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Prediction of Germination During Drying of
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Carlos Eduardo Lescano

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F.W. Bakker-Arkema
Major professor

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PREDICTION OF GERMINATION DURING DRYING OF CORN SEEDS USING THE NORMALLY DISTRIBUTED DEATH APPROACH

By

Carlos Eduardo Lescano

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ABSTRACT

PREDICTION OF GERMINATION DURING DRYING OF CORN SEEDS USING THE NORMALLY DISTRIBUTED DEATH APPROACH

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Germination and moisture content loss data were collected using a laboratory thin-layer dryer for Great Lakes 579 shelled corn seeds with moisture contents ranging from 15.18 to 32.43% (w.b.), air temperatures from 40 to 75 C, and exposure times from 1 to 180 minutes. An average drying air velocity of 0.9 m/s was used.

A germination retention model is proposed based on the normally distributed death rate theory (NDD), and an empirical three-term exponential equation for the standard deviation of death rate:

$$\sigma = \frac{1}{\bar{M}^{C_2}} .\exp\ (C_1 - C_3\ \bar{\theta})$$

where σ is the spread of distribution of deaths with respect to time, $\bar{M}$ the average moisture content (% w.b.), $\bar{\theta}$ is the temperature of the grain (C); and C_1 to C_3 are the viability constants determined from the experimental thin-layer drying data.

The NDD model was attached to a concurrentflow (CCF) dryer model, and tested against viability data of corn seed dried in a commercial two-stage CCF dryer. Acceptable agreement between the predicted and experimental viabilities was observed.

The effect of the CCF dryer design, and of several operating parameters, on the loss of corn seed viability was analyzed with the model. Results indicated that a multi-stage CCF dryer requires two stages for safely drying 18% moisture seed, three stages for 20% seed, and four stages for 25% corn seed.

Simulations with the NDD-CCF dryer model showed that high quality corn seed can be produced by drying at air temperatures well above 100 C. High-temperature CCF drying of corn seeds should be further investigated as part of a new harvesting/drying/ handling system.

Approved F.W. Bakker-Arkema
Major Professor

Approved Donald M. Edwards
Department Chairman

Dedicated to my wife, Graciela;
to our children, Carlos Enrique and Rocio Giselle;
and to my parents.

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A	constant
A_1	constant
A_2	constant
A_3	constant
A_d	temperature dependent rate constant, h^{-1}
a	constant
$\mathbf{a}$	kernel specific surface area, m^2/m^3
B	constant
b	constant
c	constant
$\mathbf{C}$	concentration, kg component/kg
C_1	constant
C_2	constant
C_3	constant
C_4	constant
c	specific heat, kJ/kg-C
D	constant
$\mathbf{D}$	diffusion coefficient, m^2/h
E	energy of activation, kJ/kg
G	total germination, decimal
$\mathbf{G}$	dry weight flow rate, $kg/h\text{-}m^2$
H	air humidity ratio, decimal, d.b.
h	convection heat transfer coefficient, $kJ/h\text{-}m^2\text{-}C$
hfg	latent heat of vaporization for water in the grain, kJ/kg
j	index
K	germination decrease reaction rate constant, min^{-1}
M	local moisture content, percent, w.b.
$\bar{M}$	average moisture content, percent, w.b.
M_d	local moisture content, decimal, d.b.
$\bar{M}_d$	average moisture content, decimal, d.b.
m	index
N	number of survivors or viable seeds
n	power law constant
n_j	order of the reaction rate of each specie j
R	gas constant, kJ/mole-K
r	reaction rate, change in quality factor per unit time
$\mathbf{r}$	kernel radial direction, m
T	cooling or heating medium temperature, C
Ta	absolute temperature, K
t	time s, min or days
$\bar{t}$	time at germination equal to 0.5
X	standardized normal deviate, dimensionless
x	bed depth direction, m

ΔH^*	activation enthalpy, kJ/kg
ΔS^*	activation entropy, kJ/kg-C

Subscripts

a	air
p	product
v	water vapor
w	water liquid
t	time
t+dt	time plus time increment
0	initial
$_{1,2,\ldots}$	numerical indexes

Greek

π	constant
σ	standard distribution of death rates
θ	local grain temperature, C
$\bar{\theta}$	average grain temperature, C
Φ	function
ϕ	function

1. INTRODUCTION

Corn (maize) (Zea mays L.) originated in the Western Hemisphere, where it was the main food of the Incas of Peru, the Mayas of Central America, and the Aztecs of Mexico. In the 20th century corn has became one of the most important foods, feeds, green forages and industrial crops of the world. Corn has the highest yield per hectare among the cereal crops, and as a source of carbohydrates per hectare, corn ranks first among the cereal grains.

Table 1.1 shows the total world, U.S. and South American production of grains (cereals and legumes), cereals (wheat, rice, corn, barley, rye, oats, millet and sorghum) and corn. Brazil and Argentina account for about 90% of the production of South America. In 1984, the total production of cereals was 1802 million MT; corn ranked third (450 million MT) after wheat (522 million MT) and rice (470 million MT) and ahead of barley (172 million MT)(Anon, 1985a).

Corn is an important food in many countries of Latin America, Africa and Asia. However, worldwide, most of the corn is used as source of feed for livestock and poultry and as an ingredient in the corn milling industry.

It is a well-known fact that rising incomes enable people to include more meat in their diets. Thus, corn has become the foundation of a worldwide meat market. The U.S. corn production annually accounts for nearly half of the world crop production. American corn represents about 80 percent of the annual world corn exports. The United States is

Table 1.1 Corn, Cereals, and Grains Production: World, U.S.A. and South America (1974-1984). (Thousands of Metric Tons)

A) CORN

Year	World	U.S.A.	South America
1974	293233	118461	29401
1975	324257	148061	27438
1976	334626	159172	27272
1977	348461	163213	31247
1978	390104	184614	26653
1979	418357	201655	29056
1980	395949	168787	30325
1981	450557	208330	37842
1982	448308	209180	35281
1983	347819	106041	31824
1984	449255	194475	34804

B) CEREALS

Year	World	U.S.A.	South America
1974	1333078	204601	59569
1975	1362153	248869	59537
1976	1487454	257719	65843
1977	1476111	263976	63833
1978	1598368	276702	61634
1979	1553428	303081	64049
1980	1564972	269952	62894
1981	1651342	333806	73560
1982	1702940	333331	80112
1983	1644421	207875	71028
1984	1801684	314372	76841

C) GRAINS

Year	World	U.S.A.	South America
1974	1380117	205775	62548
1975	1406604	249896	62577
1976	1549922	258725	68510
1977	1534094	264877	67031
1978	1649120	277836	64674
1979	1593350	304220	67134
1980	1605401	271440	65636
1981	1693763	335496	76777
1982	1704817	334752	83937
1983	1690955	208832	73403
1984	1849591	315536	80307

Source: Anon (1985a).

the world's leader in corn production (Novotny and Shull, 1985).

U.S. grain production expanded rapidly during the seventies. Corn represented 56 percent of the total U.S. grain output in 1979. Increases in corn production were mainly due to better yields which peaked at 7.1 MT/ha (113.2 Bu/acre) in 1984 (Anon, 1985b).

The large expansion in corn production in the United States during the last decade was driven by the increased world demand for feed grains. World consumption of corn grew more than 50 percent during the seventies (Leath et al., 1982).

About 80 percent of the U.S. corn crop is grown in the Corn Belt, Great Lake States, and the Northern Plains. About two-thirds is consumed on farms where it is produced (Leath et al., 1982).

In the United States, corn is used for food, for wet- and dry-milling, for alcoholic beverage production, for seed, and for livestock and poultry feed (see Table 1.2). Livestock and poultry feed accounted for 88 percent of the total U.S. domestic corn consumption in 1979/80. Use of U.S. corn for food and industrial purposes expanded during the seventies; the products exhibiting the greatest growth potential are corn sweeteners and alcohol fuel (gasohol). About 52 thousand metric tons of corn seed are annually produced in the United States; the author estimates that more than 80 percent of this total is artificially dried.

The most dramatic change in the corn scenario since 1950 has been the total volume exported. The U.S. corn export volume increased over 370 percent during the seventies (Leath et al., 1982). The emergence of an alcohol fuel industry, the deregulation of rail rates, and the unstable export demand will likely shape the future growth of the U.S. corn industry.

Table 1.2 United States Corn: Domestic Use and Exports (1950-1980)

YEAR	DOMESTIC USE (Million Metric Tons)					EXPORTS
	FOOD AND INDUSTRY	ALCOHOLIC BEVERAGES	SEED	FEED	TOTAL	
1950/51	4.84	1.85	0.31	63.9	70.92	3.01
1951/52	4.58	1.44	0.31	65.82	72,15	2.11
1952/53	4.71	1.21	0.31	59.56	65.79	3.74
1953/54	4.53	1.37	0.33	65.51	67.72	2.68
1954/55	4.84	1.26	0.31	57.75	64.17	2.65
1955/56	4.95	1.39	0.31	60.95	67.59	3.09
1956/57	4.95	1.47	0.28	61.26	67.95	4.74
1957/58	4.95	1.47	0.28	65.28	72.05	5.15
1958/59	5.44	1.67	0.33	71.69	79.13	5.92
1959/60	5.54	1.60	0.31	78.39	85.86	5.92
1960/61	5.64	1.65	0.28	79.65	87.25	7.52
1961/62	6.05	1.78	0.28	82.17	90.88	11.21
1962/63	6.36	1.67	0.28	81.30	89.62	10.72
1963/64	6.80	1.67	0.28	77.51	86.24	12.88
1964/65	6.98	1.73	0.28	76.14	85.14	14.68
1965/66	7.14	1.83	0.33	86.61	95.88	17.70
1966/67	7.26	1.88	0.36	85.60	95.23	12.55
1967/68	7.50	1.91	0.33	90.78	100.10	16.31
1968/69	7.01	1.93	0.31	92.92	102.16	13.81
1969/70	7.16	1.91	0.33	98.53	107.97	15.77
1970/71	7.70	1.78	0.44	92.56	102.47	13.22
1971/72	8.35	1.80	0.39	102.58	117.11	20.50
1972/73	9.25	1.93	0.41	110.56	122.15	32.41
1973/74	10.61	1.70	0.49	81.92	94.72	29.60
1975/76	11.13	1.83	0.52	91.96	105.44	44.08
1976/77	11.75	1.91	0.52	91.99	106.16	43.38
1977/78	12.88	1.80	0.52	96.44	111.64	50.18
1978/79	13.68	1.78	0.52	111.39	127.36	54.95
1979/80	15.02	1.85	0.52	116.36	133.77	62.67

Source: Leath et al. (1982).

The types of corn are: dent, flint, flour, sweet, popcorn and pod corn. Except for pod corn, these traditional designations are based on the characteristics of the endosperm. Special-purpose corns (waxy corn, high-amylose corn and high-lysine corn) are also available.

Most of the U.S. corn harvested for grain is dent corn. Its name is derived from the indentation in the crown of the kernel caused by shrinkage of the starch as the corn kernel dries. In the U.S. technical literature, the term corn usually refers to dent. Yellow dent corn is the predominant type of corn grown in the United States. In South American countries, the flinty types are more common.

The white corn area in the U.S. averages about a half-million acres. White corn is a specialty crop grown primarily for food use; the annual production has been about 40 million bushels since 1975. Crop yield is the major factor that favors yellow corn over white corn; the white corn/yellow corn yield ratio is about 0.75.

U.S. hybrid dent corn is used primarily as feed, but also serves in the U.S. as a raw material for industrial use. Yellow dent corn sells at feed market price as it enters the normal feed grain or milling channels; however, white dent corn receives a premium price in some sectors of the dry milling industry because of its whiter flour (Brown et al., 1985). Sweet corn and popcorn are grown primarily for food use. A limited area of waxy corn and high-amylose corn (amylomaize) is grown in the U.S. under contract with wet-corn millers.

In the grain industry, the grower can greatly affect the quality of the final product. The aim of the post-harvest grain handling, storage and processing treatments is to preserve the desired quality factors of the product. The quality trait of interest is defined by the end-user; the seed producer, wet miller, dry miller, distiller, and animal feeder favor particular, and often conflicting, factors of quality.

In grain dryer design, desirable properties of the dried corn are (Brooker et. al., 1974): (1) appropriately low and uniform final moisture content, (2) low mold count of the dried kernels, (3) low percentage of broken and damaged kernels, (4) high viability, (5) high head-yield, (6) high baking-quality, (7) high oil recovery, (8) high starch-yield, (9) high protein content, and (10) high test-weight.

The development of models for the prediction of the rate of change of the grain quality factors under certain processing conditions is essential for the optimum design, operation and control of processing equipment, including grain dryers.

Quality deterioration models have been proposed for breakage susceptibility of corn, molding of corn, production of carbon dioxide as a measurement of deterioration of corn (dry matter losses), baking quality of wheat and viability decrease of several seeds (Bakker-Arkema, 1984). In some cases the quality deterioration models have been coupled to specific dryer models.

Seed viability can be considered a limiting quality factor during drying, because grain with a high viability exhibits increased processing yields and has a higher nutritional value (MacMasters et al., 1959). However, a seed can exhibit low or no viability due to freezing, mechanical damage, insect infestation, or natural aging , but still exhibit excellent processing and nutritional qualities (Freeman, 1973).

Seed-science researchers have modeled the viability decrease of seed during storage (Ellis and Roberts, 1980a). Nellist (1981) proposed a viability deterioration model to be applied in drying simulation. Viability constants have been developed for barley and other seeds but not for corn.

The deleterious influence of high temperature, high moisture content and excessive exposure time on seed viability during drying is well known. Each type of dryer provides a unique pattern of grain temperature, grain moisture content and retention time as the grain passes through the dryer. Thus, the viability is affected differently in different dryer types.

The concurrentflow dryer treats the grain gently, requiring only short contact times between the grain and the air, thus resulting in relatively low temperatures (Bakker-Arkema, 1984). The characteristic temperature and moisture content profiles in concurrentflow dryers probably cause only a slight reduction in seed germination. No research has as yet been conducted to quantify the extent of the damage. Since actual experimentation with commercial-sized seed concurrentflow dryers is economically not possible, simulation becomes an important tool to provide insight for future designs and applications.

Corn hybrids exhibit differences in grain quality and also in processing characteristics. Stroshine et al. (1986) showed that different corn hybrids and varieties have different dry milling quality, breakage susceptibility, drying rate, storage mold resistance, test weight, and thousand kernel weight characteristics. Varietal differences in harvesting damage have also been observed (Duncan et al., 1972; Racop et al., 1984). Further quality improvement through breeding and selection offers distinct advantages to farmers, seed companies, merchants and users in the wet and dry milling industry.

Economic and practical considerations have driven the U.S. corn industry to adopt highly mechanized, high capacity harvesting and post-harvesting techniques. The introduction of high-speed, high-temperature continuous-flow dryers was necessitated by early harvesting and the need to rapidly reduce the high moisture content of the harvested grain in order to avoid spoilage. However, the current practice of combine harvesting and drying the corn at high temperature subjects the grain to breakage and other quality deteriorations.

Because the largest market for dent corn is the feed industry, quality standards have reflected the main requirement of this market, namely acceptable nutritional quality. The nutritional quality can be preserved by subjecting the wet grain to a temperature as high as 120 C for 120 minutes (Mühlbauer and Christ, 1974). These conditions are considered by the wet and dry millers to be deleterious for the quality of their products. A drying air temperature below 60 C is usually recommended for the corn milling industry (Freeman, 1973; Kent, 1974; Brown et al., 1981).

Corn to be used for milling and for seed is very sensitive to high temperatures. Corn intended for seed is usually dried on-the-cob in bins at air temperatures not exceeding 43 C (Justice and Bass, 1978; Rao, 1983). The correct moisture content, grain temperature and exposure time relationship during drying is the key factor for preserving quality.

The conventional harvesting and post-harvest processing practices in the seed corn industry are conservative and do not appear to take advantage of recent research findings such as the concurrentflow dryer design. The seed industry will benefit financially by adopting new equipment and practices. An analysis of each component in the seed production system is in order, most importantly of the drying operation. Nellist (1978), in a review on safe grain drying temperatures, stressed the need of a more systematic and comprehensive examination for the effects of temperature on specific grain quality characteristics.

Viability decrease during drying is related to the deterioration of certain quality traits measured in the dry and wet milling industry (e.g. baking quality, malting potential, etc). However, no conclusive results involving these key drying parameters related to viability loss are as yet known.

It appears to the author that viability can be used as a single criterion for quality assessment for some of the processes in the wet and dry milling corn industry. One of the drawbacks of germination as a routine test for quality is the time-consuming nature of the determination (it normally takes a week to obtain results). However, some promising research results on rapid measurement of germination have recently been published.

The use of concurrentflow dryers controlled by a germination-decrease criterion appears to be an efficient and economic option for drying corn in the milling industry. In addition, evidence indicates that, if concurrentflow drying of seed is properly accomplished, it may not be the quality limiting operation in the chain from seed grower to crop producer. The ultimate aim of this research work is to make a contribution to the fascinating quest for the single quality factor to evaluate drying processes in the food and seed industries.

2. OBJECTIVES

The specific objectives of this investigation are:

1) To measure the changes in viability of shelled corn seed as affected by moisture content and exposure time to drying air of different dry bulb temperatures.

2) To develop a viability loss model for the drying of a thin-layer of corn seed.

3) To modify a concurrentflow dryer model by incorporating the seed viability retention model and to validate the combined model in a commercial concurrentflow dryer.

3. LITERATURE REVIEW

Selected topics related to seed viability, germination testing, and the modeling of viability loss during drying are covered in this chapter.

First, the most frequently applied techniques to determine germination capacity and vigor in drying studies are evaluated. Some viability tests of potential practical use are also presented.

Next a discussion follows on heat damage to grains with emphasis on corn. Wheat and oilseeds studies are reviewed because viability is an important quality factor for these crops.

Finally, the modeling of viability losses during drying, in particular during concurrentflow drying, is discussed.

3.1 Seed Viability and its Measurement

Seed viability denotes the degree to which a seed is alive and, therefore, is related to tissue viability as well as viability of the entire seed. A viable seed is metabolically active, and has the enzymes required for catalyzing metabolic reactions leading to germination and seedling growth. Germination is the initiation of active growth by the embryo, culminating in the development of a young plant from the seed (Copeland and McDonald, 1985).

Various tests can be used to determine seed viability. They are based on: (1) germination, (2) biochemical reactions, (3) electrical conductivity, (4) excised embryo growth, and (5) radiographic contrast (Roberts, 1972). The seed germination test and the biochemical, conductivity and radiographic tests appear to be the most relevant for the study of viability decrease during drying.

3.1.1 Standard and Cold Germination Tests

The common seed germination test, conducted under controlled and standarized laboratory conditions for each seed specie, stresses the presence of the essential biological structures required for germination and their ability to produce a normal seedling under favorable conditions (A.O.S.A., 1981). The standard germination test is the most commonly used to determine seed viability, even though is limited in its interpretation as a general index of seed quality (Copeland and McDonald, 1985).

Variations of the standard germination test take into account vigor determinations. The concept of vigor arises from the need to better predict field emergence and performance potential of a seed and from the need to assess seed quality and performance under stress conditions of drying, freezing and storage (Delouche and Caldwell, 1960; Grabe, 1963; Perry, 1984; Loeffler et al., 1985). Slower and/or faster potential rates of germination and seedling growth are attributes associated with the term vigor (Roberts, 1983).

The cold test is a germination test for assessing seed quality and performance under simulated stress conditions, such as planting in cold, wet field conditions; mechanical damage; chemical seed treatment or other damaging factors (incluiding drying at high temperatures) (Obendorf, 1972; Jugenheimer, 1976; Perry, 1984; Loeffler et al., 1985).

the Vigour Test Committee 1980-1983 of the International Seed Testing Association considered the cold test for corn seeds to be sufficiently reproducible for acceptance as a vigor test since it relates well to field emergence (Perry, 1984).

Traditionally, a cold test consist of the exposure of seeds for seven to ten days to regular non-sterile field soil at 60 to 70% of moisture content at 10 C followed by a period of seven days at 25 to 30 C; Burris and Navratil (1979) have questioned the use of regular soil in the cold test because of the lack of a standard medium. Loeffler et al. (1985) compared the rolled paper towel and the traditional soil test for use in corn drying studies; they obtained comparable results and therefore recommended the use of the rolled-towel method because of its simplicity.

3.1.2 Biochemical, Conductivity and Radiographic Viability Tests

The biochemical, conductivity and radiographic tests provide faster results (within hours) than the tests discussed in Section 3.1.1 (which require at least seven days). These fast methods are used in research and in some specific applications but they have not been generally accepted yet. The rapid determination of seed viability is their main advantage (International Seed Testing Association, 1985).

The topographical tetrazolium test is the most frequently used of the biochemical tests (Copeland and McDonald, 1985). The test is based upon the activity of the dehydrogenase, a seed respiratory enzyme. Dehydrogenase enzymes react with substrates and release hydrogen ions to the colorless tetrazolium salt (2,3,5-triphenyl tetrazolium chloride or bromide solution), which changes to red triphenylformazan as it is reduced by hydrogen ions from the living cells (International Seed Testing Association, 1985). Unfortunately, the accuracy of the method is highly dependent on the operator.

Conductivity tests are based on the increasing water permeability of the seed coat, and the consequent release of ionizable compounds, as the deterioration progresses. A seed soaked in water under controlled temperature conditions shows, after a few hours, an increase in the electrical conductivity of the soaking liquid. The conductivity change of individual seeds can be measured in batches of a hundred kernels (McDonald and Wilson, 1979; Siddique and Goodwin, 1985). The reliability of the test is still questioned (Copeland and McDonald, 1985). Therefore, the conductivity test has not been standardized and has not found general acceptance yet. However, the use of the conductivity test as a routine method to determine variation between corn seed lines, and to study environmental effects, has been reported by Stone (1983). Keys (1982a, 1982b) and Keys et al. (1984) have developed a computerized and automated seed analyser system based on conductivity.

Radiographic methods of seed viability testing are also based on membrane deterioration. The tests reveal internal seed injuries associated with immediate or premature loss of viability (Copeland and McDonald, 1985). A high atomic number salt solution is used to impregnate the seeds. For routine tests an impregnation treatment in a 20% barium solution is recommended (Smith and Grabe, 1985). A radiograph of a low viability seed shows a difference in the contrast between the necrotic (less dense) and non-necrotic areas of the seed. Smith and Grabe (1985) recently reported a high contrast quantitative radiographic method for the rapid determination of the viability and vigor of corn seeds; the method minimizes the operator dependence. Densimetric measurements of the contrasts showed good agreement with the seedling growth rate and conductivity tests. High cost, the need of skilled operators, and vigor and germination reductions due to toxicity of the contrast agents are drawbacks of the method.

3.2 Heat Damage to Grains

Heat damage to grains during artificial drying is dependent on the grain moisture content, grain temperature and time of exposure of the grain to the heating medium. Experiments on heat damage have been conducted under constant temperature and moisture conditions (sensible heating in hermetically closed containers), under constant temperature and decreasing moisture conditions (thin-layer drying and fluidized bed drying); and under variable grain temperature and moisture content conditions (deep bed drying experiments in different dryer types).

Nellist (1978), in a comprehensive review of safe temperatures for drying grain, noted that optimum drying temperatures are a function of the dryer design and dryer operating conditions. Both affect the grain temperature and moisture content of the seed as it passes through the dryer.

3.2.1 Heat Damage to Corn Seeds

Nellist (1981) established that loss of viability of seeds in any environment depends mainly on: (1) the initial quality, (2) the temperature of the grain, (3) the moisture content of the grain, and (4) the time of exposure of the seed to the environment.

Effects of heating on corn seed quality with and without evaporation will be considered.

3.2.1.1 Effect of heating without evaporation

Research on the effect of constant temperature on the viability of corn seeds in sealed containers was first conducted by Robbins and Petsch (1932). 50-grain samples of corn were heated in test tubes to 45-80 C for two hours at rewetted moisture contents between 5 to 35% wet weight (w.b.) basis. In this work, the moisture content will be implied as expressed in wet weight basis (w.b.), unless otherwise explicitly stated as in dry weight basis (d.b.). They established the temperatures for 75% kill and expressed the data graphically in 25%-viability versus time curves for different temperatures and moisture contents.

Bratersky (1963) (cited by Nellist and Hughes, 1973) heated freshly harvested corn in thin-layers (initial moisture contents were not given) at 45 C for 120 minutes; the treatment did not adversely affect germination or germination vigor.

Sokhansanj (1974) immersed 16% moisture content corn seeds in hot water for 60 to 90 seconds and found almost a complete kill at temperatures of 82.2 C. An increase in viability was observed at 60 C due to the break in dormancy of the seeds.

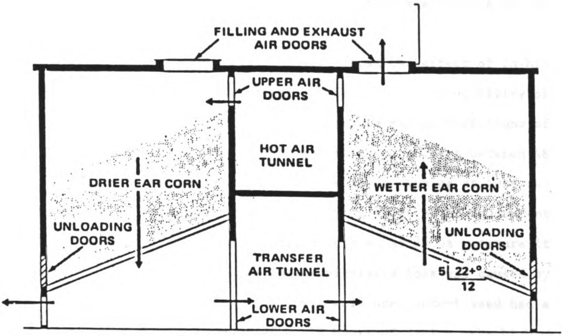
Gygax (1977) used sealed thermal-death-time (TDT) cans for heat treatments at constant moisture content and various temperature-time combinations. The moisture content ranged from 14 to 28%, the heating temperature from 51 to 100 C. Heating times between 3 to 130 minutes were considered. The results show that viability loss is a function of moisture content, heating temperature and time of exposure. Gygax proposed a model for the germination loss which will be disscused in Section 3.3.

Nofsinger et al. (1980) investigated the effect of microwave oven heating (48 to 72 C, for 2 to 4.5 min) on high-moisture shelled corn (Dekalb 64, 24%; Dekalb 43, 25%; Pioneer 3535, 26.8%); the germination at all three moisture contents was substantially reduced at 55 C and higher temperatures; at 72 C the germination was zero for all samples. No specific differences in the results for the three varieties were reported.

3.2.1.2 Effect of heating with evaporation (drying)

Traditionally, corn seed in the United States is dried as ear corn from an initial moisture content of 30 to 40 percent to a final moisture content of 11 to 13%. Either batch-type deep-bed dryers (see Figure 3.1) or cribs are employed. A small amount of seed corn is harvested by combines or picker-shellers at 12 to 16 percent moisture content in California and in some southern states of the U.S.A. (Airy et al., 1961; Jugenheimer, 1976); however, this practice is not advisable because of the higher field losses and limitations in harvesting capacity.

In the double or two-pass drying system shown in Figure 3.1 (Justice and Bass, 1978) the heated drying air is first directed through a bin containing nearly dry seeds, where the air picks up a small amount of moisture and loses a little of its heat. The air is then transferred and exhausted through a bin of high moisture content seeds, which need warming up. It is claimed that the double pass provides added protection



Source: Justice and Bass (1978)

Figure 3.1 Double or Two-pass Batch-type Corn Seed Dryer.

to the viability of the seeds by using cooler air (27 to 32 C) on the higher moisture seeds; only the relatively dry seeds are subjected to a possible 43 C. It is important to note: (1) that the first contact is between the hot air with the dry seed, just the reverse of the concurrentflow dryer case, and (2) the controversial nature of the statement regarding the viability retention.

