THERMAL TREATMENTS FOR SHORT-TERM STORAGE OF POTATO (*Solanum tuberosum L.*)

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by

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ABSTRACT

Byrappa Ranganna Ph.D. (Agri & Biosystems Eng.)

The potential of hot water dipping, vapour heating or ultraviolet irradiation to eliminate the use of chemicals for control of sprouting and post-harvest diseases of the potato (*Solanum tuberosum L.*) was examined. The microorganisms on which these treatments were tested were the fungal dry rot (*Fusarium solani*) and the bacterial soft rot (*Erwinia carotovora* pv. *carotovora*), two major post-harvest pathogens of potatoes. The study focused on short-term storage (three months) at 8°C or 18°C, which are representative of storage temperatures used by producers in northern temperate and semi-arid tropical regions, respectively.

Response surface methodology was used in experimentation to facilitate analysis of data and identification of optimal operating conditions for the treatments. The following parameters were used to assess tuber quality after the treatments and 3-month storage: firmness, color and structure.

It was found possible to obtain 100% control of sprouting and diseases for the three-month storage without resorting to the use of chemicals. This was achieved without significantly altering the quality attributes of the tubers under certain conditions of hot water, ultraviolet radiation or combinations of these two with storage at 8°C for three months. Although 100% control was not possible for the storage at 18°C, treated tubers performed much better than the controls. Vapour heat (50-70°C) was much less effective at controlling sprouting and was therefore not tested on the pathogens.

A numerical model of the heat transfer phenomenon in the tuber was also developed. It was used to predict the transient temperature distribution in the tuber. The model was solved using the line-by-line technique and model simulations were validated against experimental data.

RÉSUMÉ

Byrappa Ranganna Ph.D. (Génie Agricole et des Biosystèmes)

Cette étude porte sur l'évaluation de trois méthodes pour substituer l'utilisation des traitements chimiques post-récoltes sur la pomme de terre (*Solanum tuberosum L.*). Des traitements d'immersion dans l'eau chaude, d'exposition à la vapeur chaude et d'irradiation aux ultraviolets (UV) ont été utilisés pour le contrôle de la pourriture sèche (*Fusarium solani*), de la pourriture molle (*Erwinia carotovora* var *carotovora*) et de la germination. Les pommes de terre traitées ont été entreposées pour trois mois à 8 ou à 18°C. Ces conditions simulent celles que l'on retrouve habituellement dans les régions tempérées ou semi-arides tropicales.

L'utilisation de surfaces de réponses a permis d'optimiser les conditions (température, temps d'exposition, intensité des UV) d'application des traitements. Les critères de qualité des tubercules compilées furent: la fermeté, la couleur, et la structure.

Les résultats ont démontré que l'utilisation de ces traitements permettaient de prévenir la germination et les maladies des pommes de terre entreposées pour trois mois à 8°C, et ce sans avoir recours à des traitements chimiques. Les meilleurs résultats ont été obtenus sous certaines conditions d'immersion dans l'eau chaude, d'irradiation aux UV et de leur combinaisons. Ces traitements n'ont pas altérées la qualité des tubercules. Quoiqu'il n'a pas été possible de complètement contrôler la germination et les maladies dans les pommes de terre entreposées pour trois mois à 18°C, les produits traités se sont toujours mieux comportés que les contrôles. L'utilisation des traitements à la vapeur (50-70°C) c'est avérée moins efficace.

Un modèle numérique a été développé pour représenter le phénomène de transfert de chaleur qui a lieu dans le tubercule. Le modèle a été résolu par la méthode ligne-par-ligne et les prédictions du modèle ont été comparées aux résultats expérimentaux.

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NOTATIONS

T = temperature (°C)

S = heat generation rate per unit volume

ρ = density (Kg/m^3)

k = thermal conductivity (W/m °k)

k_p = harmonic mean of thermal conductivity (W/m °K) used in Eqns. 4.19..4.22

K_e = thermal conductivity at the control volume face, e

k_e = arithmetic mean of K_p and K_E

r, l = coordinates along axial and radial directions (m)

T_i = hot water bath temperature (°C)

T_s = temperature at the potato tuber surface (°C)

T_∞ = constant bath temperature (°C)

Δx, Δr, δx_e, δx_w, δr_n, δr_s = geometric constants used in Eqns. 4.13..4.16

h = convective heat transfer coefficient (W/m^2 K)

P, E, W, N, S = grid points

p, e, w, n, s = control-volume faces between grid points

a_E, a_p = coefficients used in Eqns.4.13 and 4.16

c_p = heat capacity (J/kg K)

e = control-volume face

f_e = interpolation factor

a_E = conductance of the material between points P and E

P = central grid point

E & W = positive and negative grid points at X-axis

N & S = positive and negative grid points at Y-axis

q = heat flux

a_E, a_w .. a_B = positive coefficients used in Eqns. 4.13..4.16

a_p = centre-point coefficient

TDMA = tridiagonal matrix algorithm

Δv	=	control volume
a_p°	=	coefficient of the "time neighbour" T_p°
$a_p^\circ T_p^\circ$	=	internal energy
t	=	time (min)
L	=	potato tuber length (cm)

CHAPTER I

INTRODUCTION

The potato (*Solanum tuberosum* L.) is one of mankind's major food staples, and ranks second only to cereals (wheat, rice, etc.). It is an excellent source of carbohydrates, principally starch, and is reasonably endowed with vitamins and minerals. The potato is produced in 130 countries and spans most climatic regions, although 85% of the total world production is in northern temperate climates (former Soviet Union, Europe, United States, Canada and Japan). FAO (1993) statistics indicate that 18.29 million hectares were devoted to potato production worldwide, the output being 277.21 million metric tonnes (Table 1.1). In developing countries, potato production has more than doubled since 1967, while total food production increased by only 50% (Figure 1.1) (Anon, 1984), indicating that the potato's contribution to the human population's nutritional requirements is on the rise.

Table 1.1 Potato production in the world for 1993 (FAO, 1993)

Continent	Area (ha) (x 1000)	Production (MT) (x 1000)
Africa	761	7, 737
N. America	762	24, 592
S. America	841	10, 237
Europe	4,040	96, 610
Soviet Union[1]	6,910	76,706
Asia	5, 171	73, 585
Total (=World)	18, 295	277, 208

[1]1979-1981 figures

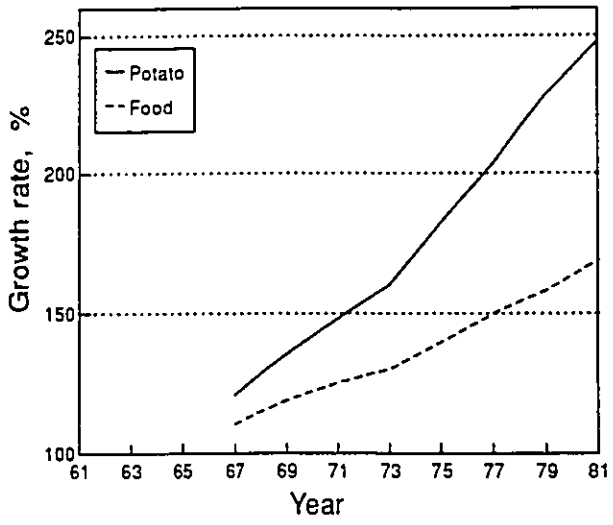

Figure 1.1 Trends in potato production and total food production in all developing countries (Anon, 1984) (Base index of 1961-65 average = 100)

The major causes of economic loss to the potato industry are bruising and cutting during harvest and post-harvest handling, as well as sprouting during storage. At present, the methods of extending the storage life of potatoes in northern temperate regions are based on minimizing disease proliferation and sprouting by refrigeration and the application of chemicals. However, it is anticipated that many of the presently used chemicals will be banned because, when they are applied at levels which control disease or sprouting effectively, they may also accumulate in the tubers (eg. CIPC (isopropyl N (3-chlorophenyl) carbamate) - Burton, 1992; maleic hydrazide - Walsh, 1995). In developing countries, both refrigeration and chemicals are also unattractive due to their higher relative cost to the economy. Thus, alternatives to disease control and sprouting must be developed, and if possible, be generally applicable to the potato industry.

Two non-chemical routes are promising to control diseases: heat treatment and irradiation. Previous work on various kinds of produce has

shown that heating the surface to a few degrees below the injury threshold effectively controls proliferation of surface pathogens and, to a lesser extent, sub-surface infections (Perombelon and Kelman, 1980; Perombelon et al., 1989; Wills et al., 1989). There are indications in the literature that heat treatment might also control sprouting (Hide, 1979). Hot water dipping is the simplest thermal treatment to apply in terms of equipment, while steam treatment is more flexible if time is a major constraint (ie. higher temperatures with shorter residence times may be achieved). Although ionizing radiations have been shown to be effective in controlling disease and sprouting (Buielaar, 1968; Mathur, 1969), these technologies are expensive, not totally accepted by the public, and may result in deleterious effects on the potato tuber, such as faster discoloration after cooking (Penner et al., 1972) as well as degradation of constituent polymers. In contrast, the less penetrating ultraviolet (UV) waveband can be used to control pathogens (eg. water disinfection - Bull, 1982; disinfection of meat surface - Stermer et al., 1987) and is inexpensive. It is not known if there is any inhibitory effect of UV on sprouting of potato tubers. However, additive or synergistic effects on pathogens could be expected when used in combination with thermal treatment. If so, UV-treatment could give an overall reduction to the energy requirements of thermal treatment.

In summary, the purpose of the research to be presented here was to investigate the potential of thermal and UV treatment, used individually or the combination of UV and hot water treatments, to provide a basis for a safer technology in resolving the post-harvest problems of the potato industry, both in the industrialized northern temperate producing nations and the semi-arid and tropical developing nations.

Hypothesis

The hypothesis entertained in this thesis is that it is possible to effectively inhibit sprouting and pathogen proliferation in short-term stored potato tubers without the use of chemicals, by using combinations of thermal

and ultraviolet treatments. It is understood that such combinations are constrained to maintaining tuber quality and limiting treatment costs.

Objectives

The main objectives of this research program were:

1. To quantify the effects of hot water dipping, steaming, UV radiation and combinations thereof, on the proliferation of pathogens and the inhibition of sprouting in potato tubers.

2. To optimize temperature, duration of treatment, radiation intensity and incubation period with quality as the constraining factor.

3. To study the effect of thermal treatments on the quality of potatoes.

Scope

The research has been limited to evaluating the effects of the treatments on sprouting and on only two of the major post-harvest potato pathogens, *Fusarium solani* and *Erwinia carotovora* pv. *carotovora*. Thermal treatments investigated were hot water dipping and vapour heat (steaming) individually and in combinations with UV radiation at 254 nm.

CHAPTER II
REVIEW OF LITERATURE

2.1 History and Production

The potato *(Solanum tuberosum L.)* is said to have originated in the Andean Plateau of South America and it appears to have been brought to Europe during the last quarter of the 16th century. By 1700 A.D it slowly began emerging as a food crop, but did not become popular due to false beliefs and prejudices. The genus *solanum* contains over 2000 species. The potato of commerce belongs to a single species, *tuberosum*. Apart from *S. tuberosum*, seven other cultivated species and 154 wild species of potatoes have been recognized.

The potato was introduced to India in the late 17th century by the British Missionaries (Hawkes, 1978). Potatoes produce more calories, protein and essential vitamins per hectare than any other major food crop in the world (Neiderhauser, 1992).

Nearly 85% of the world potato production is in the countries of the northern temperate zone: the former Soviet Union, Europe, United States, Canada and Japan. In North America, potatoes are sold fresh, frozen, dehydrated, and as chips. The annual per capita consumption of potato in the United States reached a peak of 82 kg in 1910 but has declined to a stable range of about 57 kg as of 1970 (Guenthner et al., 1991).

The potato is an important crop in Canada where about 122, 391 ha were under cultivation in 1991. A total of 16, 098 farms were reporting potato production. Prince Edward Island, with only 0.5% of the country's population, reported 26% of the total cultivated area. Manitoba, New Brunswick and Quebec each reported about 15% of the total area (Statistics Canada, 1992).

The potato is well suited to India's ecological and agronomic conditions. The total potato production is around 10 million tonnes per year, or 25% of the Asian production, making India one of the major potato growing countries on

that continent (FAO, 1982). The potato crop is cultivated during different seasons in different parts of the country. Many regions raise three crops in a year. There is a tremendous demand for increased production of potato in the country owing to its increasing population.

A major part of the crop in the country is harvested in spring and is to be stored in the ensuing summer months, when the temperatures range between 20 and 38°C. The present method of storing potatoes at high ambient temperatures and low relative humidities has led to problems of moisture and dry matter loss, sprouting, and high risk of disease infestation resulting in a greater percentage of spoilage of stored potatoes. These postharvest losses are enormous and assume importance both from the economic and nutritional stand points. In view of these problems, the potato growers have no option but to market their produce soon after the harvest. This has resulted in a market glut, adversely affecting the economics of crop production. The price of potatoes is lowest at the time of harvest and reaches a peak in the off-season. These price fluctuations can be avoided if storage performance can be improved since this would even out the supply and distribution through the year.

2.2 Morphology and Anatomy of Potato

The potato tuber is a modified stem with a shortened axis and poorly developed leaves (Artschwager, 1924). It is formed at the tip of the underground lateral shoots or 'stolons'. The shape of the tuber is characteristic of the cultivar: it can be round, oval or elongated.

2.2.1 Anatomy of the tuber

Tuberization first becomes visible as a thickening of the youngest elongating internode of the stolon tip. This thickening is mainly due to enlargement of the pith cells of the stolon (Artschwager, 1924) and to cell division in all parts of the stolon. Cell size increases as tuber size increases.

The sectional view of the anatomy of the potato tuber is presented in Figure 2.1. The outermost skin is the periderm. When the tuber tissue is

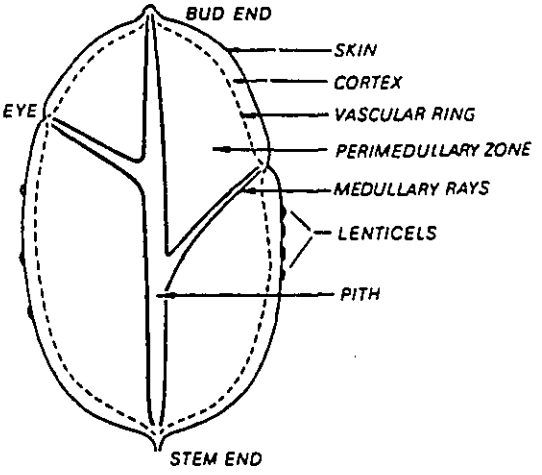

Figure 2.1 Longitudinal diagram of a potato tuber (Reeve et al., 1969).

wounded, this layer is reformed by a new layer of suberized cells and is called "wound periderm", this process being called "wound healing". A number of lenticels are seen in the periderm depending on the soil type, tuber size, weather condition during growth, etc,. Lenticels are pores located on the surface of a potato skin with loosely arranged parenchyma cells beneath, formed during the dimensional expansion of the potato tuber during growth. The lenticels facilitate the passage of air into the tuber and allow escape of carbon dioxide, the resultant product of respiration. Next to the periderm is the parenchyma tissue forming the cortical portion of the tuber. The parenchyma cells contain starch grains which are the reserve food material. The cortex also comprises the vascular tissues, xylem and phloem. The xylem

connects the stem end with two eyes. Medullary rays run from stem end to the eyes. The medulla, or pith, forms the central portion of the tuber. The pith parenchyma has less starch and looks translucent (Figure 2.2).

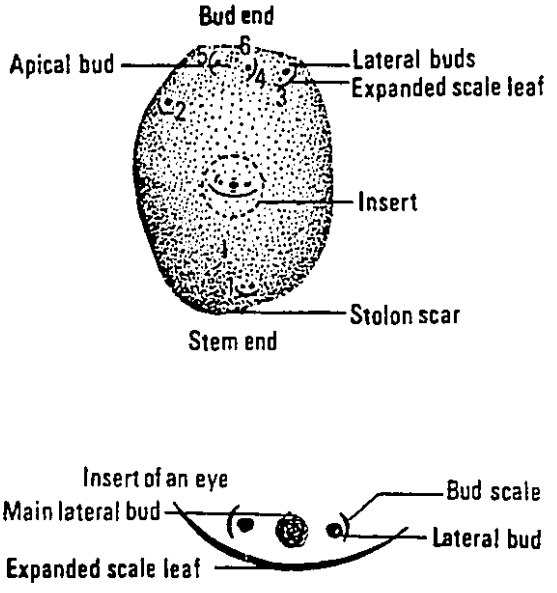

Figure 2.2 Morphological details of potato tuber.

2.2.2 Eyes

The end of the potato attached to the stolon is called the 'stem end' and the other end is called the 'bud end' or 'rose end'. The eyes are arranged spirally on the tuber. The bud at the apex is called the 'apical bud'. The eyes often contain several buds, of which one is the main bud and the rest are small later buds. As many as 20 or more buds may be present on a tuber (Krijithe, 1962). Each eye lies in the axil of an originally existing scale leaf. The apical eye is the last one to be formed and contains the physiologically youngest bud (Figure 2.2); small tubers will have a larger number of eyes per unit centimetre length than the larger ones, indicating continuous elongation and

incorporation of new internodes during the development (Goodwin, 1967). The eye depth is a cultivar characteristic. The number of eyes per tuber increases with tuber size, but the increase is not linear (Figure 2.3)

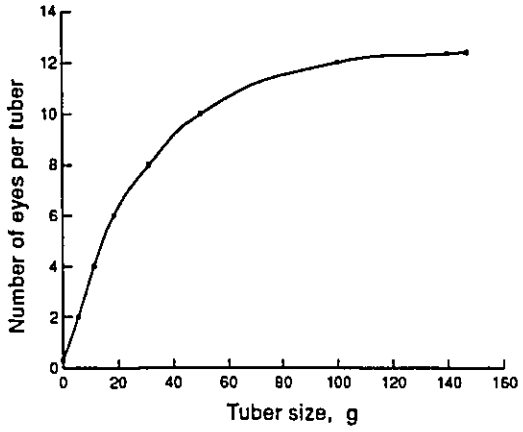

Figure 2.3 Relationship between the number of eyes per tuber and tuber size (Allen, 1978)

2.3 Morphology of the sprout

One or more sprouts develop on a tuber at the end of the dormancy period. The structure of the sprouts formed depends on the conditions during growth - mainly temperature and light. All the buds present on the tuber can sprout if conditions are favourable; and the rate of growth depends on the storage period and temperature.

In dark storage, sprouts are formed with elongated internodes. The apex of the sprout, with young leaflets, is often curved. Since chlorophyll does not form in the dark, the sprouts are light in color except at their base which may be red to purple because of anthocyanin production. The actual shade is a

cultivar characteristic. If the apex of the sprout is damaged, the lateral buds sprout and branching occurs, and tubers become physiologically old (Rastovski et al., 1987).

2.4 Dormancy and apical dominance

The potato bud dormancy period has been defined by Emilsson (1949), and Burton (1963, 1978b). It is the time after harvest during which the tubers will not sprout even under favourable conditions (Emilsson, 1949). The length of the dormancy period varies from 6 to 16 weeks depending upon the cultivar, tuber maturity, soil in which it is grown and the storage temperature and humidity conditions. Extremely cold, wet weather increases the dormancy period by about four weeks while extremely dry, warm weather reduces it by some nine weeks (Krijthe, 1962; Burton, 1963). At the end of the dormancy, the apical bud is the first one to be released from dormancy and the axillary buds sprout only after the death of the apical sprout or when the apical sprout ceases to grow. This is due to the phenomenon called "apical dominance" exhibited by the tuber.

The biochemical changes occurring in the tuber at the time of sprouting and the hormonal balance during dormancy and sprouting have been studied by many workers. Hemberg (1949), suggested that the bud dormancy in potato is correlated with the level of endogenous growth inhibitor in the tissue. The quantity of the plant growth regulator, gibberellin, was found to increase by a factor of thirty during sprouting (Rappaport and Smith, 1962). Studies by Hemberg (1958) support the assumption that the rest period in potato is regulated by inhibitor B, which was later shown to be abscisic acid (ABA). Goodwin and Cansfield (1967) have suggested that this inhibitor is the controlling factor in potato tuber apical dominance. Studies by Madison and Rappaport (1968) have confirmed that initiation of sprouting of potato buds requires RNA, DNA and protein synthesis and the availability of gibberellic acid (GA_3).

2.5 Dry matter content (DMC)

The dry matter content is an important factor in potatoes. There is no homogeneous distribution of dry matter content within the tuber and it is similar to the chemical distribution (Reeve et al., 1969). The bud end and the stem end of a tuber being of different physiological age show a variation in the DMC. The highest DMC is seen in the storage parenchyma; and it is affected by a number of factors such as variety (Burton, 1966), maturity (Appleman and Miller, 1926), fertilizer application (Beukema and Van der Zaag, 1979), and climate and soil (Burton, 1966).

2.6 Suberization

Suberization of cells involves the deposition of suberin along the cell walls. Suberin (cork) formation is an important process, as suberin protects the tissue from moisture loss and microbial attack. During the suberization period, the following developments will occur:

- Tuber wounds will heal. During this phase of wound healing, suberin is deposited inside the walls of the outer layer of cells in the wound area.
- The skin or the periderm of the immature tubers will continue to develop. During this phase new cells are formed under the wound area. Bruises heal and exterior cell walls of the potatoes, damaged during harvest, will be converted to a corky tissue, resulting in good tuber storage characteristics and visual appearance. This is also known as the 'curing period' since it helps wound healing.

The primary goal of management during suberization is to ensure that physiological healing occurs at a faster rate than damage due to microbial activity.

2.7 Aspects of Chemical Composition Relevant to Storage

Starch is the major carbohydrate of the potato and accounts for 65-80% of the dry matter content of the tuber (Burton, 1966; and Smith, 1975). Potato starch is easily digestible and is a valuable infant food. Potato starch contains 21-25% amylose and 75-79% amylopectin (Weaver et al., 1978; Chung and Hadziyez, 1980).

The major free sugars present in potato are the reducing sugars glucose and fructose, and the non-reducing sugar, sucrose. The total free sugar content varies from 0.1 to 0.7% on fresh weight basis depending upon the variety (Burton, 1965) and the storage temperature (Burton, 1965; and Burton, 1969). The differential behaviour with respect to sugar content is also associated with senescence, sprouting and possible sprout inhibition. Varieties having low specific gravity tend to accumulate more sugar. The sugar content is closely related to the color development in the product during processing.

Potatoes can be stored well at temperatures from 24.7 to 36.2° C without any change in the sugar content (Verma et al., 1974). Low temperature storage (below 10° C) results in high sugar accumulation due to the conversion of starch into sucrose and breakdown of sucrose into glucose and fructose by the activity of invertase (van Es and Hartmans, 1981). Although these sugars can be reconditioned by storing at higher temperatures, the original sugar level will not be attained (Burton, 1975).

Potatoes contain a substantial quantity of vitamin C and vitamin B. One medium size potato provides 15 mg of vitamin C, which is about 20% of the recommended allowance of 75 mg/man/day (Pushkaranath, 1976). The vitamin C is higher in immature tubers. Vitamin C is lost during long term storage but increases at the time of sprouting (Gebauer, 1958).

The potato is one of the richest sources of calories for human energy. The potato has the capacity to produce more energy and protein than any other single food crop (Table 2.1).

The balance of protein to calories, the balance of amino acids in the protein, and the level of minerals and vitamins make the potato second only to eggs in nutritional value as a single food source (Swaminathan, 1982).

Table 2.1 Composition of edibles per 100 g fresh weight of rice, wheat and potato (Pushkaranath, 1976).

Crop	Calories	Water	Protein	Fat	Carbo-hydrates	Ash
Rice	360	13	6.7	0.7	79.1	0.7
Wheat	334	12	12.2	2.3	73.9	1.7
Potato (flour)	349	7	8.5	0.4	81.7	4.1

2.8 Specific gravity

Specific gravity is a measure of the potato's solid or water contents. Different techniques are used to determine specific gravity. The hydrometer method is the most common practice, but is not as reliable as the weight in water method (Lulai and Orr, 1979). The advantage of the hydrometer method is that it is quicker and simpler to use. When using the weight in water method, the user should be careful to make sure that the tuber and the water temperature are the same or make appropriate adjustments. Lulai and Orr (1979), have shown that the specific gravity of individual tubers within a sample will vary 0.006 above or below the average specific gravity of a given sample. According to the method of weight in water, the specific gravity is calculated as follows:

$$Specific\ Gravity = \frac{(Weight\ in\ water)}{(weight\ in\ air) - (weight\ in\ water)} \quad (2.1)$$

A correction to this value is required if the tuber temperature is different than the water temperature. Correction factors are available from various tables. Highly significant correlations exist among specific gravity, percent dry matter, and percent starch in the tuber. Table 2.2 shows the typical relationship between the specific gravity, water content, dry matter, and starch content (Gould, 1986).

Table 2.2 Relationship between specific gravity, water content, dry matter and starch in potatoes.

Specific gravity	% Water	% Dry Matter	% Starch
1.040	86.4	13.4	7.80
1.050	84.5	15.5	9.60
1.060	82.6	17.4	11.41
1.070	80.8	19.2	13.11
1.080	78.8	21.2	15.00
1.090	77.0	23.0	16.71
1.100	75.1	24.9	18.51
1.110	73.3	26.7	20.22
1.120	71.4	28.6	22.01

Respiration will have a tendency to decrease specific gravity, while evaporation will increase specific gravity as specific gravity of the tuber is greater than that of water. Since in normal storage the relative humidity is kept very high, it is expected that the specific gravity of the tuber will either

not change, or increase to a relatively very small degree (Table 2.3) (Schippers, 1971b).

Table 2.3 Effect of storage temperature and humidity on specific gravity (Schippers, 1971).

		Specific gravity		
		1966	1968	1969
Temperature (°C)	5.0	0.0044	0.0023	0.0002
	7.5	.....	0.0017	-0.0003
	10.0	0.0039	0.0009	-0.0002
	15.0	0.0018	.....	.....
Humidity (%)	low	0.0048	0.0040	0.0022
	medium	0.0036	0.0021	-0.0001
	high	0.0017	-0.0012	-0.0024

2.9 Storage methods

The purpose of potato storage is to maintain tubers in their most edible and saleable condition and to provide a uniform flow of tubers to market and processing plants throughout fall, winter and spring. Good storage should prevent excessive loss of moisture, development of rots and excessive sprout growth.

In India, the entire crop is harvested during the season in a two month period and is marketed practically at the same time, resulting in a glut in market and a low selling price. Therefore, the excess has to be stored for a few months. Long term storage of 8-9 months is required only in regions that produce one crop per year. However, in tropical regions where 2-3 crops can be raised per year with short, medium and long duration cultivars, the

potatoes only require to be stored for a short duration (maximum of four months). During this period of storage, it is important to control or minimise the losses occurring due to sprouting and diseases.

The storability of potatoes is determined by many factors such as: cultivar, soil type, weather conditions during growth, diseases before harvest, stage of maturity and handling practices during transport.

The common storage types used are:

- Clamp storage
- Compartment storage
- Evaporative cool storage (ECS)
- Refrigerated storage

2.9.1 Clamp storage

This is the simplest field storage method wherein the potatoes are stored in bulk in the form of heaps on the ground. These heaps are covered with a layer of straw and plastics to protect from rain and light. In this method, due to very limited ventilation and temperature control, there is significant rotting, moisture accumulation and sprouting. This method is suitable only for very short storage period even in temperate countries. However, clamp storage may be better suited to the hills of tropics and sub-tropics where night-time temperatures are low enough to keep the potatoes relatively cool during the day. Better storage life has been achieved in ventilated clamp storage than in unventilated clamp storage.

2.9.2 Compartment storage

Small quantities of potatoes in sacs or crates can be stored for 2-3 months by this method. Long term storage is not possible as the compartments are not insulated. The sacs must be small enough to permit free air movement throughout the heap. The bags must also be made of loose-weaved material.

2.9.3 Refrigerated storage

Mechanically refrigerated storage is very essential for long term storage in tropical and sub-tropical regions. Cool temperatures can be achieved either by: a) using a cooler suspended in the refrigerated compartment or by b) blowing outside cold air into the store. The optimum temperature for long-term storage ranges from 4 to 10°C. Temperature is the most important factor which influences the storage behaviour of potatoes. Several storage temperatures and humidity conditions have been recommended for the successful storage of potatoes.

Nash and Lennard (1970) demonstrated the possibility of potato storage at 2-4°C by using cool outside air through a proper ventilation system. According to the Israel Standards Institute (1973), potatoes not pre-treated with any chemical inhibitors are to be stored at 4.5±1°C and RH 85-92%, and an air flow rate of 0.1 to 0.5 m/s without illumination. The International Organisation for Standardization (1974) recommended an optimum storage temperature of 3-6°C and an RH 85-95% for storing potatoes for six months. Feddersen (1975) successfully stored 50 tons of potatoes for six months in south Australia at temperatures between 6.5 and 7.5°C, and an RH of 95% with an air flow of 40 m^3/min. Temperatures above 10°C tend to increase the respiration rate and fungal activity (Burton, 1977; Emond, 1976).

2.9.4 CA/MA storage

Much research efforts have been made since 1920 to prolong the dormancy period of potatoes using controlled atmosphere storage concept. Controlled atmosphere storage has not shown to lengthen the storage potential of table stock potatoes. Kidd (1919), found that a concentration of 20% CO_2 in the storage atmosphere inhibited sprouting. Braun (1931) showed that a storage atmosphere with a CO_2 content of 2.2 - 9.1% clearly stimulated growth in potatoes irrespective of the stage of dormancy. Tubers developed off flavours with increased decay, surface mold and blackheart just after one week

of CA storage at 15 to 20°C (Lipton, 1967). Storage of potato cultivar Kennebec in 10% CO_2 or higher at 4°C increased decay and did not lengthen storage life (Butchbaker et al., 1967). It has been reported that exposure of tubers to atmospheres with more than 50% CO_2 increased the sprout growth (Paterson, 1969). A notable observation was that storage of potatoes in 5% oxygen or less inhibits periderm formation and wound healing. A low temperature (5°C) lessens these deleterious effects but provides no distinct benefits of low oxygen.

Information in the literature on the effects of controlled atmosphere on sugar accumulation and subsequent chip color is still inconclusive. Color was darker in chips made from potatoes stored in high carbon dioxide atmospheres (Butchbaker et al., 1967). Others have reported that storage in 2.5% oxygen for 1 month at the chilling temperature of 1°C subsequently reduced sucrose accumulation in some cultivars over that of controls in air and these tubers produced chips with acceptable color (Sherman and Ewing, 1983).

2.9.5 Evaporative cool storage (ECS)

Recently in tropical regions, much emphasis is being given to low cost storage containers at the farm level since refrigerated storage is not economical. Several workers have shown the possibility of extending the storage life of fresh vegetables by storing them in chambers having lower temperature than that of outside air. The low temperature inside the chamber is corrected by using the principle of evaporative cooling.

Storing potatoes in the evaporative cooling containers results in cooling of the commodity, which involves heat exchange between the air and the potato present inside the EC container. The mechanism of sensible and latent heat transfer between the potato and the surrounding air is explained by Rastovoski et al. (1987). The change in the sensible heat content of the potato during cooling is proportional to the mass of the material (m), the specific heat (C_p) and the temperature change ΔT:

$$Q = m \times C_p \times \Delta T, \text{ Joules} \qquad (2.2)$$

Specific heat (C_p) of potato = 3.6 kJ/kg.°C

From the above equation, it is possible to determine the amount of heat supplied or removed from a known quantity of potato.

The cooling process is also accompanied by vapor exchange, resulting in water loss from the tuber. This vapor exchange is nothing but the transfer of latent heat (mass transfer) from the potato to the air. Presence of a positive vapor pressure difference between the potato and the air results in evaporation of water from potato and subsequent weight loss of the commodity. Storing potatoes in good condition using evaporative cooling has been studied by Sparks (1982). Considerable reduction in weight loss was observed by storing potatoes in evaporative cooling chambers (Maini et al., 1983).

2.9.6 Other storage methods (India)

In India, storage houses are constructed using bricks with thatched roofs. These houses have a verandah which is used for the periodic sorting as well as for de-sprouting of potatoes. This type of house is seen in Bihar, Uttar Pradesh and West Bengal. Storage under river sand is also prevalent where sand is often sprinkled with water to keep the commodity cool by the mechanism of evaporative cooling. Here also, the tubers are periodically examined and tubers with symptoms of rotting are removed.

Pit storage is in practice in the Maharastra and Madhya Pradesh states of central India. The bottom of the pit is covered with neem (*Azaderacta indica* Linn) leaves. The depth of pit is usually 50 cm. It is covered with a thick layer of grass or straw. A trench is dug around the pit and water filled to keep the commodity cool. The common problems with all these country type of storage are excessive rotting of tubers due to diseases and sprouting.

2.10 Potato postharvest problems and their control measures

The potato tuber poses a serious storage problem due to its bulkiness and perishability. Unlike in temperate countries, the produce has to be stored

at high ambient temperatures due to inadequate cold storage facilities. In India, only about 33% of the produce is stored in cold storage and the rest is stored at room temperature where, unfortunately it is subject to significant losses such as sprouting, spoilage due to diseases and pests, and physiological weight loss. This deterioration during storage reduces the quality and marketability. Therefore, the farmers are compelled to dispose off their produce immediately after harvest. This results in a glut in the market leading to low prices, adversely affecting the crop economics and stressing the potato growers.

The extension of the shelf life may be achieved either by cultivar improvement (i.e., developing a cultivar having a longer dormancy period, and cultivars resistant to postharvest diseases) or by developing a proper post-harvest storage technology. The postharvest technology of potato involves: (a) sprout inhibition, (b) control of bacterial and fungal rots, (c) minimisation of weight loss during the storage when stored at high temperature.

2.10.1 Sprouting

The nature of the tuber and storage conditions greatly affect sprout growth during storage. Sprouting of potatoes can result in relatively high weight losses. The number of sprouts per tuber is directly proportional to the tuber size (Allen, 1978). Sprouts of smaller tubers grow at a slower rate than the larger ones (Krijthe, 1962). The storage temperature strongly influences the onset of sprouting. Much greater losses occur as a result of intensive evaporation of water from the sprout surface. Sprouted potatoes have various disadvantages both for the grower/owner and for the consumer/processor. Sprouting has direct relationship with respiration and evaporation. Moisture loss is greater in sprouted tubers, and is almost double compared to the unsprouted tubers. It has been established that the epidermis of the sprout is 100 times more permeable to water vapour and it corresponds to 1% increase in the tuber surface area, resulting in aggravated moisture loss and shrivelling

of the sprouted tuber (Burton, 1955).

Sprout control is very important when potato tubers must be stored for a long period. After the curing period, if the storage temperature is lowered to 2-4°C, sprouting can be kept to acceptable limits. However, in this temperature range, "low temperature sweetening" will develop due to an increase in reducing sugar content. Depending on the cultivar and growth circumstances, internal browning and a bitter processed product may result. Many of the treatments having sprout inhibiting effects will also suppress suberization and the formation of wound periderm, thus favouring microbial infections and consequent rotting. Although several chemicals have been reported to suppress sprouting, only a few of them have been accepted commercially (Dean, 1994).

Until the 1950s, manipulation of the storage temperature was the main technique used for the control of sprouting. In recent years, a large number of chemical compounds have been used to control sprouting. Chemical sprout inhibitors have been used on a commercial scale since 1945 (Denny, 1945; Smith, 1946). These chemical inhibitors are applied in the form of sprays, dusts, and in waxes or in washing water to keep the tubers sprout free till the end of the storage period. Sprout inhibition is now an important quality control program of the producer-to-consumer chain. At present, sprout inhibition is achieved by:

* Temperature control
* Application of chemicals
    - Pre-harvest sprout inhibitors
    - Postharvest sprout inhibitors
* Irradiation
* Using volatiles and other chemical agents

2.10.1.1 Temperature control

A natural property of potatoes is that they do not sprout at temperatures below 4°C. In regions where the outdoor temperature falls to 4°C or lower, one can cool the potatoes with ambient air. In tropical countries, such temperatures can only be obtained by mechanical refrigeration. Some of the disadvantages of low temperature storage are: a) accumulation of reduced sugars, making potatoes unsuitable for chipping and french frying; b) excessive and quick sprouting after the removal from the cold storage; c) high initial and maintenance cost of refrigeration system for long storage; and d) frequent cold storage disorders cause "black heart" (Rastovski et al., 1987).

The following are the storage temperatures recommended for different end uses of potato (Buitelaar, 1987):

Ware potatoes:	4 to 7°C
Potatoes for french frying and drying:	5 to 8°C
Potatoes for chipping:	7 to 10°C

The above storage temperatures permit the use of chemical sprout suppression agents during storage. The sprout inhibitors can be either used as pre-harvest sprays or can be used as post-harvest dips.

2.10.1.2 Chemical agents

a) Pre-harvest sprout inhibitors

Maleic hydrazide (MH) is a well known chemical inhibitor used as a foliar spray in the form of an aqueous solution of diethanolamine or sodium salt. Reaction of various potato cultivars to MH has been studied by Vechar and Snyatkov (1969). The extent of sprout inhibition was directly proportional to the amount of MH infiltrated into the tuber. Further, higher doses of MH applications not only reduce storage losses due to sprouting at higher temperature, but also result in abnormal storage properties (Poapst et al., 1970). Trojanowski (1969) found reductions in sprout length by spraying potato with 0.5 and 0.75% MH-60 two weeks before harvest. An experiment

by Rakitin Yu and Strel'nikova (1973) on five potato cultivars has shown that application of MH spray retarded sprouting, improved the firmness, and prevented loss of nutrients from the tubers. However, the treatment impaired the tuber quality. Combination treatments with fungicides (Bavistin or Calixin) and MH, reduced sprouting and spoilage more effectively than either of them alone (Mallikarjunaradya, 1982). Research reports suggest that the residual levels of MH in the tubers are of great concern due to carcinogenic effects on consumers. The MH residue in the tuber varied in the range of 8.0 - 22.7 mg/kg fresh weight depending upon the cultivar. van Es and Hartmans (1981) reported that MH is completely prohibited in the Netherlands.

b) Post-harvest sprout inhibitors

Isopropyl N-(3-chlorophenyl) carbamate (CIPC) is reported to be much more effective and efficient in suppressing sprouting (Rhodes et al., 1950; Marth and Schultz, 1950; Reeve et al., 1963). An application of 1 ppm of CIPC inhibited wound periderm formation. Potatoes were sprayed with 20 ppm isopropyl N-phenylcarbamate (IPC) and subsequently stored at 10°C for 7-8 months without sprouting (Baraldi and Miuccio, 1975). Investigations have been carried out by Leach (1978) to study the combination of thiabendazole, chlorine and CIPC for the control of tuber sprouting and rots during storage. However, there are reports of the ill effects of CIPC on the tuber. When applied to freshly harvested tubers, CIPC prevented wound healing, resulting in heavy rotting. Application of too low a concentration of CIPC may cause the development of internal sprouting (Dean, 1994).

c) Irradiation

Ionizing radiations have been used to inhibit sprouting (Mathur, 1969; Ziden E. Abdel-al, 1969; Tokano at al., 1972; and Pohissa Campa et al., 1972). Irradiation of potato tubers inhibits sprouting during storage, but may also inhibit wound healing (Dean, 1994). Kazakov (1964) observed that the best

storage life resulted from a 55 rad/min dose. He stored the tubers at 3-5°C and 65-75% relative humidity (RH). The starch content decreased sharply during storage. Penner et al. (1972) compared the qualities of tubers treated with gamma irradiation and chemical inhibitor (CIPC and IPC) treated tubers. Some of the radiation treated tubers showed grey discoloration during processing due to high sugar accumulation, likely caused by hydrolysis of starch, cellulose and hemicelluloses. Chips from irradiated tubers were consequently darker. Tubers irradiated at 3-5 kilorads inhibited sprouting for 3 months and at the end of 5-6 months the tubers showed heavy softening (Goburdhun, 1978). The difficulties of moving the potatoes into storage for curing and then moving them again to be irradiated, plus the volume of tubers to be handled and the costs involved, have prevented irradiation from being used commercially (Dean, 1994).

d) Volatile compounds and other chemicals

There are several essential plant oils which are now used in the food and cosmetics industries as fragrance and flavouring substances, which have been reported to exhibit sprout inhibition properties (Beveridge et al., 1981a). Small-scale experiments have shown that essential oils such as perillaldehyde and menthlacetate have sprout inhibiting characteristics. A number of readily available volatile compounds have been screened at a concentration of 100 µg/l in air by Meigh (1969) as inhibitors of sprouting for stored potatoes. Of the several compounds Meigh has tried, only nonyl alcohol was found to be effective and no compound of exceptional merit was found. Both amyl and nonyl alcohols have been used commercially on a small scale for the control of sprouts. Sprouting could also be controlled with 1 mg/l of air with amyl and nonyl alcohol (Burton, 1965). Meigh et al. (1973), have studied some of the volatile aromatic compounds produced by *Solanum tuberosum* during storage. These chemicals were comparable with CIPC used commercially in potato storage.

Sprout inhibition has been achieved by Said et al. (1973) when tubers were treated with 0.1, 0.3 and 0.5% sulphuric acid. A treatment at 10% level of mineral oil like petroleum ether inhibited sprouting at 15°C and 60-80% RH (Jadhav, 1974).

