	60	333	34	0.0	85.3	4	52	11.9	7	10	55	L	M	Aut
SLP	Slopedown	24.7	37	319	54	0.0	0.0	0	0	0.0	0	0	50	L	L	Aut
NVA	Invercargill Aero	23.0	55	340	22	0.0	85.5	4	50	6.9	7	6	40	L	L	Met