Harrison and Wright (1929) investigated the effect of in-bin (1.5 to 2.1 m depth-bed) drying at 40 to 70 C on the viability of ear-corn during 72 hours of drying using alternating directions of airflow every twelve hours; the initial moisture content was between 48 to 62.8%, the final moisture content from 2 to 15.4%. Drying at 40 to 45 C did not cause any decrease in viability. Drying 62.8% moisture content ear corn at 50 C decreased the viability to 32%; at 39.6% moisture it decreased to 7.4%. The difference in the viability loss was caused by the different initial viabilities. The lower moisture content seed had a lower initial viability, because after 12 hours of drying, the higher moisture content samples showed a 99% viability while the lower moisture content corn had a viability of only 80%. Drying 38% and 44.6% ear corn at 60 C, resulted in a complete killing of the seed after 24 and 36 hours, respectively; after the first 12 hours of drying, the lower moisture samples showed a viability of 92% and the higher moisture samples 99%. When a drying temperature of 70 C was used, the viability of 42.4% and 48% moisture ear corn decreased to 58% and 86% after 12 hours of drying. At 24 hours all ear corn was killed at 70 C. It should be noted that the moisture content of the whole ear-corn is reported in the study of Harrison and Wright.

Kiesselbach (1939) confirmed the results of Harrison and Wright (1929); drying temperatures of 40 to 43 C were recommended for corn seeds at less than 50% kernel moisture content, and less than 40 C when the initial moisture content is of 50%.

Wileman and Ullstrup (1945) detected no appreciable reduction in germination by drying corn at 48.9 C and 54.4 C at kernel moisture contents of 20 to 25% and 20%, respectively.

McRostie (1949) reported no significant viability loss when air temperatures up to 54.4 C were used to dry ear corn seed at an initial moisture content of 30%.

Navratil and Burris (1984) used a batch type experimental thin-layer ear corn dryer (Navratil and Burris, 1982). The initial seed moisture content ranged from 25 to 45%; the final moisture content was 12%, the drying air temperature was varied from 35 to 50 C. Three hybrids were tested; differences were observed between hybrids. No appreciable difference in viability was found at temperatures from 35 to 45 C; at 50 C the germination of the high initial moisture content (35 to 45%) showed a larger decrease than the samples at lower moisture contents (25 to 30%). The samples at the lower initial moisture content range exhibited an appreciable retention of viability.

Arora et al. (1973) investigated the critical drying temperatures of a 0.01 m layer of shelled corn. Drying took place in a chamber for four hours. The initial corn moisture content ranged from 17.3 to 25% d.b.; drying temperatures from 50 to 130 C were used; germination counts were conducted at 5, 10, 15, 30 and 45 minutes and 1, 1.5, 2, 3 and 4 hours. The results show that 60 C or below did not appreciably reduce the germination at any of the grain moisture contents; at temperatures of 60 and 80 C, the viability does not decrease below 90% during the first half-hour of drying. It was also established that temperatures above the 100 C kill corn seeds of any moisture content in a very short period of time. Unfortunately, only the graphical results, and not the experimental data were reported, thus limiting subsequent analysis and comparisons with similar investigations.

Silva et al. (1980) researched the effect of oven-drying at 66, 71, 77 and 85 C on the germination of shelled corn seeds at 26% moisture content. They applied the kinetics rate theory to develop a model for prediction of the changes in viability at different temperatures; this approach will be discussed in Section 3.3.

3.2.2 Heat Damage to Corn Used for Milling

The U.S. corn milling industry has moved from a user of ear corn to a user of shelled corn. The change was brought about by the increased use of the picker-sheller and combine, in the early 1950's.

The first study on the processing characteristics of artificially dried corn was conducted in the early 1950's (Gausman et al., 1952). The investigation was carried out on ear corn; the experimental dryer used consisted of a vertical duct in which the individual ears were placed parallel to the airflow. The ears varied in moisture (kernels basis) from 24 to 75% and were dried at high (82.9 C), medium (53.9 C) and low (43.2 C) air temperatures, and at an air velocity of 0.26 m/s. Above 82.9 C poor processing characteristics were obtained; at 53.9 C the wet milling properties were acceptable but viability had decreased but not substantially. At 43.2 C both processing characteristics and viability were preserved. Each of the drying experiments lasted over one hour.

MacMasters et al. (1959) conducted an extensive investigation on the wet milling properties of shelled corn from five crop years, harvested at 20 to 30% moisture content, and dried at six temperatures ranging from 43.3 to 48.9 C, and at relative humidities of 15 and 40%. Drying conditions lasted over one hour; thus, it was assumed that the grain temperature reached the air temperature during the drying process. No information about the moisture and temperature history of the samples in the dryer was provided. Fedewa (1985) summarized the experimental results of MacMasters et al. (1959) (see Table 3.1) and concluded that corn reaching a temperature above 60 C during drying show a definite decrease in viability, and can be considered to be lowered in quality for use in starch production. An interaction viability-grain temperature-grain moisture content was suggested as an important factor in quality deterioration. Based on the criterion of starch recovery, no acceptable wet-milling processing was obtained in the laboratory when the grain temperature had reached 71.1 C.

Table 3.1 Mean Percentage of Starch Recovery and Mean Percentage of Protein in Starch Associated With Drying Temperatures.

Drying Temperature C	Starch Recovery %	Viability Range %	Protein In Starch %	Approx. Drying Time h
Control	83.10	95-99	0.836	
48.9	82.45	28-99	0.836	6.0-9.0
54.6	82.44	26-98	0.741	3.0-7.0
60.0	80.41	0-90	0.807	2.0-4.0
65.6	81.71	0-89	0.837	2.0-5.0
71.1	80.87	0-29	0.801	2.0-4.0
82.2	79.46	0	0.958	1.0-2.5
93.3	74.03	0	1.032	1.0-1.5

Source: MacMasters et al. (1959); as presented by Fedewa (1985).

Watson and Hirata (1962) dried shelled corn in a laboratory-scale batch-type dryer (MacMasters et al., 1954) and in a small-scale cross-flow type dryer. Experiments with the batch dryer considered: (1) corn hybrid No. 1227 at two initial moisture contents, 32 and 21%; (2) drying air temperatures of 48.9, 60, 71.1 and 82.2 C at two relative humidities, 15 and 40%; (3) final moisture content of product between 8 and 11.8%, with drying times varying from 1.17 to 8.27 hours. The data show that corn at an initial moisture content of 21% can be dried safely at 48.9 C in a batch-dryer to 11.5% without affecting the viability; also that the corn viability is maintained at 70%, after drying for 3.5 hours at 60 C and a relative humidity of 40%. However, at 60 C and 40% of relative humidity, initial and final moisture content of 32 and 10%, the viability is completely destroyed after four hours.

Watson and Hirata (1962) dried corn from 21% to 14 - 15.5% moisture content, in a small-scale crossflow dryer. They concluded that viability is the most sensitive index of heat damage. A drying temperature of 65.6 C caused no damage (82% viability) at low airflows (60 m^3/min-MT), but caused medium (72%) and high (62%) viability damage at medium (128 m^3/min-MT) and high (188 m^3/min-MT) airflows. The viability was decreased at an air temperature in the range of 87.8 C to 104.3 C, however damage was least at lower airflow rates. The sharp reduction in the millability scores with increasing temperature indicates that the temperature levels of 87.8 and 104.3 C caused detectable damage to milling properties of corn. At 65.1 C, the milling properties of corn were not adversely affected by the drying process, at any of the three airflows tested.

Foster (1965) reported that starch yield in wet milling decreases with increasing drying air temperature up to 143.3 C.

Lasseran (1973) reported that drying air temperatures up to 90 C, in one-pass experimental dryer of 0.20 m stirred bed, did not adversely affect the wet milling quality of corn dried from 32 to 16%.

Brekke et al. (1973) investigated corn drying in the dry-milling industry. The decrease in germination due to artificial drying of corn in a laboratory fluidized-bed dryer was analyzed with a grain depth of 0.12-0.15 m. Between 95 and 143 C the yield of first break grits (grits passing through a four mesh and retained in a six mesh per inch sieve) decreased from 45 to 12%. Also the stress cracks in the kernels increased from 7 to 84%, and the undesirable fat in grits from 0.4 to 1.1%.

Peplinsky et al. (1975) investigated the effect of harvest and drying conditions on the quality of several varieties of yellow dent corn; the change in germination, test weight, broken corn and foreign material (BCFM), total percentage damaged and heat-damaged kernels, odor, proximal analysis and solubles was measured. A fluidized-bed dryer was used, to dry corn from 34-17% to 16% at a drying temperature from less than 32 to 148.9 C. Between 82.2 to 148.9 C viability of the corn was destroyed. For lots dried at 48.8 C, the viability decreased to 25% when corn was harvested at 32% moisture, and to 76-88% for corn harvested at 20 and 25% moisture; for lots dried at 32.2 C or less, the germination values remained at about 90%. A considerable increase in corn breakage, as measured by the Stein breakage tester, resulted from the drying process in the two temperature ranges. Because of higher airflows and a temperature of the grain rapidly reaching the temperature of the drying air, these tests are closer to the thin-layer cases than to commercial dryer types currently in use.

Studies on the correlation between the composition and physical characteristics to dry milling performance of corn were carried out by Manoharkumar et al. (1978). Corn was dried from 35 to 15% of moisture content at a drying air temperature up to 60 C. There was a strong correlation between percentage of floaters and the dry milling quality of the corn.

Brown et al.(1979) studied the effect of three drying methods on quality of corn dried from 20 to 30%: (1) high-temperature crossflow batch drying, (2) dryeration and (3) in-bin drying. The drying air temperature was varied from 45 to 60 and to 80 C in the experimental crossflow dryer; 60, 80 and 100 C were used in the high-temperature stage of the dryeration; in-bin drying took place with ambient air. Viability was found to be the most sensitive quality factor; it was markedly reduced at temperatures above 60 C. Viability, test weight, and stress analysis were reported to be correlated with the steeping index as a measure of wet-milling quality.

Brown et al. (1981) investigated the drying of 29-31% corn to 15% in stainless steel screen baskets at a grain depth of 0.04 m. The dryeration process was simulated, using 80 and 100 C for the high-temperature drying stage, and ambient temperature (21 C) for the final drying stage. The suitability of the dried corn for the wet milling process was rated by a steeping index. The results demonstrate that the high temperature used deleteriously affected the corn quality. They recommended that, in the wet milling industry, corn at 25% or above should be dried at 60 C or less.

Le Bras (1982) studied six drying methods: (1) one-pass 0.20 m deep stirred bed, (2) two-passes 0.20 m deep stirred bed with intermediate aireation, (3) dryeration, (4) ear corn crib drying, (5) two-stage drying, and (6) multi-stage drying processes. He concluded that a starch recovery rate of 90% can be obtained from corn dried at 95-100 C in one-passing, at 110-120 C in two-passing with intermediary aeration and at 110-115 C with dryeration. Covered cribs with narrow width (maximum 0.80 to 0.95 m in width) provided more satisfactory results than wide un-covered cribs. Two stage and multi-stage drying systems were found to provide acceptable corn quality at higher temperatures than the other drying methods; 150 and 95 C in the two-stage dryer, and 180, 150, 120, and 90 C in the four-stage dryer.

Peplinsky et al. (1982) studied the effects of harvesting and fluidized-bed drying on corn quality for dry-milling. Air drying temperatures of 49, 82, or 150 C were used, with subsequent tempering times of 0.25 to 0.5 hours; cooling was done at ambient air. The initial moisture content of the corn was 32, 25, 20 and 17%, the final moisture content between 11 and 14%; the drying temperature ranged from -1 to 150 C. Yields evaluation of prime products (grits, low-fat meal, low-fat flour), corn germ, and fat in the germ indicated an increasing trend with decreasing drying temperature. Corn harvested at 25% or lower moisture content and dried at 82 C or lower temperature yielded optimum product recovery and quality.

The quality of corn dried by combination drying and conventional low-temperature drying was compared with a high-temperature crossflow drying by Otten and Brown (1982). Combination drying resulted in less breakage, BCFM, stress cracking and breakage susceptibility, and in higher test weights and viability counts. It should be noted that the viability was uniformly low for all cases probably due to a low initial germination percentage.

Peplinsky et al. (1983) investigated the dry-milling characteristics of corn dried with intermitent ammonia injection. Corn at 26-27% moisture content was dried in bins with and without stirring in 45 days to 12.7 to 14.5% moisture. The ammonia treatments lowered the kernel germination to 10% or less. The kernel weight and hardness were unchanged, the breakage significantly increased as did the percentage of stress-cracked kernels. Dry-milling yields were unaffected by the type of drying treatment; all the grits had satisfactory flavor.

The influence of varietal differences on the quality of dried corn for dry-milling has been demonstrated by Stroshine et al. (1981, 1986). Different corn hybrids and varieties have different dry milling quality, breakage susceptibility, drying rate, storage mold resistance, test weight and thounsand kernel weight characteristics.

Viability loss and dry-milling quality of corn are closely related to breakage and stress cracks. The effect of breakage susceptibility in the dry-milling of corn has been analyzed by Paulsen and Hill (1985); the lack of a standard method for breakage testing has delayed the use of breakage susceptibility measurements in routine applications. Some recent research has demonstrated differences among several methods currently used to determine breakage susceptibility (Watson and Herum, 1986; Pomeranz et al., 1986).

3.2.3 Heat Damage to Wheat and Oilseeds

Heat damage to the quality of wheat has been extensively researched. Drying of oil seeds and investigations on high temperature grain disinfestation have been focussed on heat damage to quality since the early 1980's. Thin-layer and fluidized-bed drying are the most frequently used techniques in these studies, thus temperature of air and grain are considered to be the same during the experiments. Critical air temperatures found can therefore be properly applied to the design of different types of dryers.

Villa et al. (1978) reported that the germination capacity of 19.2% moisture soybean seeds was completely destroyed during ten days of storage at 39 C, but 17.9% moisture seeds lost only 4% of germination at 20 C and the same storage time. They developed an empirical model to simulate low temperature drying which will be detailed in Section 3.3.

Schreiber et al. (1981) gathered extensive data on the influence of drying temperature (50 - 100 C), moisture content (10 - 22%) and of drying time (1 - 1000 min) on the germination, bread volume and wet gluten content of wheat. A zero-order reaction kinetics equation was applied to these data to model the quality changes as a function of the drying parameters. This model is treated in detail in Section 3.3.

Sutherland and Ghaly (1982) investigated the effect of fluidized-bed drying on the quality of sunflower and rapeseed by measuring the germination and some properties of the oil. Safe drying temperatures of 55, 60 and 65 (16, 14, and 12% of moisture content, respectively) were found for sunflower. For rapeseed an inlet temperature of 60 C caused no loss of germination for each initial moisture content. However, 16% moisture content sunflower and rapeseed heated at 60 C for four hours in sealed tubes were completely killed, indicating that heating at constant moisture content has a more deleterious effect than drying on seed quality. They pointed out that the safe temperatures reported are the maximum grain temperatures to be considered in drying design; important differences in grain and air temperatures should be kept in mind with some particular types of dryers such as the concurrentflow.

Wheat at 12 and 14% of initial moisture content when dried in a

0.34 m diameter fluidized bed with air temperatures of 60, 80, 100 and 120 C for periods between 5 to 120 min and an airflow of 145 l/s showed that drying at 60 C during two hours do not adversely affect the functional properties (Ghaly and Taylor, 1982). Germination was shown to be a sensitive and reproducible test that correlates well with baking tests for detection of heat damage.

Ghaly and Sutherland (1983) researched the effect of air inlet temperatures (40, 50, 55, 60, 70, and 80 C) on the quality of soybean seeds dried from 14, 16 and 18% moisture content in an experimental fluidized-bed dryer. An airflow of 0.03 kg/s (2.4 to 2.7 m/s of air velocity) and four hours of drying were considered. Seed germination and seedling vigor determinations indicated the onset of damage. Safe drying temperatures (germination capacity between 82 to 84% as related to the control) of 65, 60 and 55 C were reported for initial moisture contents of 14, 16, and 18%, respectively. Heating soybeans up to 60 C at a fixed moisture content (sealed tubes) increased the susceptibility to damage; a similar effect to the one observed by Sutherland and Ghaly (1982) with sunflower seed and rapeseed.

Ghaly and Sutherland (1984) investigated heat damage to wheat and safflower. An experimental 0.12 m diameter fluidized bed dryer was used; indicators of heat damage were: germinative energy (4 day count), germinative capacity (eight day count), seedling mass and lengths of plumule and radicle for wheat and total germination and some oil properties for safflower. Wheat of different hardness at 12% of initial moisture content were not significantly affected by heating air at temperatures up to 75 C. For the safflower safe drying temperatures of 65, 60, and 55 C, based on non-decrease of germination, were obtained. Due to the nature of the experiments, the seed and inlet air temperature were considered the same.

3.3 Models for Viability Loss

Theoretical, semi-theoretical and empirical models have been proposed to explain seed viability losses in drying, tempering and storage. Data from the heating of seeds in sealed containers or from actual storage experiments at constant temperature and moisture content constitute the basic information used to model viability losses during storage. The steady state data is also employed to simulate the viability losses in drying during which both the grain temperature and moisture content change continuously.

The dependence of the parameters in the viability models on temperature is generally assumed to follow Arrhenius's equation; however, other models have been proposed. The dependence of the parameters on moisture content is generally described empirically.

Models for viability loss based on the multicellular death theory, the kinetic rate theory, and the normal distribution of deaths have a theoretical basis. The first two are considered in detail in this section, the last one is the basis for the author's model and is discussed in Chapter 4. Empirical viability loss models are also reviewed.

3.3.1 Multicellular Death Theory

Rosenberg et al. (1973) proposed the use of the kinetics of protein denaturation and the thermodynamics of rate processes to describe the death of multicellular organisms at constant temperatures.

Gygax (1977) used the multicellular death theory to predict the germination loss of corn seed heated in sealed containers (thermal death cans) at constant temperature and moisture content. The characteristic features of the model are: a) the equation's three parameters; b) the temperature dependent parameter follows Arrhenius's law; and c) the integral and differential form of the function can be tested, depending on the nature of the data.

The model assumes that the death rate at a given moisture and temperature increases as a power law function of time:

$$dN/dt = N(t)\ A_d\ t^n \qquad (3.1)$$

where:

$N(t)$ = the population as a function of time

A_d = temperature dependent rate constant

t = time

n = power law constant, dimensionless

Integration of equation (3.2) results in:

$$N(t) = N_o \exp(A_d \frac{t^{n+1}}{n+1}) \qquad (3.2)$$

where:

$$A_d = C_1\ T_a \exp(\frac{C_2}{R} (\frac{1}{329.} - \frac{1}{T_a}) - 64.9) \qquad (3.3)$$

where:

T_a = temperature, degrees absolut

R = gas constant, J/mole-K

N_o = the initial population

C_1 and C_2 constants determined by regression analysis

The values 64.9 and (1/329) correspond to a and b of the linear dependence assumed between the activation entropy (ΔS^*) and the activation entalpy (ΔH^*) in protein denaturation:

$$\Delta S^* = a + b \ \Delta H^* \tag{3.5}$$

Equation (3.3) is coupled to equation (3.1) or equation (3.2) to find C_1, C_2, and n. Thus, the thermal death at any given moisture content and at various temperatures can be described.

Gygax (1977) succeeded in fitting equation (3.1) to thermal death data for corn seeds at 14, 16, 17, 20 and 24% moisture heated at constant temperatures ranging from 54.4 to 76.7 C for different time periods (2 to 130 min). The model's best fit was for cases with a small germination loss; for cases of rapid germination decrease there was a tendency to under-estimate high viabilities and to over-estimate low viabilities. The n values for corn ranged from 0.54 to 2.04 and was not constant as predicted by the multicellular death theory; a zero value had to be assumed for 28% moisture content seed to describe the rapid viability loss thus converting the function to a first-order reaction in reaction kinetics theory (Gygax, 1977).

The germination model proposed by Gygax also failed to predict the experimentally measured decreases in germination of concurrent and fluidized-bed dryers. The viability loss model predicted complete killing within 6 minutes in the fluidized-bed dryer and 36 seconds in the concurrentflow dryer while the actual dryers produced seeds with germinations above 50%.

Gygax's research constitutes the first attempt to model viability deterioration of corn seed during drying. The experimental data provides an insight into the phenomenon studied.

The following criticism should be made of Gygax's work: (1) heat transfer under non-comparable conditions may have occurred affecting the rate at which the grain reached the heating medium temperature; thus, the basic assumption of constant grain temperature may not have been obtained; (2) A low heat convection rate outside and inside the container governed the heat transfer; besides, two heating mediums were used: steam and hot water; (3) the initial viability was not obtained for each test; the use of an average value affected negatively the data analysis and conclusions; (4) the experimental concurrent dryer may have not properly simulated the heat and mass transfer in a commercial-sized concurrentflow dryer due to air channelling; (5) the multicellular model does not adequately describe the viability loss during drying.

3.3.2 Kinetics Rate Theory

The reaction rate kinetics theory is generally expressed by the equation:

$$r = - \frac{dG}{dt} \quad K\,\Phi(C_j) = K \,.\, C_1^{n_1} \,.\, C_2^{n_2} \quad \ldots . \; C_m^{n_m} \qquad (3.5)$$

for $j = 1,2,3 \ldots m$

where:

r - the reaction rate, at constant temperature and initial concentration.

$\Phi(C_j)$ - functional dependence of the concentration rate of the various (m) chemical species (C_j).

n_j - order of the reaction of each of the components with respect to the species j.

K - reaction rate constant, may be temperature and concentration dependent.

The kinetics theory has been applied to model the effect of storage and drying on seed viability. The deterioration of seed is a complex biological process which encompasses a series of changes before the seeds lose viability; the principle causes of loss of seed viability are still not clear (Roberts, 1982). Figure 3.2 illustrates the complexity of the phenomena.

The chemicals which cause the deterioration of seeds are unknown. It will be assumed that one chemical effects the heat damage. Thus the kinetics theory can be simplified to:

$$r = - \frac{dG}{dt} = K\,\phi(G) = K\,G^{n} \qquad (3.6)$$

where:

n - the order of the germination decrease reaction

K - the germination-decrease-reaction rate constant

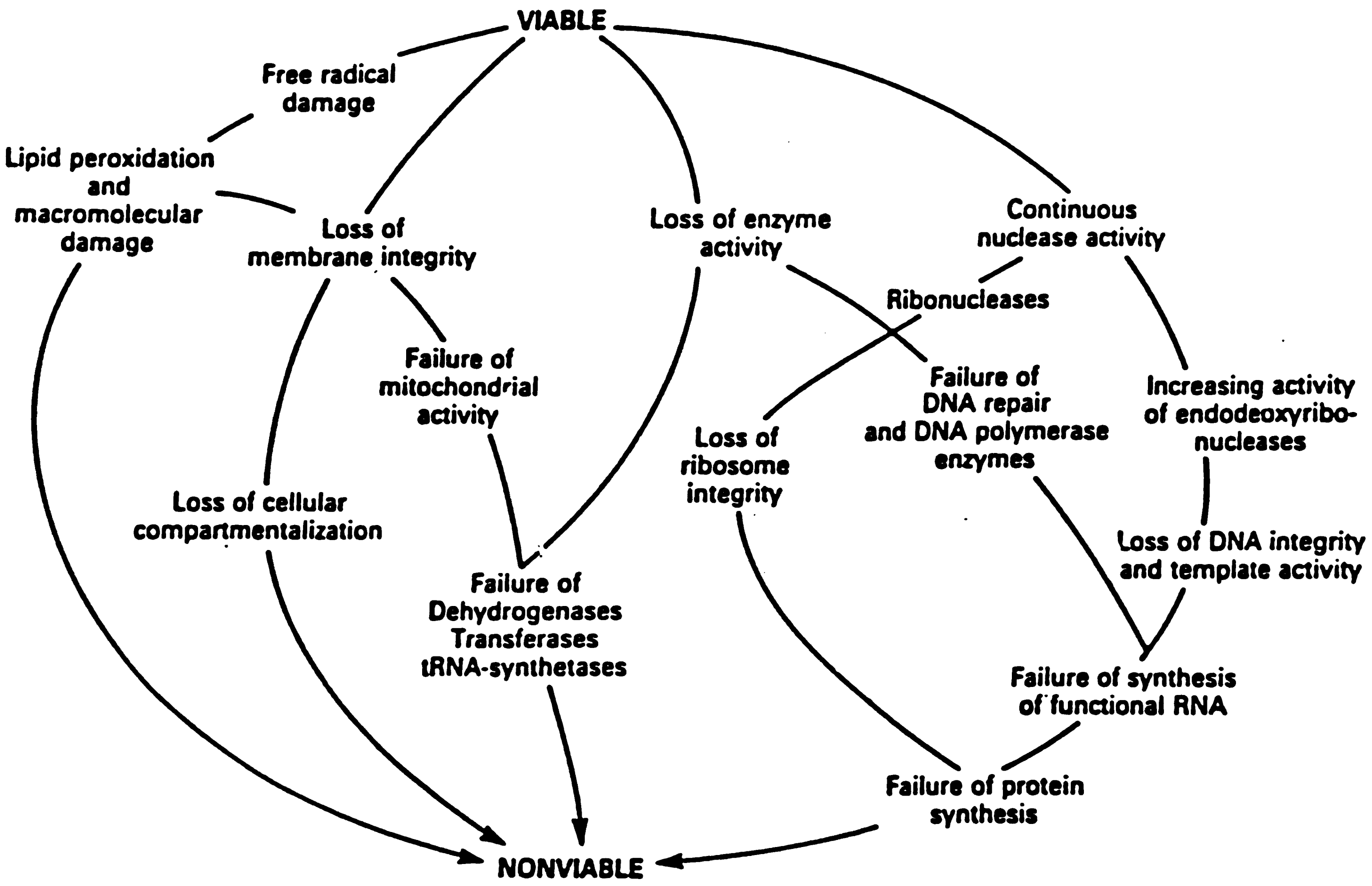


Figure 3.2 An Scheme to Illustrate the Variety of Causes for the Loss of Viability in Stored Seeds.

T = the temperature
t = the time
G = the total germination

The rate of reaction (-dG/dt) is considered to be the rate of decrease of the surviving germ.

In classic kinetics theory research, the order of reaction (n) and the rate constant (K) are determined from experimental data from constant temperature and constant moisture content tests (Mishkin et al., 1983). From experimental values of K obtained at different sets of constant temperature and constant moisture tests the relationship between the rate of reaction (K) and the temperature (T) and moisture (M) can be established. Different empirical equations containing moisture and temperature terms can be assumed, and with the aid of linear or non-linear multiple regression techniques, the best fitting model can be found.

In semi-empirical models describing the deterioration of food (Mishkin et al., 1983), the temperature and moisture dependence of the rate of reaction is often assumed to be described by the Arrhenius model:

$$K = A \exp\left(-\frac{E}{R}\frac{1}{T_a}\right) \qquad (3.7)$$

where: A is the frequency factor or the pre-exponential factor, expressed as a function of moisture content and E is the energy of activation, also a function of moisture content.

The order of reaction is normally the first parameter to be determined. Deterioration of a food can be described by a kinetics rate of zero, such as enzymatic degradation, non enzymatic browning, and lipid oxidation; of one, for example, microbiological growth and heat treatment death, rancidity of salad oils and dry cereals, microbial production of off-flavors and slime, vitamin losses, and loss of protein quality in dried food (Labuza, 1982). Most reported fractional values represent empirical fitting to experimental data (Hill and Grieger-Block, 1980).

The kinetics model applied to seed viability can be considered a simplification of the multicellular-organism death model (Gygax, 1977).

3.3.2.1 Zero order kinetics model

Schreiber et al. (1981) investigated data gathered for several quality factors of wheat heated at different temperatures and moisture contents. They assumed zero-order kinetics and a moisture and temperature dependence of the reaction rate constant as given by equation:

$$\ln K = \ln A_1 + A_2 \bar{\theta} + A_3 \bar{M} \qquad (3.8)$$

where: A_1, A_2, and A_3 are empirically determined constants, $\bar{\theta}$ is average grain temperature and $\bar{M}$ average moisture content in percentage, wet weight basis.