Huelin (1932) has found that the presence of 0.1% of ethylene in the atmosphere is effective in controlling sprouting. Rylski and Rappaport (1974) have studied the effect of ethylene on the sprout growth of potatoes. They observed that ethylene markedly shortened the duration of the rest period but inhibited sprout elongation during extended treatments.

e) Trace elements

Shashirekha and Narashimham (1990) reported that sprouting and diseases caused by *Erwinia carotovora* pv. *carotovora* and *Fusarium oxysporum* could be reduced by dipping tubers in aqueous solutions of trace elements such as iron, copper and zinc when stored at ambient conditions.

2.10.2 Postharvest diseases and their control

2.10.2.1 Fungal disease - Dry rot

Fusarium species have been known to cause potato tuber rots since the last century, but they have become a serious pathogen because of their character as wound pathogens (Seppanen, 1989). The *Fusarium* fungi are wound parasites which occur in all types of soils. It has been well established that *Fusarium* cannot enter the tuber periderm directly (Dean, 1994). The fungus infects the tubers through wounds caused during lifting, transport and grading or through broken-off sprouts. More than 20 *Fusarium* species have proven to be pathogenic to potatoes. Only a few of them are aggressive pathogens and of significant economic importance. *Fusarium solani* has been the subject of greatest interest since the damage caused by the pathogen has been reported in all the potato growing countries in the world. Favourable conditions for the fungus are high humidity and high temperature (15 to 20°C).

An important factor in the occurrence of *Fusarium* is the tuber susceptibility. During storage, potatoes may be affected by this fungus which may spread extensively in appropriate conditions. Infected tubers exhibit sunken patches on the outside surface on which numerous white-pink fungal cushions can be seen. The skin shrinks locally and more or less in clearly defined concentric rings and becomes soft. The tubers rot slowly, so that the affected patches remain quite dry. The tuber eventually shrivels up. The storability of a lot largely depends on whether or not this fungal condition is present. Resistance to this disease is at a maximum at the time of harvesting. For this reason wounds occurring during harvesting, particularly if they heal rapidly, do not generally lead to *Fusarium* attack.

The primary methods of controlling *Fusarium* is to prevent the tuber damage during harvest, grading and transportation. Apart from this, several fungicides have been used to control the dry rot caused by *Fusarium* species. Benomyl and thiabendazole (500 ppm) greatly decreased the rotting (Anne and Wood, 1972). Benlate (1200 ppm) and Mertect (1500 ppm) applied as dips or sprays reduced the incidence of dry rot. Applying the above chemicals at harvest, and before storage and maintaining a storage temperature of 5°C and 95% RH reduced the incidence of rot from 15 to 3%. Thiabendazole has been extensively used for the control of dry rot during storage (Lashin and Henriksen, 1977; Henriksen, 1978a,b; Marie et al., 1978; Dowies, 1979; and, Hide and Bell, 1981).

2.10.2.2 Bacterial disease - soft rot

Bacterial soft rot is one of the causes of microbial spoilage of potatoes and is a most important disease that can spread extensively in the potato stores. Losses due to this disease may range from 0-100% depending upon the method of potato handling. The extent of damage depends upon the degree of inoculum, maturity and physiological conditions of the tuber and the degree of mechanical damage. The potato is converted to a foul smelling slimy mass due

to this infection. Soft rot is generally caused by the *Erwinia* complex. *Erwinia* is present in the soil and gains entrance through wounds and natural openings such as lenticels (Smith, 1977). The bacterium does not have the ability to hydrolyse epidermal cuticles to gain entry directly (Dean, 1994). When plants are affected by soft rot of the stem (*Erwinia carotovora* pv. *carotovora*) the diseased mother tuber rots in the soil (Meijers, 1987).

Warmbier and Muller (1977) have recommended a 0.5% sodium hypochlorite wash after water washing potatoes to reduce the soft rot. Proper sanitary measures and chlorine water wash are recommended to reduce loss during storage (Lund, 1979).

At present, there appear to be a few chemicals which can destroy the bacteria, but it may be difficult to eliminate the soft rot entirely by this means without residual toxicity building up in the tuber. To date, no chemical agents capable of completely controlling bacterial rotting during storage are known (Meijers, 1987).

2.11 Methods of tuber inoculation

2.11.1 Surface disinfection of tubers

The potato tubers are normally surface-sterilized for disinfection of extraneous contaminations. The tubers are washed and surface sterilized in a solution of Chlorous (1 g/l available chlorine) for 10 min and rinsed prior to inoculation (Bain and Perombelon, 1989). A 2% formalin washing for 30 seconds was adopted by Boyd (1952), while Theron, (1991) used a 3% NaOCl for 15 minutes.

2.11.2 Inoculum concentration

2.11.2.1 *Fusarium*

Shashirekha and Narashimham (1990) assessed microbial spoilage by inoculating tubers. The tubers were dipped for 1 min. in an aqueous suspension of fungal spores 50,000/ml and air dried. Tubers inoculated with

fungal spores were incubated at 28 ± 1°C.

In another study by Leach et al. (1981), the inoculum of *Fusarium* spp. was prepared from 7 day old cultures grown on potato dextrose agar (PDA) in petri plates at 24°C. Conidia were washed from petri plates with distilled water, passed through four layers of cheese cloth to remove mycelium and diluted with additional water to give a suspension of 50,000 propagules per ml.

2.11.2.2 *Erwinia carotovora*

In a study to evaluate cultivar resistance to *Erwinia* species (Workman et al., 1976), a 0.01 cc of suspension of 2.88×10^6 bacterial cells was inoculated to a depth of 2.5 cm into the potato tuber at two locations. One inoculation was placed 1/3 of the length of the tuber from the bud end and the second from the stem end. Bain and Perombelon (1989), used an inoculum concentration of 10^7 cells on 0.02 sterile water in Tween 20 and placed in the holes (7 mm dia. and 3 mm depth) using a sterile cork-borer.

2.11.3 Method of inoculation

Boyd (1952), in his disease estimation studies, developed and used a 1 ml hypodermic syringe to carry out wounding and inoculation in one action. The tuber was wounded to a uniform depth of 7 mm by forcing the needle block into the tissue, while the shoulder of the syringe prevented further penetration. In another method, the researchers Bain and Perombelon (1989) used the inoculum strength on wounds made with a 3 mm dia. drill in two locations along the axis on one side of the tuber, one towards the rose (apex) end and the other towards the heel (attachment) end of the tuber.

2.11.4 Incubation period

2.11.4.1 *Fusarium*

Shashirekha and Narashimham (1990), incubated potato tubers after inoculation with *Fusarium* species in an incubator at 28 ± 1°C. Theron (1991),

incubated the *Fusarium* infected tubers in an incubator at 25 ± 2°C and 50-70% relative humidity.

2.11.4.2 *Erwinia carotovora*

Shashirekha and Narashimham (1990), used an incubation temperature of 37 ± 1°C after inoculation with bacteria. Workman et al. (1976) incubated the potato tubers at 17°C and 95% relative humidity for four days.

2.12 Sprouting and disease control by thermal treatments

2.12.1 Hot water dip

Mackay and Shipton (1983) conducted studies on the control of diseases caused by *Erwinia carotovora* subsp. *atroseptica* (Eca) through heat treatment. When dipped in a circulating hot water at 55°C for 5 or 10 minutes all the *Erwinia* present in severely infected tubers were killed. Even when the tubers were used as seed potatoes, the highest yields were observed for tubers that had been hot water dipped at 55°C for 5 minutes. *Erwinia* on the surface and in the lenticels of tubers could be killed by 5 min at 53°C or 10 min at 51°C. In a study by Hide (1975), there were no dead tubers at 55°C hot water treatment for 10 minutes and control of sprouting was effective.

Robinson and Foster (1987) reported that inactivation of bacteria in potato tubers by immersion in hot water was being examined as a method for blackleg control. Studies on the *in vitro* heat resistance of representative pectolytic *Erwinia* have enabled prediction curves for the selection of suitable times and temperatures of pasteurisation. High levels of contamination on some tubers require heat treatment that will reduce *Erwinia* population by more than 80% to ensure that only innocuous levels remain.

Shirsat et al. (1991) studied microbial spoilage during storage and observed that hot water treatment at 55°C for 5 min or 44.5°C for 30 min significantly reduced surface and lenticel contamination of seed potatoes by *Erwinia* spp. and resulted in reduced incidence of black leg. Hot water

treatment followed by sufficient time for wound healing before irradiation may be more logical treatment combinations than hot water as a post-irradiation treatment.

2.12.2 Vapour heat

Not much work has been reported on the application of vapour heat for controlling sprouting and diseases of potato tuber. In a study by Rama and Narashimham (1985), the researchers tried vapour heat application for the suppression of sprouting of potatoes at different temperatures (60, 65 and 70°C) and duration of treatments (15-60 min). Vapor treatment at 60°C and 60 min duration was able to control sprouts for a storage period of 3 weeks at 22-30°C and a repeated second treatment at the end of 3 weeks storage suppressed sprouting for a further period of 5 weeks under the same conditions of storage. No work has been reported until now on the application of vapor heat for the control of potato diseases.

In the recent years vapor treatment has been largely tried as an alternative to chemicals for some fruits and vegetables. Example: vapour treatment has been employed as one of the quarantine treatments for disinfestation of mediterranean fruit fly in mango, as well as for extending shelf-life of some fruits and vegetables (Rama & Narasimham, 1985; Sharp, 1992; and Smith and Worthington, 1965), at temperatures below the threshold levels of the product.

2.12.3 Ultraviolet radiation

Ultraviolet radiation (UV) is an effective treatment for microorganism inactivation in the wavelengths ranging from 240 - 280 nm. The rays kill microorganisms by causing a photochemical reaction that damages their nucleic acids. The most potent wavelength for DNA damage is approximately 260 nm. The inactivation of microorganisms by UV is proportional to the intensity (erg/mm^2 or J/cm^2) multiplied by the time of exposure(s). The

intensity of the UV light rapidly decreases with the increase in distance between the UV source and the microorganisms. Out of the three categories of UV rays, the UV-C band has the best bactericidal properties. This implies that low pressure lamps have the highest germicidal efficiency.

Many studies of UV germicidal effects have been conducted. It has been used as a disinfecting agent in drinking water treatment (Bull, 1982), and in waste water treatment (Jolley et al., 1982; ; Lee et al., 1982; and Qualls, et al., 1985). Penrose et al. (1987), investigated the UV light as a potential anti-fungal agent for water treatment. UV radiation resulted in a reduction of the viable spore numbers in the wash water and the number of fruit wounds which developed storage rots. The authors observed that the UV radiation gave a significant reduction in rots but did not result in total rot control on the stored fruits or total sterilization of the dip water.

Stermer et al. (1987) studied the effectiveness of UV in reducing bacteria on the surface of fresh meat. They used germicidal lamps at 253.7 nm placed at 1 m from the sample. A radiation dose of 150 $mW \cdot s/cm^2$ (i.e. 275 $\mu W/cm^2$ for 550s) reduced bacteria on the smooth surface of meat by about 2 log cycles (99% kill). Since UV radiation does not penetrate most opaque materials, it was less effective on rough surface cuts of meat such as round steak because bacteria were partly shielded from the radiation. UV radiation was very effective in reducing bacterial counts on the beef samples. Since UV can kill only exposed bacteria, it was found more effective on smooth surfaces where the meat fibres are parallel to the surface.

Lu et al. (1987), conducted a study to determine the effectiveness of gamma, electron beam, and UV radiation on the control of storage rots and the quality of onions. In all cases, UV irradiated onions exhibited the most noticeable reduction in post-harvest rots and improvement in storage life and marketability. Further, no significant differences in nutrient content were observed in the UV treated onions and the UV treatment did not affect the texture, color, or sensory quality. The effect of UV on sugar content was not

evident probably because UV do not penetrate deep into the onion tissue.

In an another study by Stevens et al. (1990), it was found that UV treated sweet potatoes had less rot compared to those treated with the fungicide Botran. The results showed no effect on the nutrients except for slightly increased starch content in the UV irradiated potatoes. This increased starch content may indicate a slower degradation rate in the UV irradiated potatoes which may be beneficial to shelf-life extension. Lu et al. (1991) conducted a study on the effect of UV on the shelf-life of peaches and apples. The rot percentage decreased with increasing UV dose. Fruits were firmer, pH and soluble solids lower and acidity higher for UV treated than non treated peaches; pH was lower, and acidity and ascorbic acid higher in UV treated apples. The results indicated that UV treatment not only reduced storage rots but also delayed ripening of peaches and apples.

UV treatments are simple, economical and, unlike fungicides, UV radiation does not leave chemical residues which are hazardous to human health and the environment.

2.13 Mathematical modelling of heat transfer

Knowledge of the rate and degree of heat penetration into the potato tuber during various heat treatment process is important in understanding the resulting effect of heat on the quality attributes of the tuber. To be able to properly constrain the quality aspects, it is important to know the temperature distribution within the tuber at different heat treatment temperature and duration levels. While there is some information in the literature on the effects of heat treatments on the carbohydrate changes of sweet potatoes (Gore, 1920; Jenkins et al., 1957), not much work is reported on the heat penetration in potatoes.

2.13.1 Thermal properties of potato tuber

Rao et al. (1975), have determined the thermal properties of the potato (cv. Russet Burbank) and the values are as follows:

Thermal conductivity (k)	:	0.571 W/m °K
Thermal diffusivity	:	1.70×10^{-7}, m^2/s

The specific heat (C_p) of potato is reported to be 3.6 kJ/kg °K (Rastovski, et al., 1987). There is no significant difference in the thermal properties among potato cultivars.

Matthews and Hall (1967) observed that the modulus of elasticity and thermal diffusivity of potatoes changed with exposure to heat. Wadsworth and Spadaro (1969), while conducting experiments to determine the thermal diffusivity of sweet potatoes, found that the thermal diffusivity increased rapidly between 65 and 74°C, reaching a maximum of 8×10^{-4} m^2/hr at 74°C. Above 74°C, the thermal diffusivity decreases reaching a value of approximately 5.5×10^{-4} m^2/hr at 90°C. It is believed that the rapid increase in diffusivity between 65 and 74°C is due to the gelatinization of sweet potato starch, which occurs in that high temperature range. The decrease in thermal diffusivity above 74°C is also attributed to the softening and separation of the starch cells, to the increase in intercellular space that occurs as the sweet potato is cooked and to the enzymatic degradation of the starch molecules.

2.13.2 Heat penetration in potato tuber

The method of finite differences was used by Matthews and Hall (1967) to calculate thermal diffusivity of potatoes, assuming them to be semi-infinite cylinders subjected to a transient heat transfer process. Wadsworth and Spadaro, (1969) studied the transient temperature distributions for various sizes of sweet potatoes heated in a constant temperature water bath (55, 70, 80 and 90°C). They experimentally measured the temperature profiles at the centre of the potato tuber and a computer program was developed to calculate the complete transient temperature distribution within a sweet potato during

immersion heating. Basically, the program solves by the method of finite differences using the partial differential equation:

$$(\frac{1}{\alpha})(\frac{\partial T}{\partial t})=(\frac{2}{r})*(\frac{\partial T}{\partial r})+(\frac{\partial^2 T}{\partial r^2}) \quad (2.3)$$

This equation describes a two-dimensional heat conduction in the irregularly shaped sweet potato. In developing a mathematical model, they assumed that the tuber was symmetrical around its longitudinal axis and that the thermal diffusivity was isotropic.

A finite-element method was used for a time dependent heat transfer problem to solve the cooling of a freshly harvested apple. The numerical solution was compared with the analytical solution by Misra and Young (1979). Pan and Bhowmik (1991) used a finite element method to develop a computer model for predicting the temperature distribution in mature green tomatoes represented by real axisymmetric shape. The vertical cross-section of one half of a tomato was divided into 104 elements and 70 node points to solve the heat conduction equation using the computer model for estimating the transient temperatures at various locations in a tomato during cooling.

CHAPTER III
PRELIMINARY STUDIES ON THERMAL TREATMENTS

The primary objective of this work was to determine whether the postharvest problems of potato tubers can be controlled using hot water, ultraviolet radiation or vapor heat, replacing the traditional chemical applications used for this purpose. Although hot water has been tried as a means for control of pests and diseases of some of the fruits and vegetables for many decades, its application has not been reported in the literature on the control of soft rot (by *Erwinia carotovora* pv. *carotovora*) or dry rot (by *Fusarium solani*) of potato. Other than one literature citation, there is no other work reported on the use of hot water for control of sprouting of potato tubers.

The preliminary studies were conducted at the Agricultural and Biosystems Engineering Laboratory and the Phyto-pathology Laboratory of Macdonald Campus. The purpose was to evaluate the efficiency of hot water and ultraviolet radiation on the control of sprouts and diseases of a ware potato (cv. Russet Burbank) locally grown in Quebec province of Canada.

3.1 Fabrication of experimental set ups

Experimental apparatuses were designed for the treatments to be evaluated: i) hot water treatment, ii) vapour heat treatment, and iii) ultraviolet radiation. These were fabricated during the fall of 1992 (Figures 3.1 and 3.2). Two storage chambers measuring 180 cm x 180 cm x 45 cm were also fabricated to store the treated potatoes at two different storage temperatures of 8 and 18°C and a relative humidity of 90%, as part of the experiment. The necessary instrumentation was assembled for temperature control during treatments and measurement of relative humidity, mass before, during and after storage, and measurement of UV intensity.

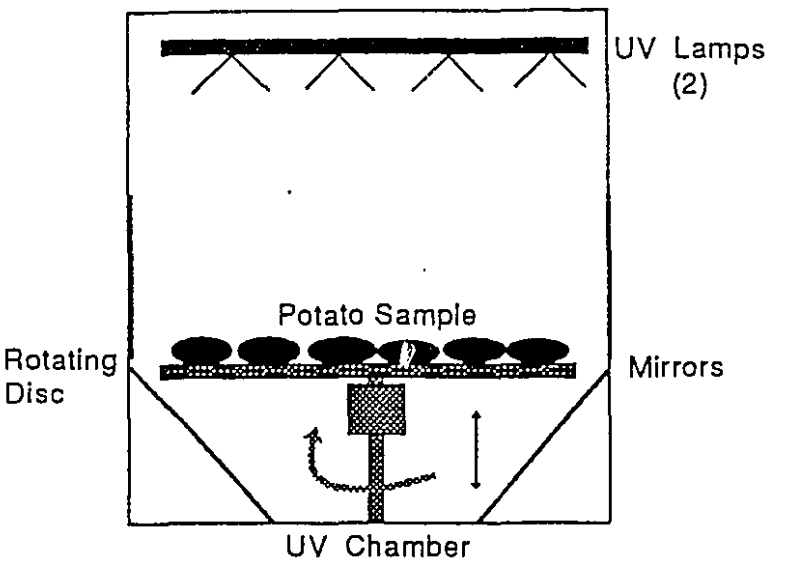

Figure 3.1 A schematic of UV apparatus

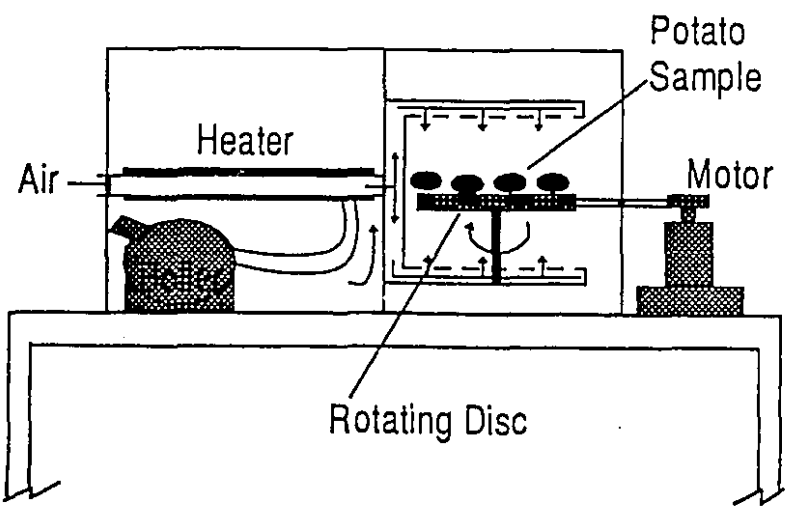

Figure 3.2 A schematic of Vapor Heat Unit

3.2 Thermal treatments

The following thermal treatments were evaluated for sprout inhibition of potato tubers cv. Russet Burbank (winter of 1992).

1. Hot water Dip
2. Ultraviolet Radiation

3.2.1 Hot water dip

The main objectives of this investigation were to study the efficiency of hot water treatment in the control of sprouting for a short-term storage of three months and to understand the tuber behaviour and response to different temperature treatments. The study was conducted at the Macdonald Campus of McGill University, Ste Anne De Bellevue, Canada.

3.2.1.1 Materials and Methods

a) Experimental Procedure

Russet Burbank potatoes were procured from a local grower in Quebec, Canada. The potatoes were stored at 5°C temperature in a dark environment and 90% relative humidity. One week before the start of the experiments the storage temperature was switched to ambient to allow the tubers to equilibrate to room conditions. During this period of storage, sprouting began. One day before the start of the experiments, the potatoes were removed from the storage environment. The potato samples were washed in tap water without causing any damage to the tuber eyes or the surfaces of the tubers. The tubers were spread on paper towels and were allowed to air dry.

A 1000 W capacity heater water bath (Lab-Line Instruments Inc., Ill, USA) was used for the hot water treatment of potatoes. The bath temperature could be controlled to ± 0.5°C. Six tubers of uniform size were selected for each treatment. The mass of each sample was recorded before and at the end of the designed storage period (3 months) using a digital weighing balance having an accuracy of ± 0.01 g (Mettler PE 3600). A 4 x 4 Factorial

experiment in randomised complete block design with three replicates was adopted. Temperature and duration of dipping in hot water were the independent factors of the experiment and percentage of sprouting was the dependent variable. Four temperature levels (50, 55, 60 and 65°C) and four residence times (10, 15, 20 and 30 min) were chosen. Temperatures above 65°C were not considered for this study since gelatinization of starch occurs above this temperature (Bertoniere et al., 1966) and enzymatic hydrolysis of starch occurs in the range of 70 and 80°C (Ikemiya et al., 1966). Soon after the treatment, the samples were quickly cooled down to room temperature, and they were put in ventilated paper sacks and sealed. The samples were then kept in shelves of a rack inside the storage chamber maintained at 8°C and 90-95% relative humidity.

b) Transient temperature distribution

During hot water dipping of potatoes, it is important to understand the tuber temperature response as a function of water bath temperature. The actual transient temperature distribution pattern at the surface was studied through series of experiments designed for this purpose. The total heat input to the tuber during treatment was also estimated. 'T' type thermocouples were used to measure the temperatures of the hot water bath, and the temperatures at the surface and centre of the tuber. The time-temperature data were gathered by connecting the thermocouples to a data logger (Scanning thermocouple thermometer version V 2.2, Cole-Parmer Instruments Company, Chicago) which was further routed to a personal computer (Figure 3.3). The time-temperature data was recorded at an interval of 4 seconds. Compression tests of the control and treated potato samples were carried out in an Instron machine (Instron 4502) to evaluate the firmness of the tubers before the treatment and at the end of three months storage. Visual observations of color were used to evaluate the quality of the tuber.

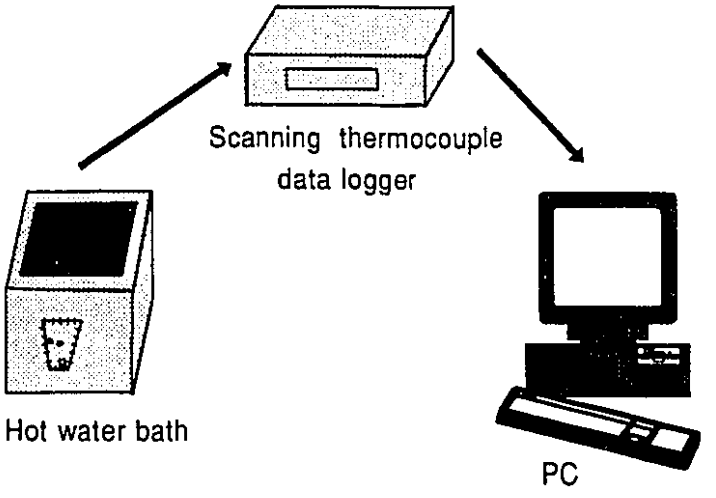

Figure 3.3 A schematic of instrumentation set up

c) Mathematical modelling

The basic heat-conduction equation for spherical coordinates (Equation 3.2) with convective boundary conditions were solved using numerical method. A finite-difference program was written in Fortran 77. Initially, some nearest value was assumed for the heat transfer coefficient and the centre temperature was calculated and compared with the experimental centre temperature. An appropriate value of heat transfer coefficient was taken for which the mean value of the sum of the square difference between the measured and calculated temperatures at the centre was the least. Important assumptions were: a) there was no internal heat generation, and b) the tuber had constant thermo-physical properties. For heat transfer calculations the potato was considered to be a sphere with an equivalent diameter (d_e):

$$d_e=(\frac{6V}{\pi})^{\frac{1}{3}} \quad (3.1)$$

where, d_e = equivalent diameter of a sphere

V = actual volume of potato tuber

Using the calculated value of heat transfer, the tuber surface temperature was calculated. The total heat supplied to each potato tuber was calculated using the following equations:

$$Q=\int_0^t q*dt=\int_0^t h*A_s*(T_{bath}-T_s)*dt \quad (3.2)$$

$$(\frac{1}{\alpha})(\frac{\partial T}{\partial t})=(\frac{2}{r})*(\frac{\partial T}{\partial r})+(\frac{\partial^2 T}{\partial r^2}) \quad (3.3)$$

The initial and boundary conditions were:

(i) $T(r, 0) = T_i$ at $t = 0$

(ii) $dT/dr\ (0, t) = 0$ at $t > 0$

(iii) $-k\ dT/dr = h\ (T_{bath} - T_s)$

The following physical properties for Russet Burbank potatoes were obtained from the literature (Rao et al., 1975; and Rastovski et al., 1981) and used in the computer programming:

Thermal conductivity, (k)	:	0.571, W/m °K
Thermal diffusivity (α)	:	1.70×10^{-7}, m^2/s
Specific heat (C_p)	:	3.6, kJ/kg°K

The heat input was calculated for all the time-temperature combinations designed for this preliminary study.

d) Results

Potatoes cv. Russet Burbank were heat treated in a constant temperature water bath at four different temperatures of 50, 55, 60, and 65°C.

Figure 3.4 shows the experimental heating curves obtained for four temperature levels, for approximately the same size and shape of potato tubers. At the beginning of the treatment, the heat absorption by the potato core at the centre was rather slow. Later, it increased exponentially with increase in time of heating. The heating behaviour was similar in nature for all the hot water temperatures used. The experimental time-temperature data compared well with the calculated data (finite-difference method). At the end of 30 minutes of heat treatment, the central core temperature was almost 90% of the water bath temperature.

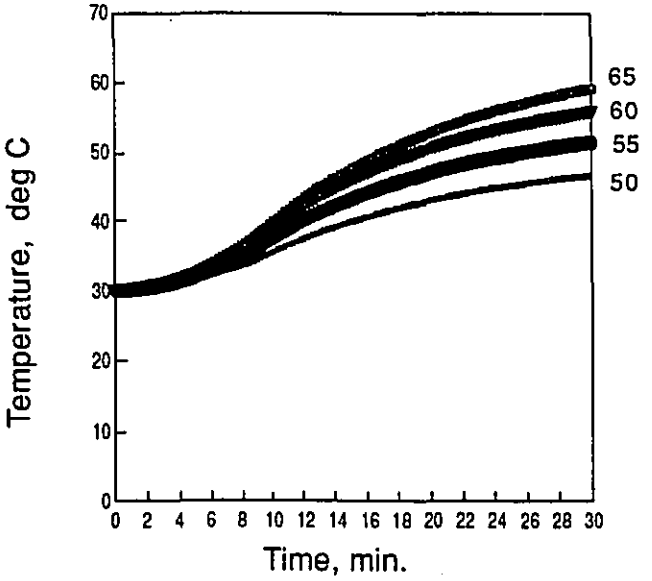

Fig 3.4 Experimental heating curves at the centre of potato tuber for different time-temperature combinations

Figure 3.5 shows the calculated transient temperature distribution at the surface of the tuber for different temperatures. The surface temperature reached nearly 98% of the bath temperature in less than a minute, and then the rise in surface temperature with time was negligible. This reveals that the maximum heat input to the tuber occurred in the first few minutes of the total duration of the treatment. The cumulative heat input increased linearly with time for all the four temperatures (Figure 3.6).

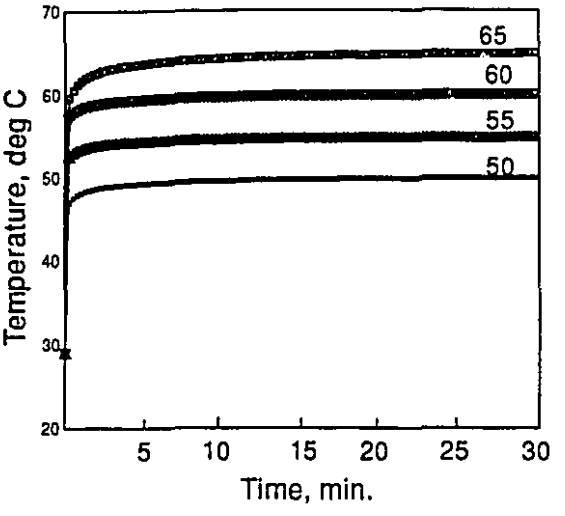

Fig 3.5 Calculated transient temperature distribution at the potato tuber surface for different bath temperatures

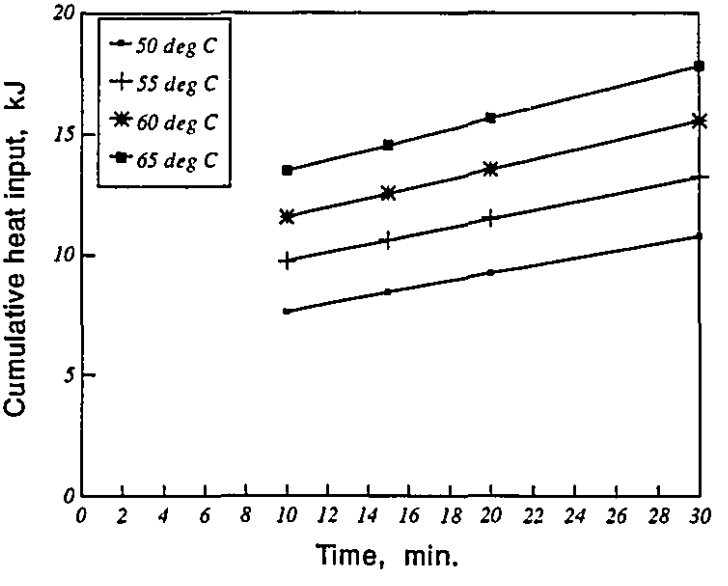

Fig 3.6 Relationship between cumulative heat inp ut and duration of hot water dip at differe nt temperatures.

The results of hot water treatment on sprout inhibition and quality of tubers at the end of the storage are presented in Tables 3.1 and 3.3. Table 3.1 showed that the heat treatment at 55°C for 20 and 30 min had completely

controlled sprouting. However, the tubers exposed for 30 min were observed slightly discoloured. The sprouts and sprout primordia located on the surface

Table 3.1 Effect of hot water treatments on potato sprouting and physical damage.

Temperature (°C)	Duration (min.)	Sprouting (%)	Physical Damage (%)
50	10	86.6	0
	15	64.7	0
	20	33.4	0
	30	17.4	0
55	10	26.5	0
	15	12.2	0
	20	0.0	0
	30	0.0	0
60	10	0.0	50
	15	0.0	100
	20	0.0	100
	30	0.0	100
65	10	0.0	100
	15	0.0	100
	20	0.0	100
	30	0.0	100

of potato had been inactivated and finally dried up as a result of heat treatment of the peripheral zone of the tuber. This was reflected well in the sprouting behaviour of tubers. The tuber sprouting was greatest (86%) at 50°C

and 10 min heat treatment, followed by 64.7% sprouting at 50°C and 15 min of treatment. At treatments 60°C and above, gelatinization of starch must have occurred at the upper layer of the tuber and hence, the potato tubers turned brownish black in color within 3-4 days of storage after the treatment and started rotting.

e) Statistical analysis

The data were analyzed as a 4 x 4 factorial experiment with three replicates. The least square means for the treatments were obtained and used for estimating the parameters (temperature and time) effect and developed a reduced regression model and the surface response was plotted. The model estimates were obtained by transforming the data into arcsin values (= (% sprout)$^{1/2}$). A best regression model was selected based on R^2 and C_p statistic (Box and Hunter, 1958).

Table 3.2 Reduced regression model to predict sprout inhibition in potato tuber as a function of hot water treatment factors (R^2 = 0.96).

Model term	Estimate[b]	T-ratio
Intercept	-0.0577623 (0.07888)	0.4682$^{n.s}$
Time	0.0057000 (0.00041)	0.0001*
Temp*Temp	-0.0080669 (0.00429)	0.0677$^{n.s}$
Time*Time*Time	0.0001539 (0.00007)	0.0416*
Temp*Time	-0.0028518 (0.00025)	0.0001***

[b] The number in the parenthesis is the standard error;
* significant at 5% level; *** significant at 0.1% level; and $^{n.s}$ not significant.

Time had a highly significant effect on the control of sprout. The interaction of temperature and time was highly significant. The model predicts that complete control of sprouting could be achieved at temperatures > 54.75°C and dipping times > 15 minutes. The model estimates, standard errors and significance levels are presented in Table 3.2.

The results in Table 3.3 show the overall quality of potato tubers at the end of the storage period. The tubers treated at 55°C for a period of 20 min were found healthy and had retained their original color. The tubers that had sprouted heavily, as discussed above, were considerably shrivelled.

The percentage of sprouting at different hot water tempratures and dipping times is depicted in Figure 3.7. The sprouting percentage decreased with the increase in the dipping duration at both 50 and 55°C, and sprout control was total at 55°C temperature and dipping times of 20 and 30 minutes.

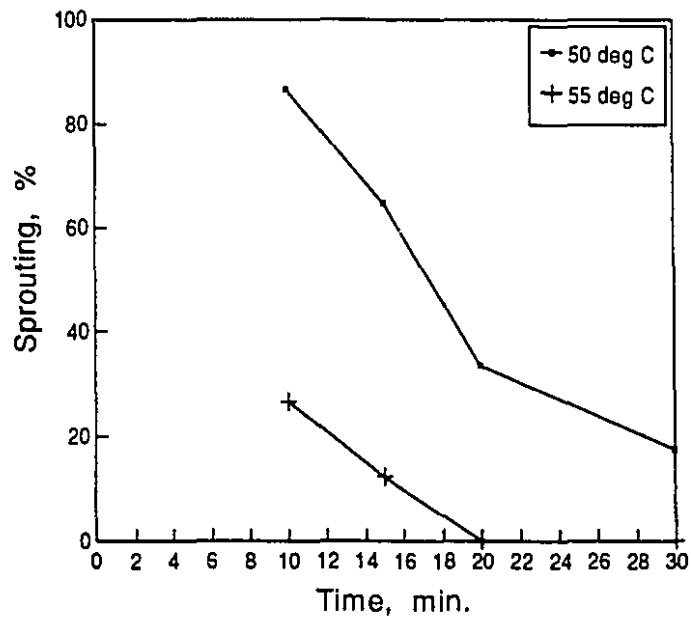

Fig 3.7 Sprout behaviour versus heat input at 50 and 55 °C temperatures

Table 3.3 Visual quality of tubers at the end of three month storage period.

Temperature (°C)	Duration (min)	Heat Input (10 kJ)	Quality (color)
50	10	7.59	good
	15	8.77	good
	20	9.52	good
	30	10.33	good
55	10	9.60	good
	15	11.07	good
	20	11.98	good
	30	12.96	fair
60	10	11.56	brown
	15	13.28	spoiled
	20	14.38	spoiled
	30	15.56	spoiled
65	10	13.29	spoiled
	15	15.34	spoiled
	20	16.65	spoiled
	30	18.08	spoiled

f) Summary

* The preliminary study of hot water dipping as a thermal treatment of potatoes for short-term storage (three months) has shown some promising trends for potato sprout control.
* The heat input to potato tuber during the process of heat treatment was studied and calculated using a finite difference method.
* The results showed a complete sprout control of potatoes (cv. Russet Burbank) at a temperature of 55°C, and 20 and 30 minutes dipping, and then storing at a temperature of 8°C and 90% relative humidity.

* No physical damage of tubers was observed at these temperature-time treatment combinations. Heat treatments at 60 and 65°C resulted in complete spoilage of the tubers.

3.2.2 Ultraviolet Radiation

a) Experimental procedure

Experiments were conducted on potato tubers using four intensity levels of UV light. To accomplish this, an UV Chamber was constructed. Two UV lamps were fitted on the inside top of the UV Chamber. Their radiation intensity was 1500 $\mu W/cm^2$ (UVP Inc., USA) each, at 254 nm. Potato samples were prepared as for the hot water treatment, and were irradiated at varying dosages at a distance of 25 cm from the lamps. The disc on which the potatoes were kept was rotated on a horizontal plane to ensure a uniform exposure to UV light. Further, after the first exposure, the tubers were tilted upside down and one more exposure to UV light was given to make sure that the entire tuber surface received UV light. A UVX-radiometer (UVP Inc., CA) was used to measure the intensity of UV radiation at 254 nm.

A sample size of six potatoes was used for each UV treatment. As in the case of hot water dip, the treated samples were stored for a short-term period of three months at 8°C and 90% relative humidity in a storage chamber built for this purpose.

The following UV dosages were used for the preliminary studies:

i) 3.2×10^4 erg / mm^2, ii) 4.8×10^4 erg / mm^2

iii) 7.5×10^4 erg / mm^2, iv) 20×10^4 erg / mm^2

b) Results

The effects of UV radiation on sprout inhibition and quality of the tubers at the end of the storage period are presented in Table 3.4. The sprouts and sprout primordia located on the surface of potato had been inactivated and they eventually dried up after exposure to 7.5×10^4 erg / mm^2. The sprouting

of tubers was observed to be greatest (31.6 %) at a dosage level of 3.2 x 10^4 erg/mm^2, followed by 24.2 % sprouting at 4.8 x 10^4 erg/mm^2 dosage. Sprout percentage (3.3 %) was least in the case of 7.5 x 10^4 erg/mm^2 dosage and increased slightly at the highest dosage. All treatments resulted in more or less uniform surface colors of the tubers at the end of three month storage period, and the quality by visual observation was good for all the treatments.

Table 3.4 Sprout behaviour at different dosages of UV Radiation.

Dosage (erg/mm^2)	Sprouting (%)	Physical damage (%)
3.2 x 10^4	31.6	0
4.8 x 10^4	24.2	0
7.5 x 10^4	3.3	0
20 x 10^4	6.8	0

c) Summary

* The preliminary study of ultraviolet radiation treatment for short-term storage (three months) of potatoes has shown some promise for potato sprout control.
* The sprouting after three months storage was lowest (3.3%) at a UV dosage of 7.5 x 10^4 erg/mm^2.
* No physical damage of tubers was caused by the UV radiation.

CHAPTER IV
NUMERICAL MODELLING

Variations in the material properties of a body and materials with irregular shapes, have long confounded engineers seeking accurate solutions for practical engineering problems. Analytical solutions of differential equations in engineering and physics are usually based upon the assumptions of homogeneity and isotropy within a body and yield good results in materials where variation is negligible e.g: steel, copper etc. On the other hand, biological materials exhibit such variations that researchers have not been able to justify the discrepancies between experimental and theoretical results. Computer-implemented numerical methods are now used extensively in solving systems of algebraic and differential equations that do not lend themselves to analytical solutions.

As seen in Chapter II, sprouting of stored potatoes is one of the major problems that confronts the potato industry. Sprouting not only decreases the nutritive value of potatoes, but makes them less attractive to the consumer. Conventionally, the problem is taken care of by the application of sprout inhibiting chemicals such as isopropyl N-phenylcarbamate, isopropyl N (3-chlorophenyl) carbamate, and maleic hydrazide. Other methods include gamma irradiation and dipping in hot oil. However, these methods are not free of residual toxicity and other problems. An alternative is the simple, low cost, and risk-free thermal treatment.

Experiments were conducted to study the efficiency of a hot water dip in the control of sprouting of potatoes for short term storage (three months). Results showed that sprouting was completely inhibited during short-term storage by dipping in hot water (55°C) for 20 to 30 minutes and then stored at 8°C. However, it is important to describe the heating dynamics and resulting temperature profile in the tuber during hot water dipping in order to predict the possible effects on the quality of potato tuber.

In this chapter, a numerical model was developed to describe the heat transfer phenomenon occurring during the thermal treatment (hot water) of potatoes. The model predicted the thermal behaviour of potato tubers treated by natural or forced convection induced by the following heat transfer media: hot air, hot water, and steam. The results from the hot water bath experiments mentioned above were used to verify the numerically calculated values. The experiments were carried out for three hot water temperatures (52, 55 and 57°C) and three exposure times (10, 20 and 30 min) at each temperature. The experimental data were compared with the numerical model predictions.