An analysis of the germination loss model proposed by Schreiber et al. (1981) for wheat shows that the germination loss rate does not change with time during heating at constant temperature and constant moisture content. An additional limitation is the use of experimental rates of survival data, which introduces approximation errors. Even though the zero order kinetics model may be applicable to Schereiber's wheat data, the author's experience is that the model does not predict germination loss during corn seed drying.

3.3.2.2 First order kinetics model

Silva et al. (1980) reported that the effect of the heat on corn during drying can be predicted by a first order kinetics equation. The effect of temperature on the rate of reaction constant was accounted for by the application of the Arrhenius equation. It was assumed that the grain instantaneously approaches the drying oven air temperature, and that the rate of moisture content decrease during drying has no effect on the germination loss. The initial corn seed moisture was 26%; drying temperatures of 66, 71, 77, and 85 C were tested. In general, the data showed predicted viability below the experimental values at the beginning of the drying time as compared to higher values at the end of the drying process, indicating an over-estimation and under-estimation of the germination losses, respectively. No moisture history curves were reported. Because of the simplifications considered, the model application to drying is limited.

Lupano and Añón (1986) have investigated the denaturation of wheat germ protein during drying using the kinetics theory in conjunction with the Arrhenius equation. They found that thermal inactivation of the germination process, the insolubilization of germ protein, and the dissappearence of polypeptide bonds followed a reaction kinetics of first order. The germination counts of Lupano and Añón (1986) (as was the case in the Silva et al. (1980) study) were made after the drying in an oven. Even though different moisture contents were used in the experiments, no mathematical function relating the moisture loss during drying was proposed, neither were the characteristic parameters for the germination loss as a function of the temperature determined. However, a graph showing a linear relationship between the natural logarithm of K and 1/T was presented, were T is the absolute temperature.

Silva et al. (1980) and Lupano and Añón (1986) studies have considered that the reaction rate constant is not a function of moisture content. This assumption constitutes an important drawback for application of this model to quantify quality impairment during the drying of seed.

Kinetics models of the zero and first order have inherent limitations which prevent complete description of the germination loss sigmoid-curve. The germination rate is described by the slope of the germination curve with respect to time at constant temperature and moisture. A kinetics rate order of zero means a constant slope, or a constant germination loss rate. This is not normally observed experimentally, since the slope is a function of the duration of heating time. First order kinetics equations are decreasing exponential functions which relate germination with heating time; the typical germination loss curve has two inflexion points and the slope changes.

Kinetics equations of both first and zero order fit better the survival curves at extreme heating or drying conditions, i.e in the neighborhood of minimum and maximum losses. Equations that consider the seed deaths to be normally distributed are theoretically better suited to represent the entire germination loss curve than the first or zero order kinetics equations.

The normally distributed death model will be discussed in the next chapter. It forms the basis for the model proposed in this dissertation.

3.3.2.3 Empirical models

Heat damage to viability of specific seeds has been modeled by several empirical equations. Nellist (1980) has summarized some of the models derived from sealed-heating and storage experiments; in general, a certain level of damage is chosen in these models, and a critical grain temperature is associated to it. The time to produce a given level of damage is exponentially related to grain temperature and moisture content:

$$t = \exp(A - B\,\bar{\theta} - C \ln \bar{M}) \qquad (3.9)$$

$$\text{or} \quad t = \exp(A - B\,\bar{\theta} - D\,\bar{M}) \qquad (3.10)$$

Equations (3.9) and (3.10) were proposed by Roberts (1972) and Hutchinson (1944), respectively.

Empirical equations have inherent limitations. They are dependent on the type of grain and on the range of variables studied experimentally. Their application is recommended only when a general theoretical model is not available.

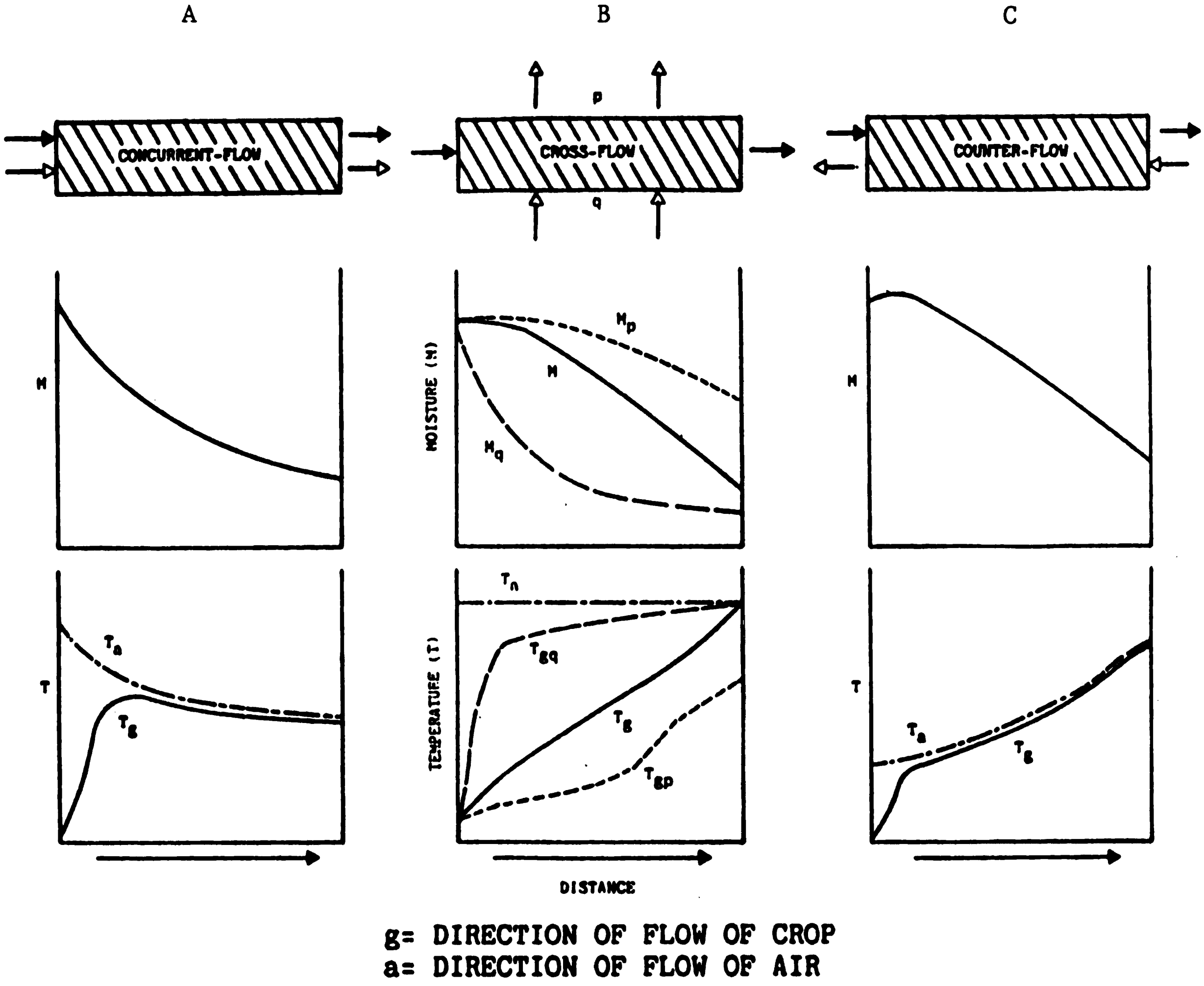
A cumulative deterioration time is usually computed for each temperature and moisture content during the simulation of the storage or drying process. Consequently, the ratio with respect to the total allowable time for a given viability decrease can be accummulated until a value of 1.0 is reached (Bailey, 1972; Bowden et al., 1983).

3.4 Concurrentflow Grain Drying

The concurrentflow, crossflow and mixed-flow dryers are high-temperature, continuous grain dryers (Bakker-Arkema, 1984). The crossflow dryer is the most commonly used type in the United States (Brook, 1977), the mixed-flow is the most popular in Europe (Nellist, 1982), and the concurrentflow/counterflow dryer has the potential to become the major drying technique in the present decade (Bakker-Arkema, 1984). Figure 3.3 shows the typical temperature and moisture content history curve of the crossflow, concurrentflow, and counterflow dryers (Nellist, 1982); the corresponding curves for the mixed-flow dryers are a mixture of the three presented in the Figure (Bakker-Arkema, 1984).

The use of concurrentflow dryers in commercial grain drying is relatively recent (Bakker-Arkema, 1984).

Concurrent/counterflow dryers have been developed in the United States by three companies: M. and M. Gear Co., The Andersons, and Blount Inc. (Nellist,1982). The first patent was granted to Öholm in 1955 (Hawk et al., 1978). In the United States on-farm concurrentflow dryers have been manufactured since the early 1970's (Graham, 1970). The first U.S. one-stage concurrentflow grain dryer was designed by Anderson (1972); several units of the Anderson dryer have been operational in Illinois (Hawk et al., 1978). Westelaken (1977) described the first commercial multi-stage concurrentflow/counterflow grain dryer.



A : Concurrentflow
B : Crossflow
C : Counterflow

Source: Nellist (1982)

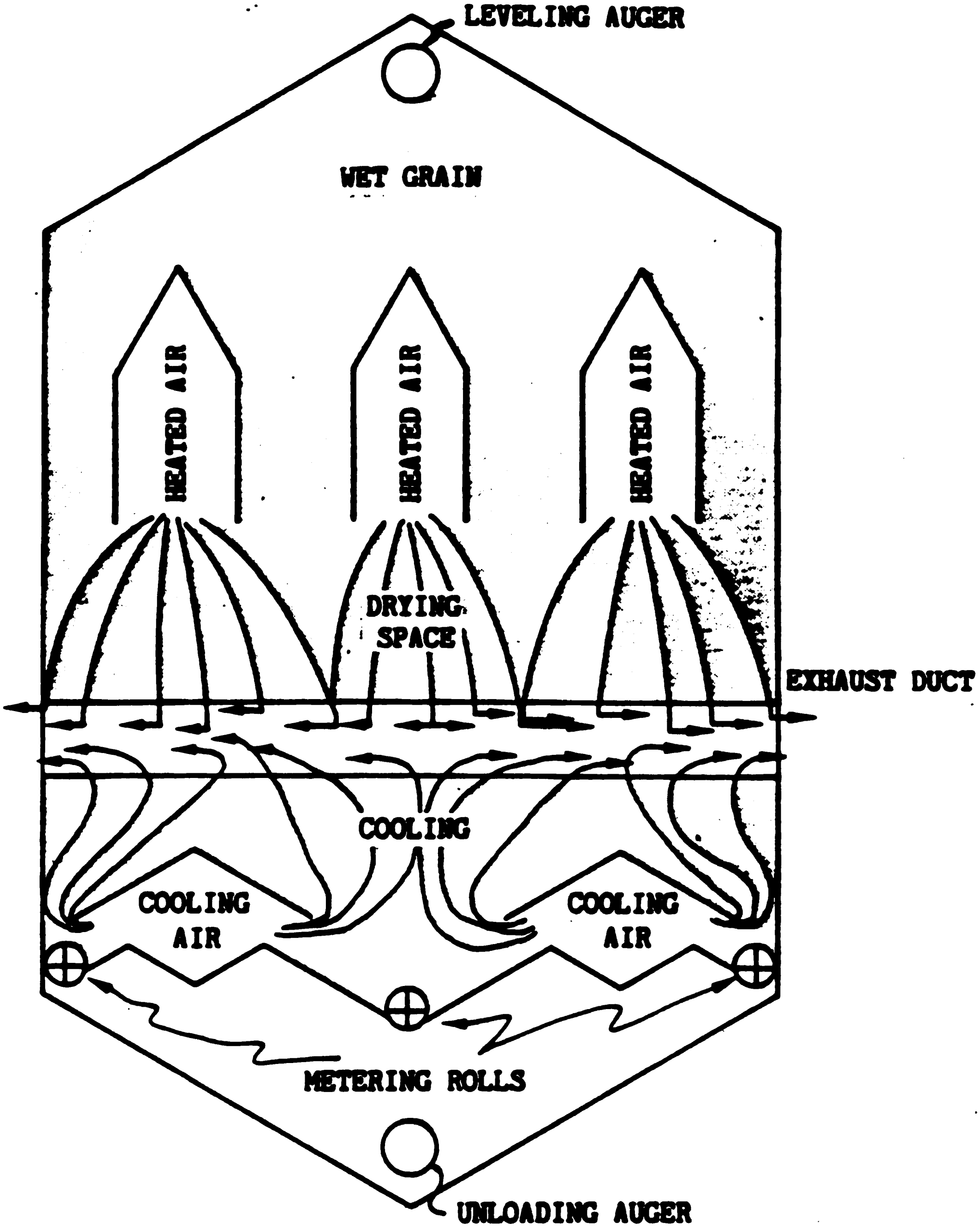
Figure 3.3 Moisture Content and Temperature Profiles During Concurrent-flow, Crossflow and Counterflow Drying.

In concurrentflow drying the air and the product both flow in the same direction through the dryer. At the top of the dryer, the wet and cold inlet grain is exposed to the hot and dry air, causing a rapid cooling of the air due to the high rate of evaporation (Brook, 1977). The high rate of heat and mass transfer between grain and drying air results in a large temperature difference between the air and the kernel temperature in the top layers of the drying bed. The relatively low maximum kernel temperature permits the use of high air temperatures, and, as a result, the air (or thermal) energy required per mass of water evaporated is relatively low. As the grain and the air move through the dryer, their temperatures equilibrate, and at the outlet, the grain is within a degree of the air temperature.

The energy efficiency of the concurrentflow dryer is between 3000-3800 kJ/kg in drying a variety of grains (Nellist, 1982; Bakker-Arkema et al., 1982), as compared to 6940, 7020, and 4380 kJ/kg for the conventional crossflow, the reversed crossflow, and the recirculating crossflow dryers (Pierce and Thompson, 1981). Mixed-flow dryers have a drying efficiency of 3500-4000 kJ/kg in drying high moisture content corn (Anon, 1979).

In a concurrentflow dryer every kernel undergoes equal heat treatment. Thus, there are no moisture and temperature gradients among the grains as is the case in other dryer types. The grain temperature- and moisture content-history profiles in a concurrentflow dryer are such that the heat damage is reduced (Gygax et al., 1974).

Commercial concurrentflow dryers may have one (Figure 3.4), two or three drying stages, with a counterflow cooling stage attached. In multi-stage units, a tempering zone is located between drying stages to improve the drying rate, grain quality and energy efficiency



Source: Brooker et al. (1974)

Figure 3.4 Schematic of an On-farm Concurrentflow Dryer

(Bakker-Arkema et al., 1982). Figure 3.5 presents an schematic diagram of a two-stage concurent/counterflow dryer. Figure 3.6 shows the section of initial contact between grain and air.

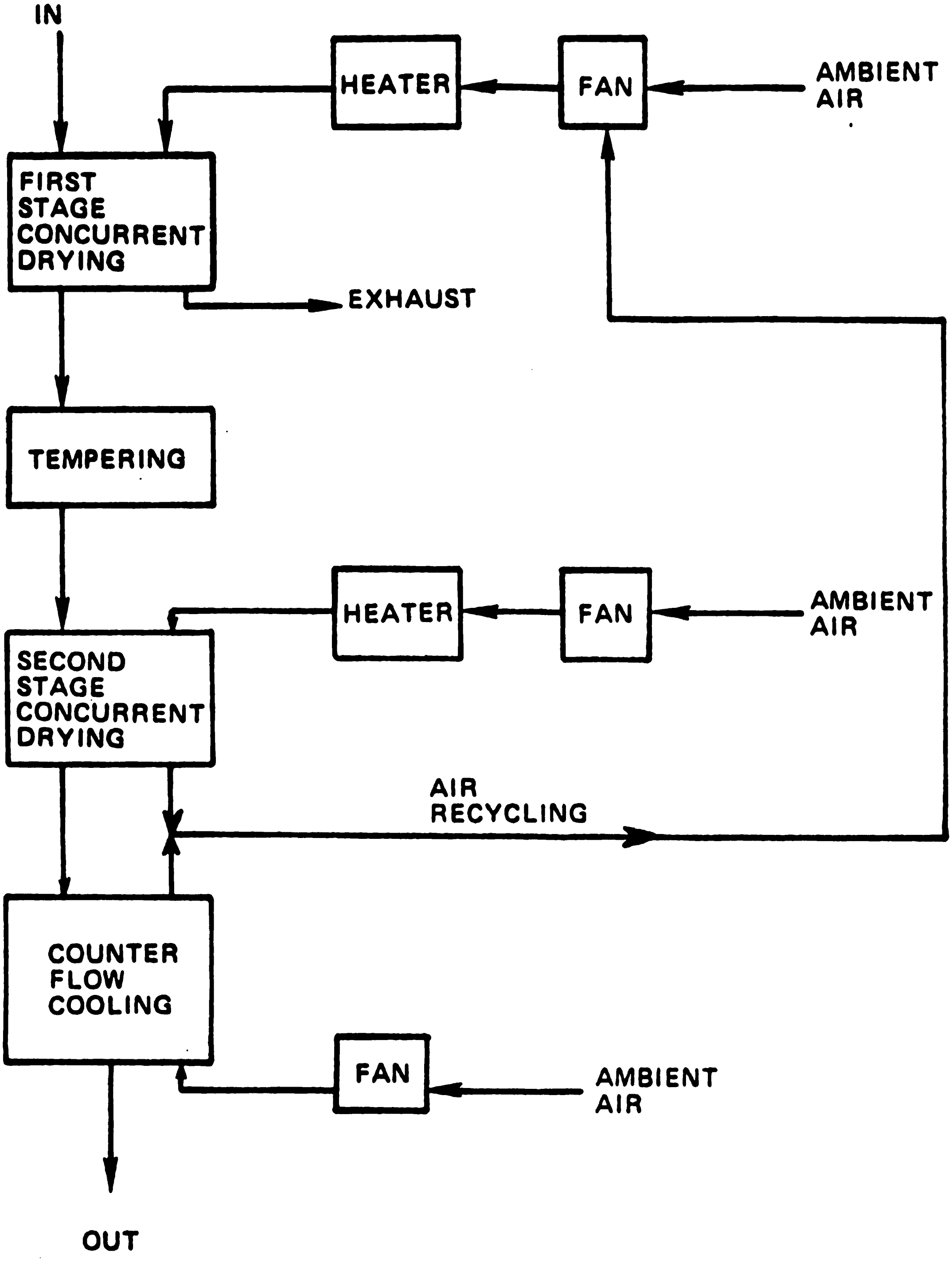
The Andersons (Hall and Anderson, 1980) developed the BIRD (Batch Internal Recycling Dryer) dryer, a single-stage concurrent/counterflow dryer which achieves multistaging by recirculating (multipassing) a batch of grain.

Single stage concurrentflow dryers are limited in capacity whenever ten or more points of percent moisture content are to be removed from the grain. The low grain capacity that must be used to acomplish the required moisture content reduction, drives the grain temperature to relatively high levels so that kernel damage may occur (Bakker-Arkema et al., 1977).

Multi-stage concurrentflow dryers eliminate the problems inherent to the single-stage type (Bakker-Arkema, 1982). The use of higher grain velocities allows the increase of the drying air temperatures. Multi-stage concurrentflow dryers provide the following comparative advantages: (1) increased capacity, (2) improved grain quality, (3) greater temperature control, and (4) improved thermal efficiency (Westelaken and Bakker-Arkema, 1978).

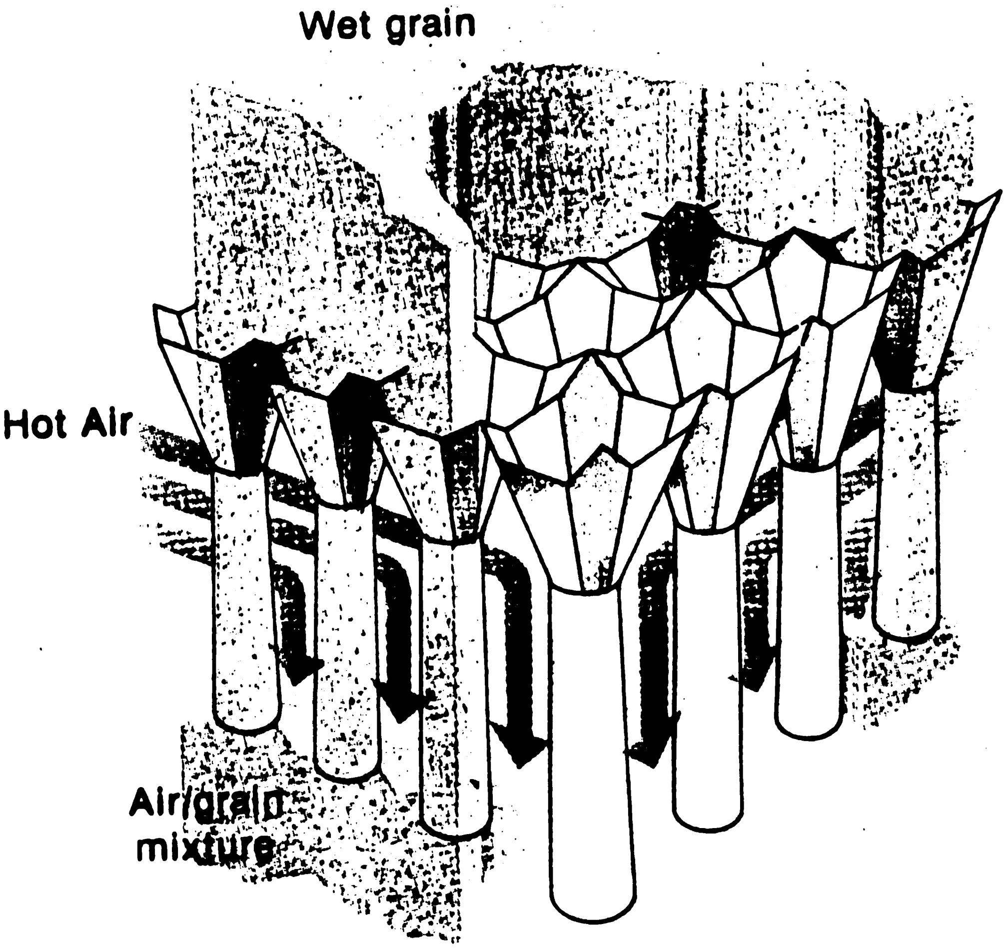
Some commercial three-stage concurrentflow dryers incorporate the recycling of the air from the second and third stages (Hawk et al., 1978). Bakker-Arkema et al. (1978) claim that the energy efficiencies in such recirculating dryers are below 3954 kJ per kilogram of water removed.

Bakker-Arkema (1984) reported that commercial concurrent/counterflow dryers are currently in operation in the corn, rice, soybean, wheat, sunflower, and sorghum processing industries.



Source: Brook (1977)

Figure 3.5 Block Diagram of a Two-stage CCF Dryer with Counterflow Cooler and Air Recirculation



Source: Fontana (1983)

Figure 3.6 Schematic of the Drying Floor of the Blount Concurrent-flow Dryer.

Concurrent/counterflow drying has been studied extensively with respect to quality traits as affected by the drying process. A review of some of these investigations follows.

Thompson et al. (1969) investigated concurrent/ counterflow drying of corn at an initial moisture content between 18 and 23%, using inlet air temperatures of 93 to 204 C, bed depths of 0.61 and 1.22 m, air velocities of 30 to 75 m/min and grainflow rates of 22 to 175 kg/h. Stress cracks, Stein breakage and wet millability, based on starch recovery, were tested. Inlet air temperatures lower than 121 C did not affect the millability quality. The percentage of kernels with stress cracks and the percentage of broken kernel both increased with increasing drying temperature.

Single-pass drying of rice from 22 to 16 percent of moisture content at 93 C of inlet air temperature was investigated by Calderwood (1970); the drying resulted in a 12 percent reduction in head-yield.

Mühlbauer et al. (1971) used an experimental concurrentflow dryer, with inlet air temperature up to 200 C, to dry corn and reported less than 5% changes in lysine content. At 248 C this loss was 9.3%.

Gygax et al. (1974) investigated quality changes in corn dried in a laboratory-scale one-stage concurrent/ counterflow dryer. Drying air temperatures of 260 C were used, in one- and two-stage configurations, to dry corn from 19.2 to 25.29% to 14.8 to 15.61%. Changes of 3.5 to 10.79% moisture content resulted in a germination decrease of 63 to 94%, and a breakage increase of 1.9 to 4.2%.

Drying corn from 38 to 16% moisture in a full-size concurrent dryer, with heating air temperatures from 129 to 148 C, and exhaust air temperatures of 42 to 61 C, reduced the fatty acid content in 37% and the lysine availability in 6.5% (Anon, 1975).

Ahmadnia (1977), drying soft wheat at 18% moisture content in a laboratory concurrent/counterflow dryer, investigated the effect of drying air temperatures between 121.0 to 204.4 C on germination, test weight, wheat flour protein, ash, viscosity, alkaline water retention capacity (AWRC), mixogram and the characteristics of baked cookies. No significant damage to grain quality was reported between drying temperatures of 121 and 150 C; at inlet temperatures higher than 176.7 C the grain viability, test weight and flour viscosity decreased and the AWRC increased sharply. A low quality grain was reported when wheat was dried in two passes (149 to 176.7 C and 176.7 to 232.2 C).

Kalchik (1977)in a laboratory concurrent/counterflow dryer, using single- and two-stage configurations and air temperatures as high as 232.2 C, dried soybeans without a loss in oil yield.

Hall and Anderson (1980) investigated the changes on quality of shelled corn dried in a one-stage multi-pass concurrent/counterflow dryer from 17.3 to 30.6% of moisture content, to final values of 13.4 to 16.1%, at drying temperatures between 260 to 431 C. Stein breakage tests of 2.5 to 3.68% and stress cracks of 0.1 and 3.2 for wet and dry samples, respectively, were reported. Germination decreases were between 49 and 97%.

Multiple-stage concurrentflow drying of corn at air temperatures between 288 to 232 C has proven to be a more energy efficient technique with lower corn breakage susceptibility than conventional crossflow drying at 93 C (Bakker- Arkema et al., 1981).

Walker and Bakker-Arkema (1981) dried rice at 120 C in a one pass laboratory concurrent/counterflow dryer from 18 to 12.5 percent moisture content using a three-stage configuration; the head yield decreased by less than two percent.

Dalpasquale (1981) dried soybeans in a laboratory concurrent/counterflow drier from 16 to 13.3% moisture content in single-, two- and three-stage configurations. Air temperatures as high as 204.4 C did not cause a significant reduction in the soybean seed viability.

Fontana (1983) reported that rice dried in commercial two-stage concurrent/counterflow commercial rice dryers from 17.3 to 13.8% of moisture content (inlet air temperatures of 149 and 79 C, and a grain velocity of 8.8 m/h) exhibited a decrease in viability of less than ten percent; head-yields were 62.9 to 79.5 percent.

Bakker-Arkema et al. (1983a) investigated three-stage commercial concurrentflow drying of rice with built-in tempering; the drying inlet air temperature between 121 and 177 C removed six points of moisture without affecting the head-yield. They pointed out that multistage concurrent/ counterflow drying can remove eight to ten points of moisture percent at air temperatures as high as 177 to 204 C, without a deleterious effect to the head-yield.

Fedewa (1985) dried sorghum in a pilot-scale one- stage concurrent/counterflow dryer (Bakker-Arkema, et al., 1983b) from 16 to 12.5% at a drying temperature of 200-220 C without affecting the wet milling quality, starch yield and acceptable protein content in the starch; germination was reduced to aproximately one half of the initial value.