Mathematical Formulation

The equation governing the unsteady heat conduction in a potato tuber immersed in a constant temperature medium can be written as:

$$\rho c \frac{\partial T}{\partial t} = div(k \nabla T) + S \qquad (4.1)$$

where T is the temperature and S is the heat generation rate per unit volume. The material properties ρ, c and k are, respectively, the density, the specific heat and the thermal conductivity.

Assumptions

The following assumptions are made to simplify Equation (4.1):

1. the potato tuber is assumed to be cylindrical, isotropic, homogeneous and constant in volume;
2. the physical properties are constant;
3. the heat generation and mass transfer to, from, and within the potato tuber are negligible;
4. the heat conduction is two dimensional;
5. the temperature distribution is symmetric about the axial dimension.

Employing the stated assumptions, Equation (4.1) can be written in the following form:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(kr \frac{\partial T}{\partial r}\right) \tag{4.2}$$

where, x and r are the axial and radial directions, respectively.

Initial condition

The temperature profile is uniform at time zero

$$T = T_0 \quad at \quad t = 0, \quad 0<r<R, \quad 0<x<L \tag{4.3}$$

where, R and L are the radius and the length of the potato tuber, respectively.

Boundary conditions

The first boundary condition for both x and r directions is formulated based on the assumed geometric symmetry of the potato tuber (the bottom of the tuber is assumed insulated):

$$\frac{\partial T}{\partial x} = 0 \quad at\ x = 0,\ t > 0 \tag{4.4}$$

$$\frac{\partial T}{\partial r} = 0 \quad at\ r = 0,\ t > 0 \tag{4.5}$$

The second boundary condition is represented by a typical convective equation for both directions:

$$k\frac{\partial T}{\partial x} = h(T_\infty - T_s) \qquad at\ x = L,\ t > 0 \tag{4.6}$$

$$k\frac{\partial T}{\partial r} = h(T_\infty - T_s) \qquad at\ r = R,\ t > 0 \tag{4.7}$$

where T_s is the temperature at the potato tuber surface and T_∞ is the constant water bath temperature.

Numerical Solution

A control volume finite difference code was developed to solve the model equations. The discretization of the differential equation and boundary conditions follows the methodology developed by Patankar (1980). The basis of this numerical method is the conversion of the partial differential equation (Equation 4.2), into a set of simultaneous algebraic equations relating the value of the temperature, T, at a certain grid point to the values at the neighboring grid points.

Because of the symmetry of the geometry and boundary conditions, the calculation domain is reduced to one longitudinal half of the physical domain and the plane of geometric symmetry is replaced by an insulator. This calculation domain is divided into small control volumes (Figure 4.1) and the differential equation is integrated over each control volume. A grid point P communicates with the four neighboring grid points denoted by E, W, N, and S through the four faces of the control volume. A typical control volume is shown in Figure 4.2. The lowercase letters e, w, n, and s denote the four faces of the control volume. A uniform grid point spacing, where all control volume widths are equal and successive grid points maintain the same spacing between them, is used in this study.

The discretization equation is derived by multiplying Equation (4.2) by r and integrating it with respect to t, x, and r over the control volume shown

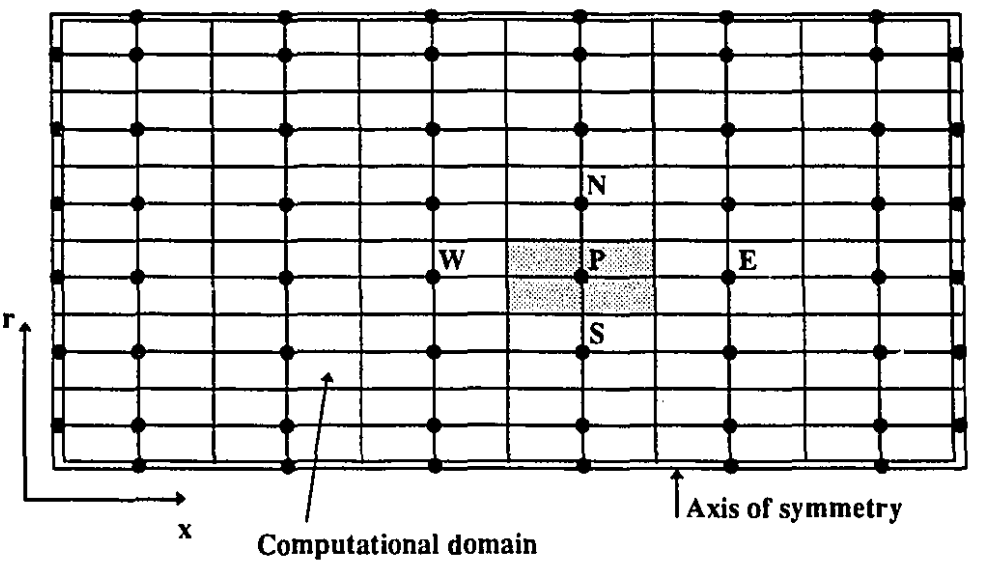

Figure 4.1 Grid points and control volumes

in Figure 4.2. The resulting equation represents conservation of T as applied to the control volume. The integral equation can be written as

$$\rho c \int_w^e \int_s^n \int_t^{t+\Delta t} r\frac{\partial T}{\partial t} dt\, dr\, dx = \int_t^{t+\Delta t} \int_s^n \int_w^e r \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) dx\, dr\, dt$$

$$+ \int_t^{t+\Delta t} \int_w^e \int_s^n \frac{\partial}{\partial r}\left(rk\,\frac{\partial T}{\partial r}\right) dr\, dx\, dt \qquad (4.8)$$

If we evaluate the derivatives in Equation (4.8) using a piecewise-linear profile, the resulting equation will be:

$$\frac{\rho c}{2}\,\frac{(r_n^2 - r_s^2)\Delta x(T_P - T_P^0)}{\Delta t} = \frac{1}{2}(r_n^2 - r_s^2)\left[\frac{k_e(T_E - T_P)}{(\delta x)_e} - \frac{k_w(T_P - T_W)}{(\delta x)_w}\right]$$

$$+ \frac{r_n k_n (T_N - T_P)\Delta x}{(\delta r)_n} + \frac{r_s k_s (T_P - T_S)\Delta x}{(\delta r)_s} \qquad (4.9)$$

Since P lies midway between n and s then

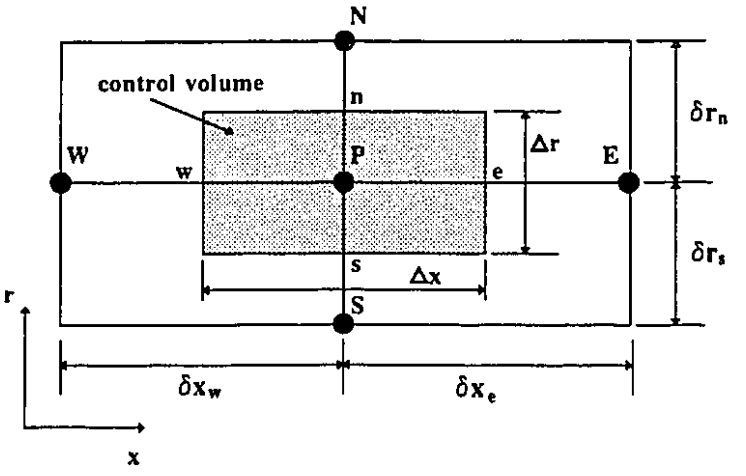

Figure 4.2 A typical two dimensional control volume

$$r_P = \frac{1}{2}(r_n + r_s) \tag{4.10}$$

and

$$\Delta V = r_P \Delta x \, \Delta r \tag{4.11}$$

Rearranging Equation (4.11) gives the final discretization equation:

$$a_P T_P = a_E T_E + a_W T_W + a_N T_N + a_S T_S + a_P^0 \tag{4.12}$$

where,

$$a_E = \frac{r_P \Delta r \; k_e}{(\delta x)_e} \tag{4.13}$$

$$a_W = \frac{r_P \Delta r \; k_w}{(\delta x)_w} \tag{4.14}$$

$$a_N = \frac{r_n \Delta x \; k_n}{(\delta r)_n} \tag{4.15}$$

$$a_S = \frac{r_s \Delta x \; k_s}{(\delta r)_s} \tag{4.16}$$

$$a_P^0 = \frac{\rho c\, r_P \Delta x\, \Delta r}{\Delta t} \tag{4.17}$$

and

$$a_P = a_E + a_W + a_N + a_S + a_P^0 \tag{4.18}$$

The geometric quantities Δx, Δr, δx_e, δx_w, δr_n, and δr_s are shown in Figure 4.2. The interface conductivities, k, are given by the harmonic mean of k_P and k's as follows:

$$k_e = \frac{2k_P k_E}{k_P + k_E} \tag{4.19}$$

$$k_w = \frac{2k_P k_W}{k_P + k_W} \tag{4.20}$$

$$k_n = \frac{2k_P k_N}{k_P + k_N} \tag{4.21}$$

$$k_s = \frac{2k_P k_S}{k_P + k_S} \tag{4.22}$$

The above derived control volume equations form a set of simultaneous linear equations with the temperature values at the internal grid points as the unknowns. This set of equations is solved using the line-by-line technique described by Patankar (1980). The main idea behind this method is to solve the equations along all the lines in the x direction (longitudinal sweep) using the tridiagonal matrix algorithm (TDMA). This is then repeated along the lines in the r (radial sweep) direction.

The input parameters to the program are: initial temperature, bath temperature, physical properties (ρ, c, k) of the potato tuber, length and radius, heat transfer coefficient, number of grid points in the x and r directions, and time increment size. An accurate solution can only be obtained when the number of grids is sufficiently large. The number of grid points needed for a given accuracy and the way they should be distributed in the calculation domain are matters that depend on the nature of the problem to be

solved. In the example taken, thirty three grid points in the x direction and seventeen in the r direction were used and the size of the time increment was 1 second.

Results and Discussion

The numerical analysis for this study was performed for the following governing parameters:

1) Heat transfer coefficient, h.
2) Potato tuber length, L.
3) Bath temperature, T_∞.

The effect of the heat transfer coefficient on both the transient center point and surface temperatures is depicted in Figures 4.3 and 4.4, respectively. Inspection of the Figures shows that as the heat transfer coefficient increases the rate of heating of the potato tuber is increased up to the point where the rate of heat penetration inside the tuber becomes the limiting factor. From this, one can conclude that increasing the heat transfer coefficient above 500 W/m^2K will not significantly affect the center point and surface temperature profiles. The role of the heat transfer coefficient is best elucidated by considering both heat transfer resistances, namely, the intra-solid temperature gradients and the temperature difference between the potato tuber and the surrounding fluid. The magnitude of these resistances is determined uniquely by the Biot number, Bi_H=h R/k, and the Fourier number, $Fo_H = \alpha t/R^2$, where h, R, k, α, and t are respectively, heat transfer coefficient, radius, thermal conductivity of the material, diffusivity, and time. From the definition of the Biot number, one can conclude that using a heat transfer coefficient higher than 500 W/m^2K will give a Biot number well above unity. Consequently, the process is controlled by the internal resistance rather than by the external resistance which is a strong function of the heat transfer coefficient. As a result, the heating rate depends only on Fo_H. After about 1 hour of heating

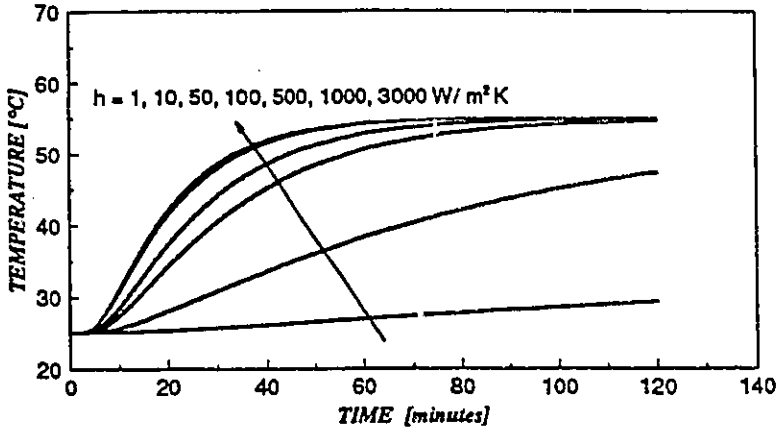

Figure 4.3 Effect of heat transfer coefficient on calculated transient center point temperature for a 10 cm long-6cm dia. potato tuber. T_{∞}=55°C and T_{o}=25°C

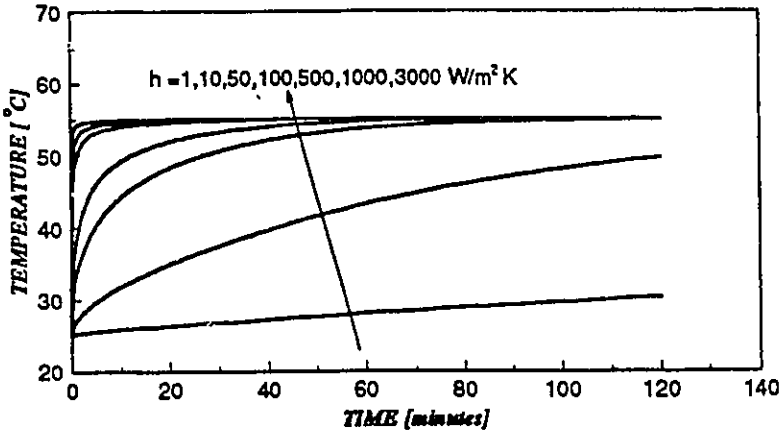

Figure 4.4 Effect of heat transfer coefficient on calculated transient surface temperature for 10 cm long-6 cm dia. potato tuber. T_{∞}=55°C and T_{o}C=25°C.

time, Fo_H reaches a value of about 0.2, and at this point the potato tuber center temperature approaches steady state.

Figures 4.5 and 4.6 display the effect of potato tuber length on the center and surface temperature evolution with a heat transfer coefficient of 200 W/m^2K and a bath temperature of 55 °C. The results indicate that an increase in the length results in a reduction of the transient temperature both at the center and at the surface of the potato tuber. This can be attributed to the fact that more thermal energy is required to heat larger potato tubers. Moreover, it can be seen that tuber of lengths greater than 10 cm, where the rate of energy penetration reaches an ultimate value, have a very small effect on the temperature profile.

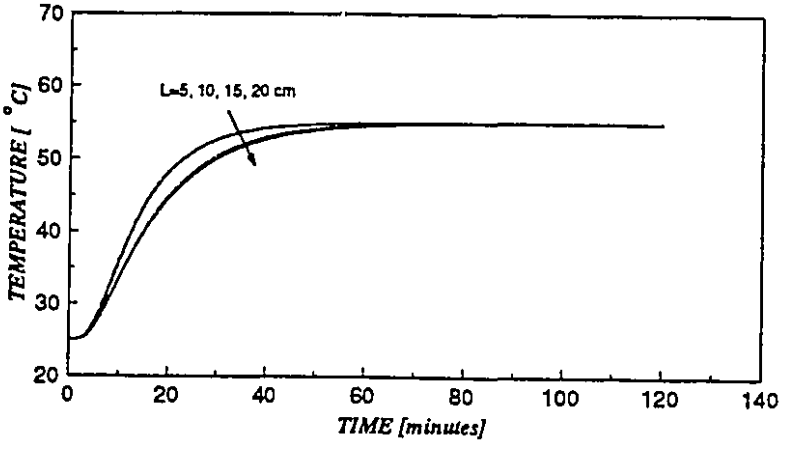

Figure 4.5 **Effect of length on calculated transient center point temperature for a 5 cm dia. potato tuber. T_{∞}=55°C, T_i=25°C, 200= W/m^2K.**

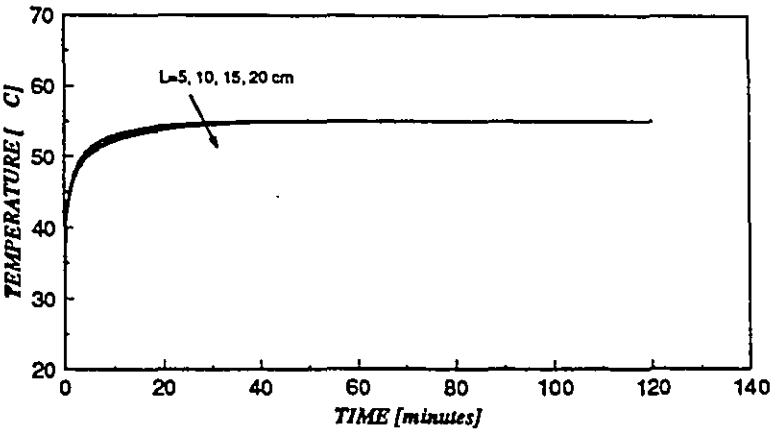

Figure 4.6 Effect of length on calculated transient surface temperature for a 5 cm dia. potato tuber. T_{∞}=55°C, T_o=25°C, h=200 W/m^{2}K.

Figure 4.7 shows the calculated heating curves obtained for five water bath temperature levels for a 10 cm long-6 cm diameter potato tuber. In the first few minutes, the heat absorption by the potato center is relatively slow (due to high internal resistance) and then increases exponentially with the time of heating. At the end of the first 30 minutes, the center point temperature reaches almost 90 % of the water bath temperature. Figure 4.8 illustrates the calculated transient surface temperature for different bath temperatures. The potato tuber surface temperature reaches almost 98 % of bath temperature in less than three minutes, after which the rise in temperature with time is insignificant. Numerical results in Figures 4.7 and 4.8 reveal that the maximum heat input to the tuber occurs in the first few minutes and this suggests that it is not practical to thermally treat the potato tuber for more than 30 minutes.

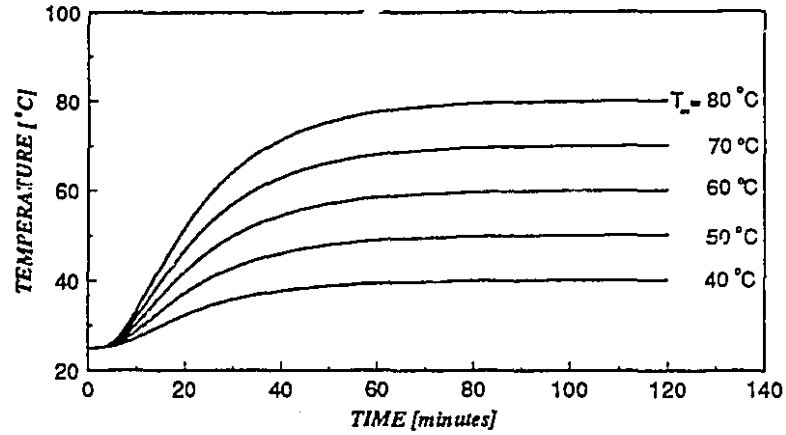

Figure 4.7 Effect of hot water temperature on calculated transient center point temperature for a 10 cm long-6 cm dia. potato tuber. T_o=25°C, h=200 W/m^{2}K.

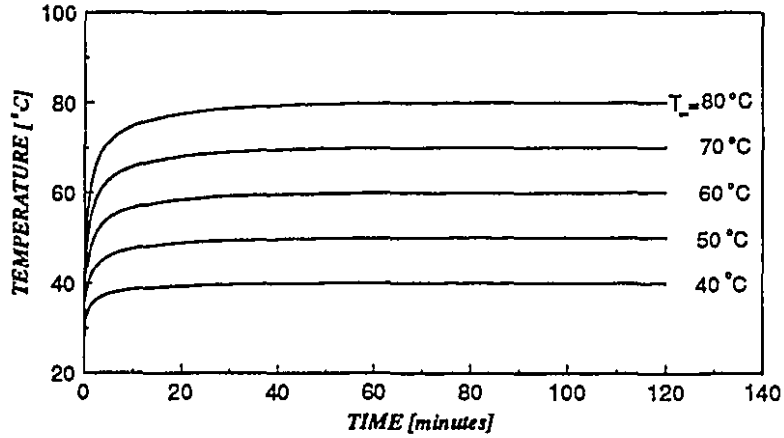

Figure 4.8 Effect of hot water temperature on calculated surface temperature for a 10 cm long-6 cm dia. potato tuber. T_o=25°C, h=200 W/m^{2}K.

The performance of the numerically solved model was verified with the experimental results obtained by thermal treatment of roughly the same size and shape of potato tubers at three different water bath temperatures of 52, 55, and 57°C for three minutes. The water bath temperature levels were chosen based on conclusions drawn from the preliminary experiments where the results showed a complete control of potatoes at 55°C and 20 to 30 minutes dipping. No physical damage of tubers was observed at these temperature-time combinations. However, heat treatments above 60°C temperature caused complete spoilage of tubers. Figure 4.9 shows that the correlation between experimental data and model predictions were very good.

Figure 4.10 shows the numerical prediction of the transient surface temperature for the same test.

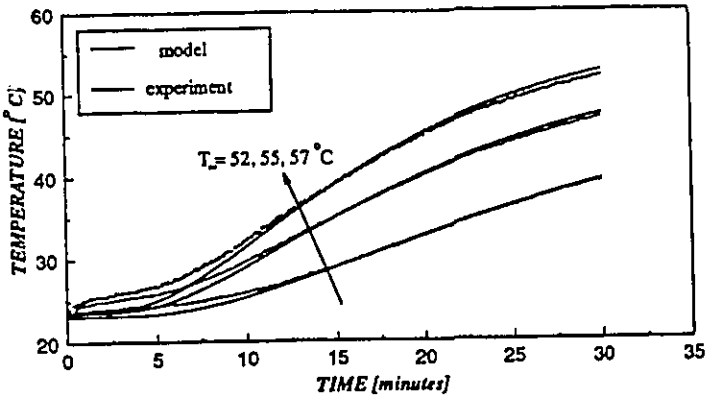

Figure 4.9 Comparison between experimental and numerical center point temperature profiles for a 10 cm long-6.5 cm dia. potato tuber.

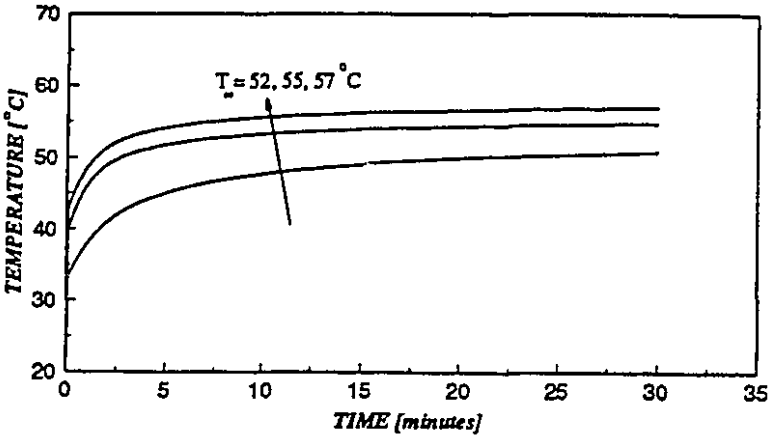

Figure 4.10 Numerical predictions for the evolution of surface temperature profiles for a 10 cm long-6.5 cm dia. potato tuber.

The surface plots for the temperature distributions within one half (i.e., the computational domain) of a 10 cm long 6.5 cm diameter potato tuber are presented in Figures 4.11 - 4.13. It is clear from the figures that the surface

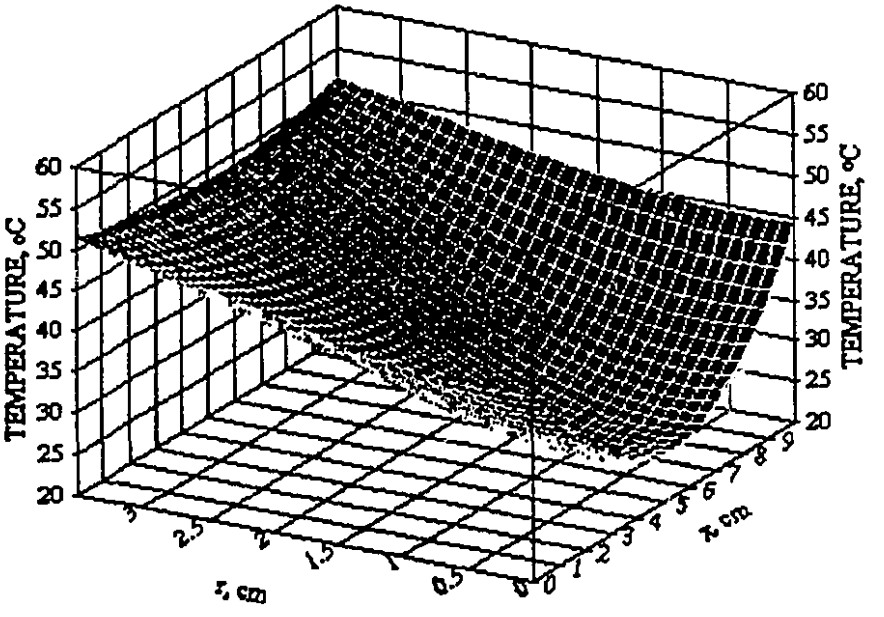

Figure 4.11 Predicted temperature distributions at t = 10 min. for a 10 cm long-6.5 cm diameter potato tuber immersed in a 52 °C water bath.

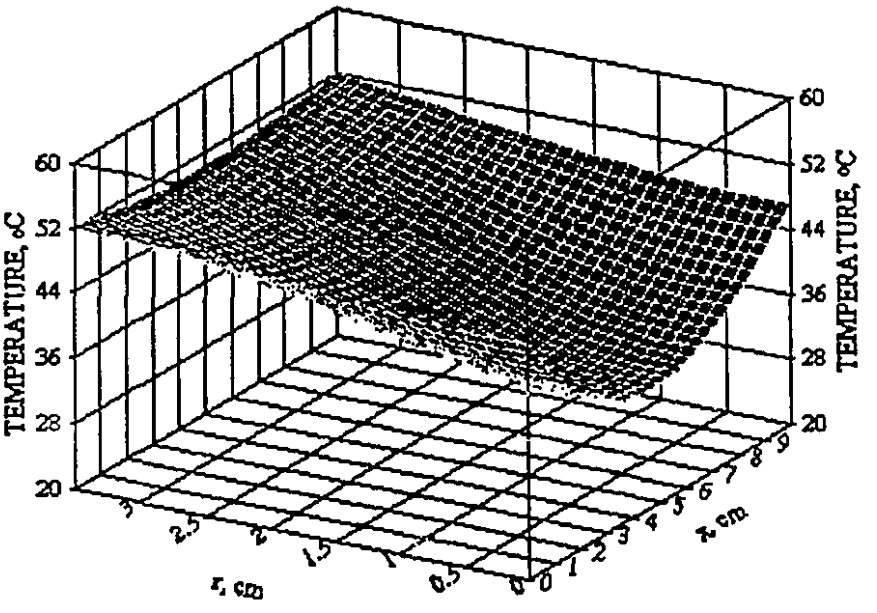

Figure 4.12 Predicted temperature distributions at t = 20 min. for a 10 cm long-6.5 cm diameter potato tuber immersed in a 52 °C water bath.

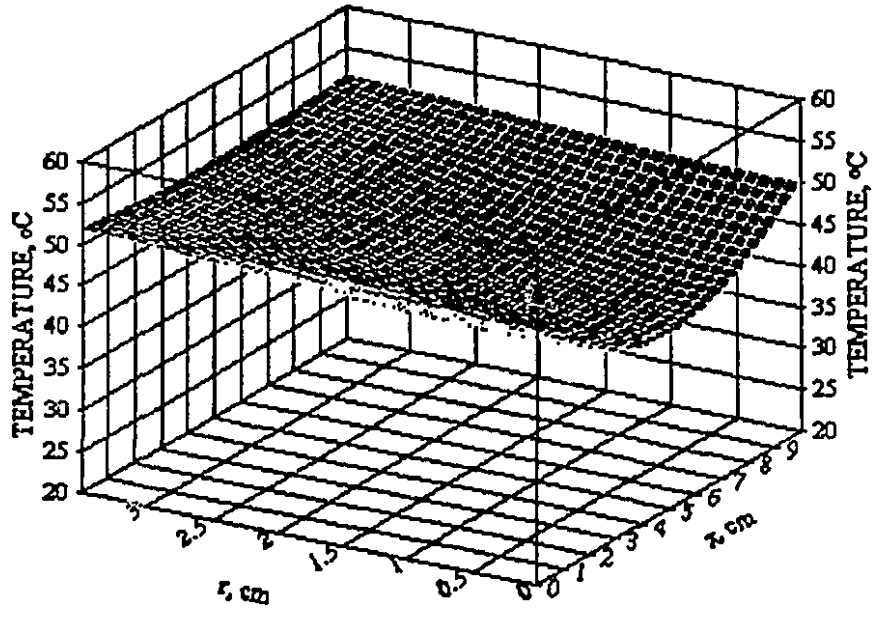

Figure 4.13 Predicted temperature distributions at t = 30 min. for a 10 cm long-6.5 cm diameter potato tuber immersed in a 52 °C water bath.

nodes approach the ambient temperature after few minutes (less than 10 minutes) while the centre line nodes need about 30 minutes to reach 90% of the bath temperature.

Summary

The numerical procedure predicted the heat transfer distribution in the potato (cv. Superior) and fitted very well with the experimental data. The developed numerical model is not restricted in its application to a single potato cultivar but can be extended to other cultivars grown in different parts of the world and may be tried on the other fruits and vegetables.

CHAPTER V
MATERIALS AND METHODS

Experiments were carried out separately for sprout inhibition and disease control using the thermal treatments under consideration. After treatments, the potatoes were stored in two separate storage chambers maintained in environments of 8 or 18°C, both at 90-95% relative humidity.

5.1 Potato cultivar and procurement

Potato cultivar Superior not treated with any postharvest chemicals was procured from a local grower in Quebec, Canada, after wound healing and dormancy. Uniformly-sized and disease-free tubers were selected for treatments in all the experiments. The required potato stock were procured in one instalment to eliminate the possibility of obtaining tubers grown in more than one site. The potatoes were stocked in a cold chamber maintained at 4°C and 90-95% RH until they were used for the experiments.

5.2 Preparation of potatoes

Two days before the start of experiments the required quantity of potatoes were removed from the cold chamber and kept at room temperature in a dark place to let the tubers reach equilibrium temperature with the room conditions and to initiate sprouting. The potato tubers were washed thoroughly to remove soil particles adhering to their surfaces. Care was taken not to damage them and they were spread on paper towels until air-dried. In the case of disease control experiments, the tubers were washed with running water and air dried as above. The tubers were then transferred inside the fume hood. The tubers were then dipped in a solution of 0.1% sodium hypochlorite for 5 minutes and rinsed with distilled water and air dried. These procedures were precisely followed for all the experiments.

5.2.1 Tuber wound making

A special wound making unit was developed (Figure 5.1) enabling inoculation of tubers with the pathogen/bacteria inoculum. Two wounds were made on both the heel and rose ends at 1/3 distance from each end. The wounds were 3 mm in diameter and 2 mm deep. They were made on one side of the tuber only for more convenient handling and treatment.

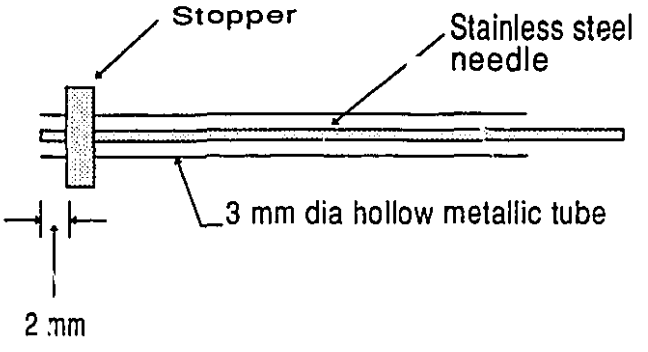

Fig 5.1 Potato tuber wound making unit

5.3 Procurement of Fungi and Bacteria

The *Fusarium solani* (HP12793-1 BRI #192965 cultures and numbers) culture was obtained from the Biosystematics Research Institute, and maintained at the Agricultural Canada Research Station, Charlottetown, Prince Edward Island, Canada. *Erwinia carotovora* pv. *carotovora* (isolate # 138) was obtained from Sainte-Foy Research Station in Quebec, Canada, in the month of November 1992. The *Fusarium solani* was cultured and stored in a soil medium. *Erwinia carotovora* pv. *carotovora* was transferred into a number of micro-centrifuge tubes and stored in the freezer maintained at -86°C.

5.4 Media and culture preparation

5.4.1 *Fusarium solani*

The required volume of potato dextrose agar (PDA) was prepared in a flask by mixing potato dextrose agar powder into distilled water at 39 g/l. The solution was warmed and well stirred. Later, the PDA was autoclaved at 15 psi for 20 minutes. The PDA was then allowed to cool to room temperature. Before the PDA solidified, it was distributed to petri-plates and sealed with paraffin. Once the PDA solidified, the fungi stored in the soil media were transferred to the petri-plates by sprinkling a few soil particles over the media. The plates were re-sealed with paraffin and finally transferred into an incubator maintained at 28°C. The incubation period was 7 days.

5.4.2 *Erwinia carotovora* pv. *carotovora*

In the case of bacteria *Erwinia carotovora* pv. *carotovora*, a nutrient agar (NA) solution was prepared by mixing the nutrient agar in distilled water (at the proportion specified) and stirred. As in the case of the fungi, the nutrient agar solution was autoclaved at 15 psi for 20 minutes. The NA was allowed to cool to room temperature and kept in the hood. It was then distributed to petri-plates and sealed with paraffin. Once the NA solidified, the bacteria stored in the freezer at -86°C (from one of the micro centrifuge tubes) were transferred into the petri-plates by spreading the inoculum in a zig-zag over the NA medium. The plates were sealed with paraffin and finally transferred into an incubator maintained at 37°C. The incubation period was 4-5 days.

5.5 Suspension concentration and inoculation

5.5.1 *Fusarium* suspension

A spore concentration of 50,000/ml was used for *F. solani*. Each wound site was inoculated with 10 µL applied through a micro-pipette. After each

inoculation the tuber was given a slight hand beat, if necessary, to make the inoculum enter the wound site easily. A haemacytometer and microscope were used to measure the fungal spore concentration.

5.5.2 *Erwinia carotovora* pv. *carotovora* (Ecc) suspension

A cell concentration of 10^7/ml was used for *E. carotovora var. carotovora*. Each wound site was inoculated with 10 µL aliquot using a micro-pipette. As before, a slight hand beat was given to make the inoculum enter the wound site easily. A spectrophotometer (Spechonic 20, Bausch & Lomb, USA) and a microscope were used to calibrate cell counts versus optical density (see section 5.6, and Figure 5.2).

5.6 Calibration curve for bacteria cell counts

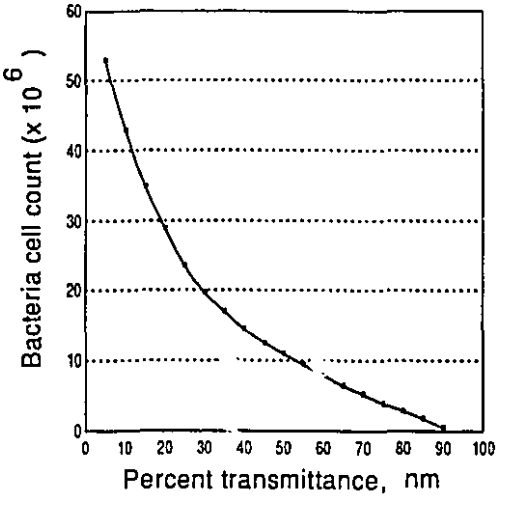

Fig 5.2 Calibration curve for bacteria cell counts

A calibration curve was developed for quick counting of the inoculum suspension of *Erwinia carotovora* pv. *carotovora* (Figure 5.2). This was developed by taking the bacteria cell counts in a well grown nutrient broth medium maintained in test tubes at different concentrations. At each concentration, the physical counts of bacteria were established using a

microscope and checked through a spectrophotometer to record the percent transmittance at 540 nm. Different transmission values were obtained for different suspension concentrations and a graph was developed (Figure 5.2)

5.7 Treatment Factors

After the incubation periods, the trays were shifted to a cold room maintained at 4°C for a short period before being used in the experiment. On the day of experiment the trays were removed from the cold room and shifted to the experimental site. The tubers were picked up at random from the trays (corresponding to the incubation period) and used for thermal treatments.

5.7.1 Incubation period

The inoculated tubers (separately for fungi and bacteria) were immediately put in rectangular plastic trays with a fine spray of distilled water and wrapped with polyethylene bags and tied airtight to maintain a relative humidity of about 90% during the incubation period. The tubers were incubated at a temperature of 28 ± 1°C for *F. solani* and 37 ± 1°C for *E. carotovora* pv. *carotovora* for three different incubation periods in each case. The tubers inoculated with fungi were incubated for 0, 1, or 2 days and those with bacteria were incubated for 0, 6, or 12 hours. At the end of the incubation period, the tubers were shifted to a cold room at 4°C for a day or two until the thermal treatments.

5.7.2 Hot Water Dipping

As was seen in the preliminary studies on sprout control (Chapter III) the hot water temperature of 55°C was effective in controlling sprouts (Chapter III) as well as keeping the tuber intact without any physical damage. Furthermore, the disease control studies by Mackay (1986) and Robinson and Foster (1987) and Perombelon (1989), showed that the temperatures in the range of 51 and 54°C were effective in controlling other diseases of potato

tubers such as eye infection, black scurf, and blackleg. Therefore, three incubation period: 0, 1 and 2 days for *F. solani* and 0, 6 and 12 hrs for *Erwinia carotovora* pv. *carotovora*, three hot water temperature levels: 52.5, 55 and 57.5°C, and three dipping times: 10, 20 and 30 minute were considered for this investigation. The factor levels are summarized below.

a) Incubation levels:	i) Fungi:	0, 1, 2 days
	ii) Bacteria:	0, 6, 12 hours
b) Temperature Levels:	i) Fungi:	52.5, 55, and 57.5°C
	ii) Bacteria:	52.5, 55, and 57.5°C
c) Duration	i) Fungi:	15, 20, 25 min.
	ii) Bacteria:	15, 20, 25 min.

5.7.3 Ultraviolet Radiation

a) Incubation levels:	i) Fungi:	0, 1, 2 days
	ii) Bacteria:	0, 6, 12 hours
b) UV:	i) Fungi:	$0.75x10^4$, $1.0x10^4$, $1.25x10^4$ and $1.5x10^4$ W.s/m^2
	ii) Bacteria:	$0.75x10^4$, $1.0x10^4$, $1.25x10^4$ and $1.5x10^4$ W.s/m^2

5.7.4 Vapor heat

a) Incubation levels	i) Fungi:	0, 1, 2 days
	ii) Bacteria:	0, 6, 12 hours
b) Temperature Levels:	i) Fungi:	50, 60, and 70°C
	ii) Bacteria:	50, 60, and 70°C
c) Duration:	40, 50 and 60 min (for both)	

5.7.5 Combination of ultraviolet and hot water treatments

In the case of combination treatments, potato samples were first treated with ultraviolet radiation, and immediately thereafter, the same samples were

treated with hot water on a continuous basis.

5.8 Experimental Design

5.8.1 Experiments on sprout control

1. Hot water treatment	:	A 3 x 3 Factorial design in RCBD with three replications
2. Ultraviolet Radiation	:	RCBD with three replications
3. Vapor heat treatment	:	A 3 x 3 Factorial design in RCBD with three replications
4. Combination treatments	:	4 x 3 x 3 Factorial experiments with three replications

5.8.2 Experiments on disease control

1. Hot water treatment	:	A 2^{3-3} CCRD design
2. Ultraviolet Radiation	:	4 x 3 factorial experiment in RCBD

5.9 Determination of percentage sprouting

The total number of sprouted and spoiled tubers in each replicate were counted and recorded at intervals of fifteen days and the percentage of sprouted/spoiled tubers were calculated as follows:

$$Percentage\ of\ eyes\ sprouted = \frac{Number\ of\ eyes\ sprouted\ in\ a\ sample}{Total\ number\ of\ eyes\ in\ the\ sample\ tubers} \times 100 \quad (5.1)$$

5.10 Disease examination and severity recording

The tubers were stored at two different storage temperatures of 8° and 18°C and 90-95% relative humidity. The treated potatoes were examined once in 15 days for infection of soft rot and dry rot during a short-term storage period of three months and read as YES or NO. In case of YES results, the diameter of infected colony in each tuber was measured and recorded in mm.