Anderson (1985), evaluated breakage susceptibility of 30% corn dried in a commercial single-stage concurrent/ counterflow dryer (M & W 450 R), operating at inlet drying air temperatures of 128.3 and 138.9 C and retention times of one and a half hours. An increase in breakage susceptibility between 9.6 and 12.1 percent was reported.

4. MODEL DEVELOPMENT

The germination model is based on the straight line which results when the normal deviates which correspond to the total seed deaths are plotted versus exposure times, at a given constant temperature and moisture content. The slopes of the straight line are a function of grain temperature and moisture content and they are related to the resistance of a seed to heat damage.

4.1 Germination Decay During Thin-layer Drying

Thin-layer seed drying is a heat and mass transfer process where heating occurs simultaneously with evaporation. Moisture and temperature states and time of exposure are closely related to heat damage during thin-layer drying of seeds.

4.1.1 The Normally Distributed Death Model

A seed population heated at constant temperature and moisture content conditions, exhibits after the treatment a frequency of individual deaths, or death rate, which can be described mathematically by a Gaussian or normal probability density function (Ellis and Roberts, 1980a). The bell-shaped probability function is a unique and flexible expression for the death rate of seeds with respect to exposure time. It does not have the limitation encountered in the theoretical models discussed in Section 3.3. The integration of the normal probability function gives the cumulative normal distribution which in turn describes the total seed death at any time (Roberts, 1972).

The survival curve, and not the death curve, is generally used to account for the number of viable seeds remaining in the total population (Finney, 1971). In the technical literature related to normal probability functions, the total germination is expressed as a decimal; thus, this unit is also used in this work.

The germination of a seed lot after a certain exposure time can be expressed as the total ideal initial germination (1.0) minus the deaths (decimal) which ocurred in that period.

Thus,

$$G = 1.0 - \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{t} \exp\left(-\frac{1}{2}\left(\frac{t - \bar{t}}{\cancel{2}\sigma}\right)^{2}\right) dt \qquad (4.1)$$

which in a standardized form is:

$$G = 1.0 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{X} \exp\left(- \frac{1}{2} X^{2}\right) dX \qquad (4.2)$$

where: $X = (t - \bar{t})/\sigma$ (4.3)

and X is the standardized normal deviate, dimensionless; t is the time of exposure; $\bar{t}$ is the time for 0.5 viability; G is the seed viability (decimal); σ is the standard deviation or spread of death with time.

Using the symmetry property of the curve, equations (4.1) and (4.2) can be transformed into equations (4.4) and (4.5), respectively:

$$G = \frac{1}{\sigma\sqrt{2\pi}} \int_{t}^{+\infty} \exp\left[\left(\frac{t - \bar{t}}{2\sigma}\right)^{2}\right] dt \qquad (4.4)$$

and:

$$G = \frac{1}{\sqrt{2\pi}} \int_{X}^{+\infty} \exp\left(- \frac{1}{2} X^{2}\right) dX \qquad (4.5)$$

Equations (4.3) and (4.5) determine either G or X uniquely from the other (Figure 4.1).

The integral of equations (4.1) and (4.4) cannot be evaluated by elementary methods, but can be expressed in terms of equations (4.2) and (4.5) of which the values are found in the literature in tabulated or equation form (Abramowitz and Stegun, 1970); algorithms are available in computer libraries (for example IMSL). The problem of calculating G given X is generally solved using an approximation to the error function (Cody, 1969). The inverse problem of calculating X given G is usually treated by approximating the error function by the Chebyshev polynomials (Strecok, 1968).

The negative straight line which relates the standardized normal deviate to the time of exposure is mathematically described by the equation (see equation 4.3):

$$X = X_0 - (1/\sigma).t \qquad (4.6)$$

for: $-\infty < X < \infty$, $\sigma > 0$, $t > 0$ and $X_0 > 0$.

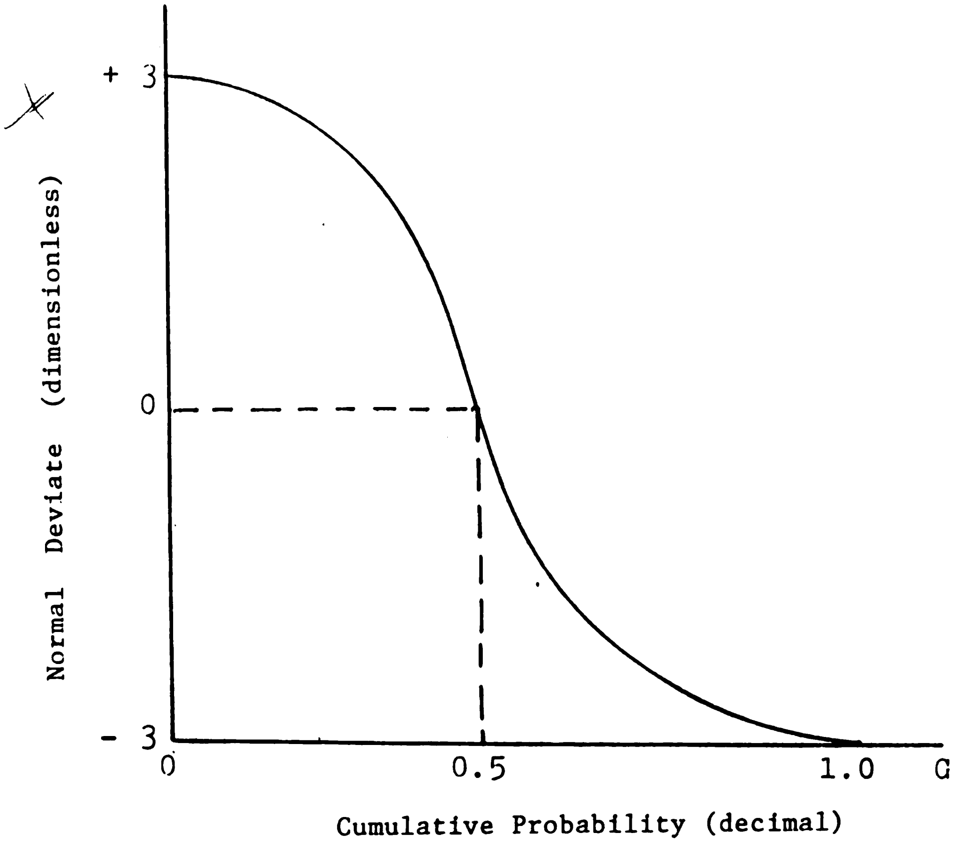


Figure 4.1 Unique Relationship Between the Normal Deviate and the Cumulative Probability.

Where X_0 is the initial value of X, i.e at condition t = 0; and $1/\sigma$ is the slope of the straight line.

Equation (4.6) is frequently used by biologists in regression analysis (Finney, 1971). To avoid a negative value of X, it is increased by 5 units and is called a "probit". The "probit analysis" is well established as a name for a group of linear regression methods which can be applied to seed viability prediction (Finney, 1971). To take advantage of the symmetrical property of the normal curve, the standard deviate and not the probit will be used in this work; this also allows programming optimization and facilitates the theoretical discussion.

Equations (4.3), (4.5) and (4.6) and their straight line representation have been used coupled to the probit regression analysis to test if seed deaths follow the negative normal distribution (Roberts, 1972). Acceptable agreement has been found for wheat, rice, broad beans, peas, barley, and tomatoes. From constant temperature and moisture content data, the slope ($1/\sigma$) and intercept (Xo) in equation (4.6) have been calculated for these crops.

Ellis and Roberts (1981) conducted hermetically sealed 40 C storage experiments of corn seeds at about 10% moisture during a 500 day period; the seed survival curve follows the normal cumulative distribution function for a cultivar at three different initial viabilities. Bould (1984) analyzed germination data of over 400 standard laboratory lots of corn seeds and also established that the seed death follows the normal cumulative distribution function. These two studies provide the basis for the application of the normally distributed death (NDD) model in this research.

4.1.2 The Effect of Temperature and Moisture Content on the Normally Distributed Death Straight Line

Ellis and Roberts (1980a) found that an estimate of the standard deviation of the seed viability decay curve under a wide range of temperature and moisture content conditions, can be obtained from the empirical expression:

$$\ln \sigma = C_1 - C_2 \ln \bar{M} - C_3 \bar{\theta} - C_4 \bar{\theta}^2 \qquad (4.7)$$

Equation (4.7) relates the spread of the distribution in time (σ) to the temperature ($\bar{\theta}$) and moisture content ($\bar{M}$) of the seed. The constants C_1, C_2, C_3, and C_4 are crop dependent but are considered independent of genotype and of initial viability (Ellis and Roberts, 1980a). The four viability constants for an specific crop can be obtained through multiple linear regression analysis of viability data collected at different times for specific temperatures and moisture contents.

The most comprehensive seed viability storage experiments to validate equation (4.7) have been conducted with barley by Ellis and Roberts (1980b). Combining equation (4.6) and (4.7), gives:

$$X = X_0 - t/\exp(C_1 - C_2 \ln \bar{M} - C_3 \bar{\theta} - C_4 \bar{\theta}^2) \qquad (4.8)$$

Ellis and Roberts (1980b) established that equation (4.8) predicts with reasonable accuracy the viability of barley (Hordeum distichum, L. cv. Proctor) stored under hermetically sealed conditions at moisture contents between 5.5 and 24.6% and temperatures of 3 to 90 C, for periods from 1 min to 926 days.

The viability constants obtained by Ellis and Roberts (1980b) for barley are: X_0-4.15; C_1-22.987; C_2-5.896; C_3-0.0921 and C_4-0.000986. The moisture content of the seed in equation (4.8) is expressed in percentage (w.b.), the temperature in degrees Celsius, the time of storage in days, and the viability as a decimal.

Equation (4.7) has been shown to apply no only to barley (Ellis and Roberts, 1980b), but also to onions (Ellis and Roberts, 1981), soybeans, cowpea, and chickpea (Ellis et al., 1982). Table 4.1 shows the viability constants for seven crops when the temperature is in Celsius degrees, the moisture content is expressed in percentage, wet basis, and the time of exposure is in days.

Ellis and Roberts (1981) also determined the constant C_1 (determining σ by probit linear regression at constant temperature and moisture content and then applying the particular version of equation (4.8)) for a cultivar of corn at three different initial viabilities; they found values of 3.87, 2.14, and 1.49 for the high, medium, and low initial viability hybrid, respectively. They concluded that even when a cultivar had a different initial viability, it can be represented by a single standard deviation value.

4.1.3 Prediction of Viability Decrease at Constant Temperature and Moisture Content

The germination decrease of a lot of seed stored at constant temperature and moisture content follows a unique negative straight line (equation 4.8) which is characteristic of the deterioration process

Table 4.1 Seed Viability Constants for Different Crops.

Crop	Viability	Constants			Source
	C_1	C_2	C_3	C_4	
Cowpea	19.987	4.715	0.060	0.00115	a
Soybean	17.820	3.979	0.122	0.00052	a
Chickpea	20.861	4.829	0.1035	0.00075	a
Barley	22.987	5.986	0.0921	0.000986	b
Onion	16.043	3.470	0.2118	0.00010	c
Apple	13.041	2.988	0.1081	0.0	d
Lupinus	10.569	0.111	0.1127	0.0	e

a : Ellis et al. (1982)
b : Ellis and Roberts (1980b)
c : Ellis and Roberts (1981)
d : Dickie and Bowyer (1985)
e : Dickie et al. (1985)

(Ellis and Roberts, 1980a). The slope of the line is given by the inverse of σ (equation (4.7)). Figure 4.2 illustrates diagramatically the process:

a) The initial germination (G_0) is transformed to X_0 using equation (4.5) or a proper algorithm.

b) The slope of the germination decay straight line is obtained from equation (4.7).

c) The standardized deviate (X) at any time can be found from equation (4.8).

d) Using equation (4.5) or an appropiate algorithm, the germination (G) is obtained from a known X value.

The germination decay is directly affected by the σ value which in turn depends on the moisture content and temperature of the seed during the treatment.

Figure 4.3 schematically illustrates the differences between three seed lots of different susceptibility to heat damage.

4.2 The Concurrentflow Drying Model

Concurrentflow dryer simulation models have been developed at Michigan State University (MSU) by Bakker-Arkema et al. (1974) and are subjected to the following assumptions:

1) The shrinkage of the bed is negligible during the drying process.

2) The temperature gradient within an individual kernel is negligible.

3) There is no kernel to kernel heat conduction.

4) The grainflow and airflow are uniform, without wall effects

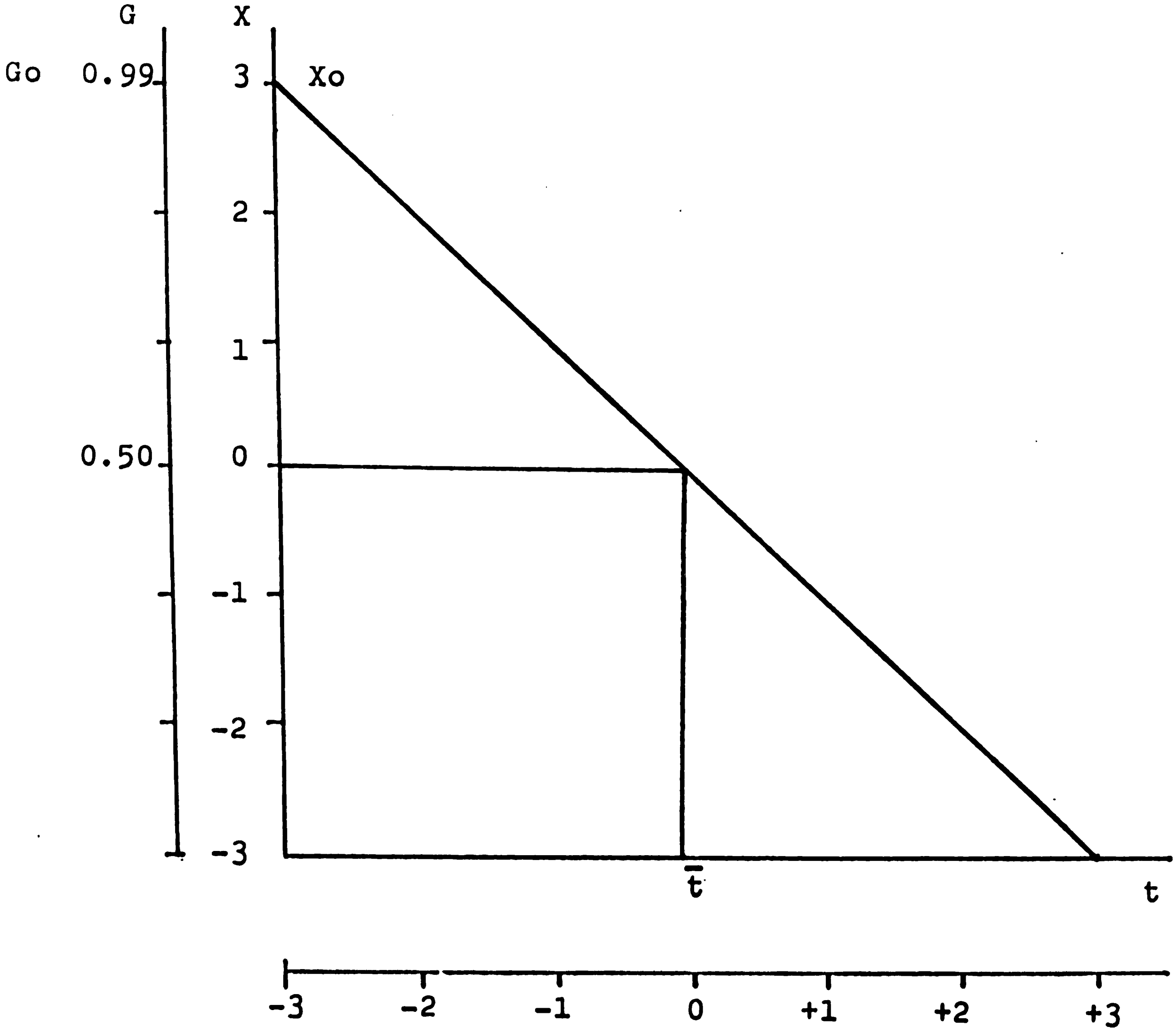


Figure 4.2 Characteristic Straight Line Describing Germination Decay of Seed Stored at Constant Temperature and Moisture Content.

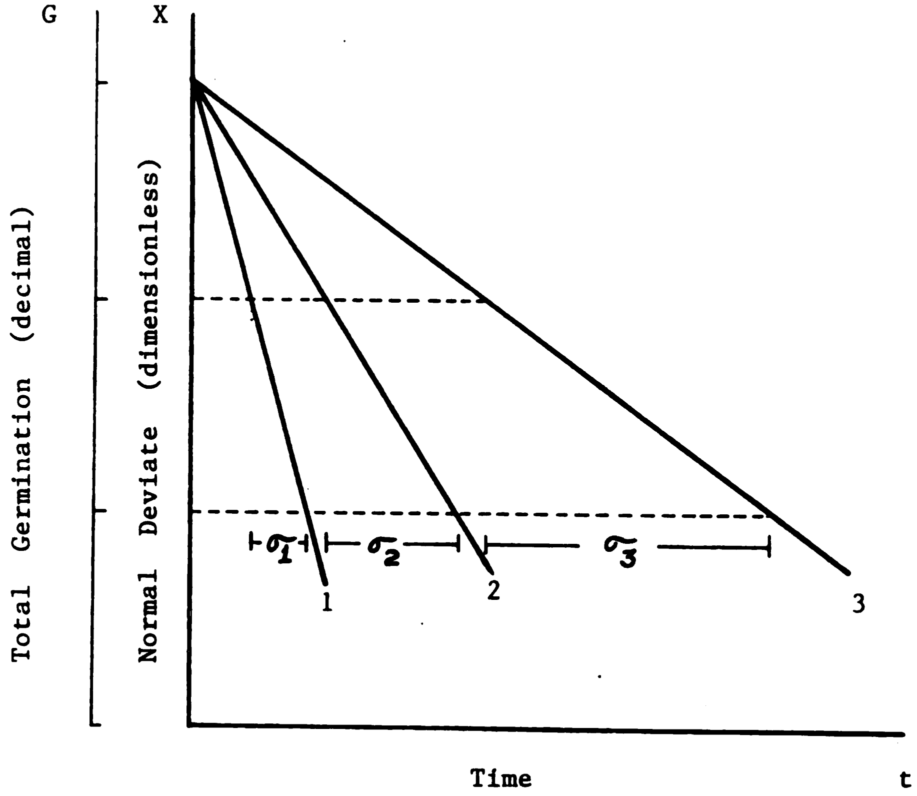


Figure 4.3 Germination Decay with Respect to Time for Three Heat Susceptibility Cases: Low (Curve 3), Medium (Curve 2) and High (Curve 1).

(plug-type).

5) $\partial T/\partial t$ and $\partial H/\partial t$ are negligible compared to $\partial T/\partial x$ and $\partial H/\partial x$.

6) The dryer walls are adiabatic with negligible heat capacity.

7) The physical properties of the grain and of the air are constant for small time steps.

8) Accurate drying rate and moisture equilibrium equations are available as well as the heat of vaporization of water in the grain, and other physical properties.

The concurrentflow model developed by Bakker-Arkema et al. (1974) is based on the laws of heat and mass transfer. The model uses a drying rate equation to predict the drying rate of a given product. The solution of the model allows the calculation of the grain temperature, the air temperature, the air absolute humidity and the grain moisture content as a function of time and position in the drying bed. Four heat and mass transfer balances result in four equations for the concurrentflow dryer:

$$\frac{dT}{dx} = \frac{-h.a}{G_a\, c_a + G_a.c_v.H} (T - \theta) \qquad (4.9)$$

$$\frac{d\theta}{dx} = \frac{h.a}{G_p.c_p + G_p.c_w.\bar{M}_d} (T - \theta) - \frac{h_{fg} + c_v(T - \theta)}{G_p.c_p.c_w.\bar{M}_d} G_a \frac{dH}{dx} \qquad (4.10)$$

$$\frac{dH}{dx} = - \frac{G_p}{G_a} \frac{d\bar{M}_d}{dt} \qquad (4.11)$$

$$\frac{d\bar{M}_d}{dt} = \text{an appropiate drying rate equation} \qquad (4.12)$$

The model used in this thesis is composed of equations (4.9), (4.10), (4.11) and the following spherical diffusion drying equation (Crank, 1979):

$$\frac{\partial M_d}{\partial t} = \frac{D}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial M}{\partial r}\right) \qquad (4.13)$$

The boundary and initial conditions are: (a) $T(0)=T(\text{inlet})$, (b) $\bar{\theta}(0)=\bar{\theta}(\text{inlet})$, (c) $H(0)=H(\text{inlet})$, and (d) $\bar{M}_d(0)=\bar{M}_d(\text{inlet})$.

Where T is the air temperature (C), x is the position in the drying bed in the airflow direction (m), h is the convective heat transfer coefficient (kJ/hr-m^2-C), **a** is the specific surface area (m^2/m^3), θ is the product temperature (C), G_a is the airflow rate (kg of dry air/hr-m^2), c_a is the specific heat of the air (kJ/kg-C), H is the air humidity ratio (kg water/kg dry air), t is the time (min or hours), c_w is the specific heat of water (kJ/kg-C), $\bar{M}_d$ is the average moisture content of the product (decimal, dry basis), h_{fg} is the latent heat of water in the product (kJ/kg).

The MSU concurrentflow dryer model used in this research (see Appendix B) has been previously used by Dalpasquale (1981) for soybean drying and by Brook (1977) for corn. The Subroutine GERMI (see Section 4.4) was attached to the dryer model to compute the germination after the moisture content and temperature of the grain have been calculated, at a given drying time. The germination decrease was followed through the several stages or passes that the drying simulation considered.

4.3 Germination Decay During Deep-bed Drying

A deep-bed grain dryer can be mathematically considered to be composed of a large number of thin layers. The moisture content and temperature changes of each layers can be calculated at a large number of small succesive time periods. It is assumed that during each of these time periods a layer is heated by air at constant temperature and humidity. The differential equations governing the heat and mass transfer during drying were presented in Section 4.2. An average grain temperature ($\bar{\theta}$) and grain moisture content ($\bar{M}$) are computed before the germination change of a layer is determined during a given drying time increment.

The decrease in germination during drying is a dynamic process. It can be conceived as consisting of a continuous sequence of short time steady state temperature and moisture treatments. Once the average grain temperature and moisture content are computed by the drying algorithm, the germination can be calculated using equations (4.5), (4.6), and (4.7) in slightly modified form. A detailed explanation will be given with the aid of Figure 4.4.

The procedure outlined by Figure 4.4 consists of the following:

at $t=0$: $\bar{M}_0$, $\bar{\theta}_0$ and G_0 are known;

at $t = t + dt_1 = t_1 = dt_1$:

a) $\bar{M}_1$ and $\bar{\theta}_1$ are computed by the heat/mass transfer drying

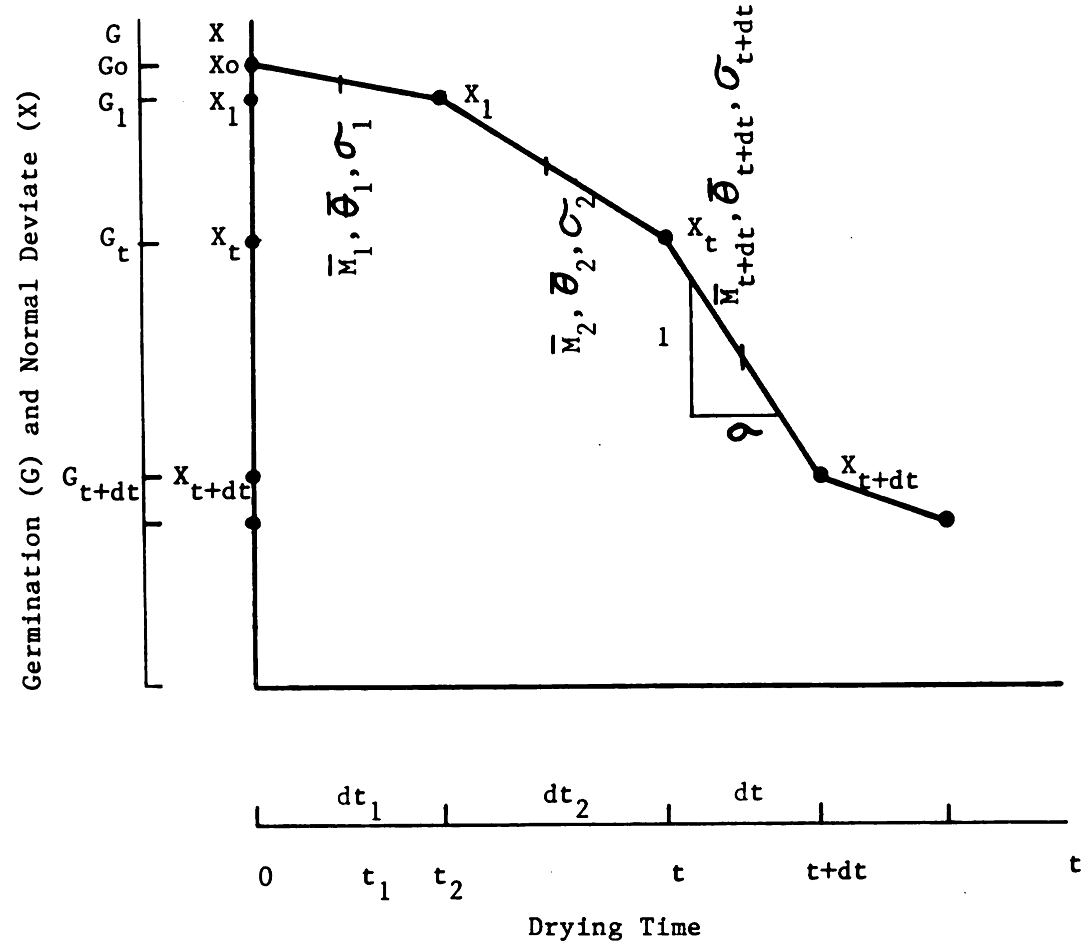


Figure 4.4 Schematic Graph Showing The Sequence of Steady-state Thin-layers Used to Simulate Germination Decrease During the Concurrentflow Drying of Seed.

model; dt_1 is also given by this model.

b) $\sigma_1 = \exp(C_1 - C_2 \ln\bar{M}_1 - C_3\bar{\theta}_1 - C_4\bar{\theta}_1^2)$

c) $X_1 = X_0 - (1/\sigma_1) \cdot dt$

d) $G_1 = \frac{1}{\sqrt{2\pi}} \int_{X_1}^{\infty} \exp(-\frac{1}{2} X^2)\, dX$

....

....

....

at $t = t + dt$:

a) $\bar{M}_{t+dt}$, $\bar{\theta}_{t+dt}$ are computed by the drying model; dt is also given.

b) $\sigma_{t+dt} = \exp(C_1 - C_2 \ln\bar{M}_{t+dt} - C_3\bar{\theta}_{t+dt} - C_4\bar{\theta}_{t+dt}^2)$

c) $X_{t+dt} = X_t - (1/\sigma_{t+dt}) \cdot dt$

d) $G_{t+dt} = \frac{1}{\sqrt{2\pi}} \int_{X_{t+dt}}^{\infty} \exp(-\frac{1}{2} X^2)\, dX$

....

....

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The calculation process is continued until the total drying time of the seed in the dryer is described.

An algorithm called GERMI has been written to perform the steps outlined above. GERMI is included within a general drying model as a subroutine.