The wound sites which showed symptoms of disease infection were recorded as YES; and these sites were rounded off by a marker pen and the disease incidence was recorded. The disease incidence is expressed as the proportion of sites infected (PSI) which is derived as:

$$Proportions\ of\ sites\ infected = \frac{Observed\ number\ of\ infected\ sites}{Total\ sites\ inoculated} \qquad (5.2)$$

The severity of the disease infection was recorded by measuring the diameters of all colonies of the infected sites and then averaging the colony diameters. The average colony diameter is derived as:

$$Average\ colony\ diameter = \frac{Total\ diameters\ of\ all\ colonies}{Total\ sites\ inoculated} \qquad (5.3)$$

The percentage spoilage of tubers was calculated by:

$$Percentage\ of\ tubers\ spoiled = \frac{No.\ of\ tubers\ spoiled}{Total\ number\ of\ tubers\ in\ the\ sample} \qquad (5.4)$$

5.11 Experimental Apparatuses

5.11.1 Hot water treatment unit

A 30 litre water holding capacity and a 1000 W heater capacity water bath (Lab-Line Instruments Inc., Illinois, USA) was used for the hot water treatment of potatoes with a temperature resolution of ± 0.5 °C. The mass of potato samples were measured before and after the treatment and at the end of storage period (three months) with the help of a digital weighing balance having an accuracy of ± 0.01 g (Mettler PE 3600, USA).

5.11.2 Ultraviolet treatment unit

A completely airtight UV Chamber was built to carry out the experiments (Figure 3.1). Its dimensions were 90 cm x 90 cm x 45 cm. Two ultraviolet lamps procured from UVP Inc., USA, were fitted at the inside top

of the chamber. Together they emit a maximum radiation intensity of 1500 $\mu W/cm^2$ at a distance of 30 cm from the UV light source. A rotating disc was provided inside the chamber on which Potato samples were placed during the treatment (Figure 3.1) to completely expose the surface of the tuber to the ultraviolet radiation. Three reflecting plane mirrors were also positioned on the sides of three walls at a 45° inclination to direct the UV rays to the bottom and sides of the tubers. A UVX - radiometer (UVP Inc., USA) was used to measure the UV radiation intensity at 254 nm.

5.11.3 Vapor heat treatment unit

A separate unit was fabricated for vapor heat treatment (Figure 3.2). A U shaped vapor impinging tube was designed on which a series of holes (2 mm diameter) were drilled so that the tuber gets vapor heat both from the top as well as from the bottom; in other words, the design ensures a uniform distribution of vapor heat inside the chamber. A rotating circular disc meshed with a plastic material was mounted on a pivot provided in between the U tube (Figure 3.2). The disc was made to rotate at a speed of about 15 rpm during the treatment period. The rotation of the disc was obtained by using a small motor with speed control mechanism. The tubers were kept equally spaced on the disc.

5.11.4 Storage chambers

Two storage chambers measuring 1.8 m x 1.8 m x 0.75 m were designed and built to store treated potato at two different temperatures of 8 and 18°C and relative humidity 90-95%. One of the two storage chambers was built in such a way that it was insulated on three sides, and at the top and bottom. To this chamber a controlled atmosphere unit was connected to maintain an environment of 18°C and 90% relative humidity. Additional humidifiers were employed in both the chambers to maintain a relative humidity of 90-95%. Steel racks were placed 30 cm apart in each storage chamber to store the

treated samples. The other storage chamber was put inside a big cold room and temperature level was adjusted to 8°C.

5.12 Instrumentation

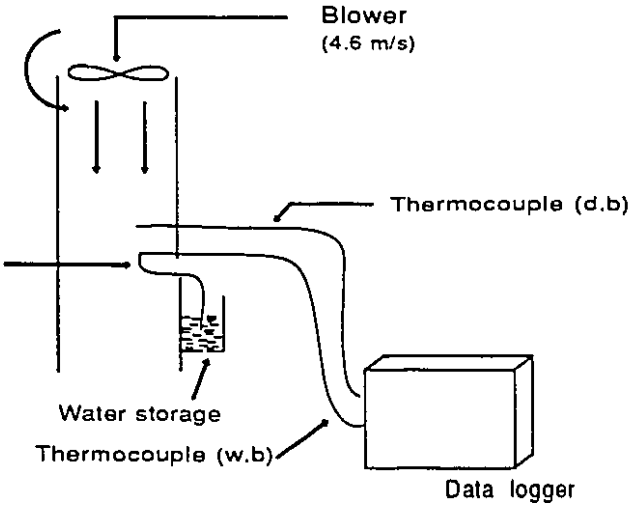

Figure 5.3 Instrumentation details for humidity measurement in storage chambers.

'T' type thermocouples were used to measure the transient temperature responses of the tubers to heating. Temperatures were monitored in the hot water bath, and at the tuber surface and centre. The time-temperature data was gathered by connecting the thermocouples to a scanning data logger (Scanning thermocouple thermometer version V 2.2, Cole-Parmer Instruments Company, Chicago) which was further routed to a personal computer. The computer recorded and stored the time-temperature data at 4 second intervals. The temperatures and humidity in the storage chambers were measured by 'T' type thermocouples connected to a data logger and by a separate set up fabricated to measure the wet bulb and dry bulb temperatures (Figure 5.3) inside the cold room. In addition to this, a humidity sensor (Tri-Sense, USA)

was also used to monitor the humidities in the storage chambers, to have a complete safety in monitoring of the storage environments. The intensity of UV radiation was measured with a radiometer (UVP Inc., USA). A stop watch was used to time the treatments. A digital weighing balance was used to record the mass of the samples (Mettler PE 3600).

5.13 Statistical analysis: Response surface methodology

This method can be defined as a statistical method which uses quantitative data from appropriate experimental designs to determine and simultaneously solve multivariate equations (Giovanni, 1983; Ellis, (1993). This method is based primarily on the work of Box and Hunter (1958). Factorial experiments, in which the levels of any factor refer to a measured quantity can be viewed as experiments planned to determine the nature of a response surface. The response can be thought of as a surface over the explanatory variables' experimental space (Ellis, 1993). The term response surface has been associated with experiments intended to identify or evaluate one or more response variable as a function of the independent variables. In particular, these response have been very useful in process optimization studies where one is presumably interested but not limited to a value near a maximum or a minimum.

Most response surface experiments focus on polynomial models with emphasis on first and second order models (Thomson, 1982; Ellis, 1993). First order models are used for exploratory purposes when little is known about the relationship of the dependent variable and candidate explanatory variables. They are used to screen the potentially significant explanatory variables for inclusion in further experiments. Second order models often provide a better estimate of the response variable in function of the independent variables. Several designs can be used for second order models, but most of the current response surface experiments use the Central Composite Rotatable Design (CCRD) (Box, 1978; Hunter and Hunter, 1978).

When the fitted response function is plotted in three or two dimensional space, the resulting graphs are referred to as response surface plots or contour maps, respectively. The main effects and interactions included in the statistical model are easily interpreted in term of such response surfaces (Steel and Torrie, 1980). These surfaces can be a variety of shapes but the most commonly generated ones are the cradle or bowl and the saddle. For the cradle-shaped surface the optimum response lies along the top edges whereas for the saddle shaped surface, it lies along the sides or in one or more of the four corners.

Response surface methodology can be thought to consist of the following strategy:

a) setting a series of experiments to provide an adequate and reliable estimate of the response variable(s) of interest;
b) determining a mathematical model that best fits the data collected from the experiments conducted and testing the hypothesis concerning the parameters estimates in the model; and
c) estimating the optimum settings of the independent variables that would yield the maximum or minimum value of the response variable(s) of interest (Khuri and Cornell, 1987; Ellis, 1993).

The statistical design for the hot water treatment for the disease control was a 3-variable 3-level Central Composite Rotatable Design (CCRD) replicated twice (Box, 1978). In comparison to a complete factorial design, the CCRD has the advantage of having less treatment combinations (Table 5.1). Furthermore, the variances are a function of the distances from the centre of the design rather than of the direction.

Table 5.1 Coded combinations for a three-variable three-level Central Composite Rotatable Design used to study the effect of hot water treatment on the control of diseases.

Run #	Variable*		
	Incubation	Temperature	Duration
1	-1	-1	-1
2	+1	-1	-1
3	-1	+1	-1
4	+1	+1	-1
5	-1	-1	+1
6	+1	-1	+1
7	-1	+1	+1
8	+1	+1	+1
9	-1	0	0
10	+1	0	0
11	0	-1	0
12	0	+1	0
13	0	0	-1
14	0	0	+1
15	0	0	0

Each run was replicated twice for a total of 30 runs.

* The actual values for the coded levels are given in Tables 5.2 and 5.3.

The design is said to be rotatable. Given a limited number of observations it is the most appropriate and sensitive design to use because of its intrinsic properties. The factor levels were coded from -1 to +1 and were equally spaced (Tables 5.2 and 5.3). The total number of runs was calculated

using the formula: $2^k + (2*k) + 1$, where k was the number of variables. The run order was completely at random. The statistical analysis of the data was performed on the average value of the 2 runs using the Statistical Analysis System (SAS, 1982).

Table 5.2 Coded levels for the real values of variables used in CCRD to study the effect of hot water treatment on dry rot (*Fusarium solani*) disease.

Variables	Coded levels		
	-1	**0**	**+1**
Incubation, days	0	1	2
Temperature, °C	52.5	55	57.5
Duration, min	10	20	30

Table 5.3 Coded levels for the real values of variables used in CCRD to study the effect of hot water treatment on Soft rot (*Erwinia carotovora* pv. *carotovora*) disease.

	Coded levels		
	-1	**0**	**-1**
Incubation, hrs	0	6	12
Temperature, °C	52.5	55	57.5
Duration, min	10	20	30

5.14 Potato quality measurements

Potato color and texture are important marketing criteria based on consumer preference. Browning may occur depending upon different thermal treatments as well as duration of the exposure. Texture as well as color are also adversely affected by severe infection.

5.14.1 Firmness

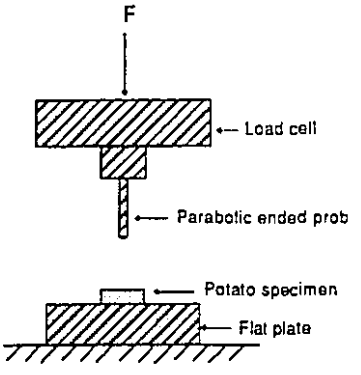

Fig 5.4 Schematic of the potato compression test

Firmness is one measure used to assess the texture of tubers. The firmness of each potato was measured at two positions (1/3 distance from heel and rose ends) of a cut specimen 15 mm thick using a puncture borer of 12 mm diameter. The thickness of the specimen was measured using a vernier calliper. Each specimen was prepared to the thickness defined and was placed over a flat plate. A puncture load was applied through a parabolic-shaped end of the cylindrical rod mounted (Figure 5.4) in the Universal Testing Machine (series 4502) with a 500 N load cell. This machine is connected though a General Purpose Interface Bus (GPIB) to a PC computer. The computer controls the Instron Machine by the Series IX automated material testing software version 5.2. The results of force and deformation during each puncture test was directly transmitted to the computer as raw data. The raw

data were used as input for the Series IX software which later converts into actual outputs such as stress, strain, modulus of elasticity, energy, toughness, etc,.

5.14.2 Color

The color characteristics are measured in L, a and b coordinates using a Chroma Meter (Minolta Chroma Meter, CR-200b, Minolta Camera Co. Ltd., Azuchi-Machi, Chuo-Ku, Osaka 541, Japan). The Chroma Meter was calibrated against a standard calibration plate of a white surface (supplied by the Minolta) with L, a and b values adjusted to 94.4, 0.313 and 0.320, respectively, according to the manufacturer's recommendations. The Chroma Meter lens was focused and flashed on a clean potato tuber for the color determination. The measurements were taken for all the tubers in each sample and the averages for L, a and b were recorded. The ratio a/b was also calculated.

5.14.3 Structure

Scanning Electron Microscopy was used to study the structural changes of potato tubers. The sample was taken from the tuber according to the method followed by Fedec et al., (1977). The potato tubers, both control and treated (hot water, UV, and combination of UV and hot water), were cut into halves along the minor axis with a razor. The parallel cuts obtained were then further sliced radially towards the centre of the pith. A tiny section of 2 x 2 x 2 mm was cut from the zone of storage parenchyma cells of the tuber. These samples were dipped in frozen liquid nitrogen. Then, the samples were freeze-dried in a freeze dryer (Lyo-San Inc., Lachute, Quebec, Canada) for 24 hours. The temperature of the condensing plate was -60°C. The dried samples were mounted on aluminium stubs, and they were gold sputtered using a vacuum evaporator. The samples were then examined in JSM-6300F Scanning Microscope (JEOL USA, Inc., Peabody, MA) at 10 kV accelerating voltage.

CHAPTER VI
RESULTS AND DISCUSSION

6.1 HOT WATER TREATMENT FOR DISEASE CONTROL

Experiments were performed to study the effectiveness of hot water treatments at controlling dry rot and soft rot diseases for two years in the fall of 1993 and 1994. These were part of the general goal of finding combinations of temperature and time that would be effective in the control of both sprouting and disease so as to evaluate the practicality of a one-stage hot water treatment. The effects could not be studied at the same time due to the impracticality of performing the experimental manipulations necessary for evaluating each effect.

As described in Chapter V, the experiments were run in CCR Design with 3 times of incubation of the pathogens, 3 water bath temperatures and 3 residence times. The data were analyzed using SAS software. Because potatoes from two years of cultivation were used, Bartlett's test for homogeneity of variances was performed prior to running the response surface analyses to determine whether or not the data could be pooled. In all cases, variances due to years were homogeneous, indicating that the potatoes from each year were similar. Thus, further analyses were run on the pooled data. The least square means of PSI, COL and SPOIL for all treatment combinations for the pooled data are presented in Table 6.1. Complete response surface models (ie. including all square and interaction terms) were examined by canonical analysis for the different dependent variables (proportion of sites infected - PSI; average colony diameter - COL; spoilage percentage - SPOIL). This was to provide an indication of the precision of predicted values near the centers of the designs and to determine whether there was lack of fit. As none of the models exhibited lack of fit, the most significant parameters in each case (interactions often eliminated) were used in a best regression procedure based on R^2 and the C_p statistics as selection criteria (Box et al. 1958). The best

models for the dependent variables are presented in Table 6.2.

Table 6.1. Least square means for *Fusarium solani* (stored at 8°C)

T[a]	Incub (days)	Temp (°C)	Time (min)	PSI[c] (decimal)	COL[d] (cm)	SPOIL[e] (%)
1	0 (-1)[b]	52.5 (-1)[b]	10 (-1)[b]	0.185 ± 0.028	1.58 ± 0.206	33.30±3.89
2	2 (+1)	52.5 (-1)	10 (-1)	0.310 ± "	1.81 ± "	33.30± "
3	0 (-1)	57.5(+1)	10 (-1)	0.040 ± "	0.40 ± "	8.30 ± "
4	2 (+1)	57.5(+1)	10 (-1)	0.100 ± "	0.78 ± "	16.6 ± "
5	0 (-1)	52.5(-1)	30 (+1)	0.140 ± "	1.26 ± "	14.45 ± "
6	2 (+1)	52.5 (-1)	30 (+1)	0.165 ± "	1.28 ± "	20.8 ± "
7	0 (-1)	57.5(+1)	30 (+1)	0 ± "	0 ± "	0 ± "
8	2 (+1)	57.5(+1)	30 (+1)	0 ± "	0 ± "	0 ± "
9	0 (-1)	55 (0)	20 (0)	0 ± "	0 ± "	0 ± "
10	2 (+1)	55 (0)	20 (0)	0 ± "	0 ± "	0 ± "
11	1 (0)	52.5 (-1)	20 (0)	0.182 ± "	1.48 ± "	20.77 ± "
12	1 (0)	57.5(+1)	20 (0)	0 ± "	0 ± "	0 ± "
13	1 (0)	55 (0)	10 (-1)	0.122 ± "	0.98 ± "	16.6 ± "
14	1 (0)	55 (0)	30 (+1)	0 ± "	0 ± "	0 ± "
15	1 (0)	55 (0)	20 (0)	0.020 ± "	0.18 ± "	4.15 ± "

[a] Treatment #, each treatment was replicated twice. [b] The numbers in the parenthesis are the coded levels. [c] PSI is the least square means of proportion of sites infected. [d] COL is the least square means of average colony diameter. [e] SPOIL is the least square means of percentage spoilage.

Table 6.2 Reduced regression models to predict PSI, COL and SPOIL due to *F. solani* as a function of hot water treatment factors.

PSI	$= -0.01328^{ns}$	$+ 0.021500I^{*}$	$- 0.08375TE^{***}$	$+ 0.068035T^{2**}$	$- 0.044750TI^{***}$	$+ 0.038035TI^{2*}$	$- 0.02062I*TI^{*}$	
	(0.0119)	(0.0074)	(0.00746)	(0.01409)	(0.00746)	(0.01409)	(0.00834)	$R^2=0.96$
COL	$= 0.65233^{***}$	$+ 0.06350I^{ns}$	$- 0.62575TE^{***}$	$- 0.30150TI^{*}$	$- 0.07500TE*TI^{ns}$			$R^2=0.73$
	(0.10787)	(0.13211)	(0.13211)	(0.13211)	(0.14770)			
SPOIL	$= 1.837857^{ns}$	$+ 1.877500I^{*}$	$- 9.36000TE^{***}$	$+ 7.867857TE^{2***}$	$- 6.86500TI^{***}$	$+ 5.792857TI^{2**}$		$R^2=0.97$
	(1.20053)	(0.74866)	(0.74866)	(1.41484)	(0.74866)	(1.41484)		

NOTE: Figures in parentheses are standard errors of estimates

[a] All the hot water treatment factors levels were coded (Table 6.1); I is the incubation period of tubers after inoculation of *F. solani*; TE is the temperature of hot water bath, and TI is the duration of hot water dipping. * significant at 5% level; ** significant at the 1% level; *** significant at 0.1% level; and [n.s] not significant.

The results for disease control by hot water dipping are presented in two major sections, one for subsequent storage at 8°C as would be the case for northern temperate regions, and one for subsequent storage at 18°C which reflects average non-refrigerated storage temperatures typical at harvest in the semi-arid tropics using the "country" storage methods described in the literature review.

6.1.1 Hot water treatment and storage at 8°C

a) Control of dry rot

i) Proportion of sites infected (PSI)

Incubation period had a significant effect on PSI ($p < 0.0205$). PSI increased linearly with increasing incubation period. However, because the interaction of incubation period and time of hot water dipping was also significant ($p < 0.0386$), the main effects cannot be interpreted alone. This interaction, being interpreted as the linear effect of incubation period, was of a larger magnitude at low dipping treatments (coded -1) whereas not much difference was attributable to longer treatment durations and the PSI always dropped off with treatment duration. The model predicted that for an intermediate incubation period (coded 0) complete eradication of *Fusarium* pathogen could be achieved by using dipping time ≥ 22.5 min and hot water temperature ≥ 55.4°C (Figure 6.1). Here, it is understood that this range must be constrained to below 60°C regardless of hot water dipping time due to the high percent of physical damage expected (50% or more, based on the results of the preliminary studies in Chapter III).

The canonical analysis indicated that the stationary point was neither a maximum or minimum but a saddle point (Incub = 26.4 hrs, Temp = 56.4°C and time = 25 min). There was no single optimum combination. A range of temperature and time combinations can be used to disinfect potato tubers from the *Fusarium* pathogen depending on the degree of pathogen growth (related to incubation time). Because the predicted values and standard errors tend to

be larger away from the centre of the design, a conservative approach would be to interpret the effects for a fixed incubation period near the centre of the design for better precision. The ridge of minimum response corresponding to temperature, time and incubation levels from 0 to +1 varied from 0.051 near the centre of the design to -0.062 at the periphery.

It was observed that the effect of hot water temperature of 55°C and dipping time of 20 minute and above resulted in total control of dry rot in the potato samples stored for a short-term storage of three month at 8°C temperature. A higher proportion of infected sites was observed at the lower temperature and dipping times (52.5°C and 10 and 20 min, respectively) followed by the lower temperature and higher dipping level. Although longer incubation periods increased the proportion of infected sites, the treatments at 55°C and above were very effective in disinfecting the tubers from *F. solani* and preventing disease symptoms.

For the lower temperature treatments where disinfection was not effective (ie. those associated with longer incubation periods), the actual disease symptoms started appearing between the fourth and sixth week after treatment. This was probably because the pathogen had spread more deeply into the tuber and was therefore not exposed to as much thermal energy as the parts of the colony close to the surface. In fact, the data show that a longer application time is generally required to achieve the same killing effect for a longer incubation time than for a shorter one. This also corresponds to the transient temperature behaviour of the tuber predicted by the heat transfer model.

The control treatment, inoculated but not treated with hot water were completely spoiled due to severe infestation of dry rot disease. The results are similar to the findings of Hide (1975) and Mackay & Shipton (1983) who demonstrated black scurf disease of potato tubers could be effectively controlled by dipping in hot water at 55°C and 10 min, in addition to reducing eye infection of tubers.

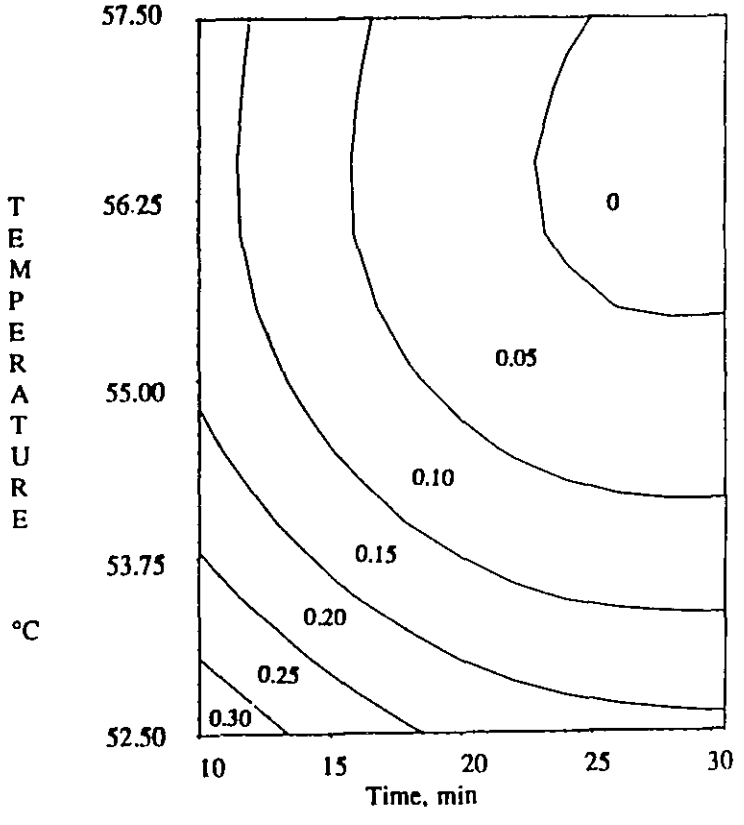

Figure 6.1: Contours PSI (dry rot) as a function of hot water temperature and dipping time (Incub = 1 day, storage = 8°C).

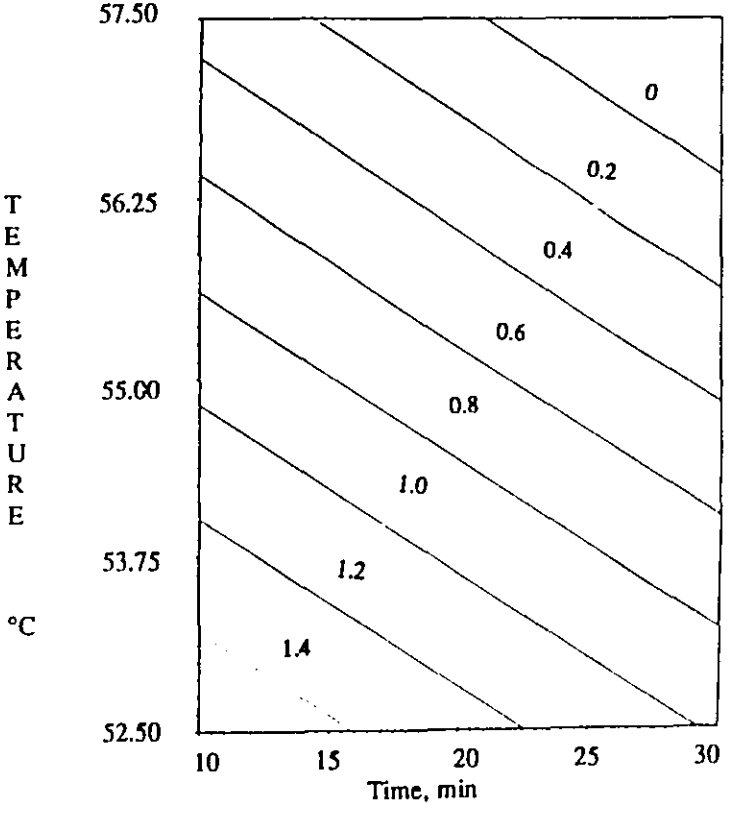

Figure 6.2: Contours COL (dry rot) as a function of hot water temperature and dipping time (Incub = 1 day, storage = 8 °C).

ii) Average colony diameter (COL)

The average colony diameter decreased with increasing temperature and dipping time. The effect of temperature was highly significant ($p< 0.0008$), whereas the effect of time was only significant at the 5% level ($p< 0.0456$). Incubation times in the range used had no significant effect on average colony diameter. No significant interaction occurred among the parameters. Therefore, some of these terms were not kept in the final model. The model estimates were used to plot the contours (Figure 6.2). As mentioned earlier, because of the nature of the CCR Design more precision is achieved for the estimates near the centre of the design. Therefore, plotting was done with incubation = 0 (coded), since incubation had no significant effect. For an intermediate incubation period, the model predicts complete control of *Fusarium* colony growth (COL = 0) for the treatment time ≥ 22 min and Temperature ≥ 55°C, again with the same physical damage considerations mentioned in the previous section.

The canonical analysis of the full model indicated that the stationary point was a saddle point (Incub= 26.16 hrs, Temp= 56.4°C and Time= 25.3 min). The ridge of minimum response corresponding to temperature and time from 0 to +1 (coded levels) varied from 0.178 at the center to -0.222 at the periphery of the design.

It was observed that the colonies among the infected sites started appearing only after fourth week in some samples and after fifth and sixth weeks in others and the development of the infected colonies was rather slow. The results of the study are comparable to the findings of Perombelon et al. (1989) who have demonstrated the satisfactory control of potato blackleg disease at 53 and 55°C hot water temperature.

iii) Percent spoilage of tubers (SPOIL)

Incubation had a significant effect on SPOIL. Spoilage increased linearly with increasing incubation period ($p < 0.0334$). However, temperature

and time significantly reduced spoilage. Both linear and quadratic components were significant. All of these components were significant at the 1% level (Tables 6.3 and 6.4). None of the interaction terms were significant and were dropped from the full model. For an intermediate incubation period the model predicts that the minimum spoilage could be achieved by using with temperature≥55.5°C and time ≥ 19 minutes (Figure 6.3).

The canonical analysis for the full model indicated that the stationary point was a saddle point (Incub = 27.12 hrs, Temp = 56.4°C and Time = 25 min 6 sec). The ridge of minimum response for corresponding temperature, time and incubation levels from 0 to +1 varied from 2.39 at the centre to -4.262 at the periphery of the design.

b) Control of soft rot

i) Proportion of sites infected (PSI)

Incubation period had no effect on PSI compared to its significant effect observed in the case of *F. solani*. Both linear and quadratic effects of temperature were highly significant ($p<0.0001$ and $p<0.0002$) followed by the significant linear effect of time ($p < 0.0014$). The PSI decreased with increasing temperature and time. However, the quadratic effect of the temperature indicated that the rate of PSI decrease was slowed down with increasing increment of temperature. The model predicts that for an intermediate incubation period (coded 0) complete disinfection of *Erwinia carotovora* pv. *carotovora* can be achieved by using dipping times ≥ 19 min and hot water temperature ≥ 54°C (Figure 6.4).

The canonical analysis indicated that the stationary point was a saddle point (Incub = 0.75 h , Temp = 56.125°C and time =21.7 min). As observed before, a range of temperature and time combinations can be used to disinfect potato tubers from the *Ecc* bacteria.

The hot water treatments at 55°C and above completely disinfected the tubers from *Erwinia* regardless of incubation time, and they stayed disease-

free until the end of storage. At lower temperatures and residence times, disease symptoms appeared only after four to six weeks storage.

Table 6.3 Least square means for *Erwinia carotovora* pv. *carotovora* stored at 8°C.

T[a]	Incub (days)	Temp (°C)	Time (min)	PSI[c] (decimal)	COL[d] (cm)	SPOIL[e] (%)
1	0 (-1)[b]	52.5 (-1)[b]	10 (-1)[b]	0.24 ± 0.014	1.45 ± 0.473	29.12 ± 2.427
2	2 (+1)	52.5 (-1)	10 (-1)	0.27 ± "	1.77 ± "	33.30 ± "
3	0 (-1)	57.5(+1)	10 (-1)	0 ± "	0 ± "	0 ± "
4	2 (+1)	57.5(+1)	10 (-1)	0.10 ± "	1.38 ± "	12.86± "
5	0 (-1)	52.5(-1)	30 (+1)	0.16 ± "	1.44 ± "	24.95 ± "
6	2 (+1)	52.5 (-1)	30 (+1)	0.16 ± "	1.46 ± "	29.12± "
7	0 (-1)	57.5(+1)	30 (+1)	0 ± "	0 ± "	0 ± "
8	2 (+1)	57.5(+1)	30 (+1)	0 ± "	0 ± "	0 ± "
9	0 (-1)	55 (0)	20 (0)	0 ± "	0 ± "	0 ± "
10	2 (+1)	55 (0)	20 (0)	0 ± "	0 ± "	0 ± "
11	1 (0)	52.5 (-1)	20 (0)	0.20 ± "	1.52 ± "	24.95 ± "
12	1 (0)	57.5(+1)	20 (0)	0 ± "	0 ± "	0 ± "
13	1 (0)	55 (0)	10 (-1)	0.10 ± "	1.54 ± "	16.60 ± "
14	1 (0)	55 (0)	30 (+1)	0 ± "	0 ± "	0 ± "
15	1 (0)	55 (0)	20 (0)	0 ± "	0 ± "	0 ± "

[a,b,c,d] details as listed in Table 6.1

The ridge of the predicted minimum response corresponding to temperature, time and incubation levels from 0 to +1 (coded levels) varied from 0.012 ± 0.010 near the centre of the design to -0.0414 ± 0.011 at the periphery.

Table 6.4 Reduced regression models to predict PSI, COL and SPOIL due to *Erwinia carotovora* pv. *carotovora* as a function of hot water treatment factors.

PSI	$= 0.02000^{ns} + 0.01225I^{n.s} - 0.09425TE^{***} + 0.09425T^{2***} - 0.03975TI^{**} - 0.01531T*T^{n.s}$ (0.0123) (0.0087) (0.0087) (0.0151) (0.0087) (0.0097)	$R^2=0.95$
COL	$= 0.30850^{n.s} + 0.17350I^{ns} - 0.62725TE^{**} + 0.59575TE^{2*} - 0.32425*TI^{*} - 0.21062*I*TI^{n.s}$ (0.10787) (0.13211) (0.13211) (0.13211) (0.14770)	$R^2=0.79$
SPOIL	$= 1.052428^{ns} + 2.121500I^{n.s} - 12.8585TE^{***} + 9.843928TE^{2**} - 3.78150TI^{*} + 5.668928TI^{2*}$ (1.20053) (0.74866) (0.74866) (1.41484) (0.74866) (1.41484)	$R^2=0.95$

NOTE: Figures in parentheses are standard errors of estimates

[a] The levels of all variables in hot water treatment factors were coded (Table 6.1); I is the incubation period of tubers after inoculation of *F. solani*; TE is the temperature of hot water bath, and TI is the duration of hot water dipping. * significant at 5% level; ** significant at the 1% level; *** significant at 0.1% level; and [n.s] not significant.

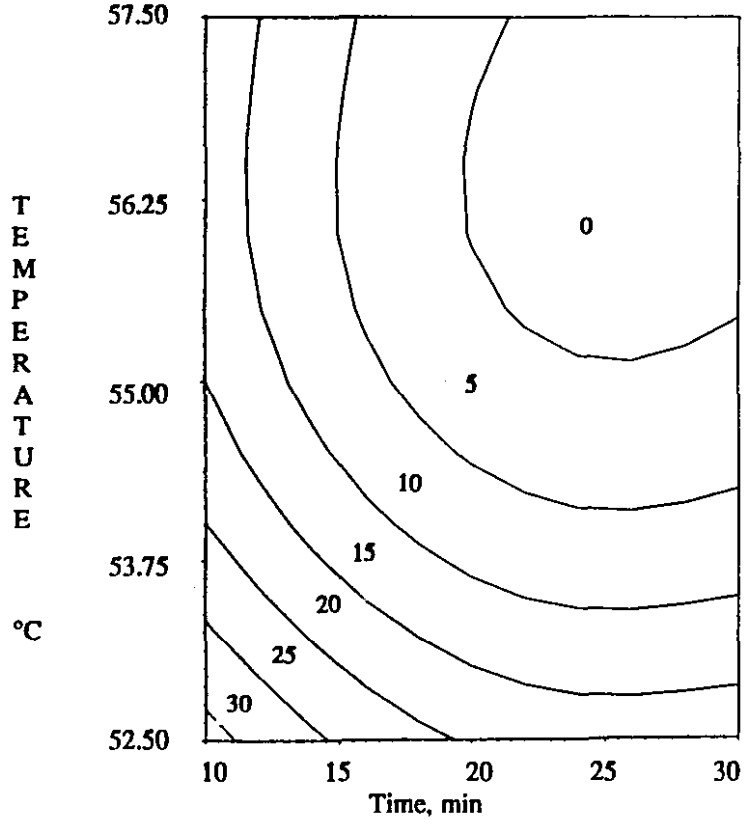

Figure 6.3: Contours SPOIL (dry rot) as a function of hot water temperature and dipping time (Incub = 1 day, storage = 8°C).

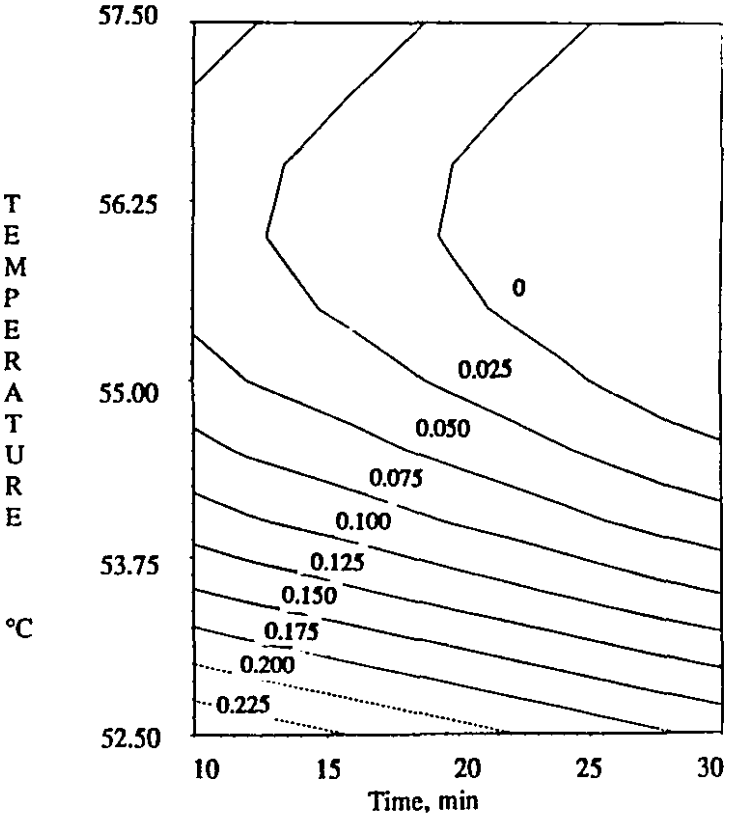

Figure 6.4: Contours PSI (dry rot) as a function of hot water temperature and dipping time (Incub = 6 hr, storage = 8 °C).

In general, for lower temperatures and the longer incubation periods disease symptoms were more drastic. This may be due to deeper penetration into the tissues by the bacterial colony. Parts of the colony having penetrated into the tissues would not be exposed to the same thermal load as that near the surface and would survive the treatment. The control potato samples that were inoculated with bacteria and not treated with hot water were completely spoiled due to infection of soft rot disease.

ii) Average colony diameter (COL)

The average colony diameter decreased linearly with increasing hot water temperature and dipping time but at a decreasing rate for increasing increment of temperature. Both the liner and quadratic effects of temperature were highly significant ($p< 0.0017$ and $p<0.0382$, respectively). Only the linear effect of time was significant at the 5% level ($p< 0.0480$). Incubation has no significant effect on the average colony diameter. No significant interaction occurred among the parameters. The model estimates, standard errors and significance levels are presented in Table 6.4. They were used to plot the surface response graph (Figure 6.5). For an intermediate incubation period the model predicts complete control of *Ecc* colony growth as COL = 0 (coded) for the treatment time ≥ 25.4 min and Temperature ≥ 55.25°C.

The canonical analysis of the full model indicated that the stationary point was a saddle point (Incub= 7.8 h, Temp= 56.625°C and Time= 24.6 min). The ridge of minimum response for the temperature, time and incubation levels from 0 to +1 (coded radius) varied from 0.210 at the center of the design to -0.398 in the periphery.

The colonies of the infected sites started appearing only after the fourth week in some and in the fifth and sixth weeks of storage. It was observed that the development of the colonies was slower at 8°C storage temperature. This may be attributed to the effect of storage temperature (8°C). The incubation period had no significant effect on the average colony diameter.

iii) Percentage of tubers spoiled (SPOIL)

Incubation had no significant effect on spoilage of potatoes. The effect of temperature was highly significant for the linear and quadratic components ($p<0.0001$) and $p< 0.0016$, respectively) (Table 6.4). However, the linear and quadratic effects of dipping times were significant at the 5% level. None of the interaction terms were significant and therefore, were dropped out considered from the reduced model. For an intermediate incubation period (coded 0), the model predicts that the minimum spoilage could be achieved by using temperatures ≥ 55.5°C and time ≥ 16 minute (Figure 6.6).

6.1.2 Hot water treatment and storage at 18°C

a) Control of dry rot

i) Proportion of sites infected (PSI)

Separate experiments were performed to investigate the effect of hot water treatment on the control of both dry rot and soft rot diseases for potato storage at temperature 18°C, as the results would be of practical importance to the semi-arid/tropical country conditions. The dependent variables were the same as in the case of storage temperature at 8°C.

The canonical analysis of the full model indicated that the stationary point was a saddle point (Incub = 22.32 h, Temp = 56.75°C and Time = 23.6 min). There was no single optimum combination. The ridge of the predicted minimum response varied from 0.051 near the centre to -0.062 at the periphery of the design.

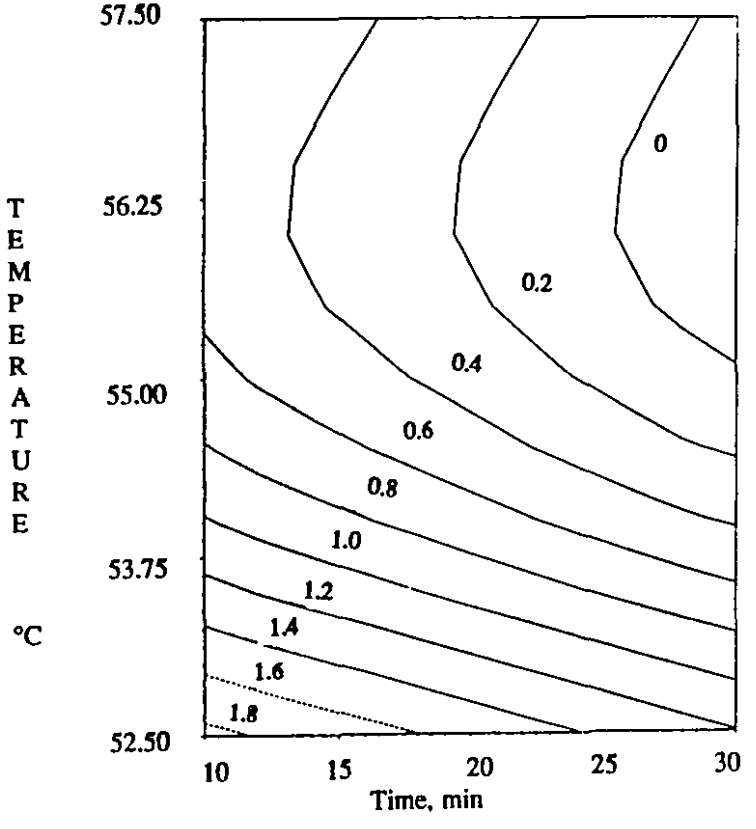

Figure 6.5: Contours-COL (soft rot) as a function of hot water temperature and dipping time (Incub = 6 hr, storage = 8°C).

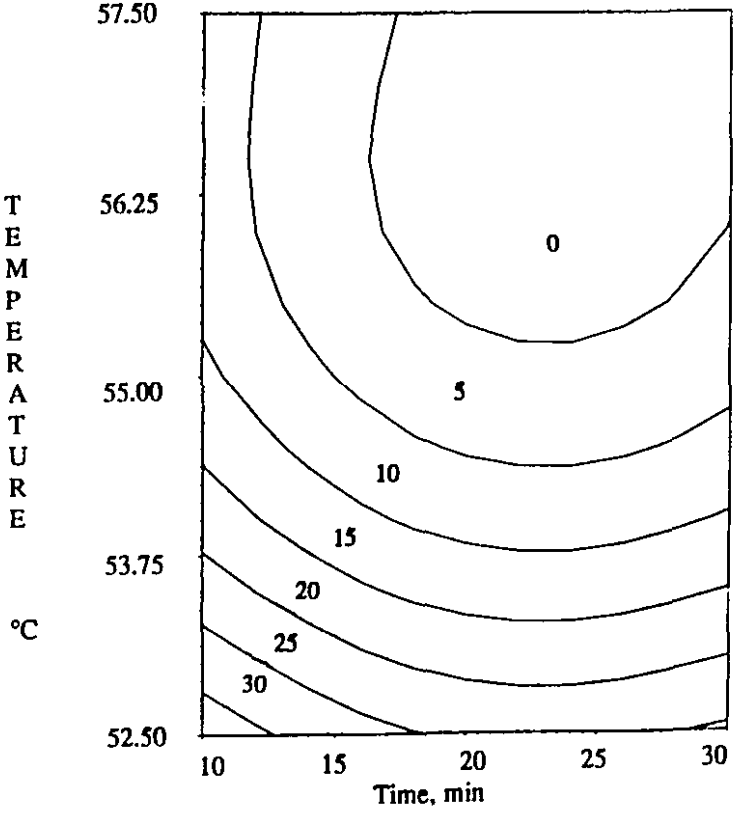

Figure 6.6: Contours-SPOIL (soft rot) as a function of hot water temperature and dipping time (Incub = 6 hr, storage = 8 °C).

Table 6.5 Least square means for *Fusarium solani* (stored at 18°C)

T[a]	Incub (days)	Temp (°C)	Time (min)	PSI[c] (decimal)	COL[d] (cm)	SPOIL[e] (%)
1	0 (-1)[b]	52.5 (-1)[b]	10 (-1)[b]	0.64 ± 0.028	4.98 ± 0.319	83.30 ± 3.99
2	2 (+1)	52.5 (-1)	10 (-1)	0.62 ± "	5.04 ± "	70.77 ± "
3	0 (-1)	57.5(+1)	10 (-1)	0.10 ± "	4.43 ± "	16.60 ± "
4	2 (+1)	57.5(+1)	10 (-1)	0.10 ± "	4.18 ± "	20.77 ± "
5	0 (-1)	52.5(-1)	30 (+1)	0.46 ± "	4.54 ± "	62.45 ± "
6	2 (+1)	52.5 (-1)	30 (+1)	0.24 ± "	4.48 ± "	33.30 ± "
7	0 (-1)	57.5(+1)	30 (+1)	0 ± "	0 ± "	0 ± "
8	2 (+1)	57.5(+1)	30 (+1)	0 ± "	0 ± "	0 ± "
9	0 (-1)	55 (0)	20 (0)	0 ± "	0 ± "	0 ± "
10	2 (+1)	55 (0)	20 (0)	0.08 ± "	2.00 ± "	12.47 ± "
11	1 (0)	52.5 (-1)	20 (0)	0.41 ± "	4.58 ± "	49.97 ± "
12	1 (0)	57.5(+1)	20 (0)	0 ± "	0 ± "	0 ± "
13	1 (0)	55 (0)	10 (-1)	0.33 ± "	4.03 ± "	41.65 ± "
14	1 (0)	55 (0)	30 (+1)	0 ± "	0 ± "	0 ± "
15	1 (0)	55 (0)	20 (0)	0 ± "	0 ± "	0 ± "

[a,b,c,d] details as listed in Table 6.1

The model estimates, standard errors and significance levels are presented in Table 6.5. The data indicate that the incubation period and temperature interaction with residence time had no significant effect on PSI

and were dropped from the final model. The interaction of temperature and time was also not significant (Table 6.6). The PSI decreased with increasing temperature and time but at a decreasing rate as both of these parameters had significant linear and quadratic effects. The model predicts the complete disinfection of the *Fusarium* pathogen by using a dipping times ≥ 18.5 min and hot water temperature ≥ 54.8°C, regardless of incubation time in the range studied. The contours of PSI in terms of temperature and residence time are plotted in Figure 6.7 for an incubation of 24 hours.

The data reveal that the effect of hot water temperature of 55°C and dipping times of 20 minute and above completely controlled dry rot (PSI=0) in the potato samples stored for three months at 18°C. A higher proportion of sited infected was observed at the lower temperature (52.5°C and 10 and 20 min) followed by the lower temperature and higher dipping times. Although some variation was observed in the proportion of sites infected among the three levels of incubation (coded -1, 0, +1), the hot water treatments at temperatures 55°C and above were very effective in disinfecting the tubers from *F. solani*. In the samples where disinfection was not effective, the actual disease symptoms started appearing between the second and third week after storage. It could be seen that the proportion of sites infected was much higher when potatoes were stored at 18°C compared to those stored at 8°C, meaning that the higher storage temperature was favourable to the growth of *F. solani*. The control tubers that were inoculated but not treated with hot water were severely infected and the spoiled samples were removed from the storage environment to avoid possible infection of the other samples.

Table 6.6 Reduced regression models to predict PSI, COL and SPOIL due to *Erwinia carotovora* pv. *carotovora* as a function of hot water treatment factors.

$$PSI = 0.044285^{ns} - 0.021875TE^{***} + 0.138035TE^{2**} - 0.10875TI^{***} + 0.095535TI^{2*} \qquad R^2=0.94$$
(0.03367) (0.02099) (0.03968) (0.02099) (0.03968)

$$COL = 0.70914^{n.s} + 0.17640I^{ns} - 1.50275TE^{***} + 1.52089TE^{2*} - 1.36550*TI^{***} + 1.24464*TI^{2*} - 0.95125TE^{2**}$$
(0.4025) (0.2510) (0.2510) (0.4743) (0.2510) (0.4743) (0.2808)

$R^2 = 0.92$

$$SPOIL = 2.0450^{ns} - 2.5025I^{n.s} - 23.2425TE^{***} + 11.1125TE^{2ns} - 13.7350TI^{**} + 21.9500TI^{2*} + 5.7312*I*TI^{ns}$$
(5.5800) (3.4798) (3.4798) (6.5763) (3.4798) (6.5763) (3.8905)

$R^2 = 0.91$

NOTE: Figures in parentheses are standard errors of estimates

[a] All the hot water treatment factors levels were coded (Table 6.1); I is the incubation period of tubers after inoculation of *F. solani*; TE is the temperature of hot water bath, and TI is the duration of hot water dipping. * significant at 5% level; ** significant at the 1% level; *** significant at 0.1% level; and [n.s] not significant.

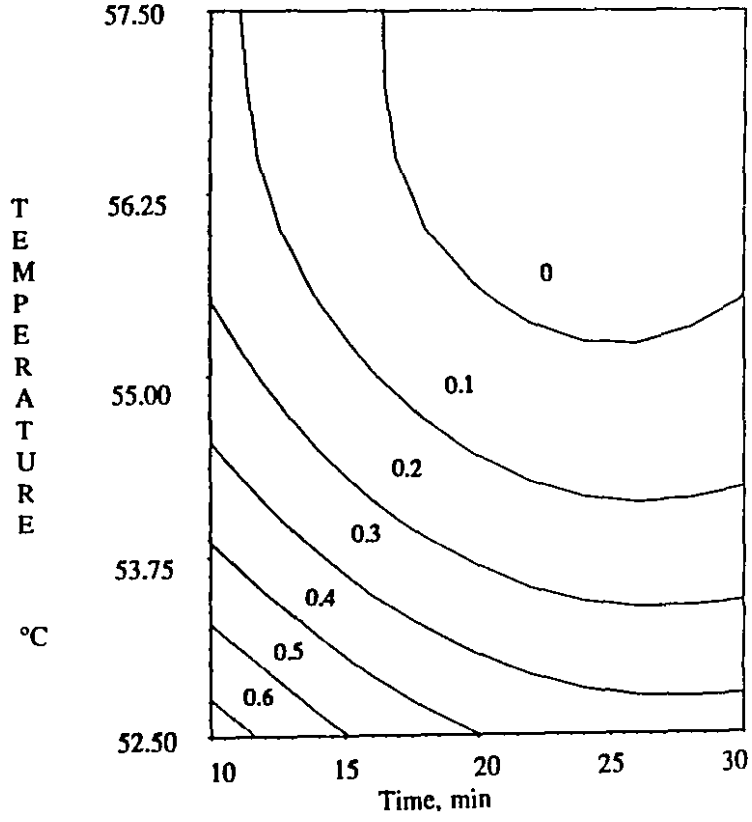

Figure 6.7: Contours-PSI (dry rot) as a function of hot water temperature and dipping time (Incub = 1 day, storage = 18°C).

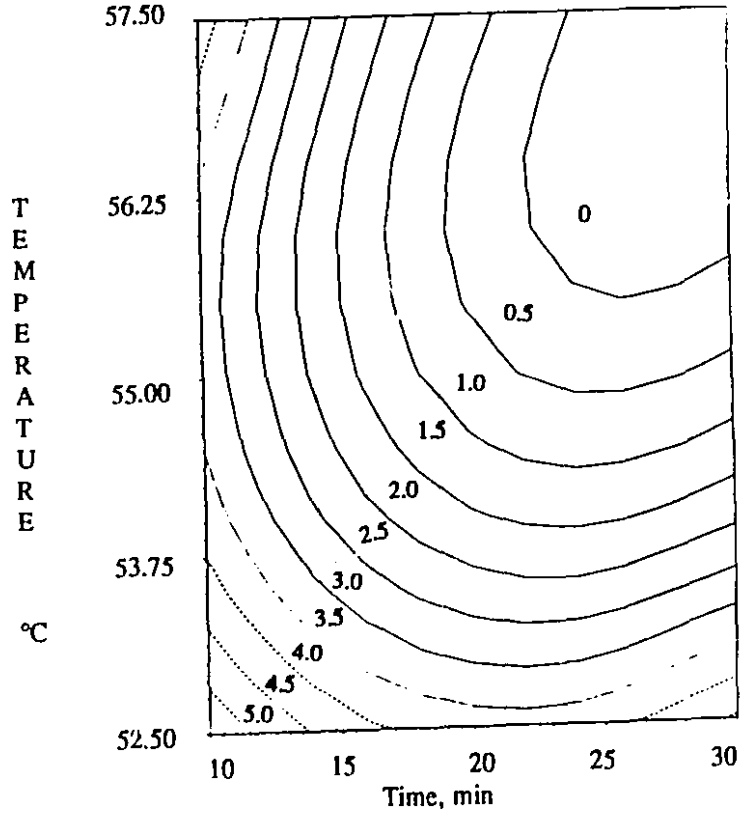

Figure 6.8: Contours-COL (dry rot) as a function of hot water temperature and dipping time (Incub = 1 day, storage = 18 °C).

ii) Average colony diameter (COL)

The model estimates, standard errors and significance levels of parameters are presented in Table 6.6. Both linear and quadratic effects of the temperature were highly significant ($p < 0.0003$ and $p< 0.0125$, respectively) on the average colony diameter. Furthermore, the linear and quadratic effects of time were also significant ($p<0.0006$ and $p<0.0305$, respectively). The interaction effect of temperature and time was also significant ($p< 0.0095$) indicating that the effect of temperature and time on the colony diameter cannot be interpreted solely by the additive effect of temperature and time. Actually the effect of increasing temperature levels was much enhanced at intermediate to high time intervals. These model estimates were used to plot the contours (Figure 6.8) for the intermediate incubation level (coded 0) only, since incubation period had no significant effect. For an intermediate incubation period, the model predicts complete control of *F. solani* colony growth as COL = 0 for the treatment time ≥ 22 min and Temp. ≥ 56°C.

The canonical analysis of the full model indicated that the stationary point (@ -0.5879) was a saddle point (Incub= 12.72 h, Temp= 57° and Time= 28.9 min). The ridge of minimum response varied from 0.658 in the center to -0.536 at the periphery of the design.

iii) Percent spoilage of tubers (SPOIL)

In the case of spoilage of tubers, only the linear effect of temperature was significant ($p<0.0002$). The percentage of spoilage decreased linearly with increasing temperature. The dipping times significantly reduced spoilage and both the linear and quadratic effects were significant ($p< 0.0043$ and $p< 0.0103$, respectively). None of the interaction terms were significant and were dropped from the full model. For an intermediate incubation period the model predicts that the minimum spoilage could be achieved with a temperature ≥ 55.5°C and time ≥ 19 minute (Figure 6.9).

The canonical analysis for the full model indicated that the stationary point (@ -15.918) was a saddle point (Incub = 26.64 h, Temp = 55.2° and Time = 22.3 min). The ridge of minimum response varied from 0.40 (centre) to -14.92 at the periphery of the design.

b) Control of soft rot

The least square means of PSI, COL and SPOIL for all treatment combinations are presented in Table 6.7.

i) Proportion of sites infected (PSI)

The model estimates, standard errors and significance levels are presented in Table 6.8. Here also, the incubation had no significant effect on proportion of sites infected (Table 6.8). Both the linear and quadratic terms of temperature and dipping time were highly significant as was the interaction effect of temperature and time ($p<0.0020$). The model predicts that complete disinfection of *Erwinia carotovora* pv. *carotovora* bacteria can be achieved at dipping times ≥ 14 min and hot water temperature≥ 55°C, at the intermediate incubation level (code 0). The contours of PSI are shown in Figure 6.10.

The canonical analysis indicated that the stationary point was a saddle point and the predicted value at the stationary point was -0.0628 (Incub = 6.78 h, Temp = 56.55°C and time = 22.9 min.). A range of temperature and time combinations can be used to disinfect potato tubers from the *Ecc* bacteria. The ridge of the predicted minimum response varied from 0.033 near the centre to -0.0977 at the periphery of the design.

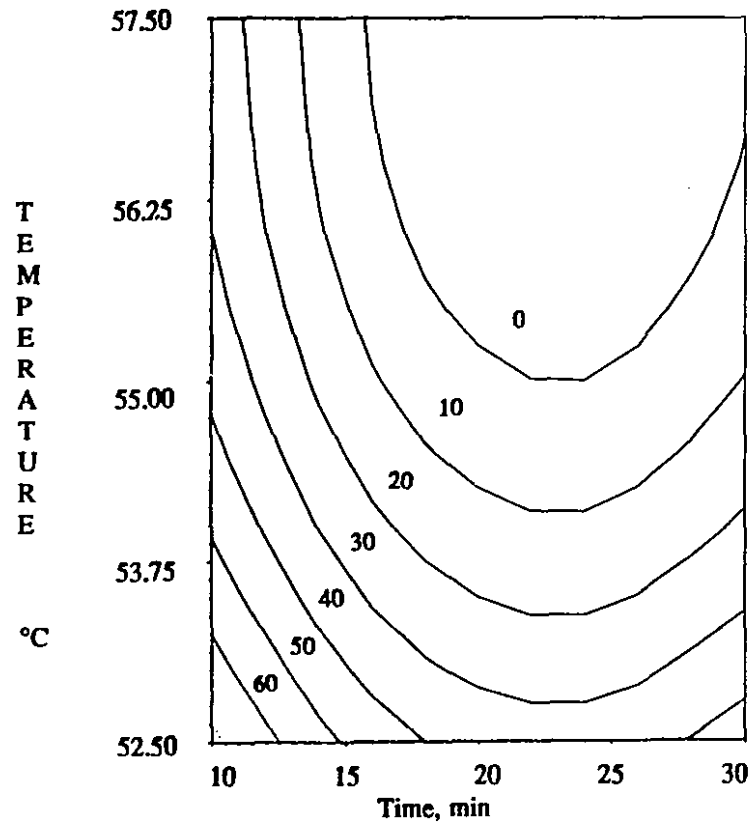

Figure 6.9: Contours-SPOIL (dry rot) as a function of hot water temperature and dipping time (Incub = 1 day, storage = 18°C).

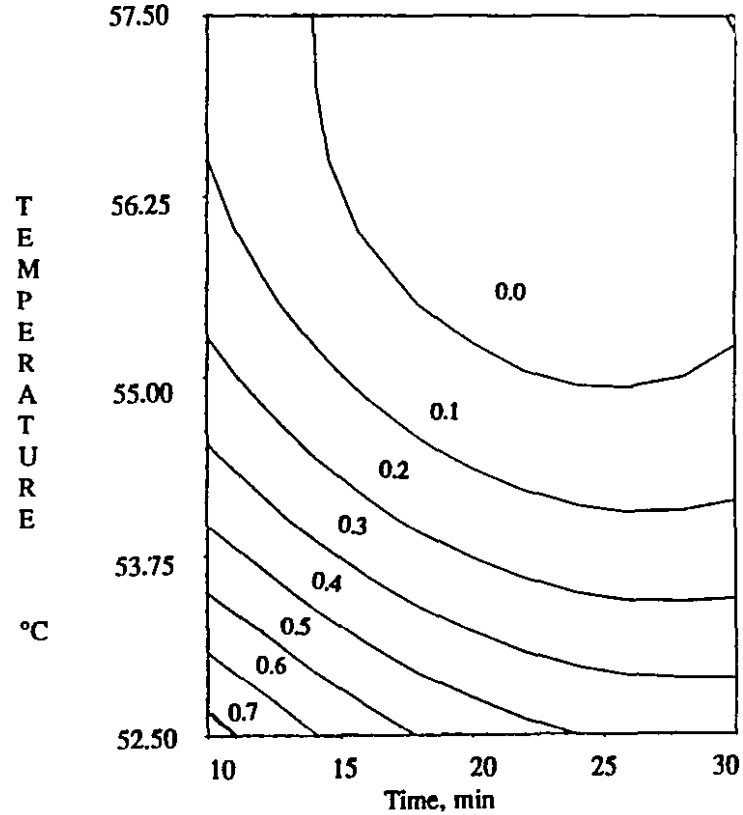

Figure 6.10: Contours-PSI (soft rot) as a function of hot water temperature and dipping time (Incub = 6 hr, storage = 18 °C).

Table 6.7 Least square means for *Ecc* (stored at 18°C)

T[a]	Incub (days)	Temp (°C)	Time (min)	PSI[c] (decimal)	COL[d] (cm)	SPOIL[e] (%)
1	0 (-1)[b]	52.5 (-1)[b]	10 (-1)[b]	0.72 ± 0.025	5.47 ± 0.372	87.47 ± 3.32
2	2 (+1)	52.5 (-1)	10 (-1)	0.72 ± "	5.30 ± "	79.12 ± "
3	0 (-1)	57.5(+1)	10 (-1)	0 ± "	0 ± "	0 ± "
4	2 (+1)	57.5(+1)	10 (-1)	0.10 ± "	2.45 ± "	12.47 ± "
5	0 (-1)	52.5(-1)	30 (+1)	0.41 ± "	5.30 ± "	49.97 ± "
6	2 (+1)	52.5 (-1)	30 (+1)	0.35 ± "	5.10 ± "	41.65 ± "
7	0 (-1)	57.5(+1)	30 (+1)	0 ± "	0 ± "	0 ± "
8	2 (+1)	57.5(+1)	30 (+1)	0 ± "	0 ± "	0 ± "
9	0 (-1)	55 (0)	20 (0)	0 ± "	0 ± "	0 ± "
10	2 (+1)	55 (0)	20 (0)	0 ± "	0 ± "	0 ± "
11	1 (0)	52.5 (-1)	20 (0)	0.46 ± "	5.32 ± "	50.00 ± "
12	1 (0)	57.5(+1)	20 (0)	0 ± "	0 ± "	0 ± "
13	1 (0)	55 (0)	10 (-1)	0.31 ± "	5.12 ± "	33.30 ± "
14	1 (0)	55 (0)	30 (+1)	0 ± "	0 ± "	0 ± "
15	1 (0)	55 (0)	20 (0)	0 ± "	0 ± "	0 ± "

[a,b,c,d] details as listed in Table 6.1

Table 6.8 Reduced regression models to predict PSI, COL and SPOIL due to *Erwinia carotovora* pv. *carotovora* as a function of hot water treatment factors.

$$PSI = 0.02150^{ns} - 0.25828TE^{***} + 0.17625TE^{2***} - 0.10975T^{***} + 0.10125TI^{2**} + 0.07281TE*TI^{**}$$
$$(0.2422) \quad (0.0151) \quad (0.0285) \quad (0.0151) \quad (0.0285) \quad (0.0168)$$
$$R^2=0.95$$

$$COL = 0.51914^{n.s} - 2.40552TE^{***} + 1.36464TE^{2**} - 0.79550TE^{2n.s} - 1.26464*TI^{2*} - 0.21062*I*TI^{n.s} - 0.3100*TI*I^{n.s}$$
$$(0.63943) \quad (0.39875) \quad (0.75358) \quad (0.39875) \quad (0.75358) \quad (0.44582)$$
$$R^2 = 0.85$$

$$SPOIL = 1.785714^{ns} - 29.5750TE^{***} + 20.53571TE^{2***} - 12.07500TI^{***} + 12.18571TI^{2*} + 7.8125TE*TI^{**} \quad R^2=0.97$$
$$(2.89745) \quad (1.80687) \quad (3.41467) \quad (1.80687) \quad (3.41467) \quad (2.02015)$$

NOTE: Figures in parentheses are standard errors of estimate

[a] All the hot water treatment factors levels were coded (Table 6.1); I is the incubation period of tubers after inoculation of *F. solani*; TE is the temperature of hot water bath, and TI is the duration of hot water dipping.* significant at 5% level; ** significant at the 1% level; *** significant at 0.1% level; and n.s not significant.

The results show that the effect of hot water temperature of 55°C and dipping times 20 minute and above had effectively killed the soft rot bacteria *(Ecc)* in the samples stored at 18°C. The trend was comparable to the results for *F. solani.* Once again, a higher proportion of sites infected was observed at the lower temperature treatment (coded -1) and dipping time (coded -1). Disease symptoms started appearing only from the third week in some samples and from the fourth week in the others. The control potato samples that were inoculated with bacteria and not treated with hot water were 100% spoiled due to severe soft rot. The results of this investigation are comparable with the findings of Robinson and Foster (1987) who observed significant reductions in *Erwinia chrysanthemi (Ech)* and *Erwinia carotovora atroseptica (Eca)* bacteria by hot water dipping in the range of 51.3-56°C for 2-30 minute duration.

ii) Average colony diameter (COL)

The hot water temperature was highly significant ($p < 0.0002$). The average colony diameter decreased with increasing temperature. Except for temperature, none of the other terms in the model were significant (Table 6.8). The contours are shown in Figure 6.11 for the intermediate incubation level (coded 0) only since incubation had no significant effect. The model predicts complete control of *Ecc* colony growth as COL = 0 for the dipping times ≥ 16 min and Temperatures ≥ 56°C.

The canonical analysis of the full model indicated that the stationary point was a saddle point (Incub= 0.78 h, Temp= 56.2° and Time= 21.2 min) and the predicted value at the stationary point was -0.1902. The ridge of minimum response varied from 0.807 at the center to -1.111 at the periphery.

iii) Percent of tubers spoiled (SPOIL)

The linear and quadratic components of temperature and time were highly significant (Table 6.8) on percent spoilage. The temperature-time interaction term was also significant. The incubation period was not

significant on spoilage of potatoes and therefore, was dropped from the final model. The model predicts that the minimum spoilage could be achieved by using temperatures ≥ 54.8°C and dipping times ≥ 14 minute (Figure 6.12).

The canonical analysis for the full model indicated that the stationary point (@ -8.134) was a saddle point (Incub = 4.86 h, Temp = 56.5° and Time = 22.8 min). The ridge minimum response varied from 2.77 in the centre to -11.39 at the periphery of the design.

Summary

As indicated in the earlier (Chapter II), *F. solani* and *Erwinia carotovora* pv. *carotovora* are the two main post-harvest pathogens that cause dry and soft rot diseases in potato storage. In this section of investigation, a study was performed to investigate hot water as a thermal treatment for successfully controlling both these pathogens for three months' storage at 8°C and 18°C. All the measured response parameters behave differently at the two storage temperatures, as one might expect, except when the treatments totally eradicate the pathogens. The response variables decreased to a zero or minimum with increasing temperature and dipping times of hot water.

Although the analyses indicated that incubation time had no significant effect on PSI, COL or SPOIL, the coefficients associated with incubation time were positive in all cases but one. This small tendency to increased disease incidence (ie. survival of the pathogen) may be due to a tendency for the pathogen to penetrate into the tuber where carbon substrates are more available, than to spread over the tougher surface tissues. Thus, the radial temperature distribution induced by the thermal treatment is less effective at killing the pathogen (ie. temperature is higher and for a longer time at the surface than towards the middle of the tuber). Unfortunately, depths of penetration of the pathogens with incubation time were not measured and the thermal mortalities were not determined independently. Ideally, such data could be used to expand the numerical model for predicting lethality and

transient temperatures at the same time.

Nevertheless, 55°C and 20 min dipping time provided total eradication of both pathogens *F. solani* and *Erwinia carotovora* pv. *carotovora*, irrespective of the incubation period, and prevented further loss in storage, without the use of chemicals or irradiation. In the next section, the possibility that the 100% eradication conditions also effectively control sprouting, is explored.

6.1.2 HOT WATER FOR CONTROL OF SPROUTING

A 3 x 3 Factorial in Randomised Complete Block Design with three replicates was performed to study sprout control as a function of hot water dipping temperature and residence time. One series was performed in the fall of 1993, the other in the fall of 1994. As discussed in the previous section of this Chapter, temperature and time combinations which could provide meaningful results in the control of both sprouting and diseases were considered in order to arrive at a one-stage hot water treatment. Thus, the same temperature levels (52.5, 55 and 57.5°C) and dipping times (10, 20 and 30 min) were used. Post-treatment storage was also done at two temperatures, 8 or 18°C and 90-95% RH.

6.1.2.1 Sprout control when stored at 8°C

The results of the treatments (for 1993) on the sprout inhibition of potato tubers are presented in Figures 6.13 to 6.16. Figures 6.13 and 6.14 show the sprout behaviour at the end of 6 and 12 weeks of storage at 8°C, respectively. In Figure 6.13 it could be seen that the sprout control was very effective compared to the control (untreated) tubers after 6 weeks of storage. Further, it was observed that the tuber sprouting was completely inhibited at 55°C and 30 min, and at 57.5°C with 20 and 30 minute dipping times. The sprouts located on the surface of the potato were completely killed, having turned black and withered.

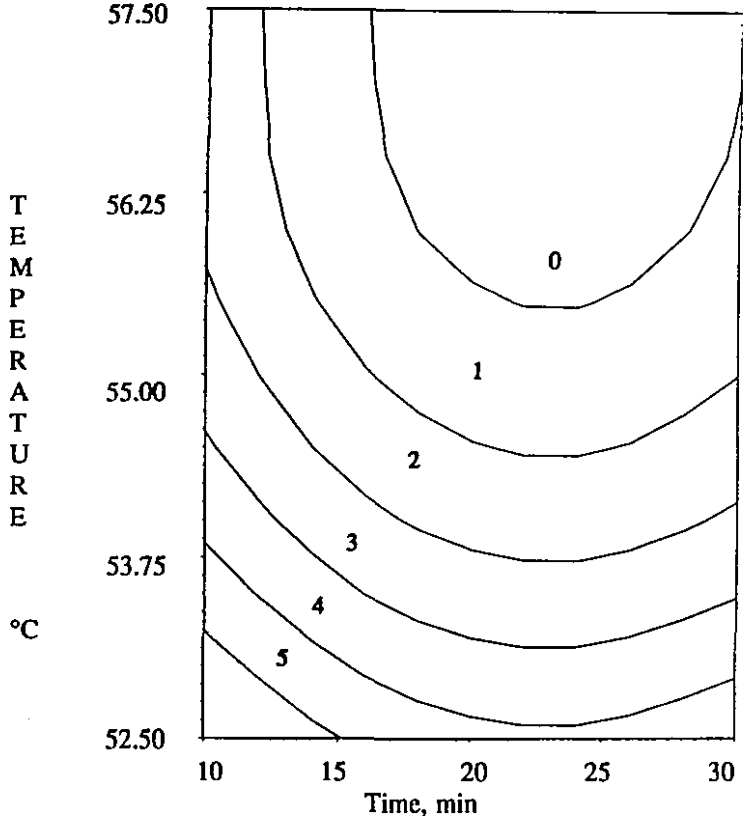

Figure 6.11: Contours-COL (soft rot) as a function of hot water temperature and dipping time (Incub = 6 hr, storage = 18°C).

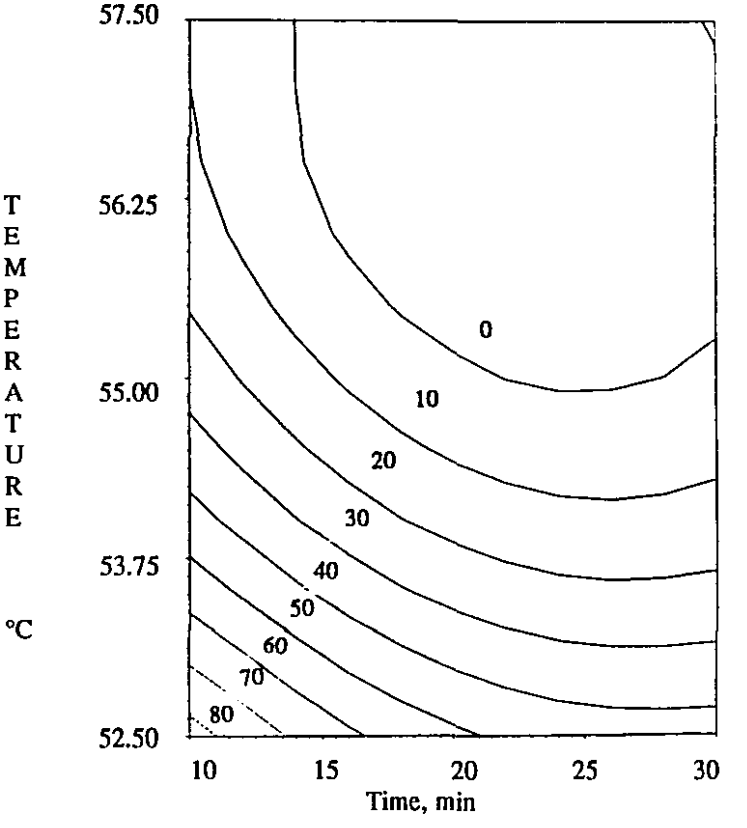

Figure 6.12: Contours-SPOIL (soft rot) as a function of hot water temperature and dipping time (Incub = 6 hr, storage = 18 °C).

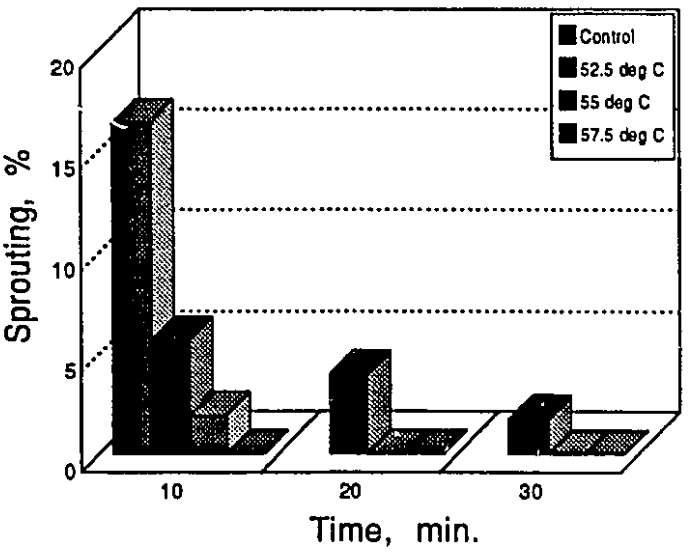

Figure 6.13 Potato sprout control due to HW treatments after 6 weeks storage at 8°C (1993).

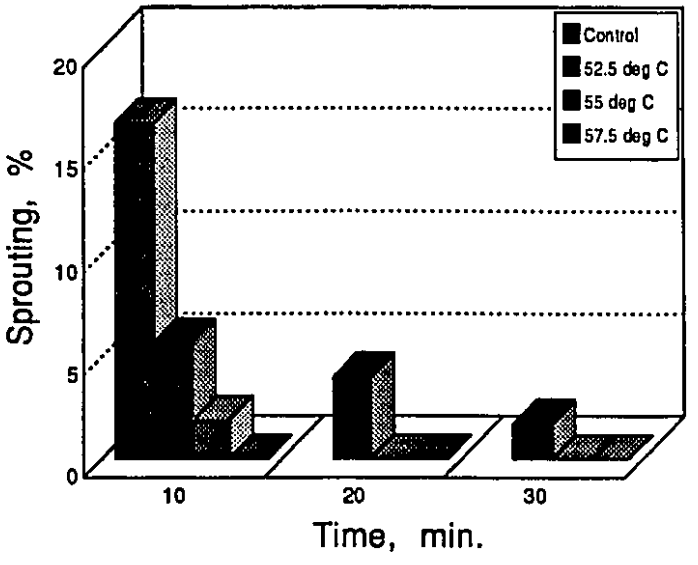

Figure 6.14 Potato sprout control due to HW treatments after 12 weeks storage at 8°C (1993).

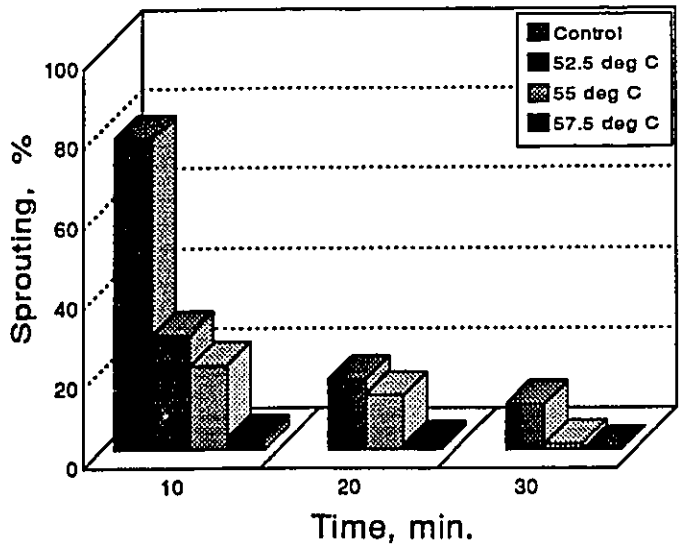

Figure 6.15 Potato sprout control due to HW treatments after 6 weeks storage at 18°C (1993).

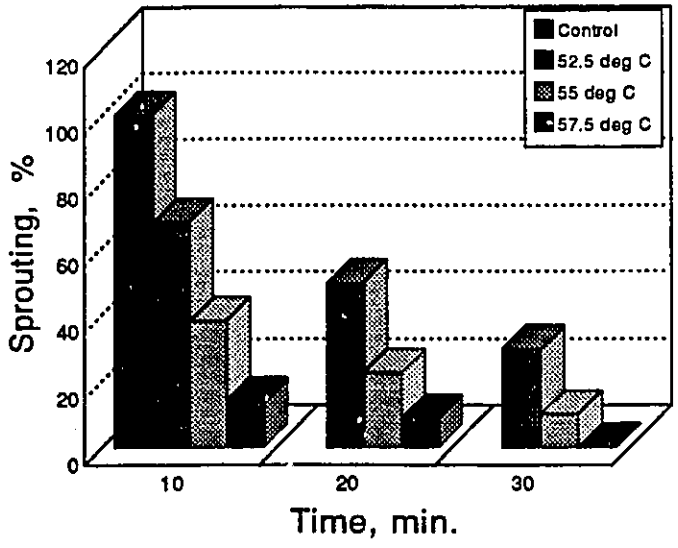

Figure 6.16 Potato sprout control due to HW treatments after 12 weeks storage at 18°C (1993).

In all other cases, control was incomplete. At a dipping temperature of 52.5°C the sprouting percentage was high (36%) at the end of 12 weeks storage period (Fig 6.16). The results are comparable with the findings of the preliminary studies (Chapter III) for cv. Russet Burbank potato. The sprout growth was slow in the initial 4 week period and slowly picked up during the later period of storage. Since uniform sized potatoes were selected for the study, there were no significant variations observed in the sprouting among the tubers.

6.1.2.2 Sprout control when stored at 18°C

Figures 6.15 and 6.16 show the results of sprout control behaviour for the same period (6 and 12 weeks) of storage when they were stored at 18°C. Figure 6.15 shows that the sprout control was less effective at the lower temperature (52.5°C) and time combinations followed by 55°C temperature-time combinations. Sprout control in the case of 55°C was very good at 20 min dipping time and nearly total at 30 min dipping time. At 57.5°C and 20 to 30 min dipping times, no sprouting occurred after 12 weeks. Similar trends were observed at the end of 12 weeks storage period (Fig 6.16).

These experiments were done again in the fall 1994. In the case of storage at 8°C (Figures 6.17 and 6.18) sprout control was complete at 55°C, and 20 and 30 minute duration and 57.5°C, and 20 and 30 minute dipping times. Although complete control was not possible with the other treatment combinations, sprouting was significantly less than for the control tubers. Figures 6.19 and 6.20 present the sprout behaviour after hot water treatment and storage at 18°C. The tendencies were similar to those of 1993, but the sprout percentage was lower both at 8 and 18°C. Sprouting was a minimum (3% of tubers) at 55°C with 20 and 30 minute dipping times. All the treatment combinations also had significantly less sprouting compared to the control. Although the sprout control at 18°C storage was not complete at the moderate temperature range (55°C), the results were very encouraging.

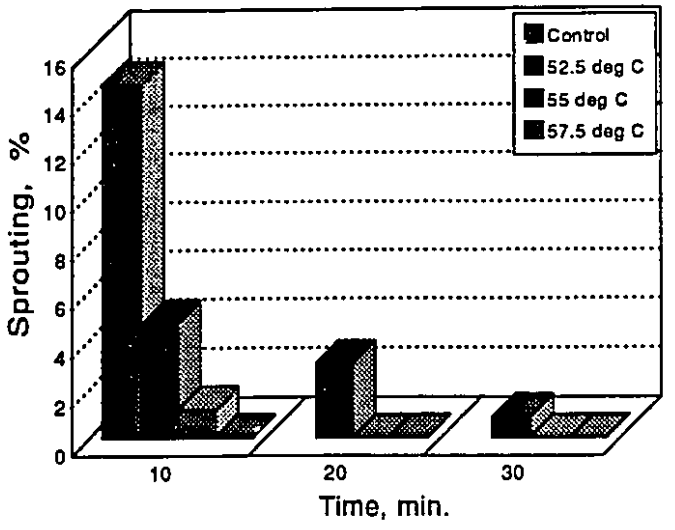

Figure 6.17 Potato sprout control due to HW treatments after 6 weeks storage at 8°C (1994).

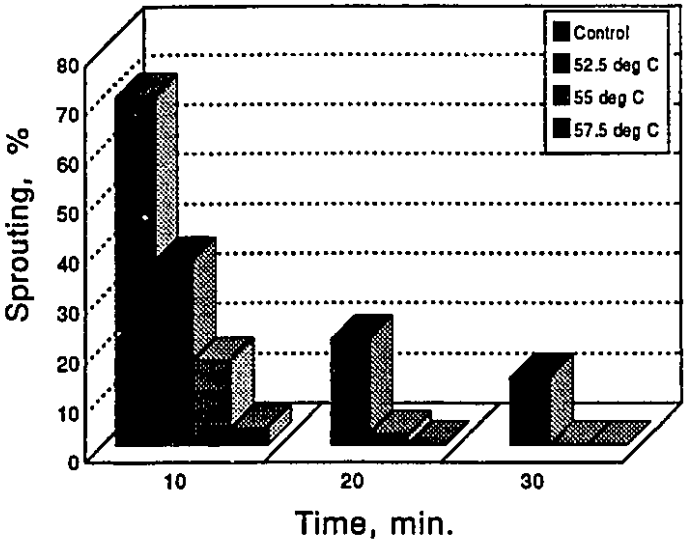

Figure 6.18 Potato sprout control due to HW treatments after 12 weeks storage at 8°C (1994).

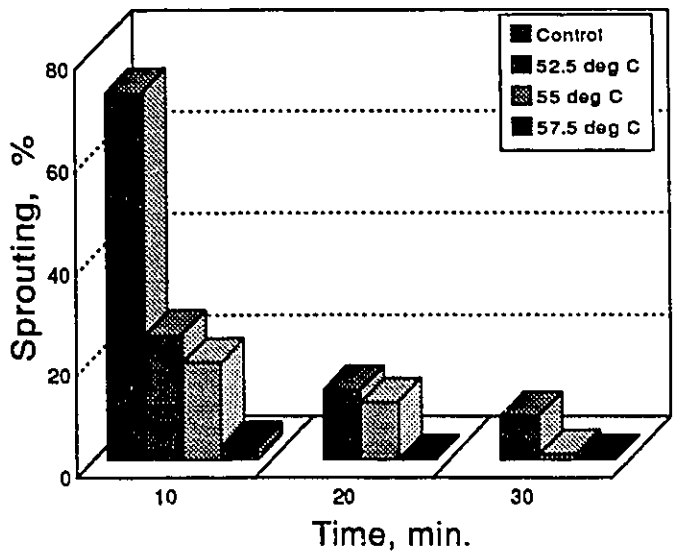

Figure 6.19 Potato sprout control due to HW treatments after 6 weeks storage at 18°C (1994).