4.4 The Subroutine GERMI

The prediction of the germination at any time during drying of corn seed is performed by an algorithm coded in FORTRAN called "SUBROUTINE GERMI" (see Appendix B). The subroutine computes the germination using equations (4.5), (4.6) and (4.7). The initial germination, the seed moisture content and temperature, and the exposure time are the initial and boundary conditions; and they are to be read along with seed viability constants.

A major portion of the germination simulator is devoted to the solution of the direct and inverse problems of equation (4.3). The computation of the total germination (decimal) given a normal standarized drying time (X) (the direct problem), or calculating X given G (the inverse problem), are performed by a table look-up procedure. Values of G and the corresponding X are obtained from an IMSL mathematical/statistical package (Anon, 1983). The algorithm is able to handle negative values of X and germination values of less than 50%.

5. TEST EQUIPMENT AND EXPERIMENTAL RESULTS

The experimental part of this reseach was devoted to the collection of data on the germination retention of corn seeds during thin-layer drying and concurrentflow drying.

5.1 Thin-layer Drying of Corn Seeds

Ear-corn seed of the variety Great Lakes 579 from the 1985 season, was provided by the Moore Seed Farm of Elfie, Michigan. The corn was harvested as ear corn with a corn picker at a grain moisture content between 25 to 40%. Samples for the tests were divided in groups of about 32, 27, 22, and 15%; the last two moisture contents were obtained by drying the ear corn at the seed farm in a bin-dryer at 40 C. The ear corn was kept for about eight weeks in a cold room at 4.4 +/- 0.5 C, and then shelled by hand. The shelled corn was cleaned using a screen with round holes of 6.35 mm (1/4 in) diameter; the kernels which passed through the screen were discarded. The shelled corn was kept in closed multi-layer paper bags commonly used for seed storage (25 kg capacity) in a 4.4 C cold room for at least one week before the drying tests were carried out.

5.1.1 The Thin-layer Dryer

A laboratory-scale thin-layer dryer was developed to perform the laboratory drying tests. A schematic of the experimental dryer is shown in Figure 5.1. The drying chamber has a 1.0 m x 1.0 m cross-sectional area, with a 0.30 m-deep plenum, and nine 0.23 m x 0.23 m drying cells.

The drying cells have a bottom composed of three fiber-glass mesh layers and one aluminum perforated sheet with round holes of 1.59 mm (open area of 23%) and a center to center spacing of 3.175 mm (1/8 in). The bottom layer of the cells is designed to provide a high pressure drop so that a uniform velocity airflow can be obtained in each drying cell.

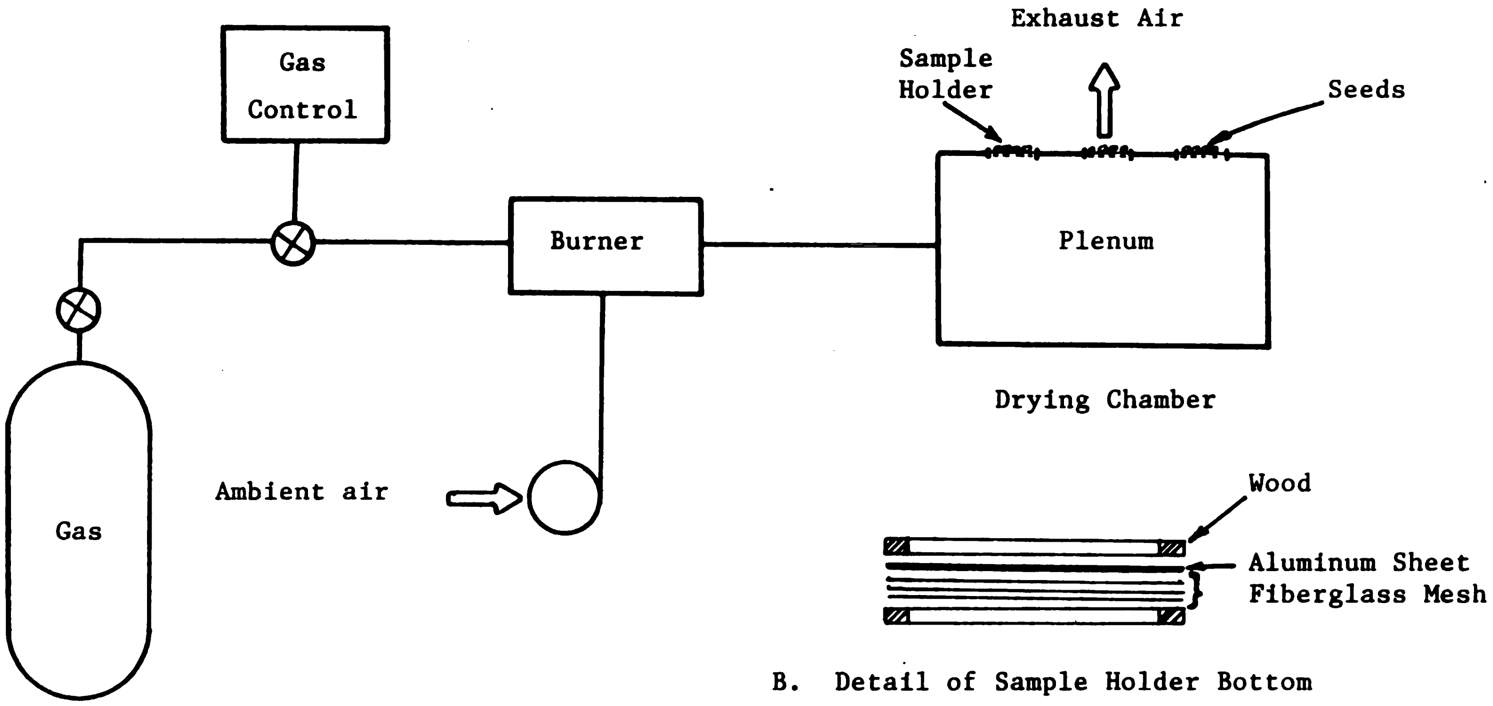
A square 178 mm x 178 mm sample holder with a wire screen bottom, adequately adjusted to the drying cell during drying, allows quick movement of the samples to and from the drying chamber at the beginning and at the end of each test.

An Aerovent centrifugal fan, PB8A model, 3/4 HP, provides an airflow of about 0.9 m/s; the air is heated by a direct-combustion propane burner; the drying air temperature is manually controlled to an accuracy of +/- 0.1 C with a gas valve.

5.1.2 The Thin-layer Tests

The drying of corn seeds was carried out from early October to late December, 1985.

The experiment was designed to test corn at four moisture contents (32, 27, 22, and 15%), seven air temperatures (40, 50, 55, 60, 65, 70, and 75 C), and different times of exposure so that gradual heat damage to germination could be observed. The final moisture contents were not the same for all the samples.



A. General Set-up

B. Detail of Sample Holder Bottom

Figure 5.1 Schematic of the Experimental Thin-layer Dryer for Germination Evaluation.

The seed samples were taken from the 4.4 C cold room and allowed to equilibrate in the bags to room temperature for three hours before the tests were performed. Next, 140-gram samples were evenly distributed one seed deep on the wire screens of each sample holder. At the end of the pre-selected drying time, the sample was rapidly taken from the drying chamber and another tray was placed in the drying cell to avoid disturbance of the airflow in the neighboring cells. The dried sample was placed in a polyethylene bag, the interior air was expelled, the bag was hermetically sealed, and the sample was stored in a 4.4 C room.

During the drying tests the dry and wet-bulb temperatures of the ambient air, and the temperature of the drying air were recorded every 30 seconds using copper-constantan thermocouples and an automatic Ramp/Processor Kaye Instruments temperature recorder, with an accuracy of 0.1 C. The velocity of the air passing through the seed layer was measured by a Weathertronics Model 2440 hot-point anemometer, with an accuracy of +/- 0.05 m/s.

Moisture content before and after the drying tests was determined by the whole kernel oven method (ASAE Standard S352.1) (ASAE, 1984).

Total germination was determined after a minimum storage period of one week at 4.4 C temperature in order to provide the low temperatures required for the cold test. The rolled paper-towel method (AOSA, 1981) was used in three sample lots of 100 seeds per germination test. The final viability count was made after two weeks at controlled laboratory conditions (AOSA, 1981). The germination tests were carried out by the author at the Seed Laboratory of the Michigan Crop Improvement Association, Lansing, Michigan.

5.1.3 Results of the Thin-layer Drying and Germination Retention Tests

The germination and moisture content data for each of the thin-layer drying cases at constant drying temperature are presented in Appendix A. Table 5.1 presents the experimental conditions under which each of the 23 thin-layer tests were performed and the number of experimental cases per test. The temperature ranged from 40 to 75 C; the initial moisture content from 15.18 to 32.43%, and the maximum exposure time from 6 minutes to 3 hours.

Figures 5.2 and 5.3 show the influence of five drying temperatures (40, 50, 65, 70, and 75 C) on the germination and moisture content of the corn at 32% initial moisture content with respect to time of exposure during thin-layer drying.

The survival curves at 65 and 70 C (Figure 5.2) are sigmoid-shaped; no change in viability ocurred at 50 C, and a rapid decline can be observed at 75 C.

Figure 5.3 shows moisture loss of the kernels at the five temperatures considered. During the 45 minute drying period, the moisture content decrease ranges from 2.8 points at 40 C to 10.92 points at 75 C.

Figures 5.2 and 5.3 are closely related with regard to viability retention, since increasing seed temperature at a given moisture content should detrimentally affect the germination. At high initial moisture (based on the usual practice of combine harvesting)

TABLE 5.1 Corn Thin-layer Germination Retention During Drying: Laboratory Tests Performed.

Test No	Drying Air Temp. (C)	Initial Viability (%)	Initial Moisture Content (%w.b.)	Maximum Exposure Time (min)	No of Cases Per Test
1	40	95.0	32.00	45	14
2	50	95.0	32.00	30	13
3(*)	65	95.0	32.00	30	19
4(*)	70	95.0	32.00	45	20
5	75	95.0	32.43	45	20
6	40	88.0	27.72	45	14
7	50	90.0	27.08	45	14
8	60	92.5	26.90	15	12
9	70	88.0	27.04	15	12
10	55	86.5	25.21	120	6
11	60	86.5	25.21	60	5
12(*)	65	86.5	25.21	30	6
13(*)	70	86.5	25.21	10	6
14	60	95.0	22.04	180	7
15(*)	65	95.0	21.80	90	10
16(*)	70	91.5	21.95	30	7
17	75	92.0	21.87	20	11
18(*)	75	91.5	21.08	6	7
19(*)	75	91.0	15.56	6	7
20(*)	70	92.5	15.54	60	13
21(*)	70	92.5	15.51	10	11
22	65	94.5	15.24	180	10
23(*)	75	91.5	15.18	6	7
		Total No. of cases :		251	

(*) Included in the analysis of model development (Table 6.1)

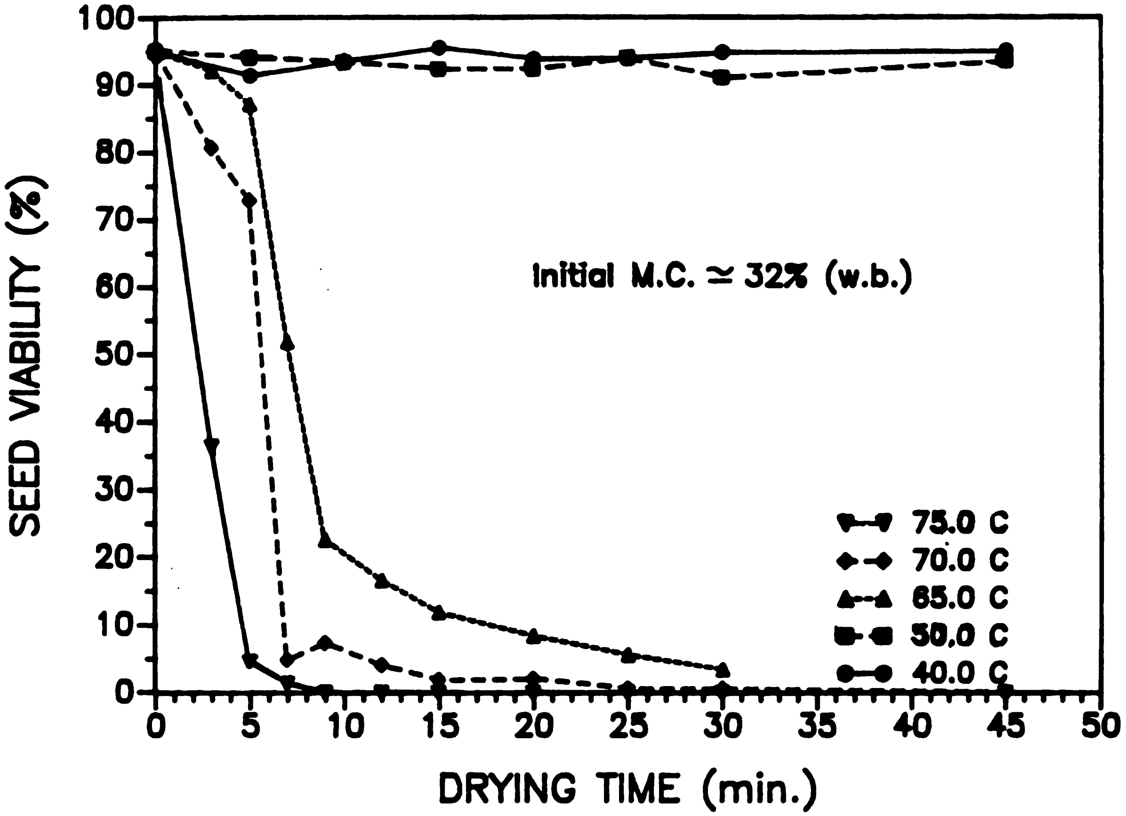


Figure 5.2 Influence of Drying Temperature on the Viability of Corn Seed at 32% (w.b.) Initial Moisture Content.

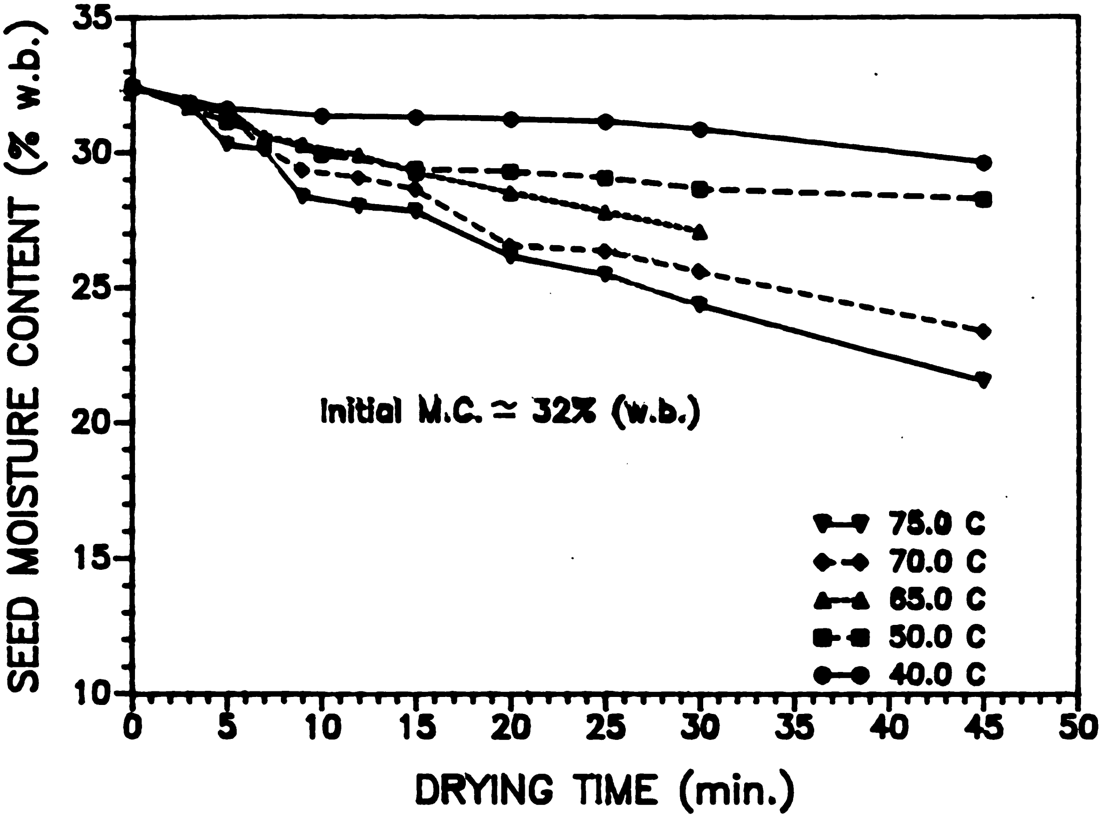


Figure 5.3 Influence of Drying Temperature on the Moisture Content of Corn Seed at 32% (w.b.) Initial Moisture Content.

here is a very narrow temperature range between complete preservation of the initial viability and total depletion. The 90% germination level is reached in less than one minute at 75 C, in about two minutes at 70 C and in less than 4 min for 65 C; at 40 C and 50 C 90% is not reached in 45 and 30 minutes, respectively. No temperature between 50 and 65 was considered; actually the span is too wide for this particular moisture content to allow any conclusions to be drawn about the intermediate temperature.

Figures 5.2 and 5.3 show that at 32% moisture content, the temperature of air is responsible for the germination decrease of the corn seeds and that this effect is not affected by the decreasing moisture during the drying.

Figures 5.4 and 5.5 show the survival curves and moisture content profiles at about 27% of initial moisture content. The influence of the initial viability on the germination retention is noted in Figure 5.4; at 40, 50, and 60 C the viability does not change (it is even increased) during the drying process. The 70 C survival curve declines sharply in less than 5 minutes and reaches a value of zero after 15 minutes of drying. The moisture content profiles during this drying test (Figure 5.5) follow the trend expected.

Figures 5.6 and 5.7 show the survival curves and moisture content profiles at 25.2% of initial moisture content. Figure 5.5 shows a viability increase during the initial periods of drying. This behavior was observed in a number of tests. This phenomenom has also been reported in the drying of barley (Ellis and Roberts, 1980b), wheat (Nellist, 1981) and corn (Sokhansanj, 1978; Ellis and Roberts, 1981), and is probably due to the breaking of dormancy of the seed by heating. The specific cause and conditions under which an increase in viability

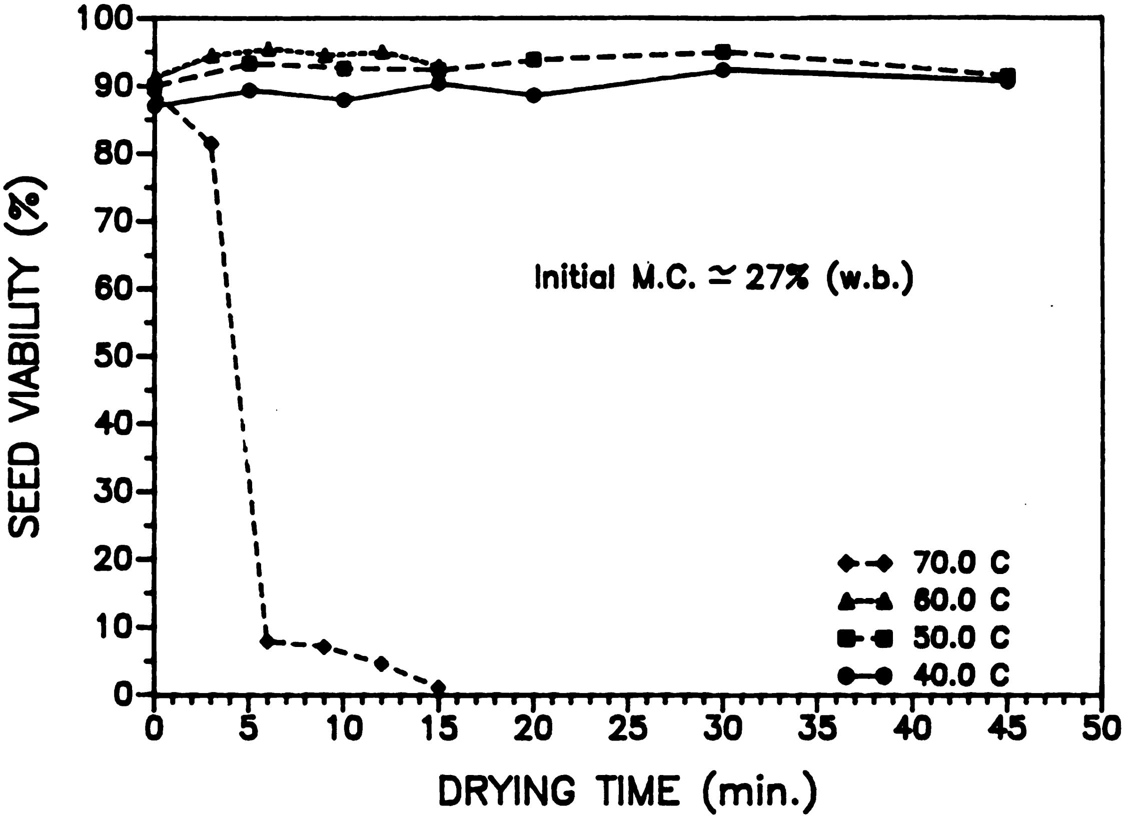


Figure 5.4 Influence of Drying Temperature on the Viability of Corn Seed at 27% (w.b.) Initial Moisture Content.

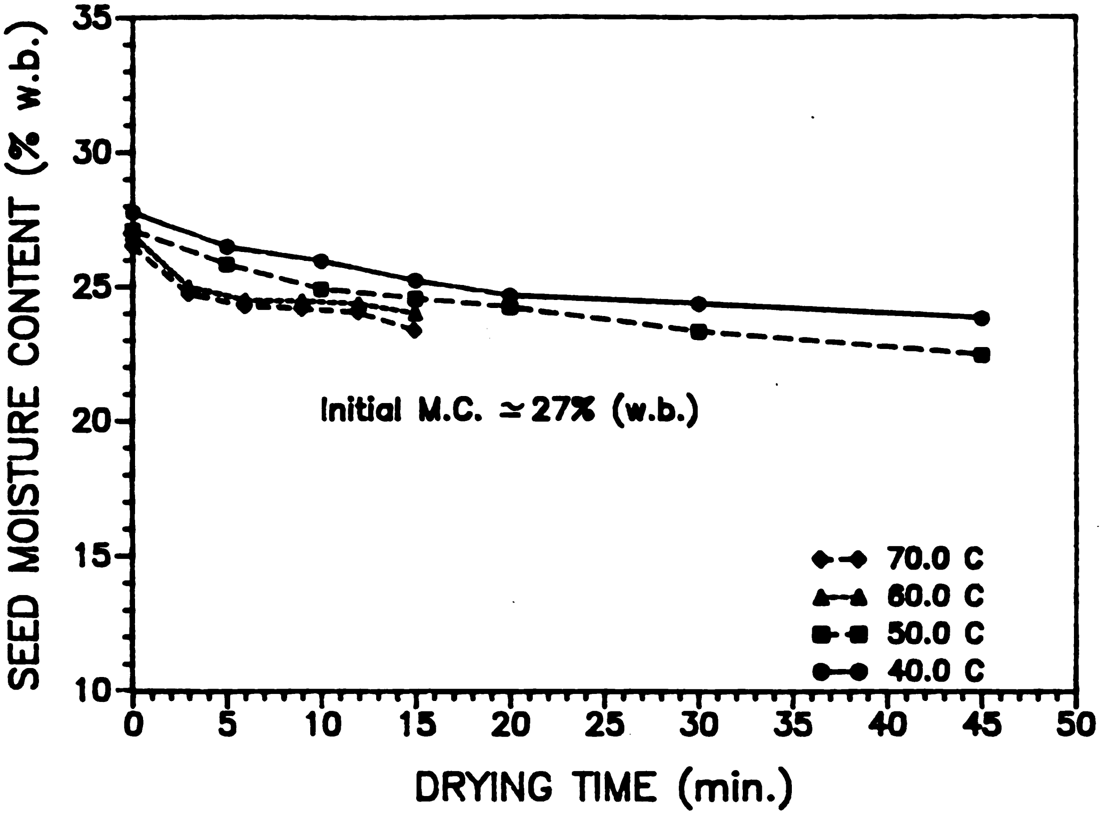


Figure 5.5 Influence of Drying Temperature on the Moisture Content of Corn Seed at 27% (w.b.) Initial Moisture Content.

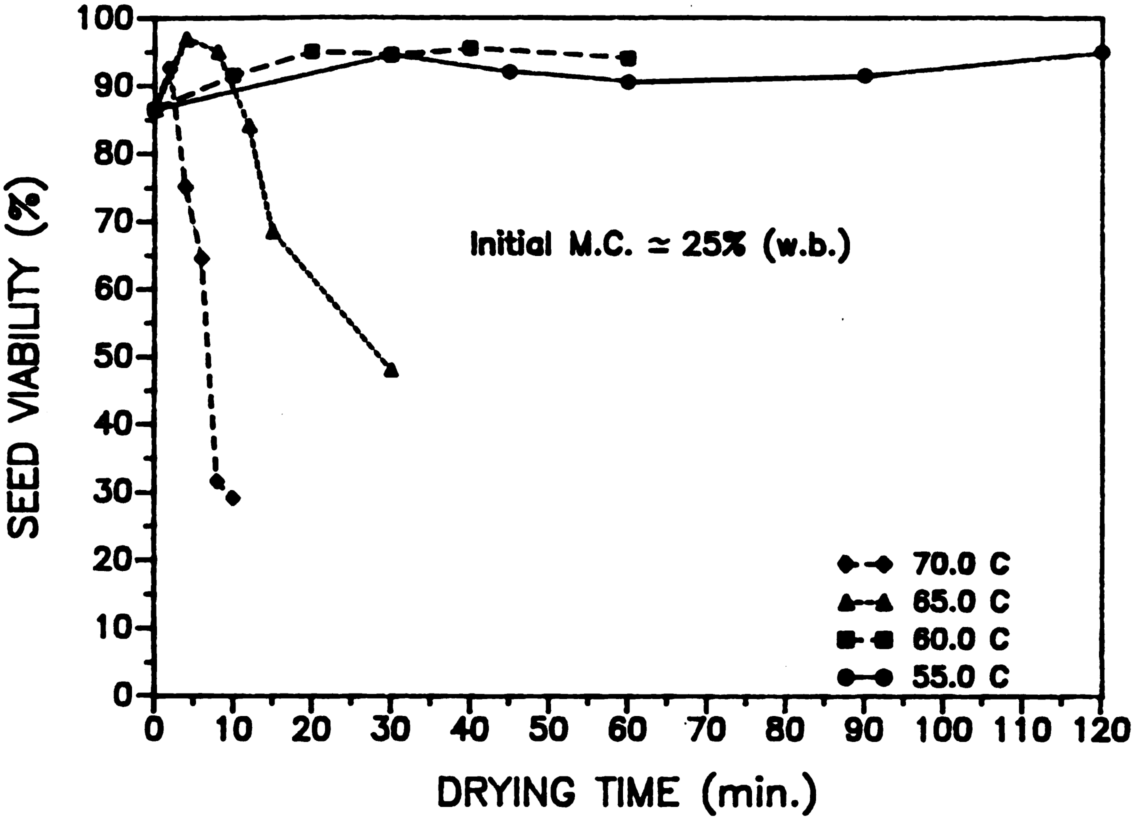


Figure 5.6 Influence of Drying Temperature on the Viability of Corn Seed at 25% (w.b.) Initial Moisture Content.

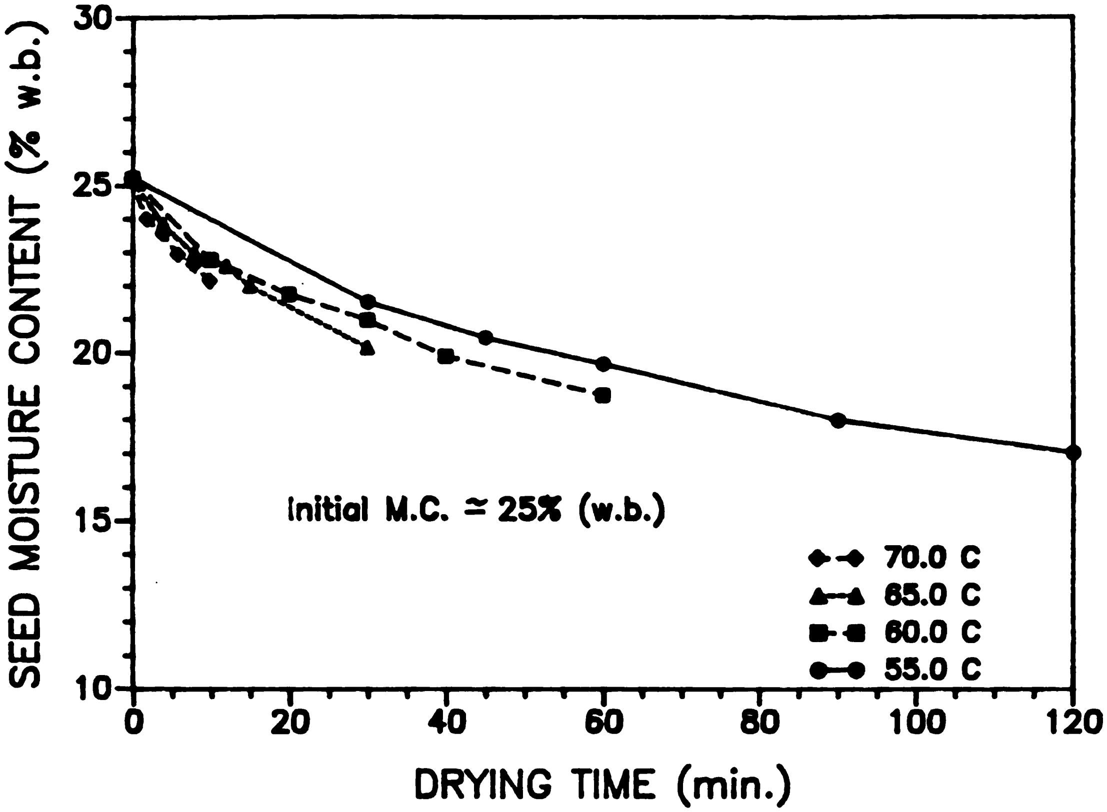


Figure 5.7 Influence of Drying Temperature on the Moisture Content of Corn Seed at 25% (w.b.) Initial Moisture Content.

occurs is not known, and thus modeling of this phenomenom is not possible.

Figure 5.6 also shows the influence of drying temperatures on the increase of viability. All survival curves at the four temperatures (55, 60, 65, and 70 C) have a maximum germination point which is reached in shorter times for the higher temperatures. It is also noted that the maximum germination peak corresponds to 65 C, an intermediate temperature between the extremes of 55 and 75 C.

Figures 5.8 and 5.9 show the survival curves and moisture content profiles at 21% of initial moiture content. Figure 5.8 shows that no change in viability occurs at 60 C during 60 minutes of thin-layer drying. At 65 C the viability still remains above 90% up to one hour of drying. There is a sharp decrease in viability at 75 C with complete death in 20 minutes. Moisture content decreases ranging from 3.78 to 8.54 percent points are observed (see Figure 5.9).

Figures 5.10 and 5.11 show the survival curves and moisture content profiles at 15% of initial moisture content. Air temperatures of 60 C or lower do not detrimentally affect the viability after 180 minutes of drying. At higher temperatures the increasing trend in viability loss is noted; at 75 C the loss reaches the maximum rate. Moisture losses ranging from 0.93 to 4.32% are shown in Figure 5.11; obvious increasing loss rates are observed at higher temperatures.

The influence of initial moisture content on the viability of corn seed during thin-layer drying at 65 C is presented in Figure 5.12. As expected, higher moisture contents cause more heat damage. These results are directly applicable to the analysis of in-bin drying of seeds, however, as it will be noted and explained in Chapter 7, concurrentflow drying causes lower viability losses at higher moisture

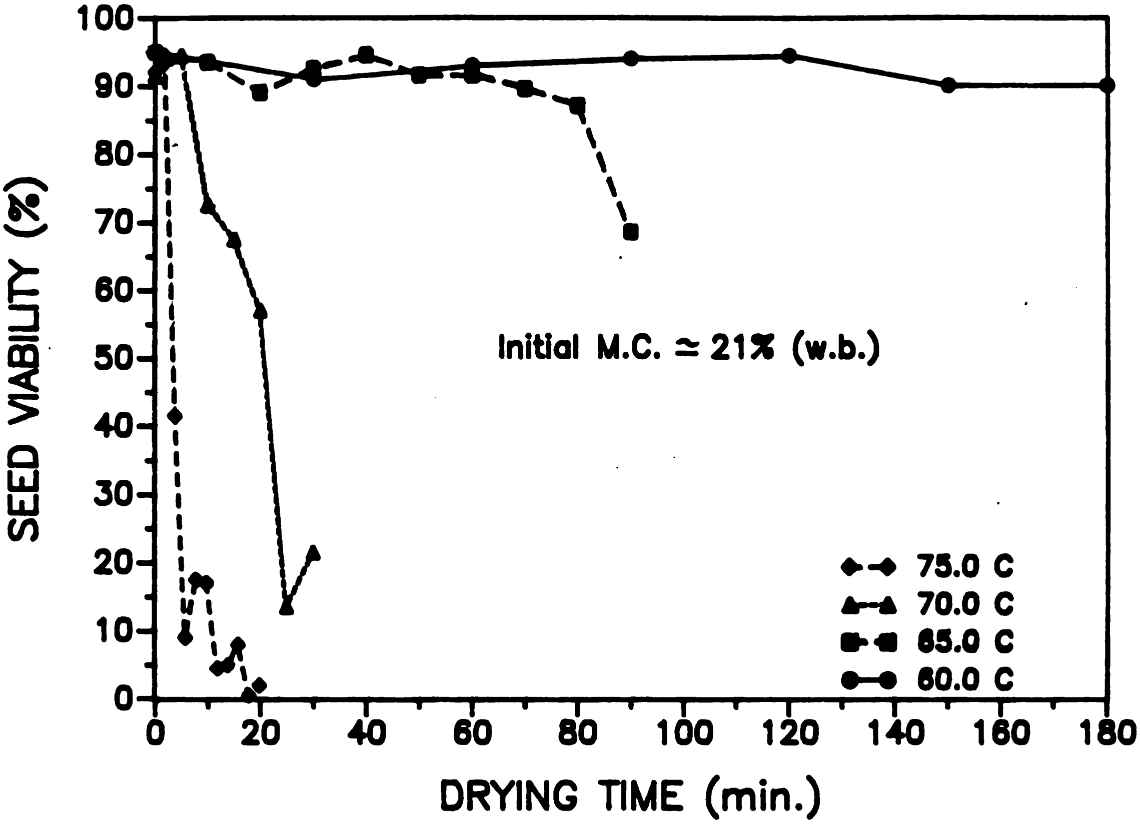


Figure 5.8 Influence of Drying Temperature on the Viability of Corn Seed at 21% (w.b.) Initial Moisture Content.

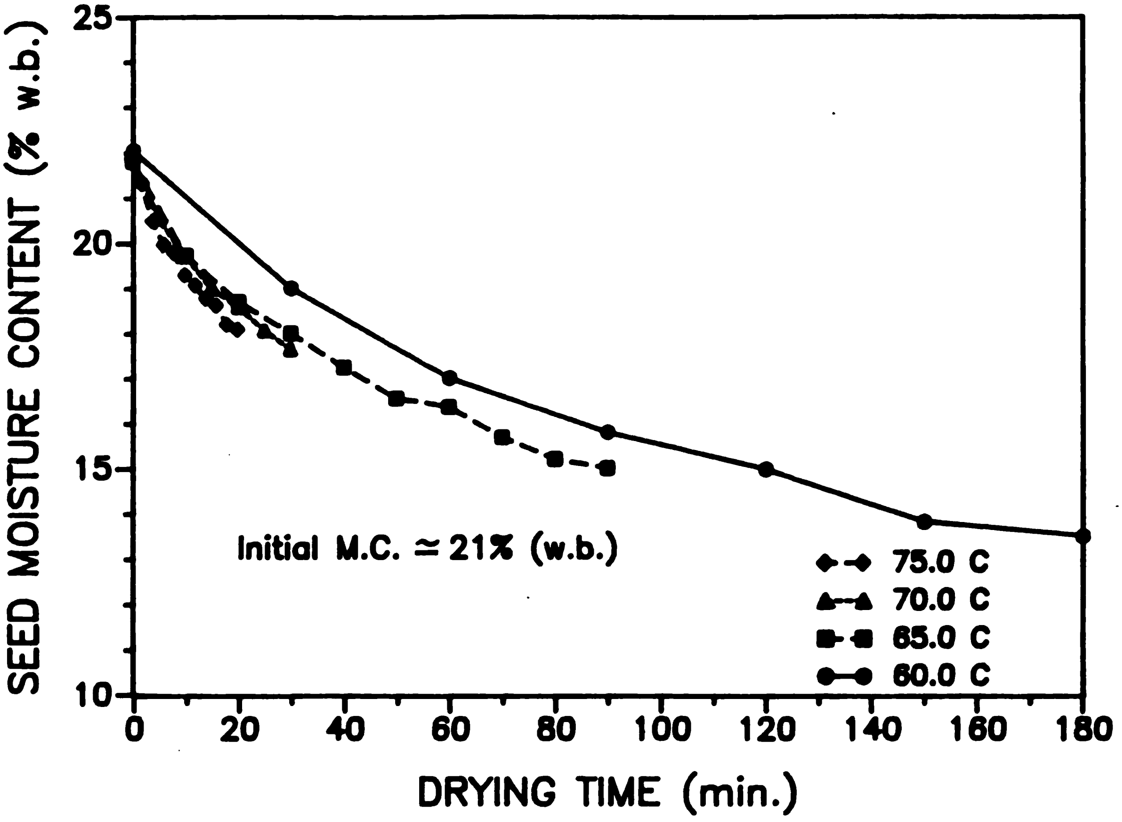


Figure 5.9 Influence of Drying Temperature on the Moisture Content of Corn Seed at 21% (w.b.) Initial Moisture Content.

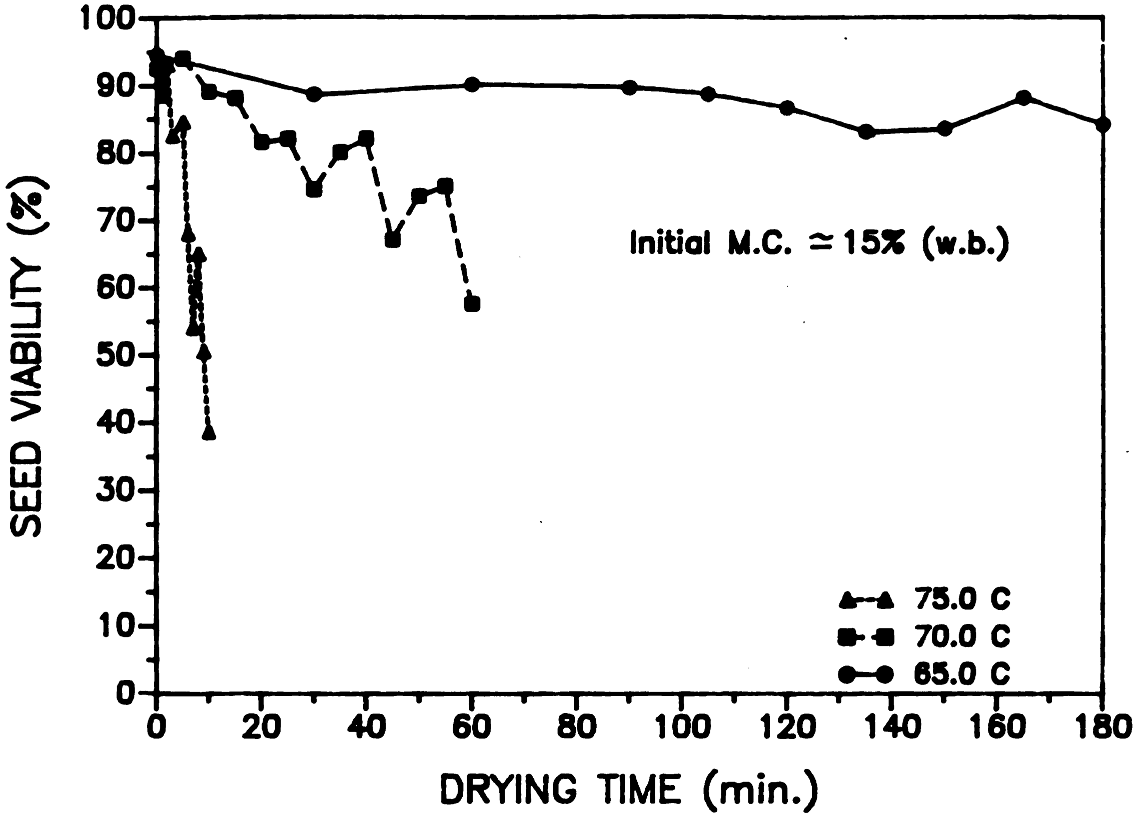


Figure 5.10 Influence of Drying Temperature on the Viability of Corn Seed at 15% (w.b.) Initial Moisture Content.

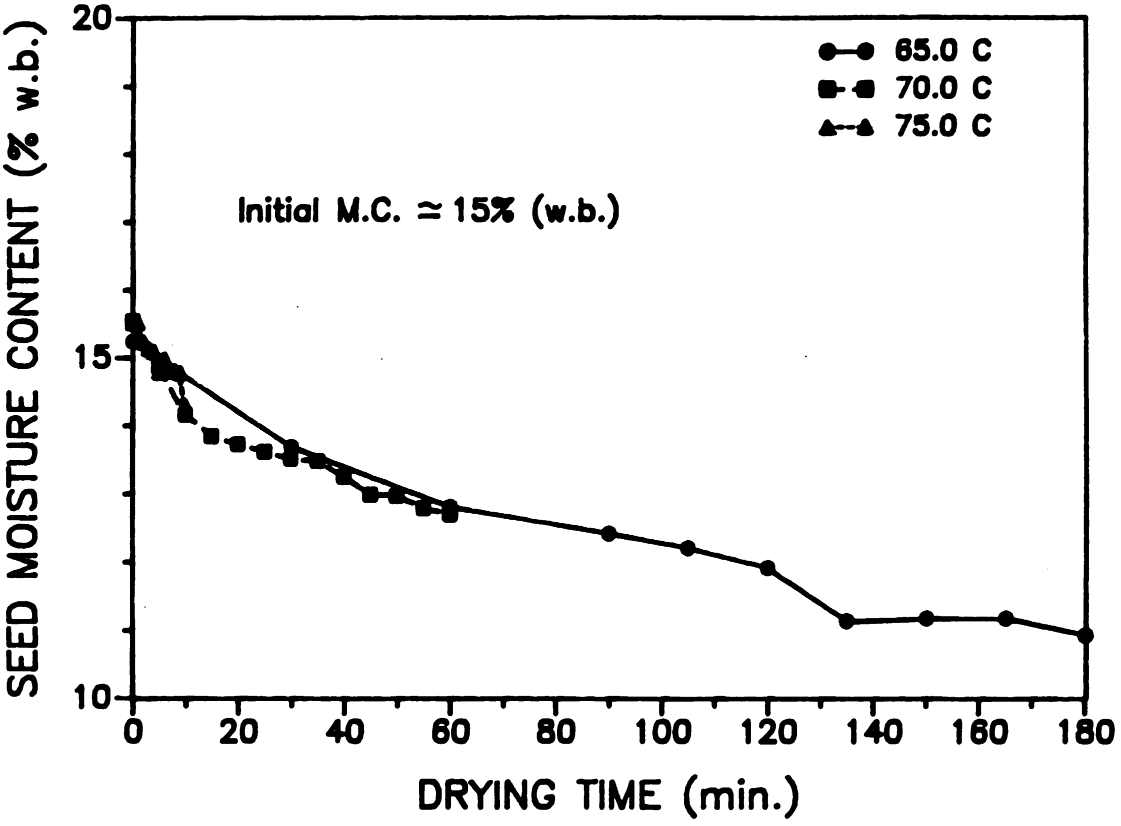


Figure 5.11 Influence of Drying Temperature on the Moisture Content of Corn Seed at 15% (w.b.) Initial Moisture Content.

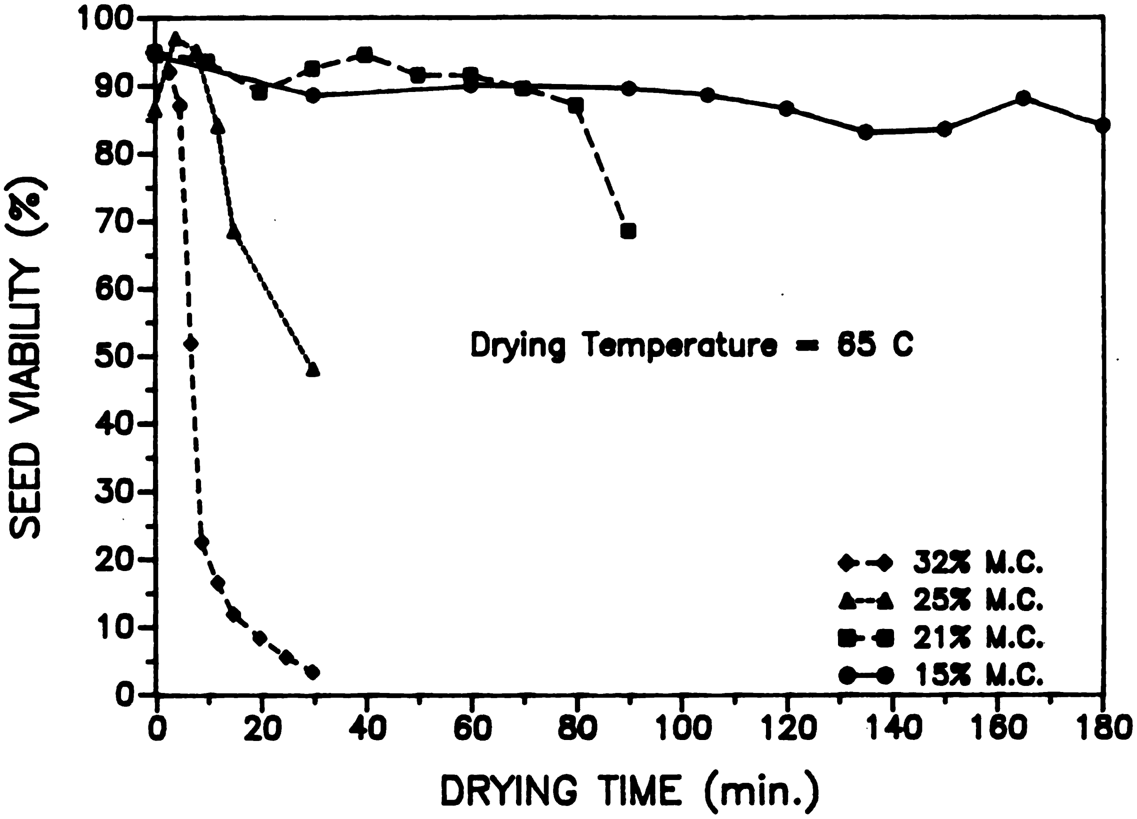


Figure 5.12 Influence of Initial Moisture Content on the Viability of Corn Seed During Thin-layer Drying at 65 C.

contents.

5.2 The Commercial Concurrentflow Dryer Tests

In order to validate the germination model at conditions found in commercial concurrentflow dryers, four drying tests were conducted at the Petersen Farms, Inc., Grand Island, Nebraska, from the 8th to the 10th of October, 1984.

A two-stage 2.4 m x 2.4 m model concurrentflow dryer manufactured by Blount, Inc., Montgomery, Alabama, was experimentally tested with NC+ male corn seed, The length of each drying section was 0.76 m, with 5.3 m long tempering bed and 1.95 m of cooling section length.

The grain velocity was set at 2 meters per hour. The ambient temperature ranged between 5 to 19 C with an average of 18.1 C. The initial average grain temperature was 18.5 C.

Four sets of inlet drying air temperatures were tested: (1) 82.2 and 71.1 C, (2) 93.3 and 71.1 C, (3) 115.6 and 71.1 C, and (4) 126.7 and 71.1 C. Thus, only the influence of the inlet drying air at the first stage was investigated during the validation trials.

Table 5.2 shows the experimental results. Even though the initial viability and moisture content were not the same for all the four tests, the trend for higher viability decrease with an increase in inlet drying air temperature is observed, with the exception of one case (126.7 C). Viability decreases of 9.0, 9.9, 16.7, and 11.5% at 82.2, 93.3, 115.6 and 126.7 C of inlet air at the first stage, respectively, were observed. The relatively low percentage of decrease at 126.7 C may be explained by the fact that seeds at higher initial viability are more resistant to heat damage (see Chapter 6). The moisture content losses during drying follow the trend expected.

Table 5.2 Germination Decrease During The Two-stage Commercial Concurrentflow Drying of Corn Seed.

Test No	Drying Air Temp. At Stage: 1	2	Seed Moisture Content Inlet	Outlet	Seed Germination Inlet	Outlet
	C	C	% w.b.	% w.b.	%	%
1	82.2	71.1	20.10	17.63	54.5	45.5
2	93.3	71.1	21.31	16.45	48.9	39.0
3	115.6	71.1	21.63	14.60	47.2	30.5
4	126.7	71.1	21.43	13.94	83.5	72.0

Table 5.3 shows the experimental and predicted results. The NDD germination model attached to the concurrentflow dryer predicts germination losses of 0.39, 0.72, 6.94 and 21.78% at 82.2, 93.3, 115.6 and 126.5 C (second stage 71.1 C), respectively; the corresponding experimental values are 9.0, 9.9, 16.7 and 11.5%. Thus, the germination model under-predicts the germination loss at the lower drying temperatures and over-predicts it at 126.7 C. The predicted outlet moisture content at 93.3 C shows excellent agreement with the actual value, but differences ranging between 1.27 and 1.65% moisture content are noted at the other temperatures.

Table 5.3 Predicted and Simulated Germination and Moisture Content Losses During Commercial Two-stage Concurrentflow Drying of Corn Seeds.

Test(*) No	Moisture Content (% w.b.)			Total Germination (%)		
	Inlet	Outlet		Inlet	Outlet	
		Experim.	Predic.		Experim.	Predic.
1	20.10	17.63	15.98	54.5	45.5	54.1
2	21.31	16.45	16.46	48.9	39.0	48.2
3	21.63	14.60	15.87	47.2	30.5	40.3
4	21.43	13.94	15.31	83.5	72.0	61.7

(*) See Table 5.2.

The germination model shows the correct trend. Lack of closer agreement with the experimental results can be due to the following causes:

1) the influence of the different types of corn hybrids used in the thin-layer and in the concurrentflow tests;

2) the inaccuracy of the drying model to predict the grain moisture content and temperature during the drying process.

3) the fail of the commercial concurrent drying process to accurately simulate the process considered by the drying model; changes in inlet moisture content and germination, sampling errors and other factors may have influenced the results of the experiments.

6. MODELING GERMINATION RETENTION DURING THIN-LAYER DRYING OF CORN SEEDS

Basic assumptions considered in modeling thin-layer drying of corn seeds are: (1) the validity of the normal distribution of deaths (described by equations (4.5) and (4.6)) and (2) the general application of equation (4.7) to any seed under storage at constant conditions.

Equation (4.7) can be expressed as:

$$\sigma = \frac{1}{M^{C_2}} \exp \left(C_1 - C_3\bar{\theta} - C_4\bar{\theta}^2\right) \tag{6.1}$$

where: C_1, C_2, C_3, and C_4 are the parameters to be determined. C_2 is a parameter which represents the influence of the grain moisture content, and C_3 and C_4 account for the influence of seed temperature on the survival curve behavior.

The model given by equation (6.1) and its validity for any seed was proposed by Ellis and Roberts (1980a). They indicated that the inclusion of the quadratic term is to obtain a better fit to the data and does not have theoretical significance. Moreover, Dickie et al. (1985), for lupinus seed, and Dickie and Bowyer (1985), for apple seed, have reported very small negative values for C_4; by dropping the C_4 term in equation (6.1), a similar residual sum of squares and multiple correlation coefficient was obtained, when linear multivariable regression was used. Since the regression technique recommends the selection of the model which provides the lowest residual sum of squares and to avoid over-parameterization (Draper and Smith, 1960), Dickie et al. were justified to omit the C_4 term in equation (6.1). Further simplification of the model is not possible (e.g. eliminating the C_2 parameter would neglect the influence of the moisture content); the use of moisture content instead of its logarithm has been discouraged by Ellis et al (1986). In this study equation (6.1) will be tested with and without the C_4 term.

Equation (4.6) can be fitted to the thin-layer experimental data using a non-linear multiple variable regression procedure (germination as the dependent variable and grain temperature, moisture content and time of exposure as the independent variables). The viability constants (C_1 to C_4 or C_1 to C_3) can be determined in the process.

The SPSS Subprogram NONLINEAR (Anon, 1982), a least-squares multiple variable non-linear parameter estimation procedure containing a Gauss's minimization technique, and available in the SPSS statistical package (Nie and Hull, 1981) was applied. Algorithm GERMI (see section 4.4) was modified to be able to accept the individual values of the seed moisture content and temperature, the cumulative drying time, and the viability constants in order to calculate the germination.

The SPSS non-linear multiple variable algorithm estimates the model parameters and together with the experimental grain moisture content and temperature and exposure time provides to GERMI the needed information to compute the germination; the difference between the predicted and the experimental germination values determines the need to calculate a new set of parameters. The iterative process is continued until a limiting condition is met.

Since a dynamic procedure is used to determine the parameters by regression, tests showing a clear interaction of all the variables under study are preferred; the tests with no change or with sudden depletion of germination with time are not considered in the analysis but they are still represented by the same equation that fits the tests selected. All experimental data different than 0% or 100% retention in time (104 points) are contained in a single data file. Thus, of the 251 cases listed in Table 5.1 41% are used in the analysis and they are assumed to represent the total of experimental data.

The parameters of the normally distributed deaths model are estimated based on the thin-layer drying tests presented in Table 6.1. The order of the tests is in increasing drying temperature and in decreasing initial moisture content.

Table 6.1 Corn Thin-layer Drying Tests Selected to Estimate Parameters of the Germination Model

Test No (**)	Drying Air Temp. (C)	Initial Moisture Content (% w.b.)	Maximum Exposure Time (min)	No of Case Per Test
3(*)	65	32.00	30	19
12(*)	65	25.21	30	16
15(*)	65	21.80	90	10
4	70	27.04	15	11
13	70	25.21	10	6
16	70	21.95	30	7
20	70	15.54	60	13
18(*)	75	21.08	6	7
19	75	15.56	6	7
21(*)	75	15.51	10	11
23(*)	75	15.18	6	7
			Total cases:	104

(*) Test presented as Figure in the text.
(**) Refer to table 5.1

Theoretically, it should be possible to use the initial viability of each of the tests in the regression analysis. However, because of a limitation in the input/output capability of the non-linear regression algorithm, a single initial viability value had to be selected in the analysis. Different initial viabilities were considered and the one which provided the smallest sum of the squares of the residuals was selected. An initial viability of 95% (X = 1.65) provided the smallest value; this value coincides with the highest experimental value.