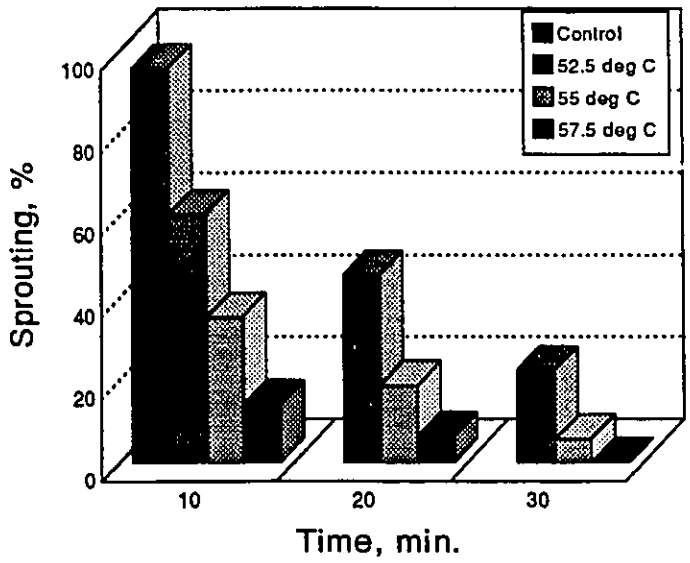

Figure 6.20 Potato sprout control due to HW treatments after 12 weeks storage at 18°C (1994).

The physical observation of the tubers reveal that the sprouts were effectively killed and that the eye sites were damaged due to heat injury without causing other physical damage to the tuber. In all the treatments, the sprout length was significantly shorter than that of control.

As seen in Chapter IV, the potato tuber surface temperature reached almost 98% of bath temperature in less than three minutes, after which the rise in surface temperature with time was insignificant. Numerical results in Figures 4.11 and 4.12 (Chapter IV) reveal that the maximum heat input to the tuber occurs in the first few minutes and this hints that it is not practical to thermally treat the potato tuber for more than 30 minutes. This was kept in view when designing the time-temperature levels.

To illustrate the performance of the numerically solved model, the control volume code was verified using experimental results obtained by thermal treatment of roughly the same size and shape of potato tubers at three water bath temperatures (52, 55 and 57°C) for 30 minutes. The bath temperature levels were chosen based on results from the preliminary experiments which exhibited a complete control of potato sprouts at 55°C and 20 to 30 minutes dipping time. No visual physical damage of tubers was observed at these temperature-time combinations. However, heat treatments above 60 °C temperature caused complete spoilage of tubers (Chapter III). Figure 4.13 in Chapter IV, shows that the experimental data and model predictions concorded very well. Figure 4.14 shows the numerical prediction of the transient surface temperature for the same test.

Table 6.9 Least square means for hot water sprout control

			Tuber sprouting, %	
T[a]	Temp	Time	8°C	18°C
1	52.5	10	34.60	64.30
2	55	10	15.30	36.65
3	57.5	10	2.83	13.91
4	52.5	20	18.66	47.90
5	55	20	1.44	20.50
6	57.5	20	0	6.99
7	52.5	30	11.33	25.83
8	55	30	0	7.83
9	57.5	30	0	0

[a] Treatment #, each treatment was replicated thrice.

The data for the two years were tested for statistical significance of the parameters. The effect of blocks was considered to be a random effect. The least square means for the treatments were obtained and used for estimating the coefficients for temperature and time. The resulting regression model was used to generate contours and response surfaces.

The regression models were developed for the pooled results of 1993 and 1994. The least square means of sprouting varied from 0 to 34.66% or 64.33% for sprouting at 8 and 18°C storage, respectively (Table 6.9). The model estimates, standard errors and significance levels for sprout control when stored at 8°C are presented in Table 6.10. The linear and quadratic effects of both temperature and time were highly significant. Also, the interaction of

temperature and time was highly significant ($p < 0.0087$). The model predicts that sprouting can be completely controlled at temperatures ≥ 54.5°C with times ≥ 16 min (Figure 6.21).

Table 6.10 Reduced regression model to predict potato sprouting (stored at 8°) as a function of hot water treatment factors ($R^2 = 0.99$).

Model term[a]	Estimate[b]	T-ratio
Intercept	3106.055612 (544.78652)	0.0107*
Temp	-103.55555 (19.80135)	0.0136*
Time	-13.46666 (1.807219)	0.0050**
Temp*Temp	0.866667 (0.179903)	0.0170*
Time*Time	0.375000 (0.011244)	0.0445*
Temp*Time	0.205000 (0.031802)	0.0076**

[a, b] details as listed in Table 6.2

The model estimates, standard errors and significance levels for sprout control when stored at 18°C are presented in Table 6.11. The sprout control was linear with temperature and significant at the 5% level. Similarly, dipping time had a significant linear effect on sprout control. Neither quadratic effects of temperature or time were significant for sprout control. However, the interaction of the temperature and time was significant at 5% level ($p < 0.0146$). The model predicts complete control of sprouting at temperatures ≥ 54.5°C with times ≥ 16 min (Figure 6.22).

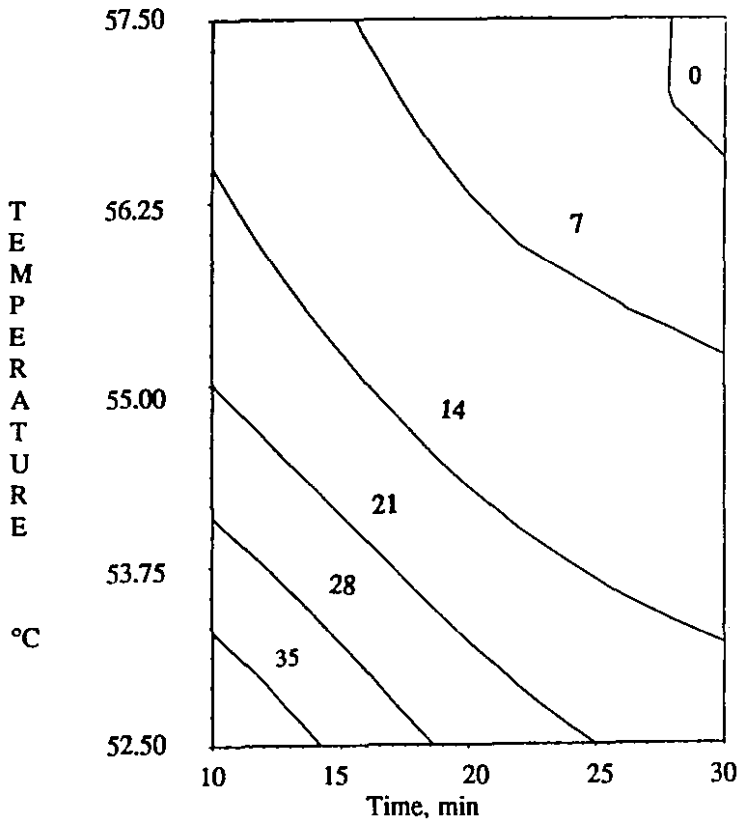

Figure 6.21: Contours of sprout percentage as a function of hot water temperature and dipping time (storage = 8°C).

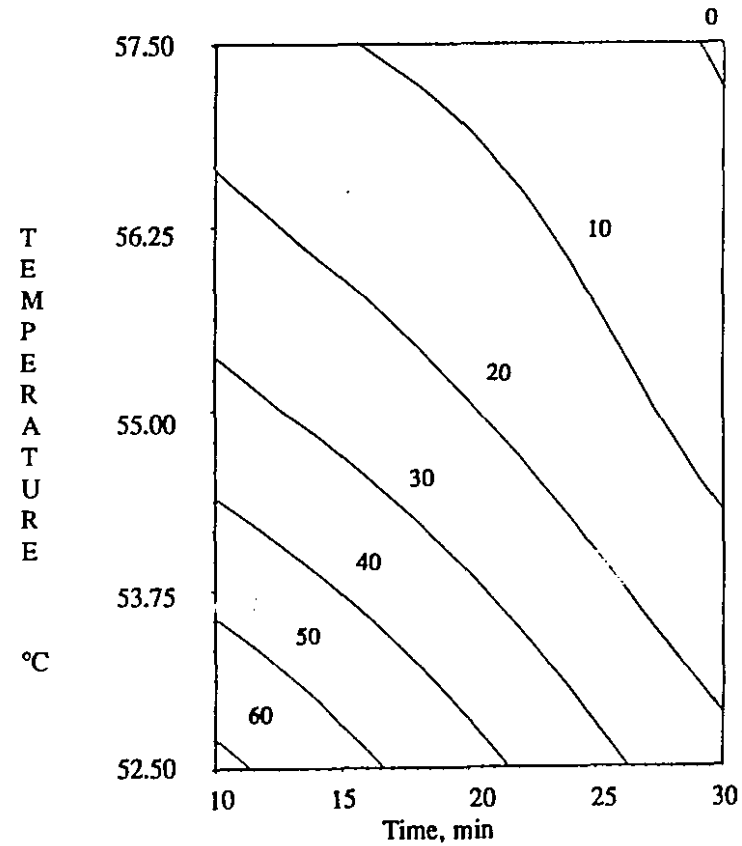

Figure 6.22: Contours of sprout percentage as a function of hot water temperature and dipping time (storage = 18 °C).

Table 6.11 Reduced regression model to predict potato sprouting (storage at 18°C) as a function of hot water treatment factors (R^2 = 0.99).

Model term[a]	Estimate[b]	T-ratio
Intercept	5011.305650 (1201.721429)	0.0251*
Temp	-161.79444 (43.678966)	0.0342*
Time	-27.39166 (3.986468)	0.0063**
Temp*Temp	1.306667 (0.396842)	0.0460*
Time*Time	0.029583 (0.024802)	0.3187n.s
Temp*Time	0.445833 (0.070152)	0.0079**

[a, b] details as listed in Table 6.2

Summary

The scale study of hot water dipping as a thermal treatment for control of sprouting of potatoes for short-term storage (3 months) indicates that complete control of sprouting of potatoes stored at 8°C can be achieved without chemicals and without causing physical damage to the tubers. One of the hypotheses of this investigation has been vindicated: that hot water treatment is not only effective in controlling sprouting but also serves as an alternative to chemicals and gamma irradiation. Although it was not possible to achieve 100% control in the case of storage at 18°C, very few tubers sprout during storage after the dipping treatment. Although complete inhibition of sprouting was attained at the highest temperature tested (57.5°C), it may be advisable to restrict the temperature to 55°C to ensure good tuber quality.

The numerical model of heat transfer behaviour suggested that it is not practical to thermally treat the potato tuber for more than 30 minutes. Given the simplicity of the hot water treatment, scale-up would be the next step for large scale treatment of the tubers. In the developing nations, solar energy could easily be harnessed to supply the thermal input.

6.2 VAPOUR HEAT TREATMENT

6.2.1 Control of sprouting

3 x 3 factorial experiments in Randomised Complete Block Design were performed using vapour heat to control of potato sprouting. Combinations of vapour temperature (50, 60 and 70°C), and treatment durations (40, 50 and 60 min) were tested. After the treatments, the tubers were stored in chambers maintained at 8°C or 18°C and 90-95% relative humidity. The data for the two years (1993 and 1994) were pooled, analyzed and presented in this section.

6.2.1.1 Sprout control when stored at 8°C

Potatoes (cv. Superior) were treated in the apparatus described in Chapter V. The pooled results of the treatments for the years 1993 and 1994 on the sprout inhibition of potato tubers are presented (Figure 6.23). Figure 6.23 shows the sprout behaviour at the end of 12 weeks of storage at 8°C. The sprout control was effective compared to the control (untreated) tubers after 12 weeks of storage. Although the tuber sprout control was positive, total sprout control could not be achieved even at the highest temperature and duration of treatment (70°C and 60 min). Although existing sprouts had blackened after two weeks of storage, new lateral sprouts had started developing, indicating that the thermal input was not sufficient to damage mother tissues below the sprout. The sprouting percentage was relatively high, particularly at the low treatment temperature/time combinations (50°C temp and 40 min) vapor heat treatment. The lowest sprout emergence (9%) was observed at 70°C and 60 min.

Figure 6.24 shows the results of sprout control for the same period (12 weeks) of storage when the tubers were stored at 18°C. Sprout control was less effective at the lower temperature (50°C) and time combinations followed by 60°C temperature-time combination. The vapour heat treatment failed to give a 100% sprout control. However, at the highest temperature (70°C) sprouting was very low (9%) even after 12 weeks of storage.

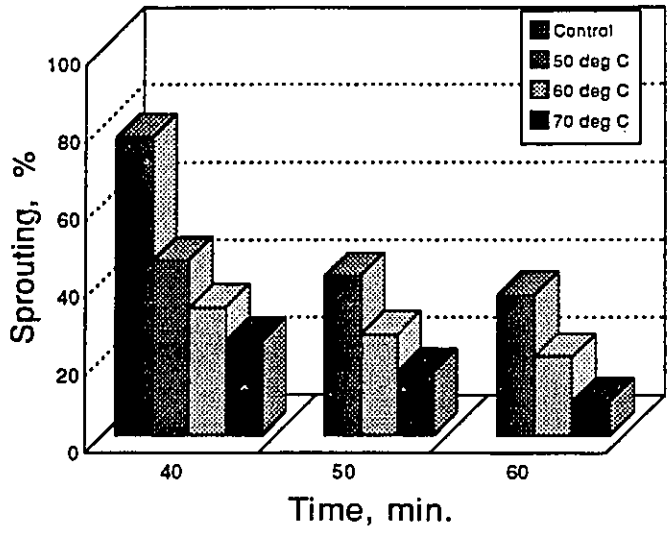

Figure 6.23 Potato sprout control due to vapour heat treatment after 12 weeks stored at 8°C (means of 1993 and 1994).

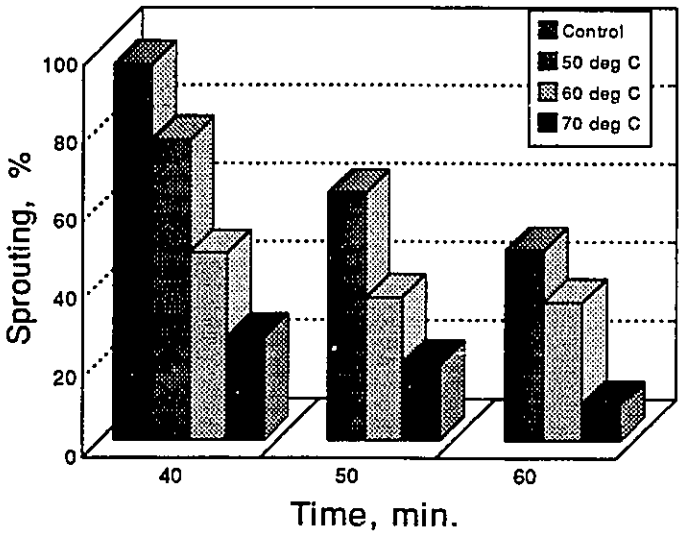

Figure 6.24 Potato sprout control due to vapour treatment after 12 weeks storage at 18°C (means of 1993 and 1994).

The results were quite different from the results of hot water dipping presented earlier. Not only was dipping more effective, but the apparatus is simpler. Because vapor treatment was poor at sprout control, this particular treatment was not tried for the control of dry rot and soft rot diseases. Higher temperatures with shorter residence times could be more effective.

The response of sprouting to heat treatments in both the years was similar and therefore, the two years (1993 and 1994) data were pooled to develop regression models to predict sprouting for 8°C and 18°C storage temperature conditions.

The least square means of sprout percentage varied from 9 to 45.17% and 76.83% for storage at 8 and 18°C, respectively treated at varying vapor heat treatment combinations (Table 6.12). The model estimates, standard errors and significance levels for sprout control when treated and stored at 8°C are presented in Table 6.13. The linear and quadratic effects of the temperature were highly significant. The interaction of vapor heat temperature and time was also highly significant ($p< 0.0033$). However, the linear and quadratic effects of duration of treatment were not significant. The model predicts that sprouting is at a minimum at temperatures $\geq$ 68.75°C with time $\geq$ 58.5 min (Figure 6.25), however, one might expect that the potatoes would come out of the treatment partially cooked and might be very susceptible to disease.

The model estimates, standard errors and significance levels for sprout control when stored at temperature (18°C) are presented in Table 6.14. Although the model was significant and had R^2=0.98, none of the parameter estimates were significant. The model predicts a minimum sprout percentage due to vapor heat treatment at temperture $\geq$ 67.5° C and time $\geq$ 53 min (Figure 6.26).

Table 6.12 Least square means for sprout control by vapor heat.

T[a]	Temp	Time	Tuber sprouting, %	
			8°C (%)	18°C (%)
1	50	40	45.15	76.80
2	60	40	32.99	47.50
3	70	40	24.50	26.17
4	50	50	41.16	63.16
5	60	50	26.16	36.16
6	70	50	16.50	19.50
7	50	60	36.16	48.83
8	60	60	20.50	35.00
9	70	60	9.00	9.16

[a]Treatment #, each treatment was replicated thrice.

Table 6.13 Reduced regression model to predict potato sprouting (stored at 8°C) as a function of vapor heat treatment factors (R^2 = 0.99).

Model term[a]	Estimate[b]	T-ratio
Intercept	162.842593 (12.88955)	0.0011**
Temp	-3.029166 (0.335773)	0.0029**
Time	0.247222 (0.291662)	0.4589[n.s]
Temp*Temp	0.021944 (0.002681)	0.0038**
Time*Time	0.001111 (0.002681)	0.7604[n.s]
Temp*Time	-0.016250 (0.001695)	0.0033**

[a, b] details as listed in Table 6.2

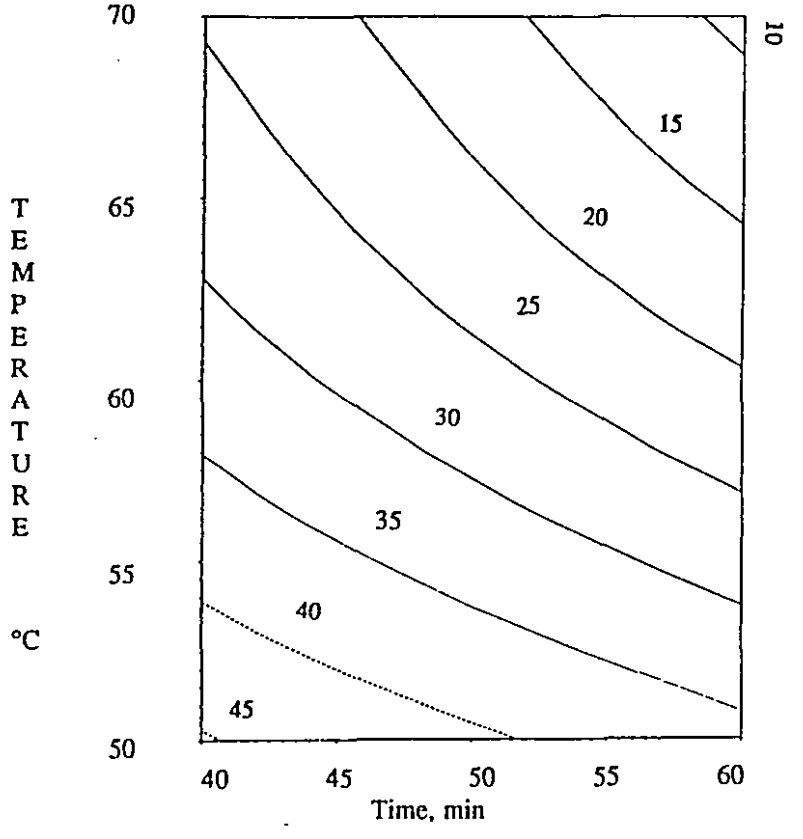

Figure 6.25: Contours of sprout percentage as a function of vapour heat temperature and residence time (storage = 8°C).

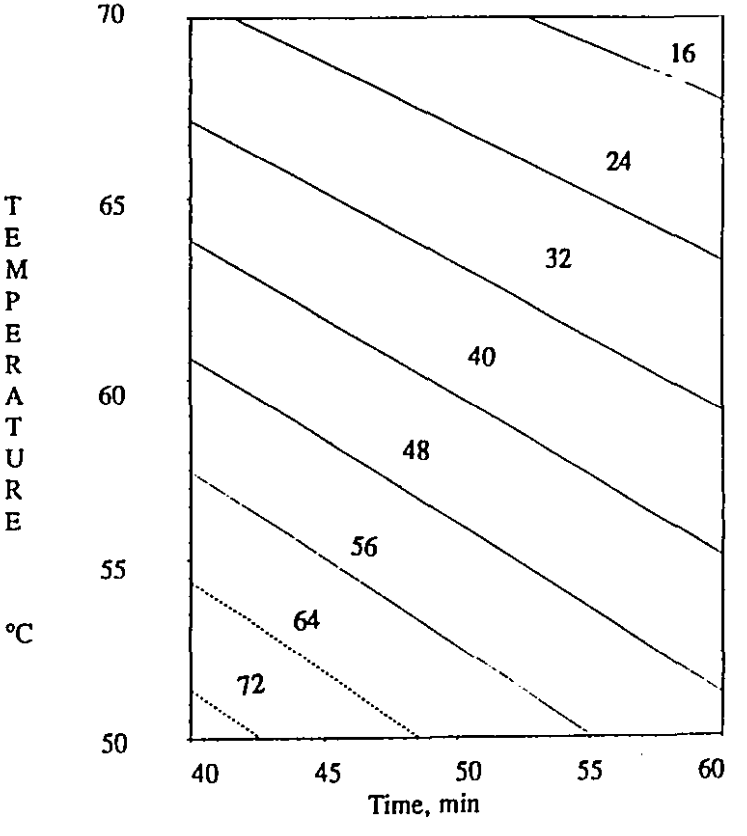

Figure 6.26: Contours of sprout percentage as a function of vapour heat temperature and residence time (storage = 18 °C).

Table 6.14 Reduced regression model to predict potato sprouting (stored at 18°C) as a function of vapor heat treatment factors (R^2 = 0.98).

Model term[a]	Estimate[b]	T-ratio
Intercept	364.26851 (143.0623)	0.0842[n.s]
Temp	-4.82916 (3.726782)	0.2857[n.s]
Time	-3.58055 (3.237191)	0.3494[n.s]
Temp*Temp	0.00972 (0.029758)	0.7654[n.s]
Time*Time	0.00888 (0.029758)	0.7847[n.s]
Temp*Time	0.02875 (0.021042)	0.2653[n.s]

[a, b] details as listed in Table 6.2

Summary

The results of the study of vapor heat on the control of sprouting for short-term storage (3 months) of potatoes demonstrated that the sprouting of tubers was very low at vapor heat combinations of 70°C and duration time of 60 minutes after subsequent storage at 8 or 18°C. Complete control could not be achieved with this treatment because of the poor convective heat transfer characteristics compared to hot water dipping. Higher vapor heat temperatures in the range of 71 to 80°C may be worth investigating. Although vapor heat did not provide 100% sprout control, there is some scope for further work.

6.3 ULTRAVIOLET RADIATION

6.3.1 Control of dry rot and soft rot diseases

This section concerns the application of ultraviolet (UV) radiation to control sprouting and diseases in tubers to be stored at 8 or 18°C for three months. The incubation periods were 0, 1 and 2 days for *F. solani* and 0, 6 and 12 h for *E. carotovora* pv. *carotovora*. UV radiation dosage levels were 0.75×10^4, 1.0×10^4, 1.25×10^4 and 1.5×10^4 W.s/m^2 at 1400 μW/cm^2 intensity of radiation and exposure duration of 536, 715, 893 and 1072 sec, respectively. Experiments were performed in fall 1993 and then in fall 1994.

The experiments were run as 4 x 3 factorials in RCB design. In all cases, variances due to years were homogeneous and further analyses were run on the pooled data. The least square means of PSI, COL and SPOIL for all treatment combinations are presented in Table 6.15. Complete response surface models (ie. including all square and interaction terms) were examined for the different dependent variables (proportion of sites infected - PSI; average colony diameter - COL; spoilage percentage - SPOIL). As none of the models exhibited lack of fit, the most significant parameters in each case (interactions often eliminated) were used in a best regression procedure. The best models for the dependent variables are presented in Table 6.16.

6.3.1.1 UV treatment and storage at 8^{0}C

a) Control of dry rot

The proportion of sites infected (PSI) as a function of UV dosage are shown in Figures 6.27 and 6.28 for the two years. The UV treatments generally reduced the dry rot disease by *F. solani* compared to the control. As shown in Figure 6.27 disinfection of the tubers was better at higher UV intensity of radiation. It was also observed that proportion of sites infected was higher at higher incubation periods (at 2 days incubation) compared to the lower incubations, indicating that the pathogens at the surface were killed by UV and the ones that has spread radially inwards into the tuber did not get

proper exposure of UV radiation.

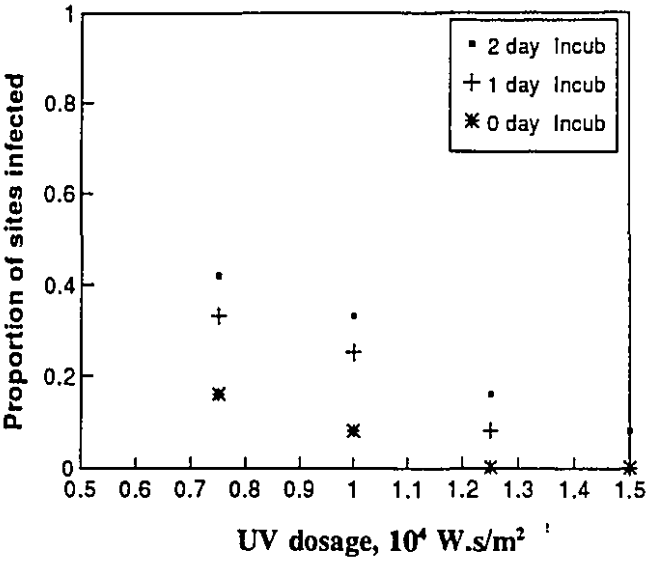

Figure 6.27 Effect of UV radiation on potato dry rot (F. solani).

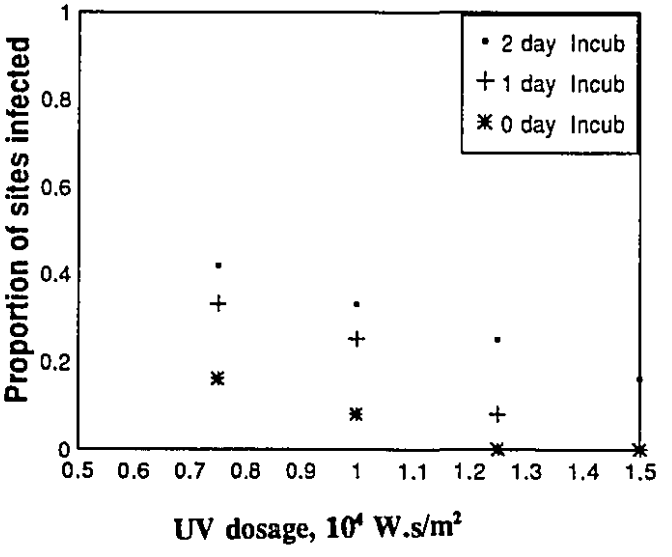

Figure 6.28 Effect of UV radiation on potato dry rot (F. solani) (1994).

Table 6.15 Least square means (LSM) for *F. solani* stored at 8°C

T[a]	Incub (day)	UVD (10^4 W.s/m^2)	Least square means PSI	COL (cm)	SPOIL (%)
1	0	0.75	0.17[b]	2.16[c]	22.16[d]
2	0	1.00	0.09	1.80	16.61
3	0	1.25	0.01	0.00	0.00
4	0	1.50	0.01	0.00	0.51
5	1	0.75	0.33	2.50	41.85
6	1	1.00	0.24	2.46	33.30
7	1	1.25	0.08	1.63	13.83
8	1	1.50	0.00	0.00	0.00
9	2	0.75	0.41	2.66	44.43
10	2	1.00	0.33	2.56	36.08
11	2	1.25	0.20	2.06	27.73
12	2	1.50	0.12	1.16	16.61

[a] Treatment #, each treatment was replicated thrice. [b] The LSM has a standard error of ± 0.0254, [c] The LSM has a standard error of ± 0.1129, and [d] The LSM has a standard error of ± 3.524.

Essentially, the UV energy is rapidly attenuated by opaque material such that deep infection is unaffected by the treatment. The results demonstrated that *F. solani* was completely controlled in the case of incubation levels of 0 and 1 day at the highest radiation dosage level (1.5 x 10^4 W.s/m^2). UV dosages above 1.5 x 10^4 W.s/m^2 were not considered since the preliminary UV experiments had shown that sprouting may be induced at higher dosages (2.0 x 10^4 W.s/m^2).

Figure 6.28, shows a similar trend for the 1994 experiments. Once again, eradication of *F. solani* was total at a dosage of 1.5 x 10^4 W.s/m^2 at the two incubation levels (0 and 1 day). Furthermore, the proportion of sites infected was almost zero at the maximum radiation intensity. The total control of the disease at a 2 day incubation level could not be achieved because the depth of UV penetration is limited to a few millimeters from the surface of the tuber and that the pathogens at the inside deeper layers are not exposed to the UV radiation.

The model estimates, standard errors and significance levels are presented in Table 6.16. Incubation period had a highly significant effect on PSI. PSI increased linearly with increasing incubation period. The proportion of sites infected decreased linearly with increased UV dosage. There was no significant interaction effect of UV dosage and the incubation period. The model predicts eradication of *F. solani* to be best at a UV intensity ≥ 1.38 x 10^4 W.s/m^2 and an incubation of ≥ 0 day (Figure 6.29).

The above indicates that the regression models developed for the three dependent parameters PSI, COL and SPOIL depend mainly on the single variable, UV dosage. Although incubation time was significant in the case of PSI, this was not true for COL or SPOIL.

For the average colony diameter (COL), the model estimates, standard errors and significance levels are presented in Table 6.16. UV radiation has a highly significant effect on COL ($p < 0.0003$). Neither the incubation period nor the interaction effects of UV radiation were significant on COL (Table 6.16). The model predicts eradication of *F. solani* by using a UV intensity ≥ 1.41 x 10^4 W.s/m^2 (Figure 6.30).

UV radiation had a highly significant effect on the percent spoilage of tubers ($p < 0.0003$). Neither the incubation time nor the interaction effects of UV radiation significantly influenced percent spoilage of potato tubers (Table 6.16). The model predicts eradication of *F. solani* at a UV intensity ≥ 1.38 x 10^4 W.s/m^2 (Figure 6.31).

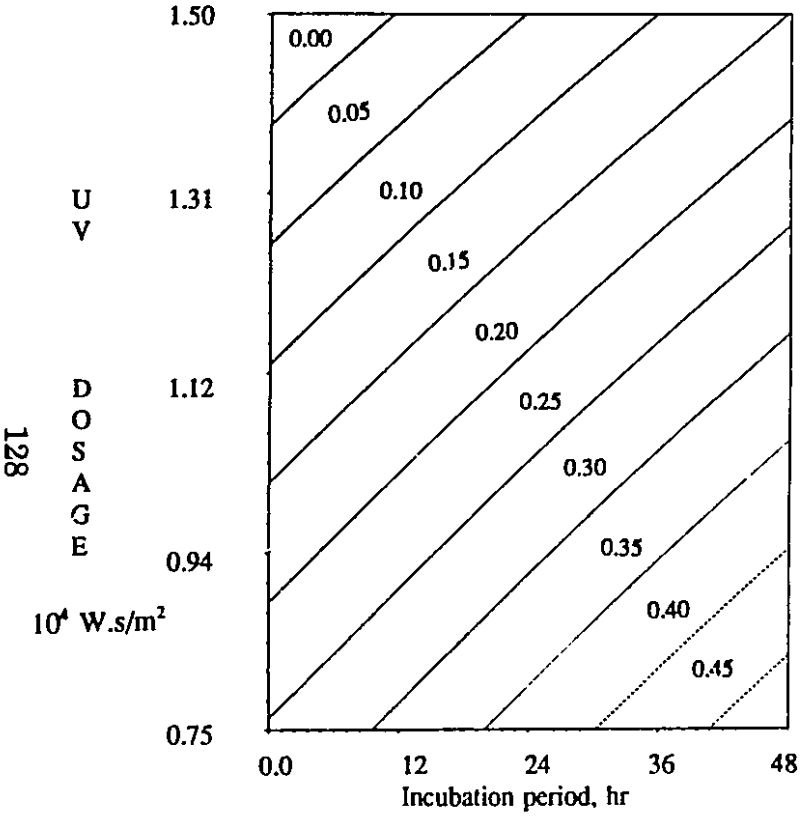

Figure 6.29: Contours PSI (dry rot) as a function of UV dosage (storage = 8°C).

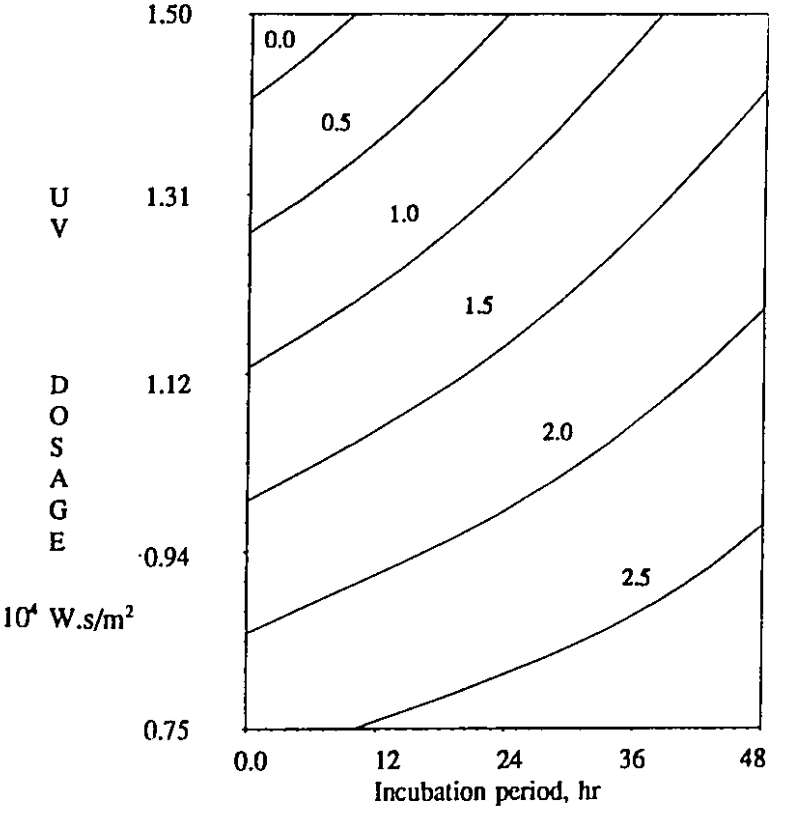

Figure 6.30: Contours COL (dry rot) as a function of UV dosage (storage = 8 °C).

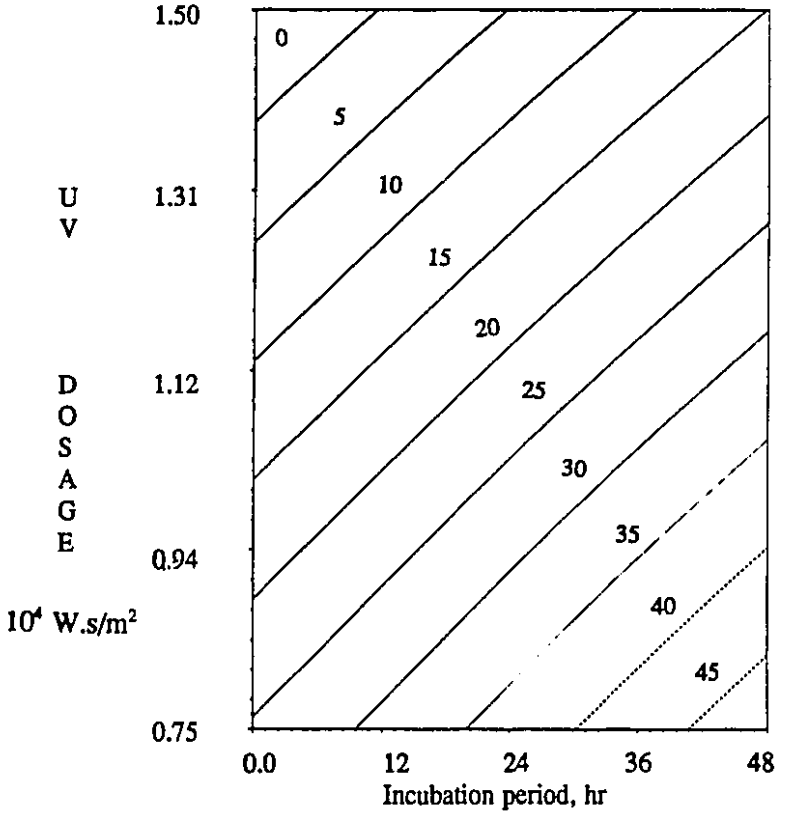

Figure 6.31: Contours SPOIL (dry rot) as a function of UV dosage (storage = 8°C).

Table 6.16 Reduced regression models to predict PSI, COL and SPOIL in potato tubers inoculated with *F. solani* as a function of UV dose.

Model term	Estimate	T-ration
Proportion of sites infected (PSI)		$R^2 = 0.95$
Intercept	0.382004991 (0.06302)	0.0003^{***}
UVD	-0.02777711 (0.00543)	0.0008^{***}
Incub	0.19412500 (0.04881)	0.0041^{**}
UVD*Incub	-0.00853383 (0.00421)	$0.0773^{n.s}$
Average colony diameter (COL)		$R^2 = 0.87$
Intercept	5.03040086 (0.80918)	0.0003^{***}
UVD	-0.35652553 (0.06980)	0.0009^{***}
Incub	-0.19264779 (0.62679)	$0.7664^{n.s}$
UVD*Incub	0.06731002 (0.05407)	$0.2484^{n.s}$
Percent spoilage		$R^2 = 0.93$
Intercept	55.74675681 (9.25936)	0.0003^{***}
UVD	-4.03227248 (0.79876)	0.0010^{**}
Incub	12.99927900 (7.17224)	$0.1075^{n.s}$
UVD*Incub	-0.20476986 (0.61872)	$0.7492^{n.s}$

b) Control of soft rot

The Figures 6.32 and 6.33 show the proportion of sites infected (PSI) as a result of different levels of UV treatments for the years 1993 and 1994. The results show that the UV treatments generally reduced the soft rot caused by *Erwinia carotovora* pv. *carotovora* in all the treatment combinations compared to the control. Further, disinfection of the tubers was better at higher UV dosages and intensity of radiation. It was also observed that proportion of sites infected was also higher at higher incubation periods (at 12 hrs incubation) compared to the lower incubation levels, indicating that the

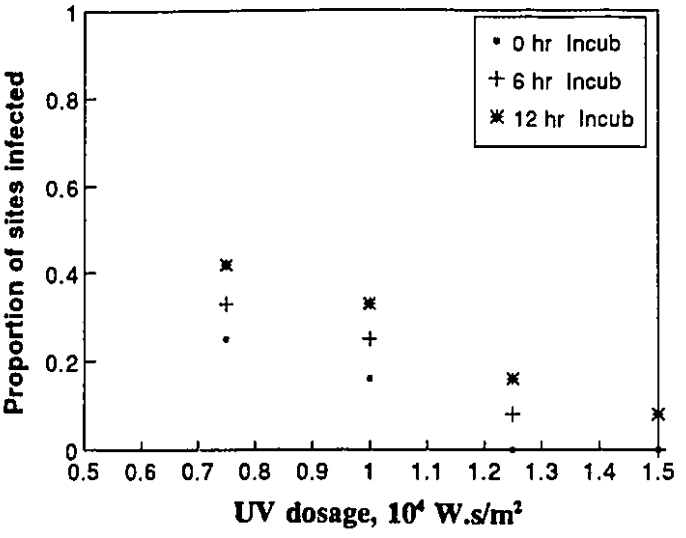

Figure 6.32 Effect of UV radiation on potato soft rot (Ecc) (1993).

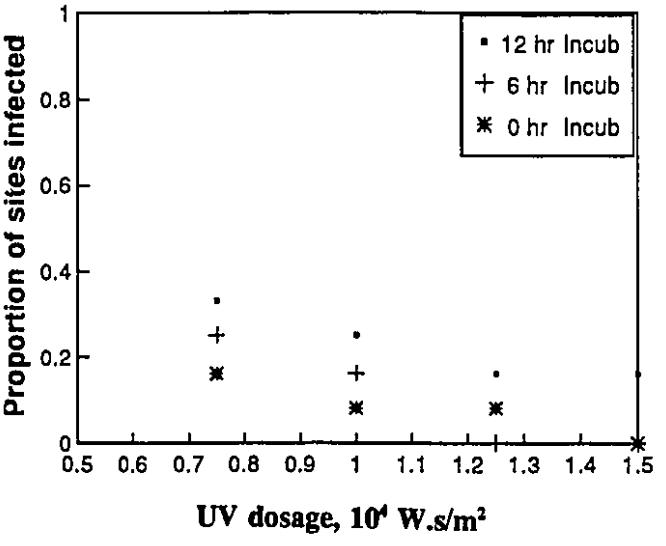

Figure 6.33 Effect of UV radiation on potato soft rot (Ecc) (1994).

bacteria at the surface were killed and that those that had spread radially inwards into the tuber did not get proper exposure of UV radiation. The results demonstrated that *Erwinia carotovora* pv. *carotovora* was completely controlled in the case of incubation levels of 0 and 1 day at the highest radiation dosage.

The least square means of PSI, COL and SPOIL with respect to *Erwinia carotovora* pv. *carotovora* are presented in Table 6.17.

Table 6.17 Least square means for *Erwinia carotovora* pv. *carotovora* stored at 8°C

T[a]	Incub (hrs)	UVD (10^4 W.s/m^2)	Least square means PSI (cm)	COL (%)	SPOIL
1	0	0.75	0.24[b]	2.16[c]	30.52[d]
2	0	1.00	0.11	1.90	16.60
3	0	1.25	0.04	0.00	8.31
4	0	1.50	0.00	0.00	0.00
5	6	0.75	0.28	2.45	33.30
6	6	1.00	0.20	2.35	22.16
7	6	1.25	0.05	1.86	11.08
8	6	1.50	0.00	0.00	0.00
9	12	0.75	0.40	2.48	44.43
10	12	1.00	0.26	2.11	30.51
11	12	1.25	0.16	1.85	24.95
12	12	1.50	0.12	1.66	16.60

[A] Treatment #, each treatment was replicated thrice. [b] The LSM has a standard error of ± 0.0242, [c] The LSM has a standard error of ± 0.0419 [d] The LSM has a standard error of ± 3.5418.

The UV radiation significantly influenced the proportion of sites infected with soft rot. The PSI decreased linearly with increased UV radiation (Table 6.18). Once again, the incubation period had no significant effect on PSI. Further, the interaction effect of UV radiation and incubation had no significant effect. The model predicts eradication of *Ecc* pathogen at a UV intensity $\geq 1.41 \times 10^4$ W.s/m^2 (Figure 6.34).

Table 6.18 Reduced regression models to predict the PSI, COL and SPOIL in potato tubers inoculated with *Ecc* as a function of UV dose.

Model term	Estimate	T-ration
Proportion of sites infected (PSI)		$R^2 = 0.94$
Intercept	0.467347000 (0.06815)	0.0001^{***}
UVD	-0.03347079 (0.00587)	0.0005^{***}
Incub	0.10502513 (0.05279)	$0.0819^{n.s}$
UVD*Incub	-0.00330418 (0.00455)	$0.4888^{n.s}$
Average colony diameter (COL)		$R^2 = 0.84$
Intercept	5.195945953 (0.85976)	0.0003^{***}
UVD	-0.36683041 (0.07416)	0.0011^{**}
Incub	-0.77856757 (0.66597)	$0.2760^{n.s}$
UVD*Incub	0.11396494 (0.05745)	$0.0826^{n.s}$
Percent spoilage		$R^2 = 0.95$
Intercept	59.64527784 (6.53475)	0.0001^{***}
UVD	-4.21377776 (0.56372)	0.0001^{**}
Incub	5.21083329 (5.06179)	$0.3334^{n.s}$
UVD*Incub	0.21533334 (0.43666)	$0.6352^{n.s}$

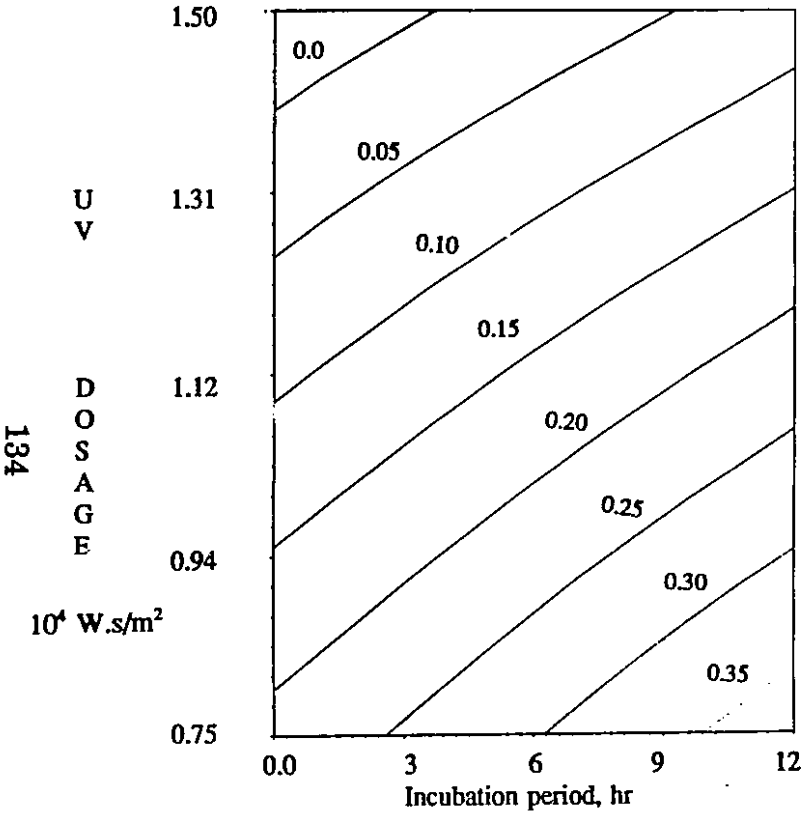

Figure 6.34: Contours PSI (soft rot) as a function of UV dosage (storage = 8°C).

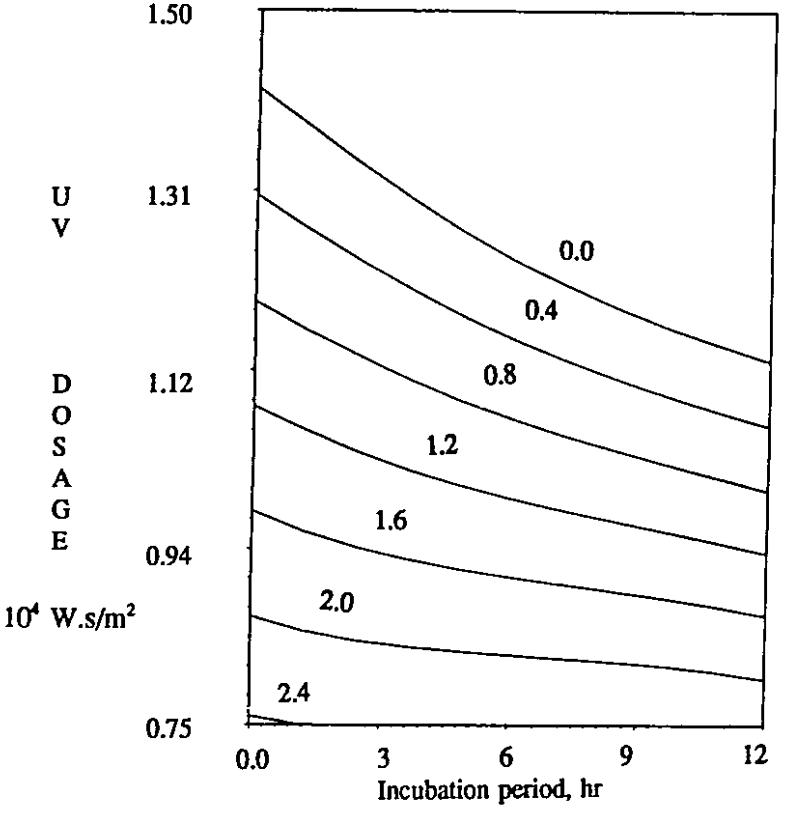

Figure 6.35: Contours COL (soft rot) as a function of UV dosage (storage = 8°C).

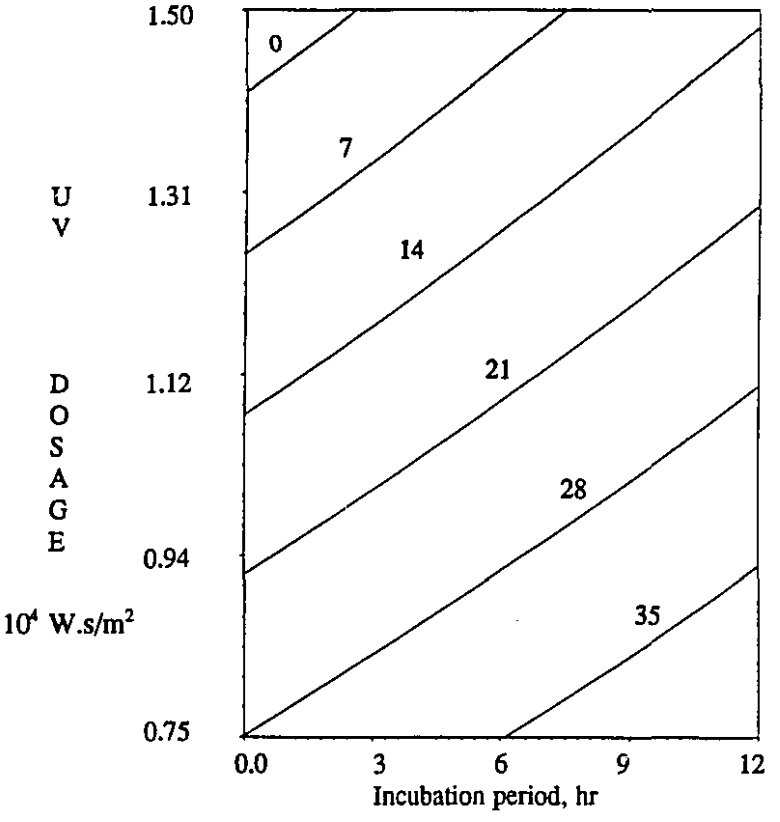

Figure 6.36: Contours SPOIL (soft rot) as a function of UV dosage (storage = 8°C).

The UV radiation influences the average colony diameter. Neither the incubation period nor the interaction of UV radiation and incubation had a significant effect on COL (Table 6.18). The model predicts eradication of *Ecc* pathogen by at a UV intensity ≥ 1.42 x 10^4 W.s/m^2 (Figure 6.35).

UV radiation has a highly significant effect on SPOIL ($p < 0.0001$). The incubation and the interaction effects of UV radiation were not significant (Table 6.18). The model predicts no spoilage at a UV intensity ≥ 1.38 x 10^4 W.s/m^2 (Figure 6.36).

6.3.1.2 UV treatment and storage at 18°C

a) Control of dry rot

Figure 6.37 shows the proportion of sites infected (PSI) after UV treatment and storage at 18°C. The UV treatments generally reduced the dry rot caused by *F. solani* in all the treatment combinations compared to the control. As shown in Figure 6.37, the effect of UV on the control of diseases

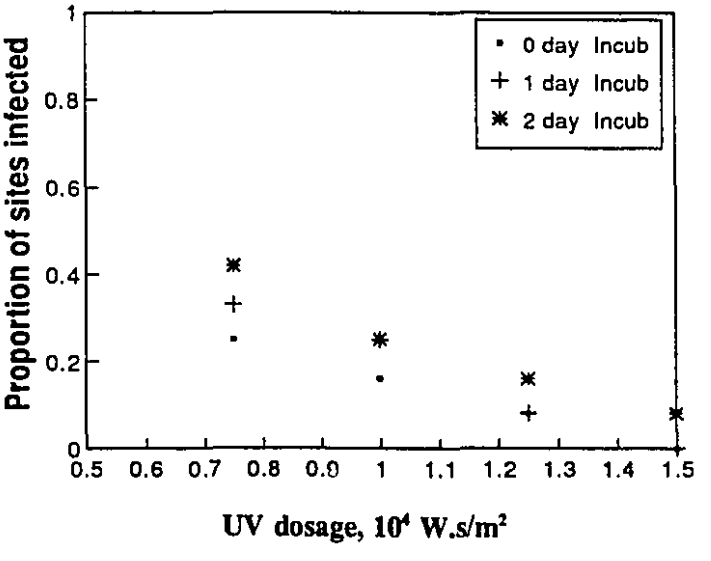

Figure 6.37 Effect of UV radiation on potato dry rot stored at 18°C (means of two year data).

was observed to be lower in the case of lower UV dosages and the infection reduced as the intensity of radiation was increased. However, the number of infected sites and the average colony diameters were larger at 18°C storage than at 8°C storage. The proportion of sites infected was again much higher for longer incubation periods (2 days incubation) indicating that the pathogens had penetrated more deeply into the tissues and were not properly exposed to UV radiation. Figure 6.37 shows that *F. solani* was completely controlled by the highest radiation dosage level (1.5×10^4 W.s/m^2) on inoculated tubers that were either not incubated or incubated for just 1 day.

Table 6.19 Least square means (LSM) for *F. solani* stored at 18°C

T[a]	UVD (10^4 W.s /m^2)	Incub (day)	Least square means PSI	COL (cm)	SPOIL (%)
1	0.75	0	0.37[b]	6.03[c]	41.65[d]
2	1.00	0	0.20	5.60	24.95
3	1.25	0	0.12	5.30	16.60
4	1.50	0	0.00	0.00	0.00
5	0.75	1	0.46	5.93	52.85
6	1.00	1	0.34	5.50	36.08
7	1.25	1	0.12	4.78	19.38
8	1.00	1	0.00	0.00	0.00
9	0.75	2	0.62	5.90	66.60
10	1.00	2	0.43	5.51	50.00
11	1.25	2	0.22	5.23	27.73
12	1.50	2	0.06	3.21	11.06

[a] Treatment #, each treatment was replicated thrice. [b] the LSM has a standard error of ± 0.0171, [c] the LSM has a standard error of ± 0.3030, and [d] the least square means has a standard error of ± 2.5829.

The model estimates, standard errors and significance levels are presented in Table 6.19. All the effects in the model were highly significant on PSI. PSI increased linearly with increasing incubation period. The proportion of sites infected decreased linearly with increased UV dosage. There were significant interactions between UV dosage and the incubation period. The model predicts eradication of *F. solani* at a UV intensity ≥ 1.19 x 10^4 W.s/m^2 and an incubation period of ≥ 0 day (Figure 6.38).

Table 6.20 Reduced regression models to predict the PSI, COL and SPOIL in potato tubers inoculated with *F. solani* as a function of UV dose.

Model term	Estimate	T-ration
Proportion of sites infected (PSI)		R^2 = 0.98
Intercept	0.709243245 (0.05139)	0.0001***
UVD	-0.04818512 (0.00443)	0.0001***
Incub	0.23622071 (0.03981)	0.0003***
UVD*Incub	-0.01387559 (0.00345)	0.0037**
Average colony diameter (COL)		R^2 = 0.89
Intercept	-4.075277784 (5.09711)	0.4497n.s
UVD	2.45033333 (0.92296)	0.0327*
Incub	-1.89833333 (1.28646)	0.1836n.s
UVD*Incub	-0.20133333 (0.11097)	0.1125n.s
UVD*UVD	-0.14466666 (0.04052)	0.0091**
Percent spoilage		R^2 = 0.99
Intercept	82.01540546 (4.68376)	0.0001***
UVD	-5.52314524 (0.40405)	0.0001***
Incub	21.51509006 (3.62802)	0.0003***
UVD*Incub	-1.10997952 (0.31297)	0.0075**

UV radiation had a significant effect on the average colony diameter (Table 6.20). However, neither incubation or the interaction of UV and

incubation influenced COL. The model predicts eradication of *F. solani* pathogen at a UV intensity ≥ 1.44 x 10^4 W.s/m^2 (Figure 6.39).

In the case of percent spoilage, all the terms in the model are highly significant. The model predicts eradication of pathogen *F. solani* by using a UV intensity ≥ 1.48 x 10^4 W.s/m^2 (Figure 6.40).

The UV treatments at all incubation levels controlled dry rot at 18°C storage to levels lower than of the control at 8°C storage. The controls at 18°C were completely spoiled and removed from the storage.

b) Control of soft rot

The least square means of PSI, COL and SPOIL with respect to *Erwinia carotovora* pv. *carotovora* are presented in Table 6.21.

The UV radiation significantly affected the proportion of sites infected by soft rot disease. The PSI decreased linearly with increased UV radiation (Table 6.22). The incubation period significantly increased PSI. The interaction of UV radiation and incubation was also significant. The model predicts eradication of *Ecc* bacteria to the least incidence level by using a UV intensity ≥ 1.39 x 10^4 W.s/m^2 in and incubation period of ≥ 0 hr (Figure 6.41).

Both the linear and quadratic effects of UV radiation were highly significant on COL. Neither incubation period or the interaction of UV radiation and incubation significantly influenced COL (Table 6.22). The model predicts that *Ecc* can be controlled to a minimum by using a UV intensity ≥ 1.26 x 10^4 W.s/m^2 (Figure 6.42).

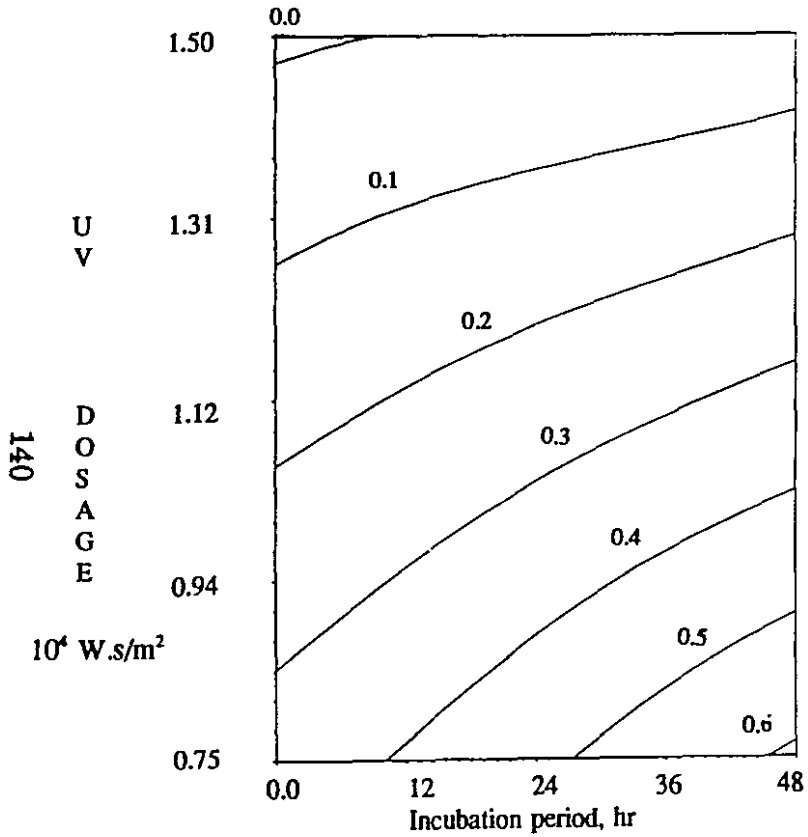

Figure 6.38: Contours PSI (dry rot) as a function of UV dosage (storage = 18°C).

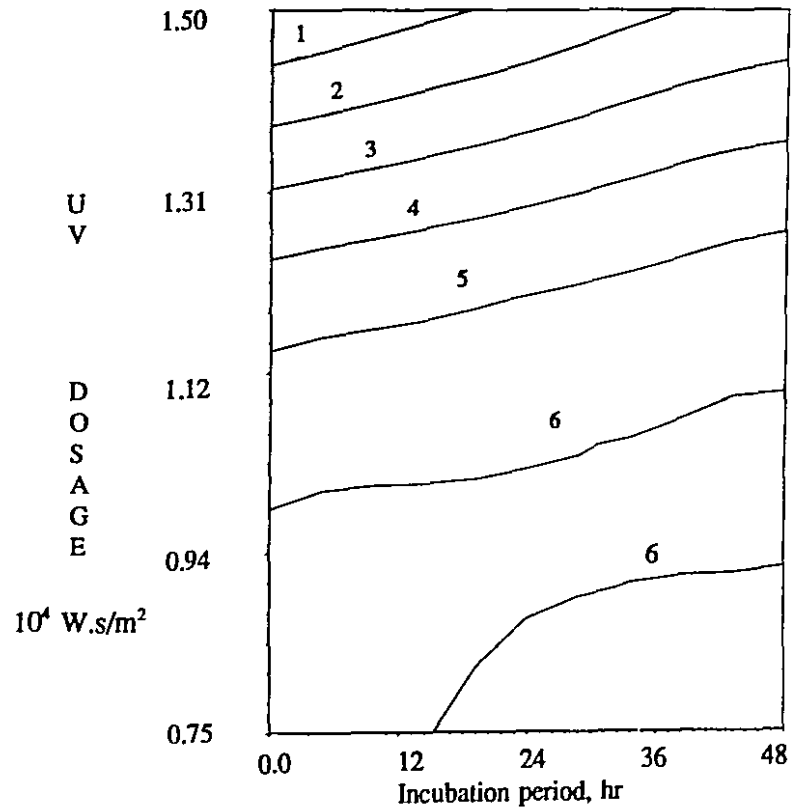

Figure 6.39: Contours COL (dry rot) as a function of UV dosage (storage = 18 °C).

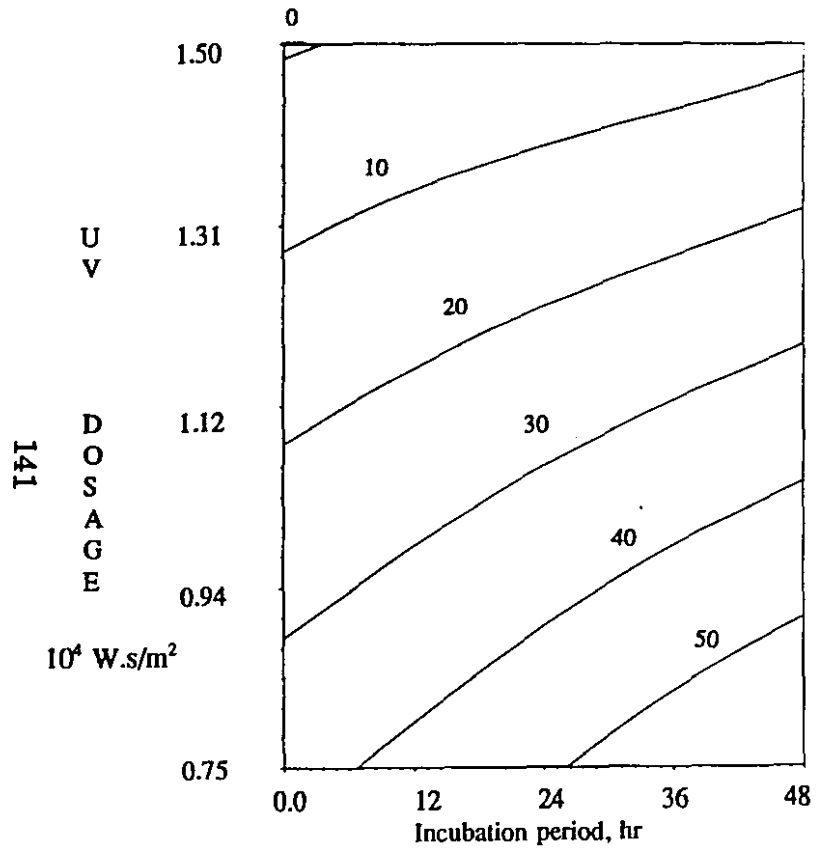

Figure 6.40: Contours SPOIL (dry rot) as a function of UV dosage (storage = 18°C).

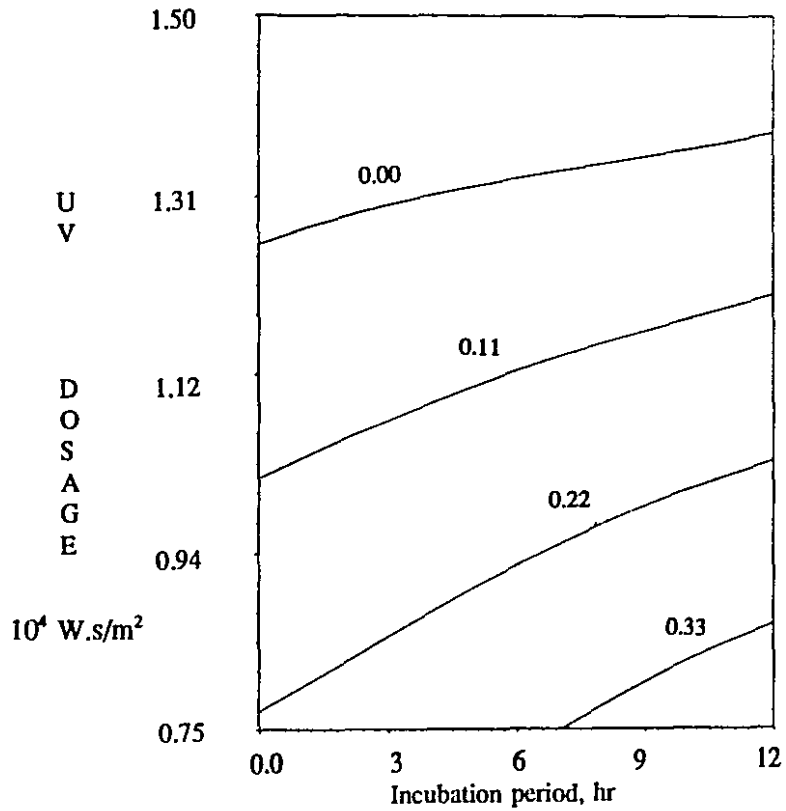

Figure 6.41: Contours PSI (soft rot) as a function of UV dosage (storage = 18°C).

Table 6.21 Least square means for *Ecc* stored at 18°C.

T[a]	UVD (10^4 W.s/m^2)	Incub (hr)	Least square means PSI	COL (cm)	SPOIL (%)
1	0.75	0	0.24[b]	2.16[c]	30.52[d]
2	1.00	0	0.11	1.90	16.60
3	1.25	0	0.04	0.00	8.31
4	1.50	0	0.00	0.00	0.00
5	0.75	6	0.28	2.45	33.30
6	1.00	6	0.20	2.35	22.16
7	1.25	6	0.05	1.86	11.08
8	1.50	6	0.00	0.00	0.00
9	0.75	12	0.40	2.48	44.43
10	1.00	12	0.26	2.11	30.51
11	1.25	12	0.16	1.85	24.95
12	1.50	12	0.12	1.66	16.60

[a] Treatment #, each treatment was replicated thrice. [b] the LSM has a standard error of ± 0.0191, [c] the LSM has a standard error of ± 3.0185, and [d] the least square means has a standard error of ± 0.0186.

UV radiation has a highly significant effect on percent spoilage of tubers. The incubation and the interaction effects of UV radiation were not significant on SPOIL (Table 6.22). The model predicted to eradicate *Ecc* bacteria by using a UV intensity ≥ 1.42 x 10^4 W.s/m^2 (Figure 6.43).

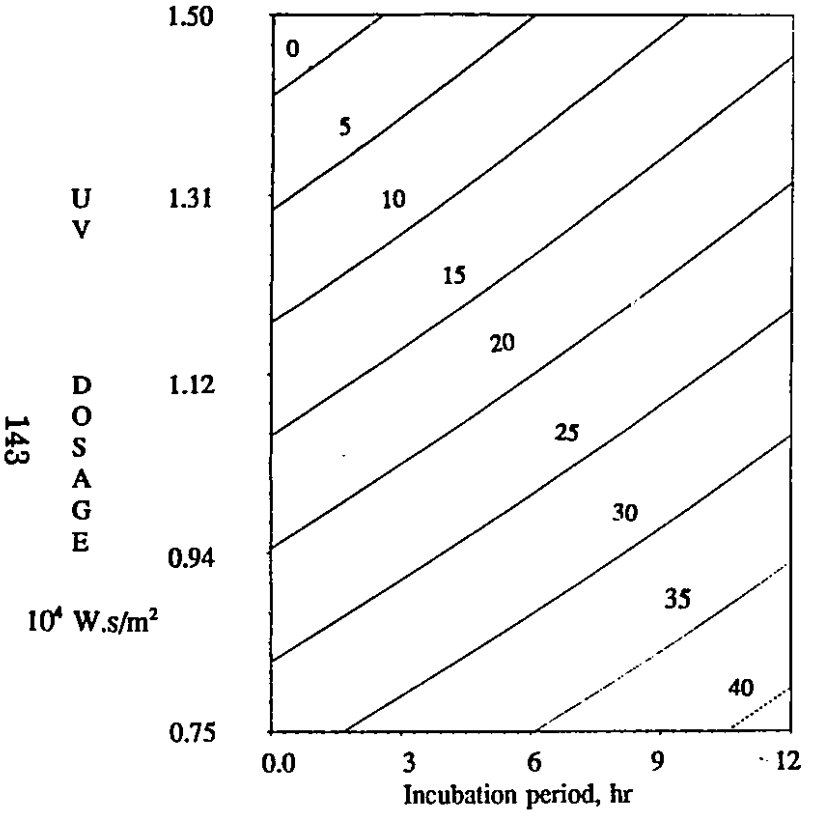

Figure 6.42: Contours COL (soft rot) as a function of UV dosage (storage = 18°C).

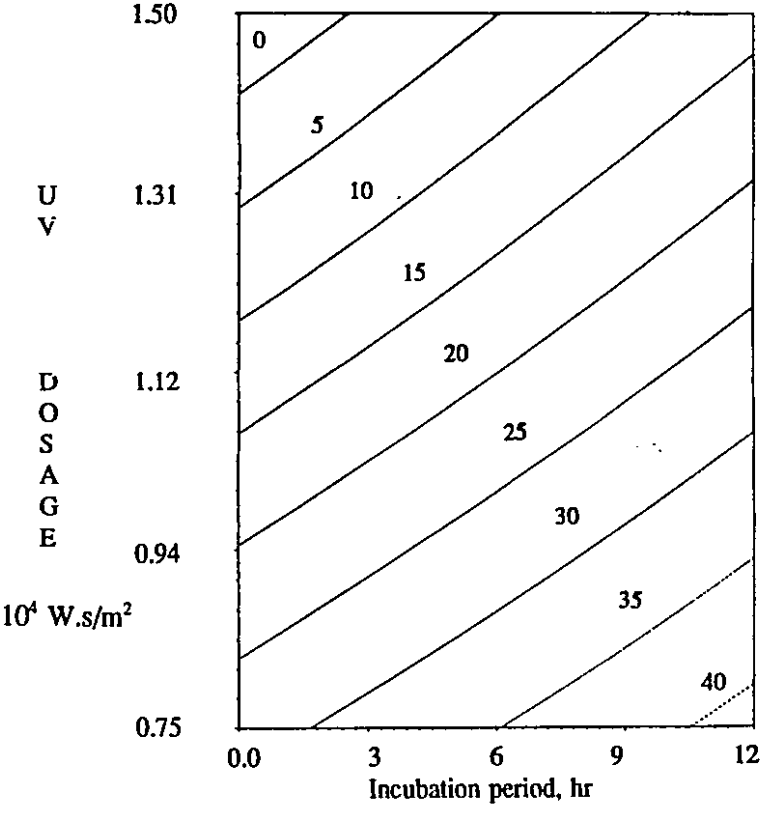

Figure 6.43: Contours SPOIL (soft rot) as a function of UV dosage (storage = 18°C).

Table 6.22 Reduced regression models to predict the PSI, COL and SPOIL in potato tuber inoculated with *Ecc* as a function of UV dose.

Model term	Estimate	T-ration
Proportion of sites infected (PSI)		R^2 = 0.97
Intercept	0.674126132 (0.05277)	0.0001***
UVD	-0.04470769 (0.00455)	0.0001***
Incub	0.15515765 (0.04088)	0.0053**
UVD*Incub	-0.00933538 (0.00352)	0.0294*
Average colony diameter (COL)		R^2 = 0.92
Intercept	-8.04612040 (4.92958)	0.1467n.s
UVD	3.26941945 (1.24574)	0.0081**
Incub	0.11359252 (0.10746)	0.3256n.s
UVD*Incub	-0.18087240 (0.03924)	0.0025**
Percent spoilage		R^2 = 0.97
Intercept	81.21063042 (6.87228)	0.0001***
UVD	-5.43691727 (0.59284)	0.0001***
Incub	11.64662175 (5.32324)	0.0601n.s
UVD*Incub	-0.53811631 (0.45921)	0.2750n.s

Summary

The high-intensity UV radiation treatment was very effective at controlling dry rot and soft rot diseases of potato tuber, particularly when the pathogens had been given at most one day to incubate. For 2-day incubation disease incidence could be controlled, but not to 100%. Although all data trends were similar, higher infection levels were observed on the tubers stored at 18°C. The results indicate that it is possible to use this as an alternative treatment. The practical application of UV should be simple but demands

proper exposure of the entire tuber surface to be highly effective.

6.3.2 Control of Sprouting

A Randomised Complete Block Design with three replications was adopted to study ultraviolet radiation to control sprouting. One series was performed in the fall of 1993, the other in the fall of 1994. Common UV dosage levels were tested which could provide meaningful results in the control of both sprouting and diseases, keeping in view the practical implications of the results to one stage UV treatment. As found in the preliminary studies on sprout control (Chapter III), the UV radiation level of 0.75×10^4 W.s/m^2 was effective in controlling sprouts. As already discussed, UV dosages above 1.5×10^4 W.s/m^2 were not considered because of induced sprouts. Thus, the same levels of UV radiation were used as had been in the disease control studies: 0.75×10^4, 1.00×10^4, 1.25×10^4, and 1.50×10^4 W.s/m^2 same used in the case of disease control experiments. Post-treatment storage was done at 8 or 18°C and 90-95% RH. First, the samples were given UV exposure for the designed UV radiation dosage. Then the samples were turned upside down and retreated.

The results are presented in Figures 6.44 and 6.45. Figure 6.44 shows the sprout control at the end of 12 weeks of storage at 8°C. Sprouting decreased linearly with increased UV dose, and was completely eliminated at the highest UV radiation level. The results are comparable with the findings of the preliminary studies (Chapter III) for potato cv. Russet Burbank. Sprout growth was not observed until four weeks of storage had passed. It was also observed that the sprout lengths were very small, when they occurred, compared to the sprouting lengths in control samples.

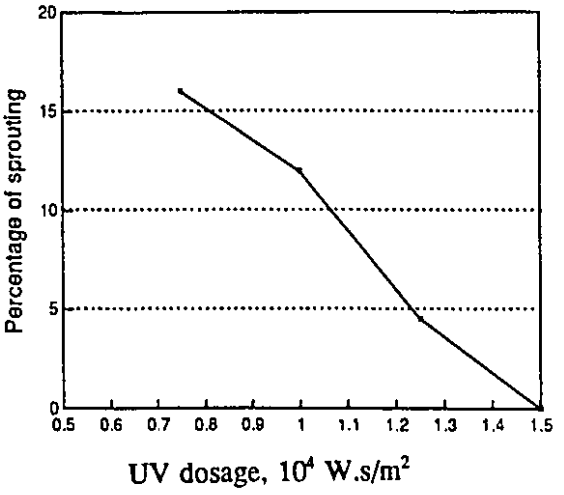

Figure 6.44 Effect of UV radiation on sprout inhibition (storage at 8°C).

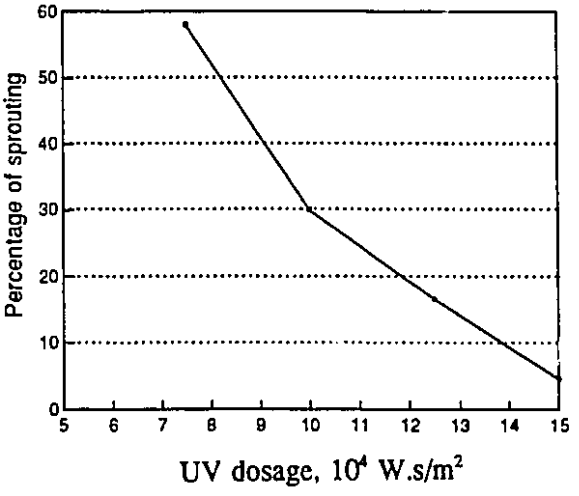

Figure 6.45 Effect of UV radiation on sprout inhibition (storage at 18°C).

Figure 6.45 shows the results of sprout control for the same period (12 weeks) of storage when tubers were stored at 18°C. It could be seen that the sprout inhibition was less poor at the lower radiation levels and linearly decreased as the UV radiation was increased. The percentage of sprouting was very low (< 5%) at the highest radiation level. Although complete sprout inhibition could not be achieved at 18°C storage, the results were very encouraging. Further, the percentage sprouting was considerably low at all the treatment levels compared to the control.

Summary

The results of the lab scale study have shown that the complete control of sprouting for three months' storage was possible at the highest UV radiation dosage. One of the hypotheses of this investigation has been vindicated: the ultraviolet radiation is not only effective in controlling sprouting but also serves as a simple and alternative treatment with chemicals. Given the simplicity of the ultraviolet radiation treatment, scale up is the next step for large scale treatment of the tubers.

6.4 COMBINATION TREATMENTS OF ULTRAVIOLET RADIATION AND HOT WATER DIPPING FOR POTATO SPROUT CONTROL

A 4 x 3 x 3 Factorial experiment in Randomised Complete Block Design was adopted to examine the potential of improving sprout control with less intensive treatment conditions by combining UV and water dipping. Two effects were hoped for: 1) a reduction in energy use, and 2) better tuber quality at the same level of sprout inhibition obtained with water dipping alone. Four UV levels, three hot water temperatures and three dipping times were used and were the same as those used in the individual treatment experiments. This series of experiments were performed for one season in the fall of 1994. As in the other experiments, the tuber samples were stored for three months in separate chambers maintained at 8 or 18°C and 90-95% relative humidity.

Table 6.23 shows the model estimates, standard errors and significance levels for tuber sprouting at 8°C storage. All the linear, quadratic and cross products in the model significantly influenced sprout inhibition. The model predicts that the hot water treatment temperature was the most important parameter, followed by UV intensity, dipping time, and the cross products. The threshold level of 100% sprout inhibition at dipping times of 20 and 30 min is shown in Figure 6.46.

Table 6.23 Reduced regression model to predict sprout inhibition in potato tubers (R^2=0.93).

Model term	Estimate	T-ratio
Intercept	2240.36944 (183.4404)	0.0001***
UV Dosage	-20.614815 (1.71914)	0.0001***
Temp	-71.624444 (6.63957)	0.0001***
Time	-8.0302222 (0.61142)	0.0001***
Temp*Temp	0.5720000 (0.06023)	0.0001***
Time*Time	0.0123750 (0.00376)	0.0014**
UVD*Temp	0.3466670 (0.03110)	0.0001***
UVD*Time	0.0363780 (0.00777)	0.0001***
Temp*Time	0.1230000 (0.01064)	0.0001***

The model estimates, standard errors and significance levels for tuber sprouting at 18°C storage temperature are presented in Table 6.24. All the linear, quadratic and cross products in the model were significant. Again, water temperature was the most important parameter. A response surface graph was plotted to show the threshold level of 100% sprout inhibition at

dipping times of 20 and 30 min (Figure 6.47). Figure 6.47 shows regions of threshold levels at 20 and 30 min of hot water dipping times.

Table 6.24 Reduced regression model to predict sprout inhibition in potato tubers (R^2=0.92).

Model term	Estimate	T-ratio
Intercept	4085.52445 (396.7065)	0.0001***
UV Dosage	-57.995259 (3.96560)	0.0001***
Temp	-127.603220 (14.3562)	0.0001***
Time	-12.7324170 (1.32204)	0.0001***
UVD*UVD	0.2349630 (0.06140)	0.0002***
Temp*Temp	1.0064440 (0.13025)	0.0001**
Time*Time	0.0219440 (0.00814)	0.0003***
UVD*Temp	0.8640890 (0.06726)	0.0001***
UVd*Time	0.1457330 (0.01681)	0.0001***
Temp*Time	0.1734170 (0.02302)	0.0001***

Summary

UV treatment was able to eradicate both dry rot and soft rot disease causing pathogens at the lower incubation periods. However, at longer incubation period UV radiation could not reach the pathogens spread deeper into the tubers. UV treatment was successful in the total sprout inhibition for the potatoes stored at 8°C. At 18°C very less sprout percent was observed compared to the control. It was found that 100% control of sprouting can be obtained at the lowest temperature (52.5°C, 30 min) with intermediate UV (1.0 and 1.25 x 10^4 W.s/m^2) levels for 8°C storage.