Equation (6.1) was tested with three viability constants with the 3P-NDD model and four viability constants with the 4P-NDD model. Results from the non-linear regression analysis provide the parameter values and the goodness-of-fit (the sum of squares of residuals). Table 6.2 contains the results. The sum of the squares of the residuals of the order of 10 to the fourth power (Table 6.2) are due to germination values expressed as percentages and to the high root mean square residual (11.76 and 13.77% for 3P-NDD and 4P-NDD models, respectively). Since germination values can range between 0 and 100%, the relatively high root mean square residuals are due to the inherently variable nature of the biological data. It is noted that the total raw experimental data was used (101 and 100 degrees of freedom for the 3P-NDD and 4P-NDD models, respectively) to fit the model, without any smoothing of the data.

The graph of residuals provided by the SPSS program shows an unbiased pattern with less than 10% of predicted values lying off the second standard deviation of residuals band, for both models. This fact also contributes to justify the results and conclusions from the non linear regression analysis procedure.

Table 6.2 Normal Distribution of Deaths Model: Values for the Three and Four Parameters Cases.

	Three-Parameter	Four-Parameter
C_1	4.198	4.769
C_2	33.20	132.27
C_3	0.267	3.051
C_4	---	- 0.0199
Sum of squares of residuals	1.397×10^4	1.895×10^4
Root mean square residual (%)	11.76	13.77

Figures 6.1 to 6.8 show the experimental and predicted viability for some of the thin-layer drying tests listed in Table 5.1.

From the eight curves in Figures 6.1 - 6.8, six were selected to estimate the parameters of the NDD model. In order to test the applicability of the model to all temperatures and moisture contents considered in the experimental plan (Table 5.1), two additional tests are shown:(1) 50 C and 32.43% moisture content, and (2) 65 C and 15.56% moisture content. The analysis that follows, complements the discussion presented in Chapter 5.

The information in Table 6.2 and Figures 6.1 to 6.8 leads to the following conclusions:

1) The three-parameter normally distributed deaths (3P-NDD) model and the four-parameter normally distributed deaths (4P-NDD) model both predict adequately the germination decrease during the thin-layer drying of corn. The fit is better for the 3P-NDD model than for the 4P-NDD model. Both models slightly over-predict the heat damage to corn seed.

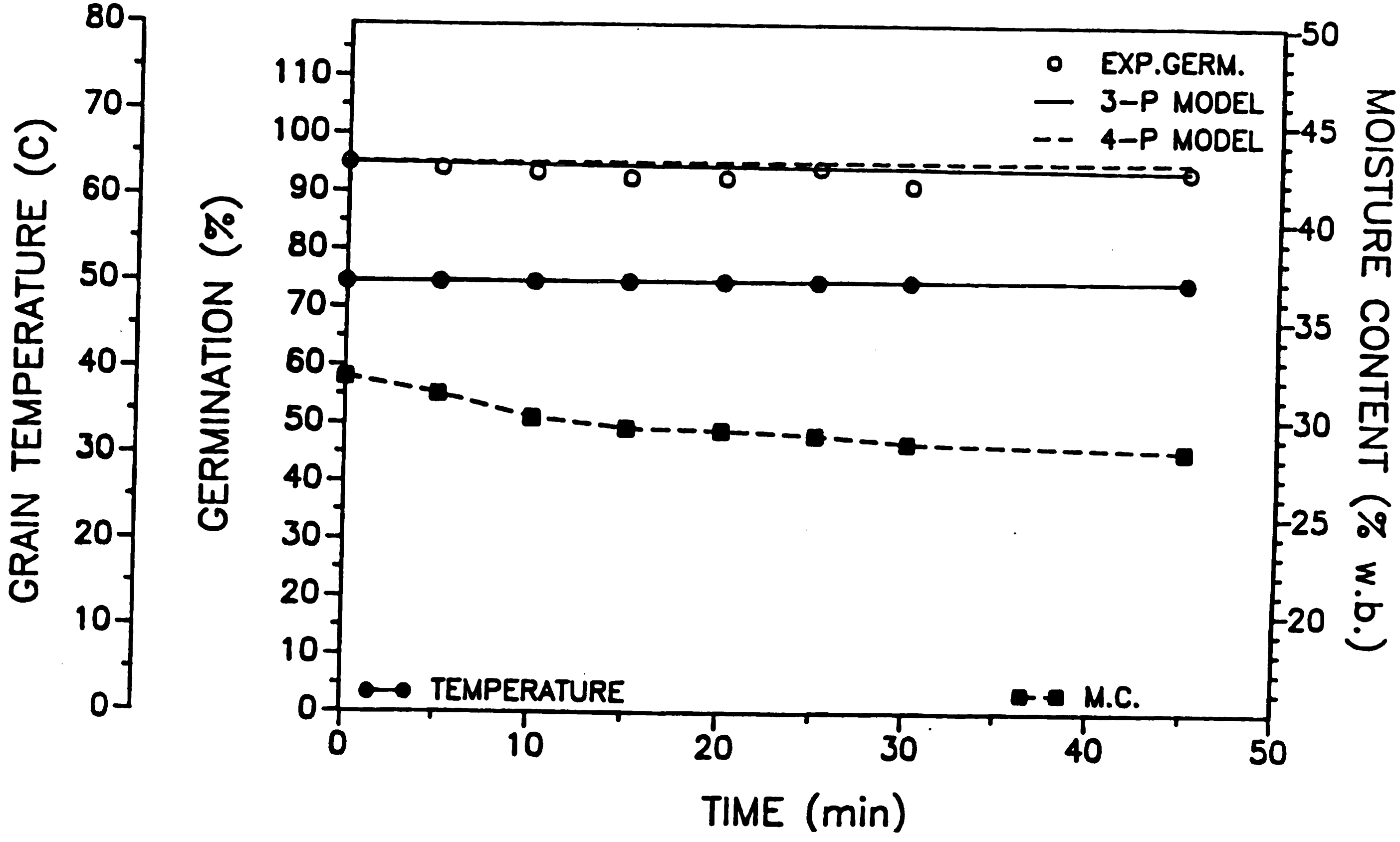


Figure 6.1 Experimental and Predicted Germination Decrease During Thin-layer Drying of Corn Seeds at Constant Temperature (50 C) and 32.43% (w.b.) Initial Moisture Content.

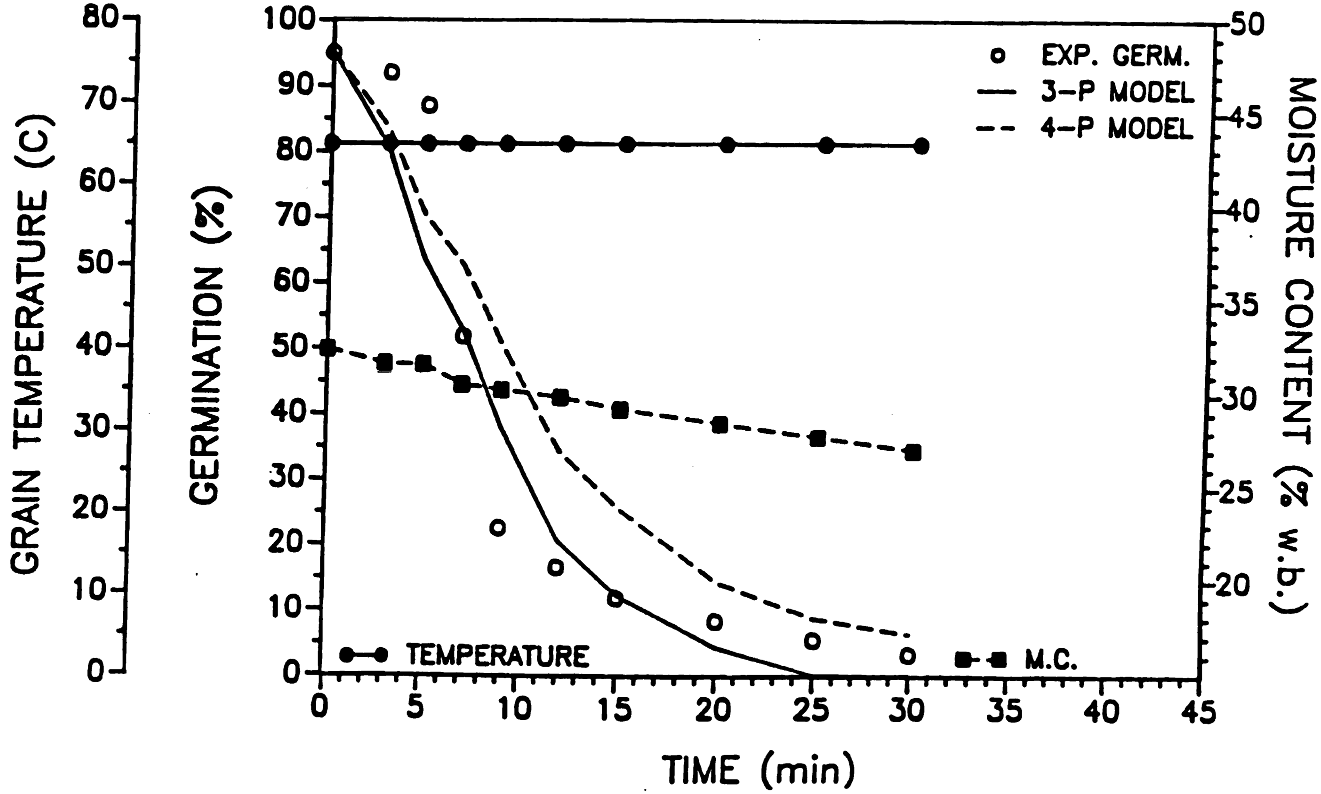


Figure 6.2 Experimental and Predicted Germination Decrease During Thin-layer Drying of Corn Seeds at Constant Temperature (65 C) and 32.43% (w.b.) Initial Moisture Content.

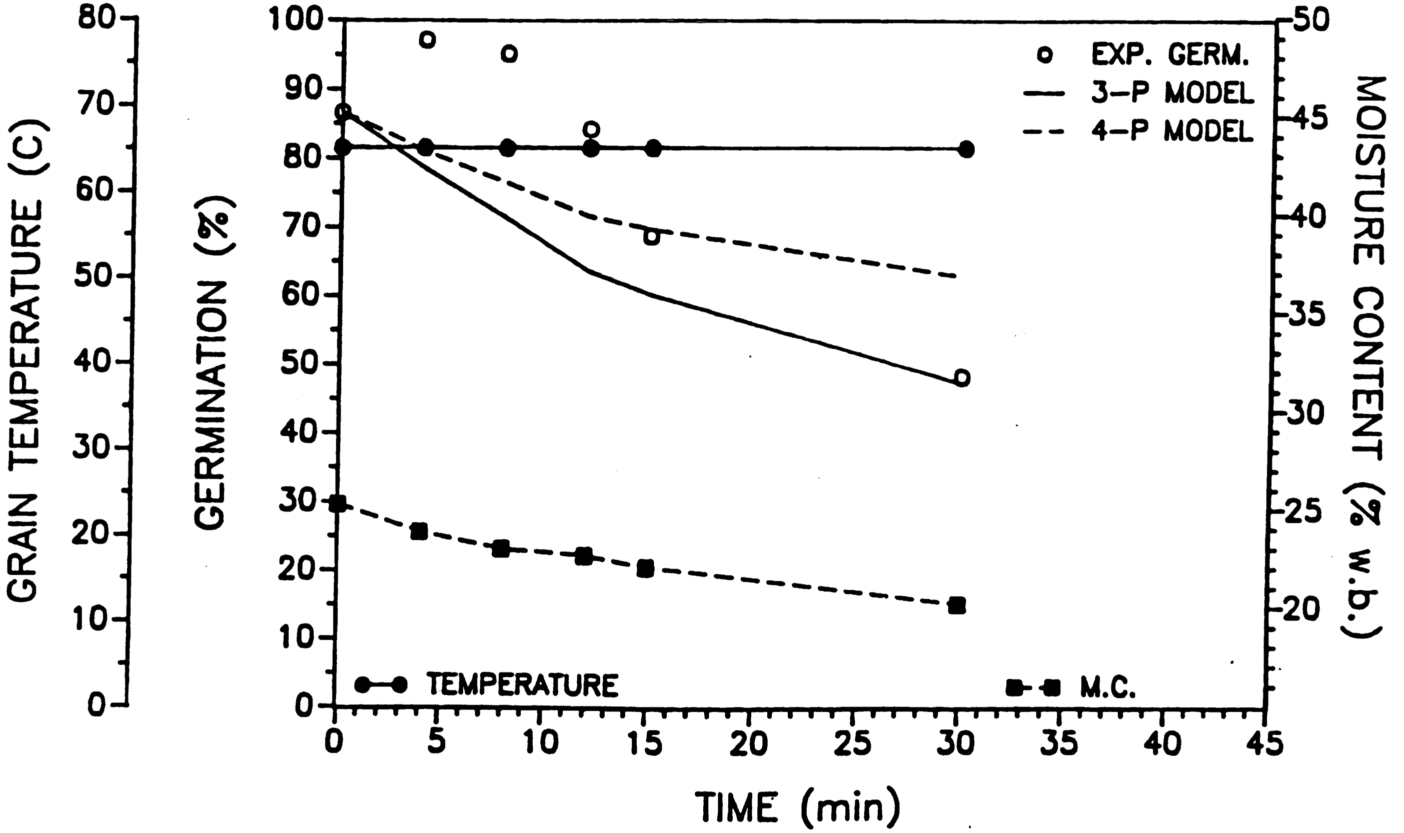


Figure 6.3 Experimental and Predicted Germination Decrease During Thin-layer Drying of Corn Seeds at Constant Temperature (65 C) and 27.35% (w.b.) Initial Moisture Content.

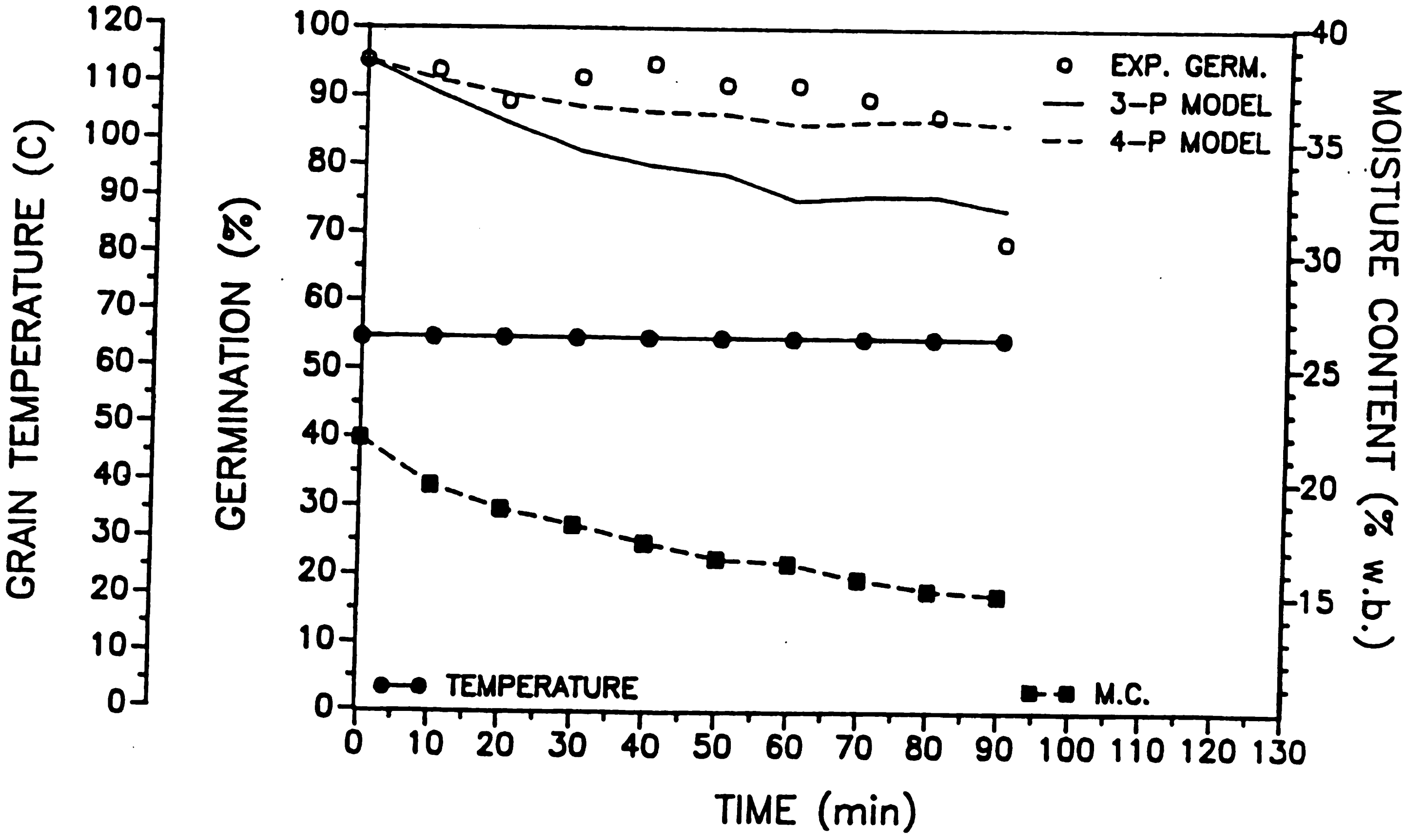


Figure 6.4 Experimental and Predicted Germination Decrease During Thin-layer Drying of Corn Seeds at Constant Temperature (65 C) and 20.32% (w.b.) Initial Moisture Content.

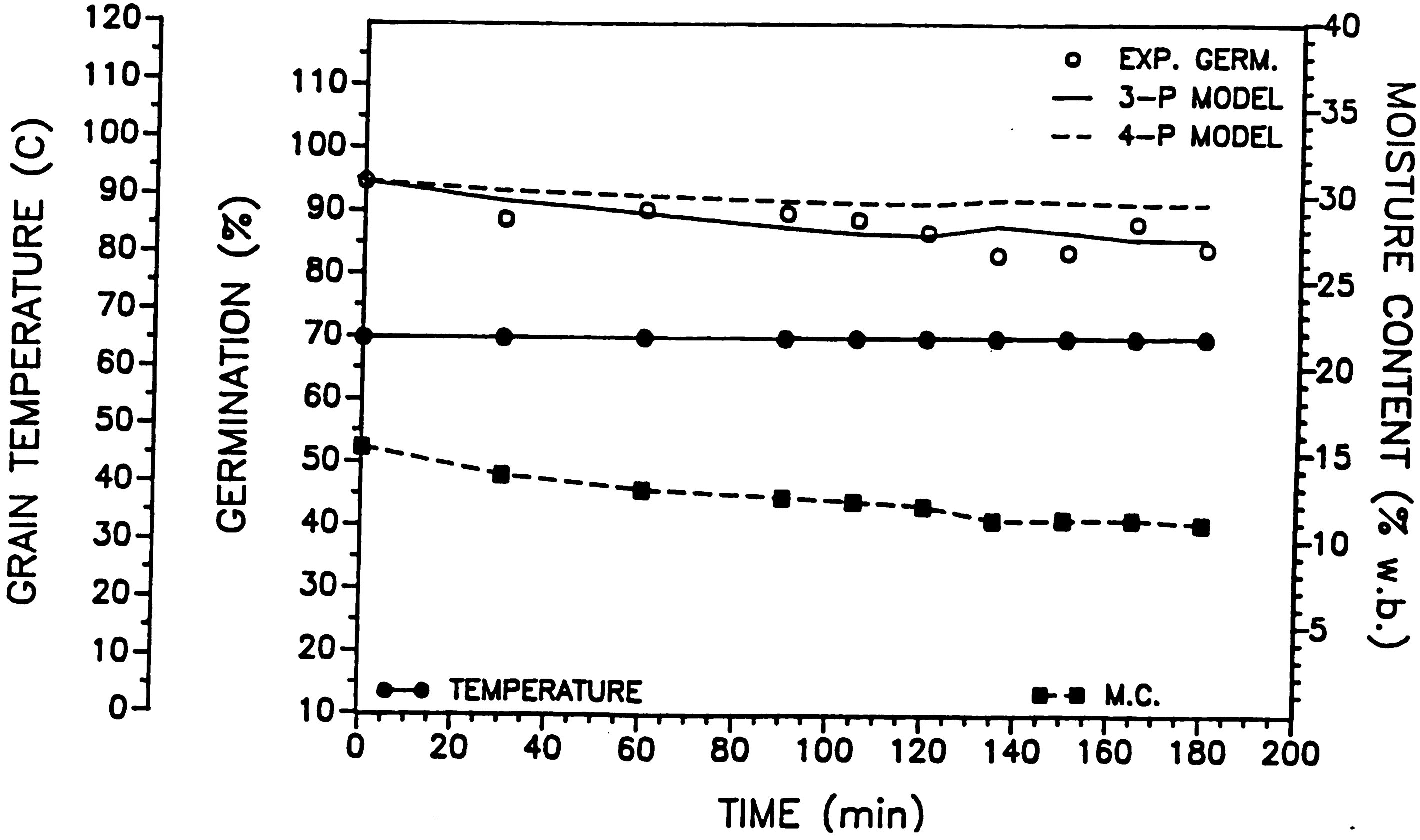


Figure 6.5 Experimental and Predicted Germination Decrease During Thin-layer Drying of Corn Seeds at Constant Temperature (65 C) and 15.56% (w.b.) Initial Moisture Content.

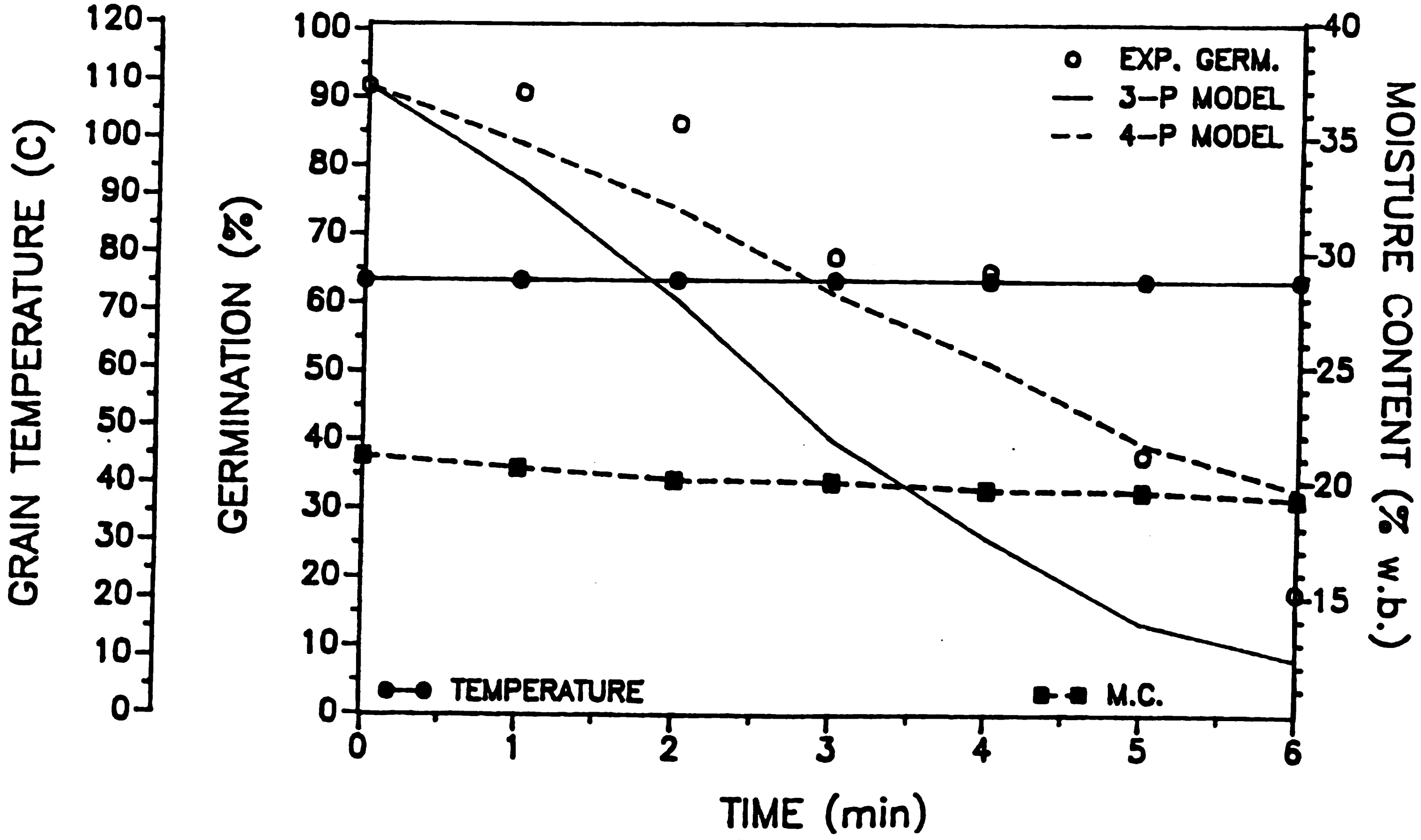


Figure 6.6 Experimental and Predicted Germination Decrease During Thin-layer Drying of Corn Seeds at Constant Temperature (65 C) and 23.76% (w.b.) Initial Moisture Content.

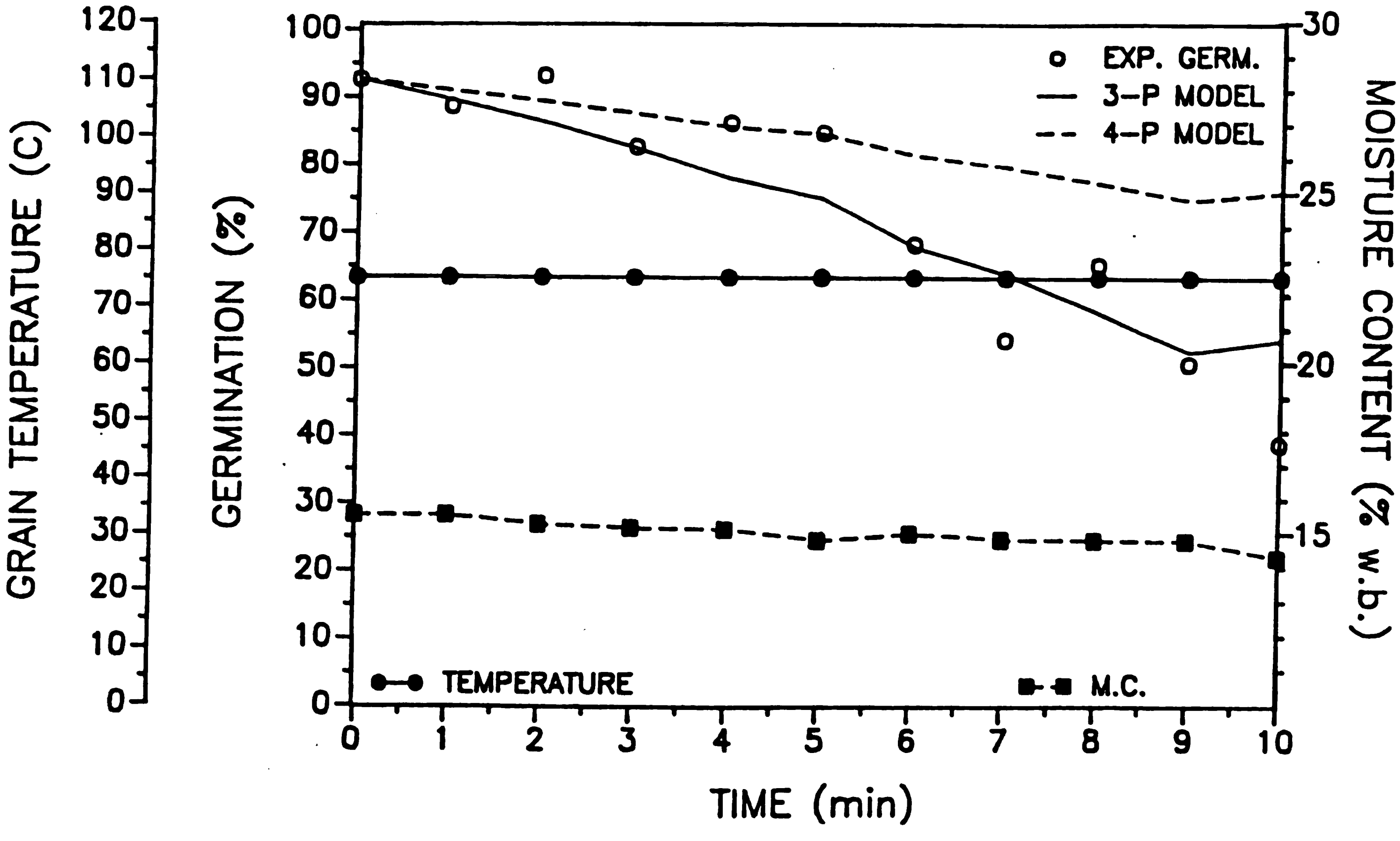


Figure 6.7 Experimental and Predicted Germination Decrease During Thin-layer Drying of Corn Seeds at Constant Temperature (75 C) and 15.56% (w.b.) Initial Moisture Content.