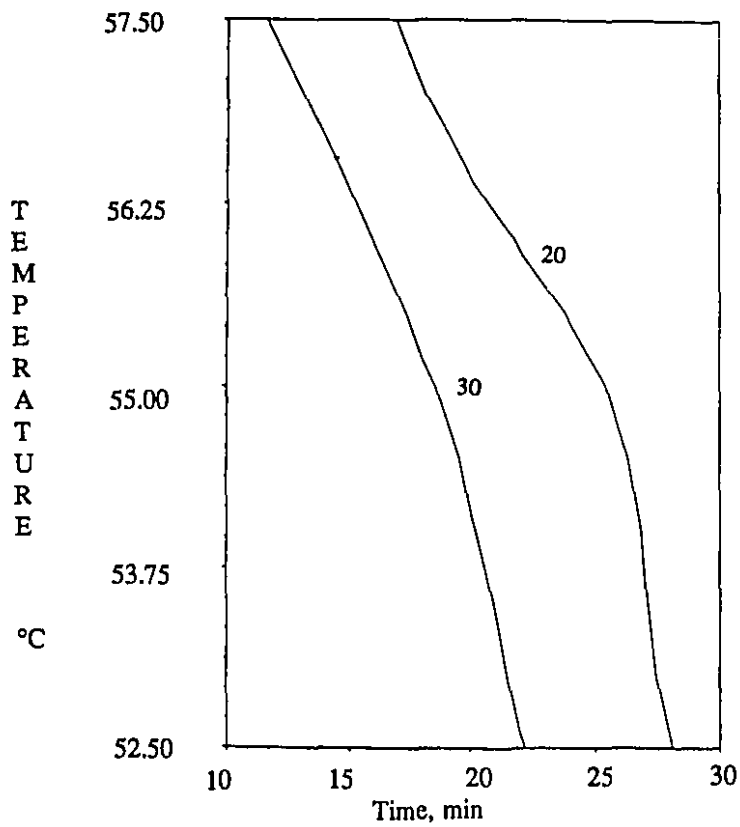

Figure 6.46: Contours showing the threshold levels of sprout inhibition as a function of UV and hot water at times 20 and 30 min (8°C).

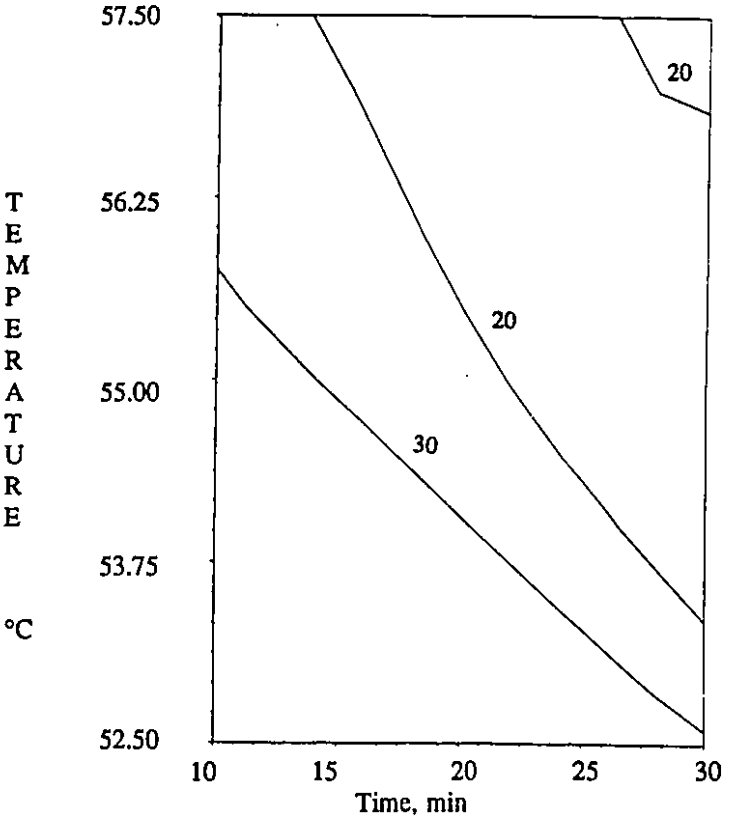

Figure 6.47: Contours showing the threshold levels of sprout inhibition as a function of UV and hot water at times 20 and 30 min (18°C).

CHAPTER VII
QUALITY ATTRIBUTES OF POTATO TUBERS

7.1 POTATO STRUCTURE ANALYSIS

The structure analysis of the raw and treated potato samples was performed using scanning electron microscopy. The most important aspect of this analysis is the preparation of the sample, the details of which were given in Chapter V. Scanning electron micrographs were made on control tubers and those treated by dipping, UV and the combination treatments of hot water and UV. However, only representative combinations (including the high dosage and/or temperature extremes) were selected due to resource constraints. The starch granules in the parenchyma were scanned by the Scanning Electron Microscope (SEM) at 10 kV accelerating voltage. A single magnification (x 1000) was used. The parenchyma were scanned since they are close to the surface, have high starch content, and because heat treatment produces visible changes in starch granules (Fedec et al. 1977).

The micrographs of starch granules of the controls are shown in Figures 7.1 and 7.2. Those of hot water-dipped tubers are shown in Figures 7.3 to 7.10. UV-irradiated tubers are shown in Figures 7.11 and 7.12, and those subjected to the combined treatments are in Figures 7.13 and 7.14. Micrographs taken on unheated and heated potatoes (65-80°C) by Fedec et al. (1977) were used as examples of the visual damages to expect. There were no visible changes (cell separation or cell rupture) in the starch granules treated by hot water at the temperatures used in the present studies. Although the size and shapes of the starch granules in Figures 7.1-7.10 vary, this is apparently to be expected (Fedec et al., 1977; Johnson et al. 1970) even within a single potato tuber. No extracelluar material appeared to exude, there was no significant swelling of the starch granules nor any observable gelatinization (seen as fusing of granules).

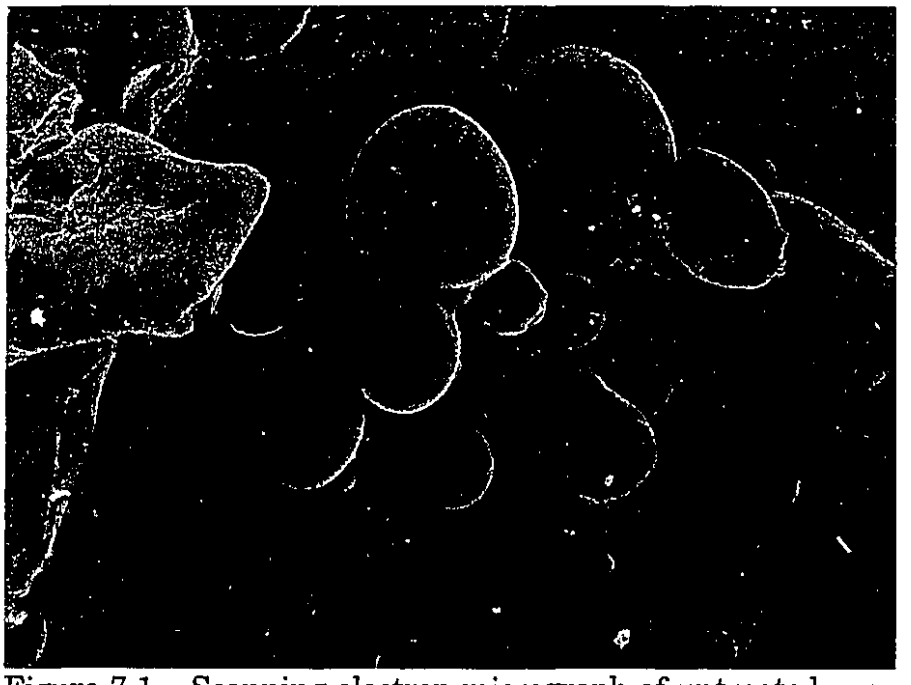

Figure 7.1 Scanning electron micrograph of untreated raw potato tuber starch granules (sample #1)

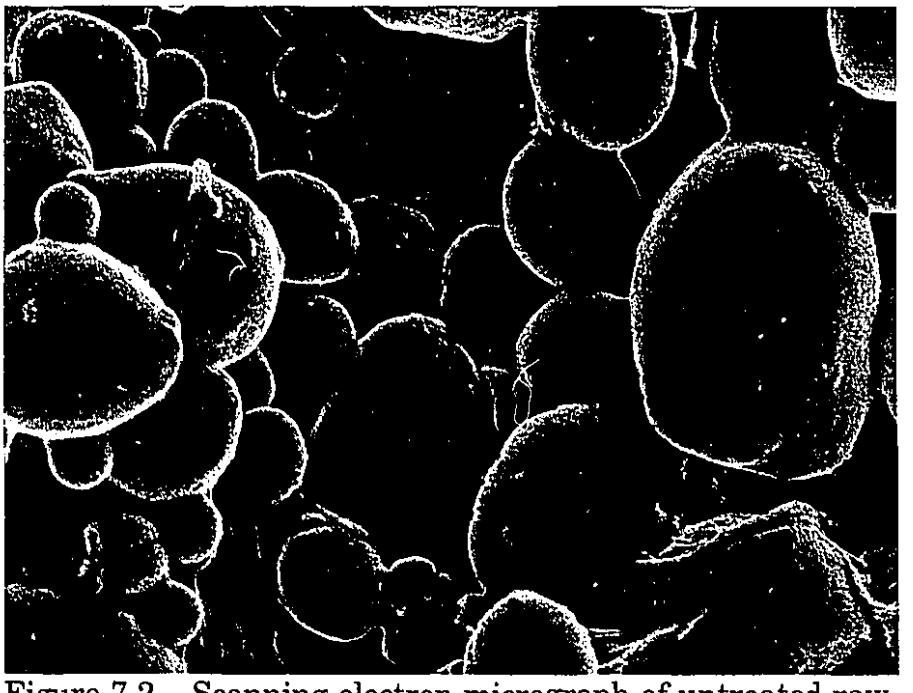

Figure 7.2 Scanning electron micrograph of untreated raw potato tuber starch granules (sample #2)

Figure 7.3 Scanning electron micrograph of potato tuber starch granules treated with hot water at 52.5°C and 10 min.

Figure 7.4 Scanning electron micrograph of potato tuber starch granules treated with hot water at 55°C and 10 min.

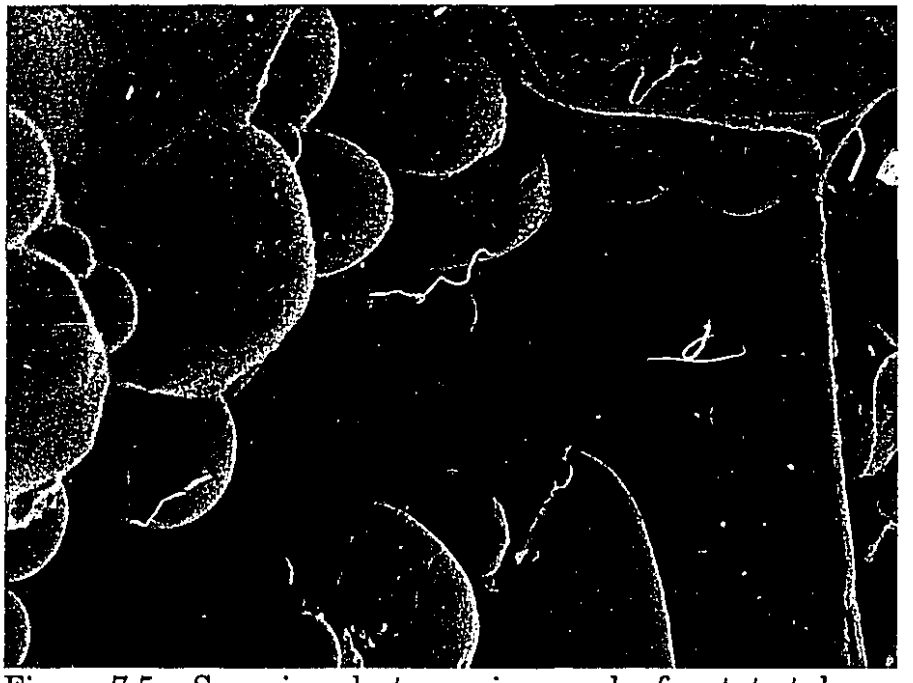

Figure 7.5 Scanning electron micrograph of potato tuber starch granules treated with hot water at 57°C and 10 min.

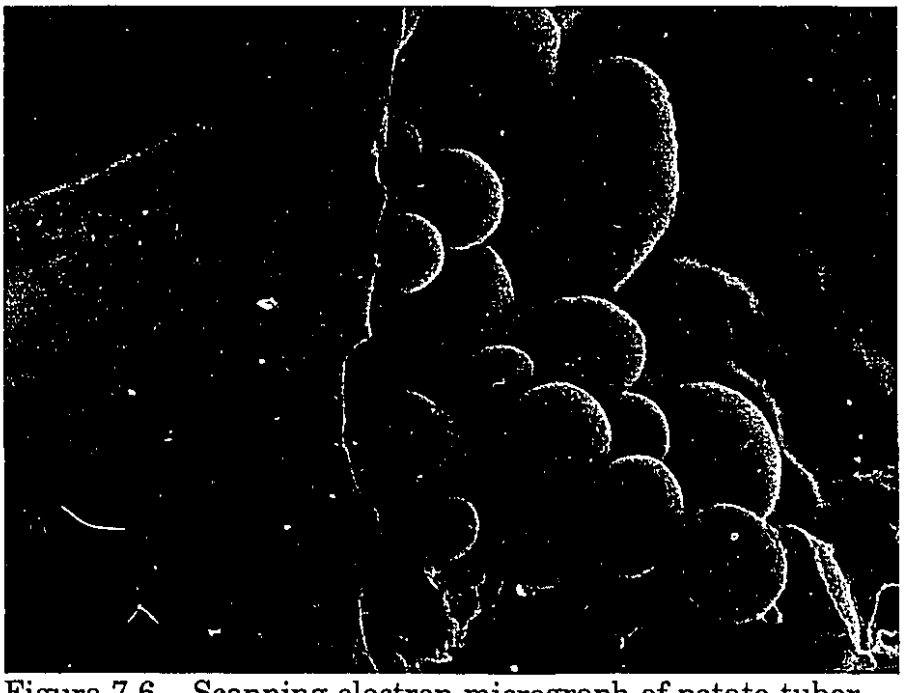

Figure 7.6 Scanning electron micrograph of potato tuber starch granules treated with hot water at 52.5°C and 20 min.

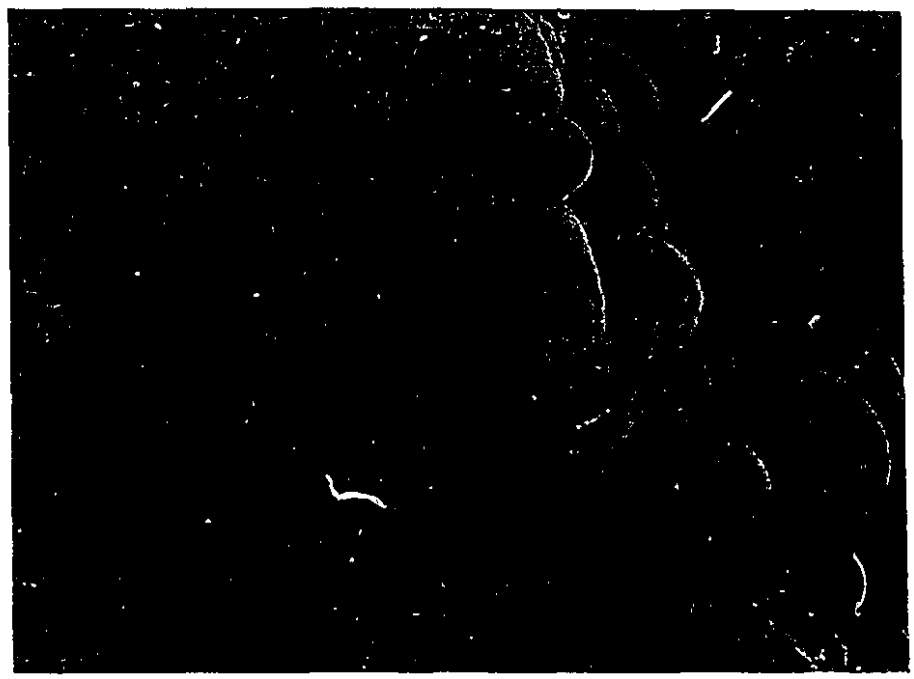

Figure 7.7 Scanning electron micrograph of potato tuber starch granules treated with hot water at 55°C and 20 min.

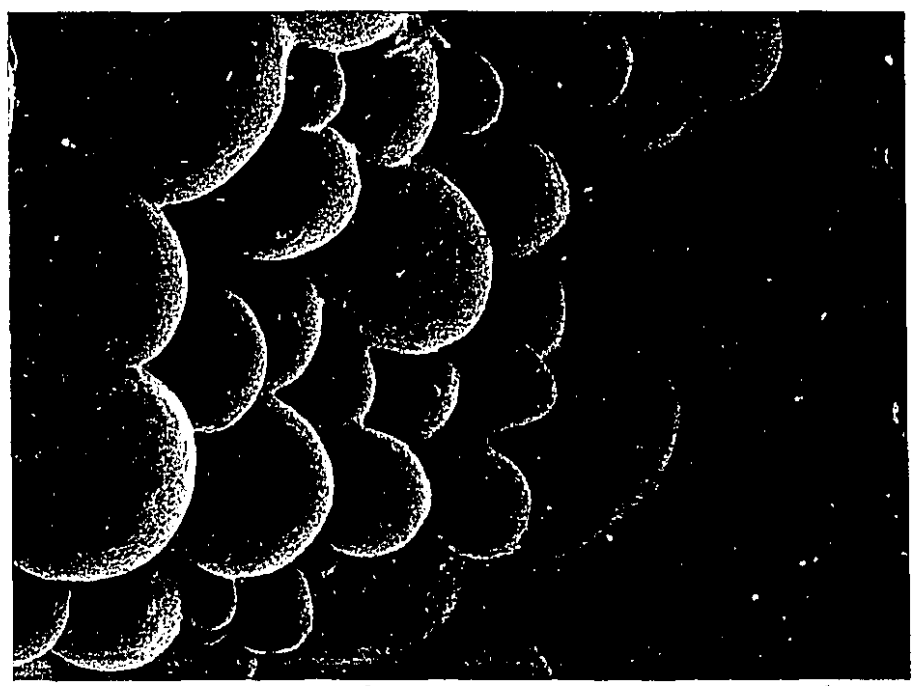

Figure 7.8 Scanning electron micrograph of potato tuber starch granules treated with hot water at 57.5°C and 20 min.

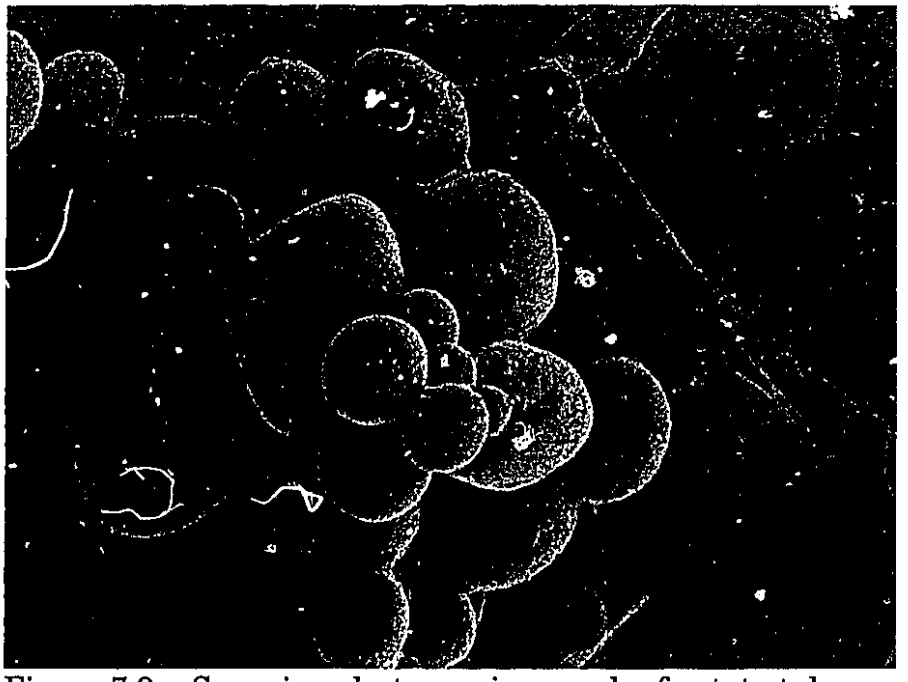

Figure 7.9 Scanning electron micrograph of potato tuber starch granules treated with hot water at 52.5°C and 30 min.

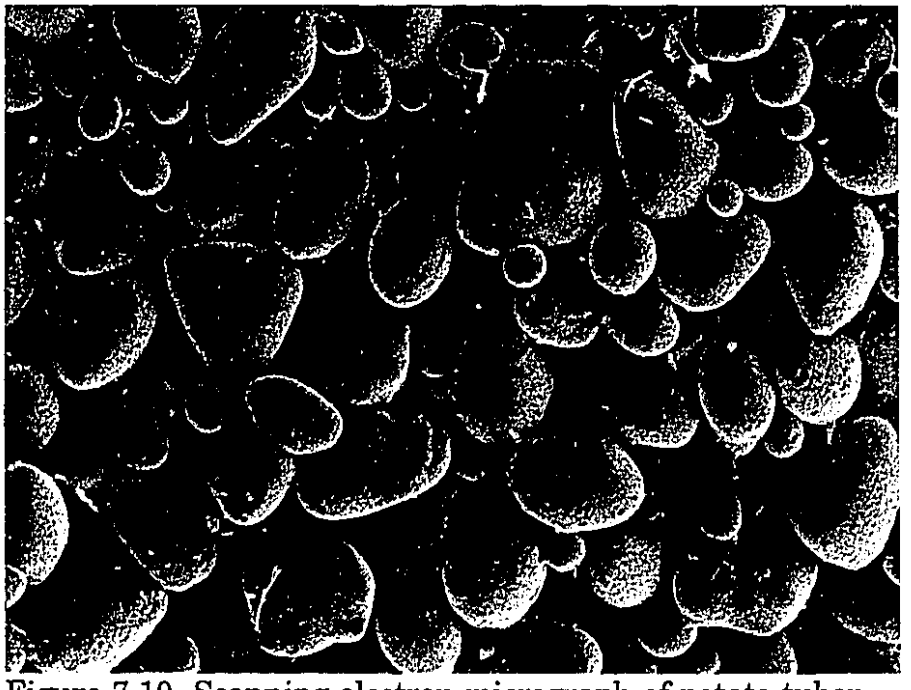

Figure 7.10 Scanning electron micrograph of potato tuber starch granules treated with hot water at 57.5°C and 30 min.

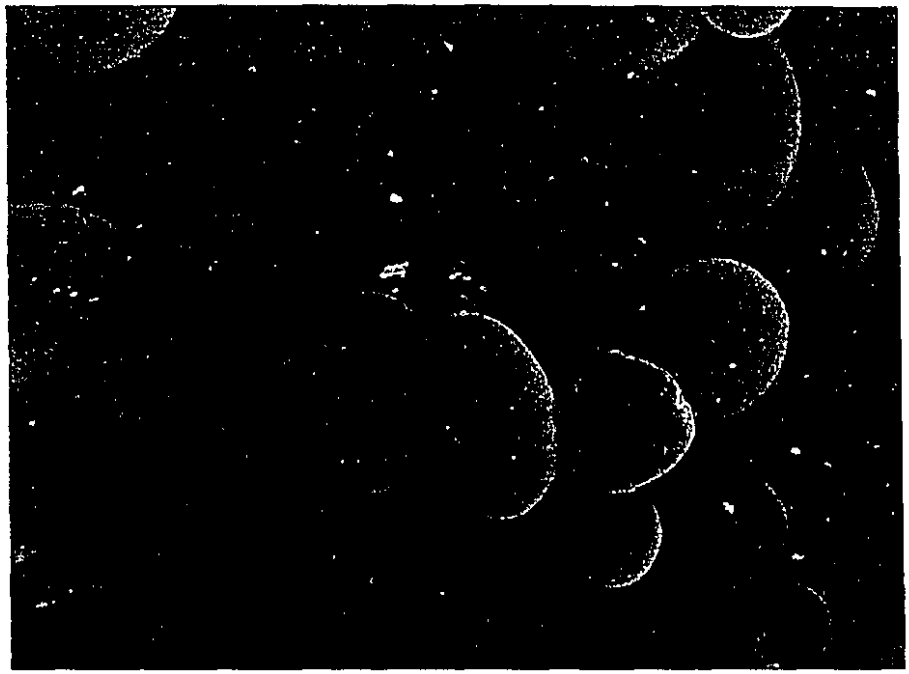

Figure 7.11 Scanning electron micrograph of potato tuber starch granules treated with UV radiation at 1.0×10^4 W.s/m^2

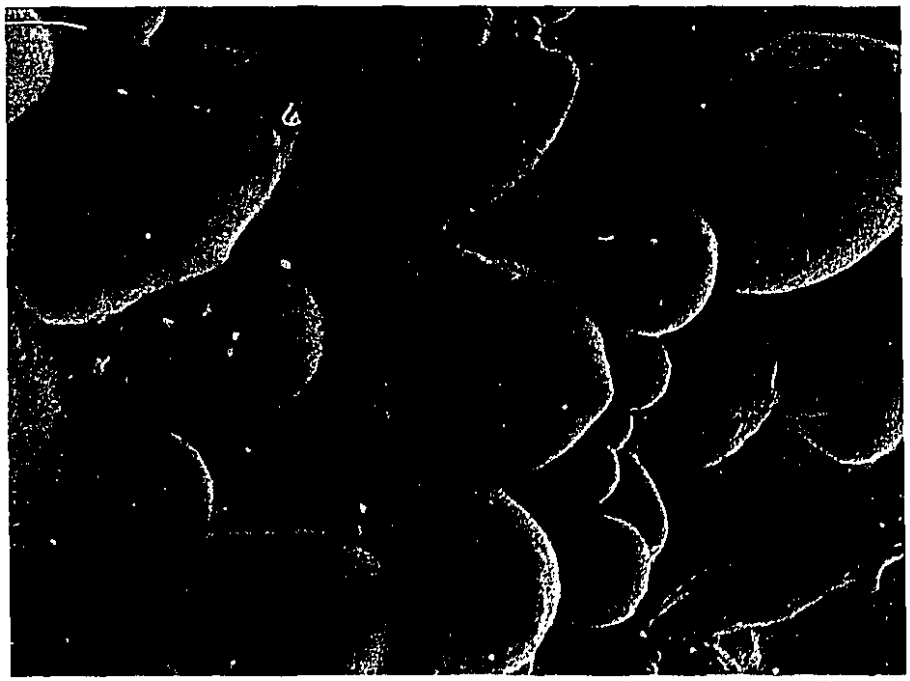

Figure 7.12 Scanning electron micrograph of potato tuber starch granules treated with UV radiation at 1.5×10^4 W.s/m^2

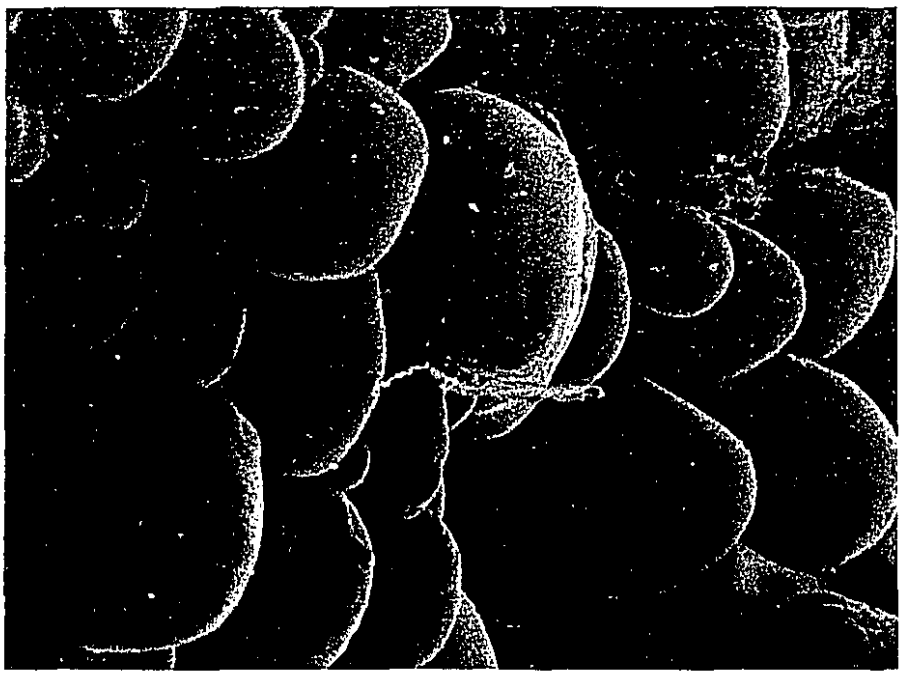

Figure 7.13 Scanning electron micrograph of potato tuber starch granules treated with UV radiation at 1.0×10^4 W.s/m^2 and hot water at 52.5°C for 30 min.

Figure 7.14 Scanning electron micrograph of potato tuber starch granules treated with UV radiation at 1.5×10^4 W.s/m^2 and hot water at 55°C for 30 min.

7.2 POTATO FIRMNESS ANALYSIS

The potato tubers were further qualified by firmness tests using an Instron Universal Machine version 4502- Series IX. Puncture tests were performed using a probe having diameter of 11.074 mm and a cross head speed of 25 mm/min. Tests were performed on samples from all combinations used in the UV, vapour heat, and hot water experiments. Samples from the combination UV/hot water treatment were not used in this testing procedure. Only two tubers were tested from each treatment.

Table 7.1 Treatment details for hot water, vapor heat and UV radiation for firmness and color tests used in Duncas's Multiple Range Test.

Treatment #	Hot water	Vapor heat	UV radiation
1	52.5° C, 10 min	50° C, 40 min	0.75 J/m^2
2	52.5° C, 20 min	50° C, 50 min	1.00 J/m^2
3	52.5° C, 30 min	50° C, 60 min	1.25 J/m^2
4	55° C, 10 min	60° C, 40 min	1.50 J/m^2
5	55° C, 20 min	60° C, 50 min	control
6	55° C, 30 min	60° C, 60 min	—
7	57.5° C, 10 min	70° C, 40 min	—
8	57.5° C, 20 min	70° C, 50 min	—
9	57.5° C, 30 min	70° C, 60 min	—
10	Control	Control	—

Table 7.2 Results of puncture tests after hot water treatment and storage on potato tuber (means of 2 replicates).

Treatment #	Max L kN	Modulus MPa	Toughness MPa
1	$0.192950^{a,b*}$	$9.740^{a,b*}$	0.41805^{c*}
2	0.206100^{a}	$10.375^{a,b}$	$0.48450^{a,b,c}$
3	0.170250^{c}	$7.901^{a,b}$	$0.45815^{b,c}$
4	0.208000^{a}	6.939^{b}	0.66735^{a}
5	0.202150^{a}	$9.187^{b,a}$	$0.64075^{a,b}$
6	$0.173550^{b,c}$	$8.351^{a,b}$	0.41470^{c}
7	0.205850^{a}	$10.160^{a,b}$	$0.53715^{a,b,c}$
8	0.206700^{a}	$10.492^{a,b}$	$0.63060^{a,b}$
9	0.193450^{a}	$7.980^{a,b}$	0.43460^{c}
10^{**}	0.211750^{a}	11.680^{a}	0.42050^{c}

* Means in the same column with the same letter are not significantly different ($p < 0.05$). Treatment # 10 is the control. ** represents control.

The statistical analyses were based on ANOVA followed by Duncan's multiple range test and are presented in Tables 7.1 to 7.3. Several mechanical properties of the test material were obtained from the puncture test analysis. However, only the "Maximum Load (kN), Young's Modulus (MPa) and Toughness (MPa)" were used for analysis. These terms are defined as (Mohsenin, 1968):

The "maximum load" or the yield point on the stress strain or deformation curve at which there occurs an increase in deformation with a

decrease or no change of force (Mohsenin, 1968).

The ratio of stress to strain (slope of the initial straight line of the force-deformation curve) may be referred to as the "Young's modulus" or modulus of elasticity.

"Toughness" is the work required to cause rupture of the material. This can be approximated by the area under the stress-strain or force deformation curve up to the point selected as the rupture point.

Table 7.3 Results of puncture tests after vapor heat treatment and storage on potato tuber (means of 2 replicates).

Treatment #	MaxL, kN	Modulus MPa	Toughness MPa
1	0.153950^{a*}	6.8740^{a*}	0.6506^{a*}
2	$0.139300^{a,b,c}$	$6.1360^{b,c,d}$	$0.5074^{a,b,c}$
3	$0.123800^{c,d}$	$5.8885^{c,d,e}$	$0.3031^{a,b,c}$
4	$0.124050^{c,d}$	$5.6415^{e,d}$	$0.4101^{a,b,c}$
5	$0.130400^{b,c,d}$	$6.1480^{b,c,d}$	0.1619^{c}
6	0.115450^{d}	5.5165^{e}	$0.2824^{b,c}$
7	$0.141950^{a,b}$	$6.2695^{b,c}$	$0.5362^{a,b}$
8	0.147900^{a}	$6.5150^{a,b}$	0.6411^{a}
9	$0.140250^{a,b,c}$	$5.8420c^{c,d,e}$	$0.4178^{a,b,c}$
10**	$0.130400^{b,c,d}$	$5.9745^{b,c,d}$	$0.3775^{a,b,c}$

* details same as in Table 7.2. ** represents control.

Table 7.2 shows the details of treatment number and treatments for hot water, vapor heat and ultraviolet treatments for the firmness and color tests

of potato tubers. Tables 7.3 to 7.5 show that the significant differences, when they occurred, were difficult to interpret. The data are generally not very consistent with the assumption that physical properties should change with heat input, other than the fact that the treatments with the lowest energy inputs (Treatment 10 - control; Treatment 1 - low temperature or low UV intensity and short times) result in the highest values of the strength characteristics. In some cases, the ANOVAs indicated that treatment differences were not significant.

These tests are clearly inconclusive. More tubers from each treatment should have been tested and perhaps more punctures should have been done per tuber, given that within-tuber and among-tuber variability could be large. On the other hand, neither visual observation of the tuber surface, hand sensing, nor the electron micrographs seemed to indicate obvious changes due to treatments. Thus, it may be fair to assume that the treatments used had little or no effect on the tuber quality.

Table 7.4 Results of puncture test after hot treatment on potato tuber (means of 3 replicates).

Treatment #	Max L kN	Modulus MPa	Toughness MPa
1	0.140300^{a*}	6.4357^{a*}	0.3152^{a*}
2	0.122500^{b}	6.1793^{a}	0.5125^{a}
3	0.143500^{a}	6.2363^{a}	0.5584^{a}
4	0.136567^{a}	6.0833^{a}	0.4319^{a}
5**	0.141400^{a}	5.7780^{a}	0.5052^{a}

* details same as in Table 7.2. ** represents control.

7.3 POTATO TUBER COLOR

The third important quality attribute of potato samples was evaluated based on chromometer values L, a and b (obtained with Minolta Chromometer). Tables 7.4 to 7.6 present the mean values from the Duncan multiple range test. In general, there were no particularly consistent differences due to treatments. Some effect was noticeable due to hot water dipping (Table 7.4), but only the model for L was significant. No differences in either L, a or b at all were observed for the vapor heat (Table 7.5) and UV (Table 7.6) samples. These qualitative measurements confirm the visual observations that were made.

Table 7.5 Chromocity in L a and b coordinates of potato tuber after hot water treatment and storage (mean of 4 replicates).

Treat #	L	a	b
1	$45.375^{a,b*}$	$29.075^{a,b*}$	$17.675^{a,b*}$
2	44.225^{b}	$29.475^{a,b}$	$17.100^{a,b}$
3	$45.400^{a,b}$	$29.025^{a,b}$	$16.700^{a,b}$
4	47.975^{a}	$29.800^{a,b}$	18.050^{a}
5	43.500^{b}	$29.675^{a,b}$	$17.650^{a,b}$
6	38.350^{c}	$28.550^{a,b}$	14.950^{b}
7	$47.125^{a,b}$	$30.225^{a,b}$	$17.350^{a,b}$
8	$45.000^{a,b}$	34.150^{a}	$16.800^{a,b}$
9	44.225^{b}	28.050^{b}	15.025^{b}
10**	$45.375^{a,b}$	$29.525^{a,b}$	$17.275^{a,b}$

* details same as in Table 7.2.

Table 7.6 Chromocity in L a and b coordinates of potato tuber after vapor heat treatment and storage (mean of 4 replicates).

Treatment #	L	a	b
1	47.500[a*]	30.750[a*]	17.825[a*]
2	46.45[a]	29.350[a]	16.125[a]
3	46.375[a]	29.875[a]	16.800[a]
4	43.875[a]	29.750[b]	16.525[a]
5	44.850[a]	29.625[a]	19.875[a]
6	46.550[a]	29.350[a]	16.200[a]
7	45.550[a]	30.375[a]	17.825[a]
8	39.400[a]	27.100[a]	16.325[a]
9	45.975[a]	29.350[a]	17.300[a]
10**	44.525[a]	29.075[a]	18.025[a]

* same as the details in Table 7.2.

Table 7.7 Chromocity in L a and b coordinates of potato tuber after vapor heat treatment and storage (mean of 6 replicates).

Treatment #	L	a	b
1	44.950[a*]	29.867[a*]	16.867[a*]
2	45.583[a]	29.333[a]	16.083[a]
3	43.800[a]	28.717[a]	16.533[a]
4	45.033[a]	29.383[a]	16.983[a]
5**	44.200[a]	28.633[a]	17.967[a]

* same as the details in Table 7.2.

Summary

The three quality attributes: structure, firmness and color have indicated that the quality of potato tubers were unaltered by the different levels of thermal treatments studied. The structure measurements indicate that the starch granules were not gelatinized and the cells were safe and intact. Although there were some significant treatment differences in the firmness results, these were not consistent, due partly to the low number of sampling units and probably also to the high natural variability of these properties within and among potato tubers from the same treatments. The chromaticities (L, a and b) did not exhibit differences due to the treatments. Thus it could be concluded that the thermal treatments considered in this research study have no influence on the quality of the treated potatoes. Essentially, the threshold for damage has clearly not been surpassed.

CHAPTER VIII

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

8.1 Summary and Conclusions

This study was aimed at the evaluation of thermal and ultraviolet treatments to replace chemicals in the control of post-harvest pathogens of potatoes and for inhibition of sprouting. The work was limited to applying these treatments for short-term storage of three months, but the evaluation was performed to determine possible application to the developing nations as well as to the northern temperate industrialized world. The evaluations of disease-control and sprout inhibition were performed separately. The following conclusions may be drawn:

1. Both dry rot and soft rot of potato may be eradicated by hot water dipping or UV-irradiation in the germicidal band (254 nm). However, UV-irradiation is not effective if the pathogen has had time to penetrate below the surface to depths greater than the attenuation threshold of this wavelength. The conditions under which total eradication were possible did not lead to any physical damage to the tubers. The above observations applied to potatoes stored at 8°C and at 18°C.
2. Sprouting was completely inhibited by hot water dipping without causing damage to the tubers.
3. UV radiation at the germicidal waveband, completely inhibited sprouting in potatoes stored at 8°C. Although not completely inhibited at 18°C storage, sprouting was nevertheless very low (<10% sprouted tubers).
4. Vapour heat at the conditions studied was not very effective at controlling sprouting due to low thermal input to the tuber. This method was therefore not tested on the pathogens.

5. UV-treatment before hot water dipping led to total sprout inhibition at lower water temperatures for potatoes stored at 8°C. Complete inhibition was also obtained by this combination for the case of 18°C storage. However, in this case, the water temperature required was higher but within the limits set for the individual treatments.
6. The numerical model developed to predict transient temperatures in the tubers performed well when tested against experimental data. The predicted behaviour indicated which temperature and time limits to use in the experiments on disease and sprouting control.

8.2 Contributions to Knowledge

This thesis has contributed to the growing philosophy that research in agriculture should focus on eliminating hazardous substances during production and processing of foodstuffs. The main contributions in this sense are:

1. It is possible to eliminate the use of chemicals for control of diseases and sprouting in short-term storage of potatoes, without causing physical damage to the tubers.
2. The technologies to replace chemicals are simple and accessible to producers in the developing nations. In fact, in semi-arid tropics, the Sun should supply sufficient energy for the hot water treatment and could provide energy for the UV-treatments through photovoltaic cells.

The other contributions are:

3. A model to predict the transient temperature distribution in the tuber was developed based on the assumption that the tuber is a cylindrical rather than a spherical body. This

model, solved by the line-by-line method, performs better than its spherical counterpart solved by the finite element method and can be used for different cultivars of potato.

4. The extent and general conditions under which sprouting and post-harvest pathogens of potatoes can be controlled by thermal or UV treatment have been determined by adoption of response surface methodology in the experimental work.

8.3 Recommendations for Further Studies

Although the treatment conditions leading to complete control of sprouting, disease and physical damage have been determined for a three month storage period, the results cannot be reliably extrapolated in time without validation. The applicability of the results obtained to other cultivars should also be verified on a case by case basis. This statement applies rather to the damage and perhaps sprouting to be expected relative to the thermal inputs applied. In the case of disease control, the developed model itself could be used to predict mortality of pathogens, if their lethality curves are known. Otherwise, efforts should be made to obtain such data.

The possibility of treating the potatoes with UV immediately after harvest should be investigated since at that time, infection levels are likely to be very low. Sprout inhibition could be done after the dormancy period by hot water dipping.

At this point, design and scale-up of treatment facilities applicable to the developing nations should be performed. Integration of solar energy into appropriate systems should not be neglected in the design. This concept is less attractive for the northern temperate except perhaps for early harvest varieties.

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* Original article not seen