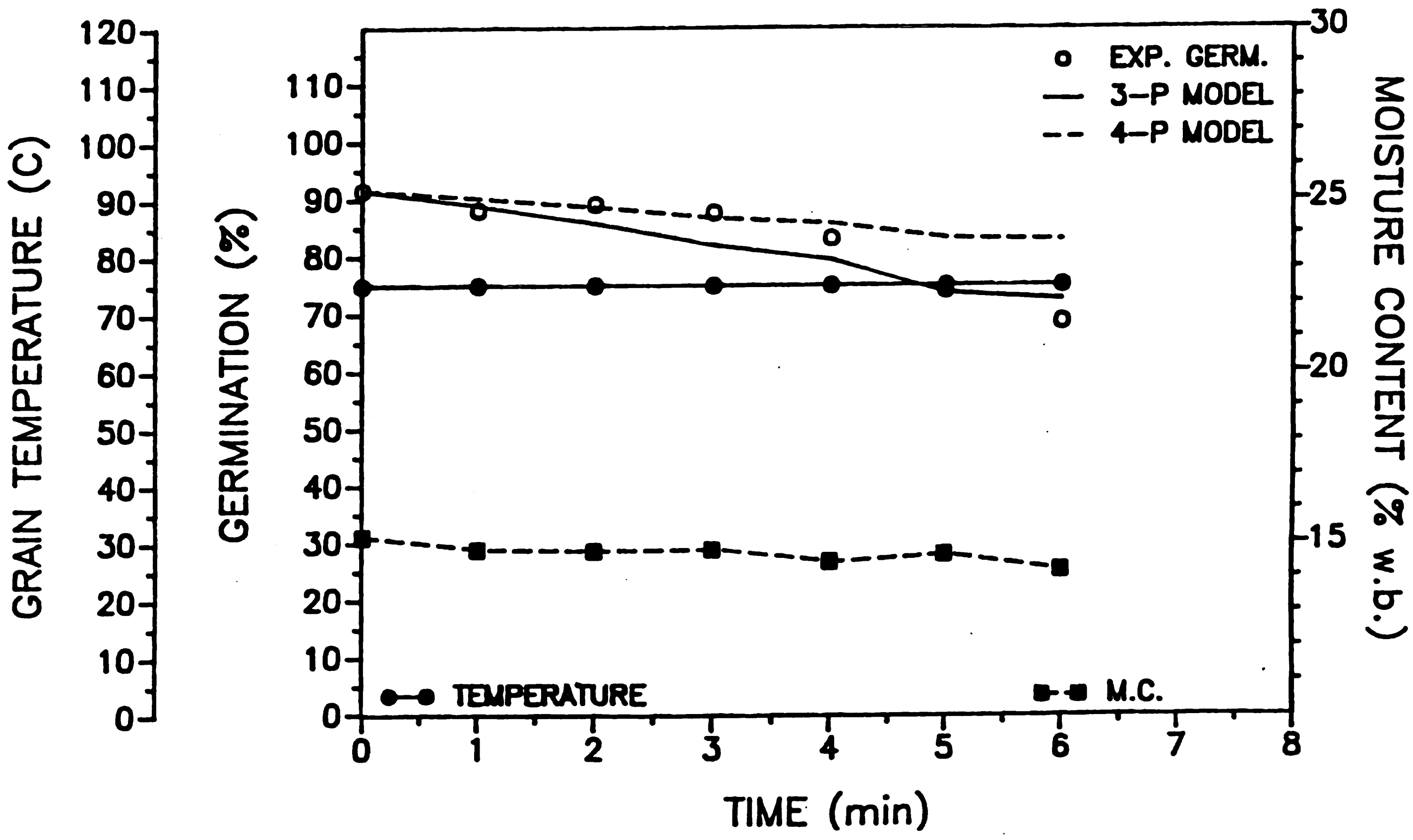


Figure 6.8 Experimental and Predicted Germination Decrease During Thin-layer Drying of Corn Seeds at Constant Temperature (75 C) and 15.51% (w.b.) Initial Moisture Content.

2) The best prediction is obtained for drying tests in which relatively minor heat damage occurs (within the 95 to 75% viability range), as Figures 6.1, 6.5 and 6.8 indicate. Figure 6.7 shows acceptable agreement between predicted and actual values of germination, even though the damage is important; Figure 6.2 shows an acceptable trend but the models over-estimate the heat damage at the begining and at the end of the drying process.

3) At high temperature and high initial moisture content (for example 75 C and 23.8%), the 3P-NDD model over-predicts the germination loss (Figure 6.6).

4) Increases in germination due to a break of dormancy by heat treatment during drying (Figures 6.3 and 6.4) are not predicted by the NDD models.

Based on the acceptable agreement obtained between the predicted and experimental values, and on the fact that low risks are incurred in grain drying design when overestimation of heat damage (as opposed to underestimation) to quality is considered, the three-parameter normal distribution of deaths model is selected for further analysis of tempering/storage and drying research. The 3P-NDD model is hereafter simply called the NDD model.

The NDD model contains three parameters in contrast with the Ellis and Roberts's model which has four parameters. An examination of equation (6.1) simplified to three parameters indicates that the spread of deaths with time of exposure is always positive for any temperature or any moisture content and therefore can be applied to any conditions normally found in storage and drying of corn seeds. Under a static standard regression procedure, the viability constants found for seed corn are valid only within the limits of temperature range between 65 and 75 C, a moisture range between 15.18 to 32%, and a time of exposure less than three hours; however, since a dynamic procedure was used, the validity of the equation is assumed for all the experimental conditions used in data collection (15.18 - 32.43% moisture content; 40 - 75 C and 0 - 180 min). The model response to conditions outside of these ranges may also be tried to test its general application.

7. SIMULATION OF GERMINATION IN STORAGE/TEMPERING AND IN CONCURRENTFLOW CORN SEED DRYING

The NDD model is able to predict the germination retention of corn seed at any given temperature, moisture content and time of exposure. Tempering and storage are essentially the same heat/mass transfer case; drying is more complex in the sense that moisture content and temperature vary with exposure time. The NDD model allows germination retention to be predicted for both cases.

7.1 Prediction of Germination in Tempering/Storage

Tempering and storage can be considered to occur at essentially constant average seed temperature and moisture content. The NDD model will be used to predict viability changes in corn seeds during these processes.

7.1.1 Predicted Versus Published Germination Values

Corn seed viability losses at constant temperature and moisture content have been reported by Gygax (1977) and Ellis and Roberts (1981).

Ellis and Roberts (1981) stored 10.1% moisture content corn seeds at 40 C and recorded viability changes with time. Figure 7.1 shows

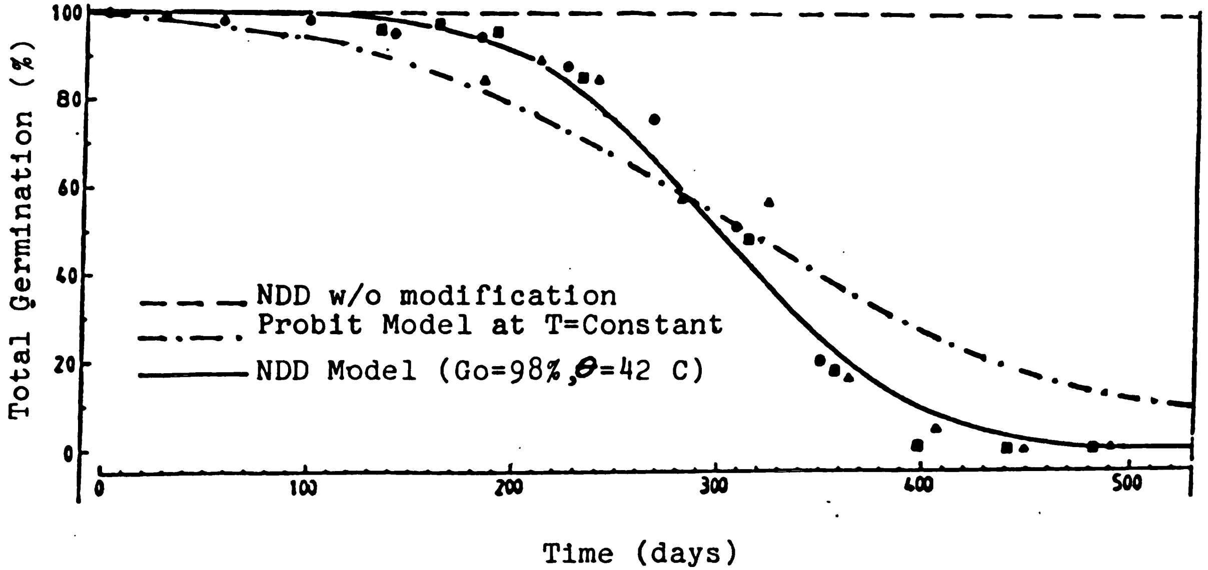


Figure 7.1 Predicted (Probit Approach and the Author's NDD Model) and Experimental Survival Curves of 10.1 +/- 0.1% Corn Seeds at 40 C Constant Storage Tempearture and 100% Initial Germination.

the experimental values, the predictions by Ellis and Roberts (1981) using the one-parameter simplified equation (6.1) with a value of C_1=3.87 and two predictions by the NDD model. The NDD model over-predicts the germination when an initial viability of 100% is assumed along with a temperature of 40 C and a moisture content of 10.1%; the predicted viability does not show a decrease during the entire storage period. However, if an initial viability of 98%, a temperature of 42 C and a moisture of 10.2% are assumed, the NDD model follows the trend of the experimental data and provides an excellent agreement with the experimental results of Ellis and Roberts. It is important to note that the experimental values considered for the initial viability, the temperature and the moisture content are realistic values for the actual experimental conditions during storage. This example shows that a precise measurement of the experimental conditions and the initial seed viability are essential for predicting the viability decrease during storage.

Experimental conditions used by Gygax (1977) were simulated using the NDD model. In all the cases considered, the model predicts viabilities that are higher than the experimental values reported. Figure 7.2 shows a typical test. The effect of experimental errors in the initial viability, moisture content and temperature were tested, but no significant improvement in the agreement between experimental and predicted values was obtained. Therefore, it is likely that the experimental results describe the behavior of a different variety of corn seed than the one used to derive the author's model. The effect of variety appears to be important in the storage/tempering of corn seed. Unfortunately, no published information has been found on this subject.

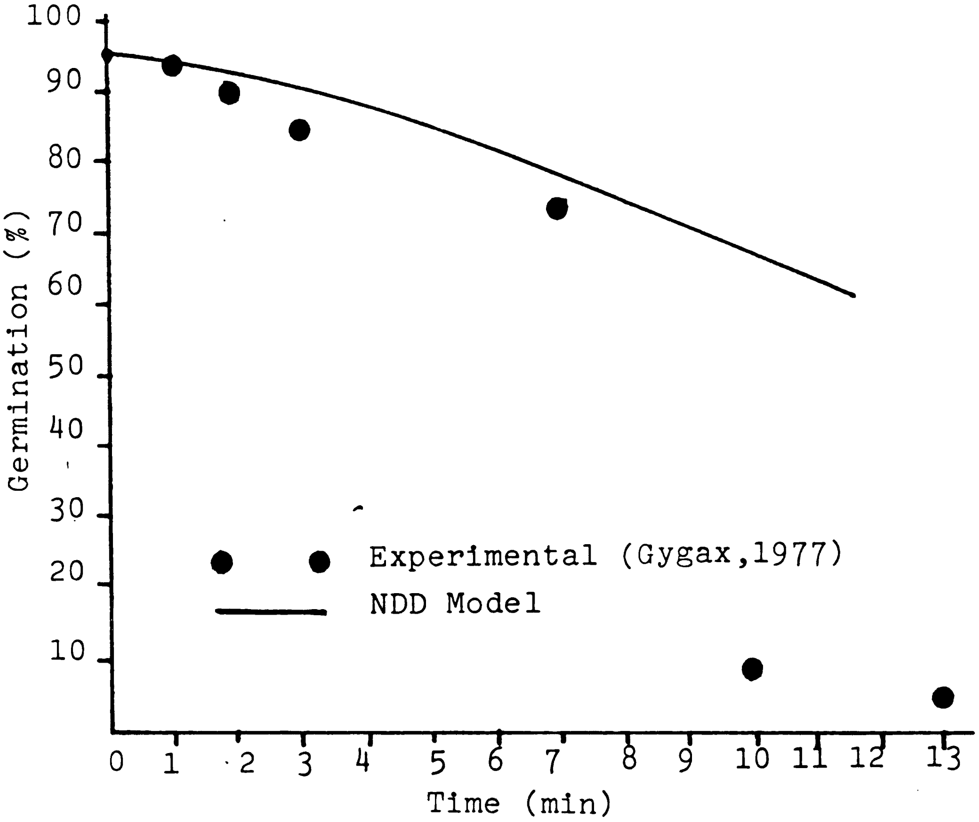


Figure 7.2 Experimental and Predicted Corn Seed Germination Retention Curve During Constant Temperature (67.8 C) and Constant Moisture Content (20% w.b.).

7.1.2 Predicted Germination During Tempering

The NDD model will be used to simulate the tempering effect on viability in drying systems, since the process occurs at constant temperature and moisture content. The effect of tempering temperature on germination is shown in this section as an example of the usefulness of the NDD model.

Figure 7.3 shows the effect of tempering temperature on the viability loss of 30% moisture corn seeds with an initial viability of 95%. As expected, higher tempering temperatures cause a higher germination decrease. For example, after 4.5 hours the seed is completely killed at 55 C but still is at the initial viability when heated for that period at 40 C. Thus, a grain temperature of 40 C or lower does not impair the viability of 95% germination corn at 30% moisture content during long term tempering.

7.2 Simulation of Germination Losses in Concurrentflow Corn Seed Drying

The usefulness of the NDD model in conjunction with a dryer model is demostrated in this section. Analysis of germination behavior during short heating times provides a better understanding of the conditions under which heat damage can be avoided during drying. Several simulation examples show aspects related to concurrentflow dryers operating conditions and design with germination as a quality criterion.

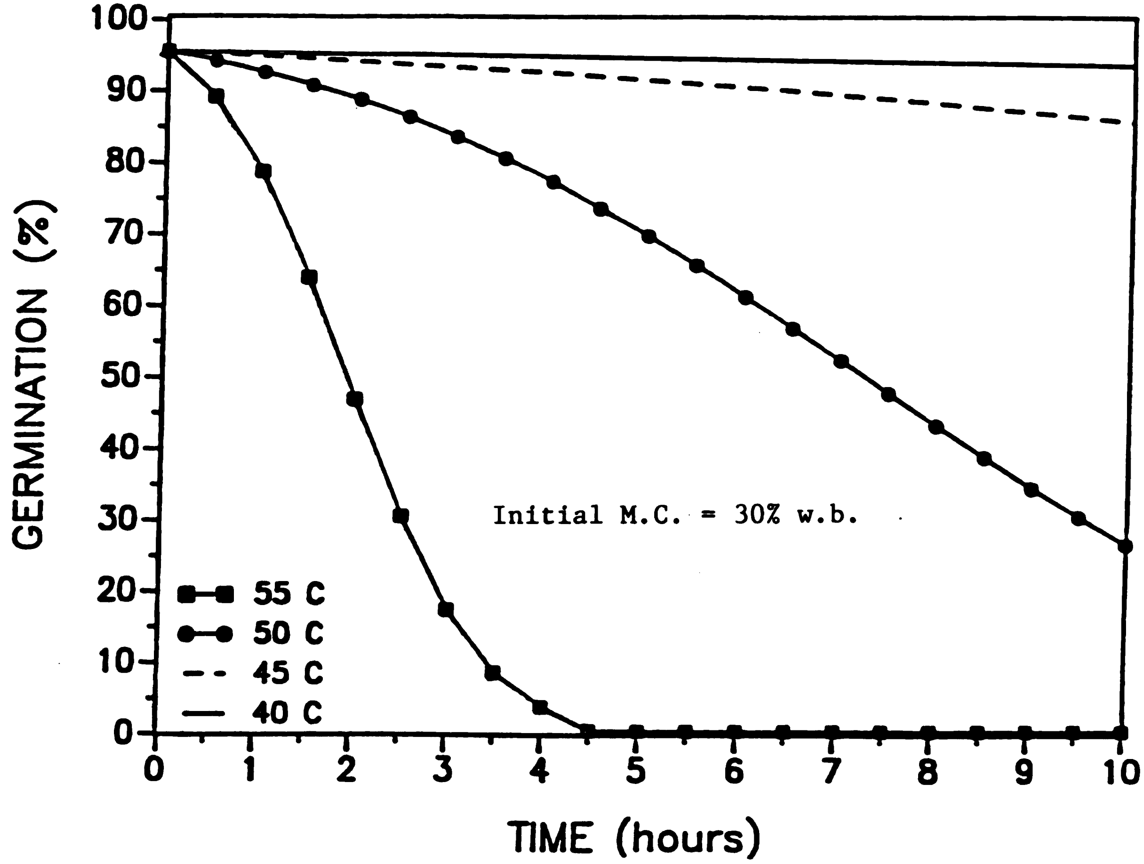


Figure 7.3 Simulated Germination Decrease During Ten-hour Tempering of Corn Seed at 30% (w.b.) Moisture Content at Four Temperatures (40, 45, 50, and 55 C).

7.2.1 Simulation of Germination Retention During Short Exposure Heating Times at Constant Conditions

Since concurrentflow drying is simulated by succesive small time steps at constant grain temperature and moisture content (see Chapter 4), it is important to understand the germination decrease during short (0.1 - 10 min) heating times at constant temperature and moisture content. Figures 7.4 and 7.5 show the effect of temperature on viability loss of seed corn during heat treatment for one and for ten minutes, respectively. The curves indicate that a grain temperature of 60 C is relatively safe for 30% moisture corn if the initial viability is 95% or higher. However, at grain temperatures above 60 C, the viability is reduced rapidly.

Figure 7.6 shows the effect of five initial grain moisture contents (in the range of 15 to 35%) on corn germination during constant heating at 65 C. The initial viability (95%) is little affected below 20% but at higher moistures the germination deteriorates; at 35% moisture, the viability of the corn is totally destroyed after 9.5 minutes.

It can be seen that an increase of five degrees in seed temperature (Figure 7.5) has a stronger effect on on germination than a five percentage point increase in seed moisture content (Figure 7.6).

Figure 7.7 shows the influence of the initial germination value on viability retention of 30% moisture corn. A high initial viability is required to successfully dry corn seed at elevated temperatures.

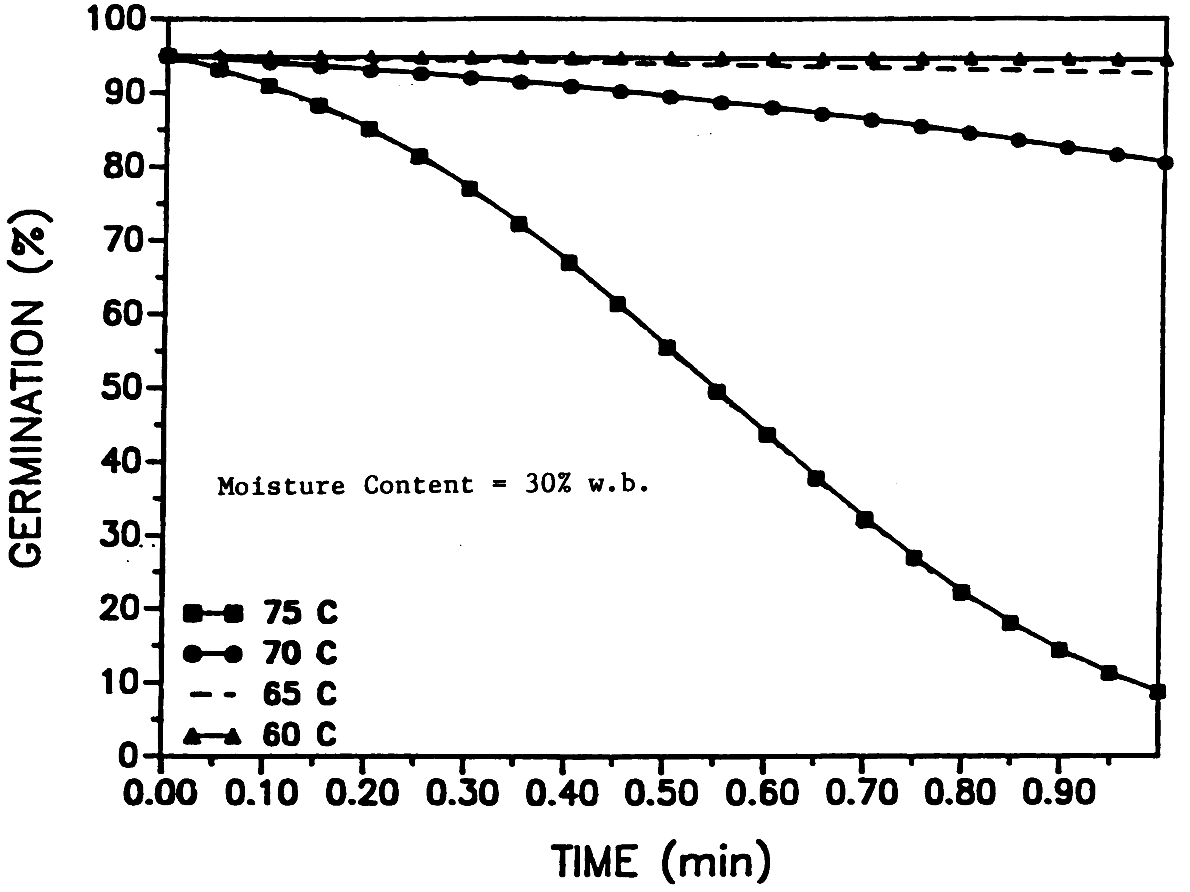


Figure 7.4 Simulated Germination Decrease During 1-minute Heating of Corn Seeds at 30% (w.b.) Moisture Content at Four Temperatures (60, 65, 70, and 75 C).

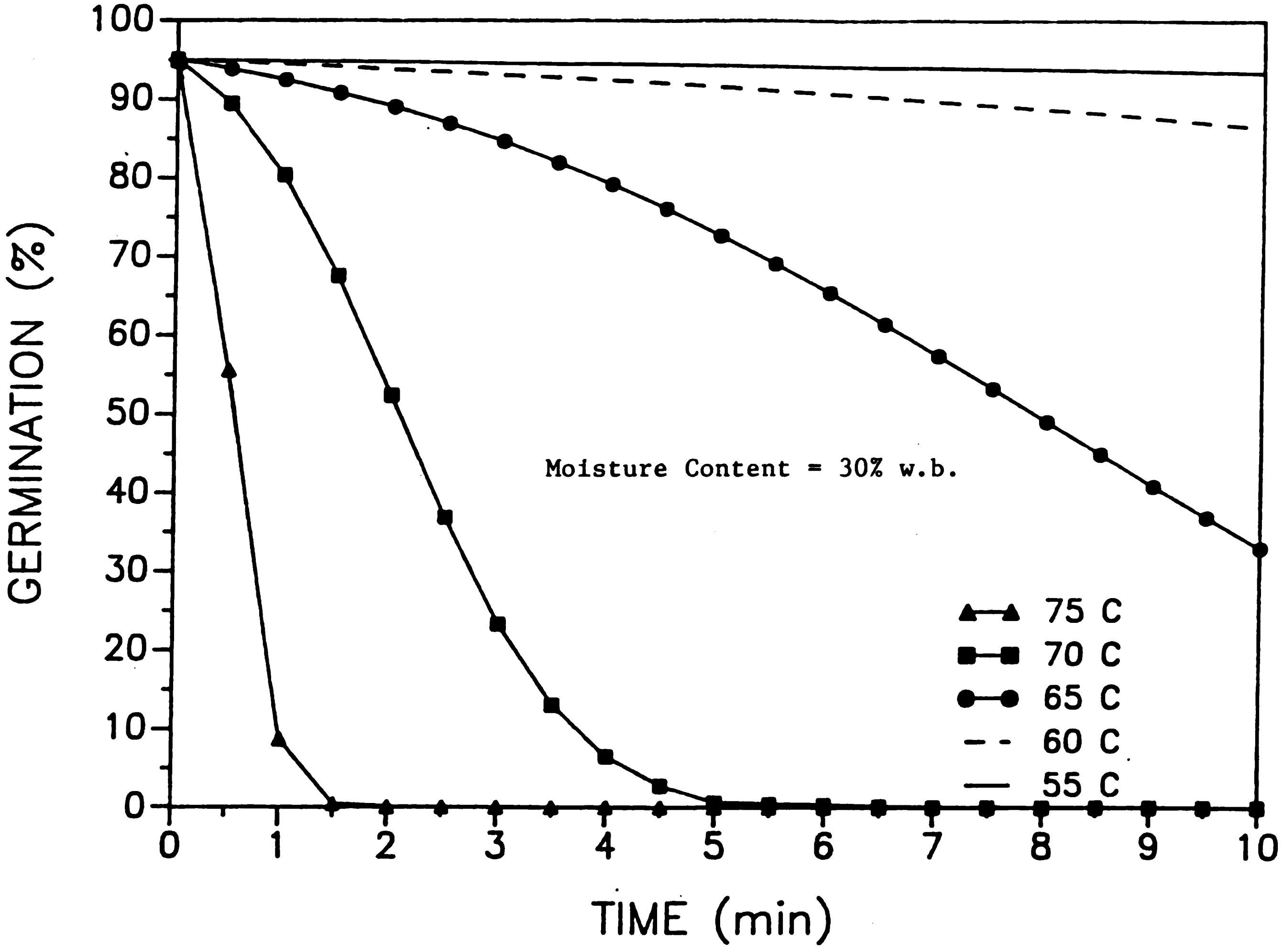


Figure 7.5 Simulated Germination Decrease During Ten-minute Heating of Corn Seeds at 30% (w.b.) Moisture Content at Five Temperatures (55, 60, 65, 70, and 75 C).

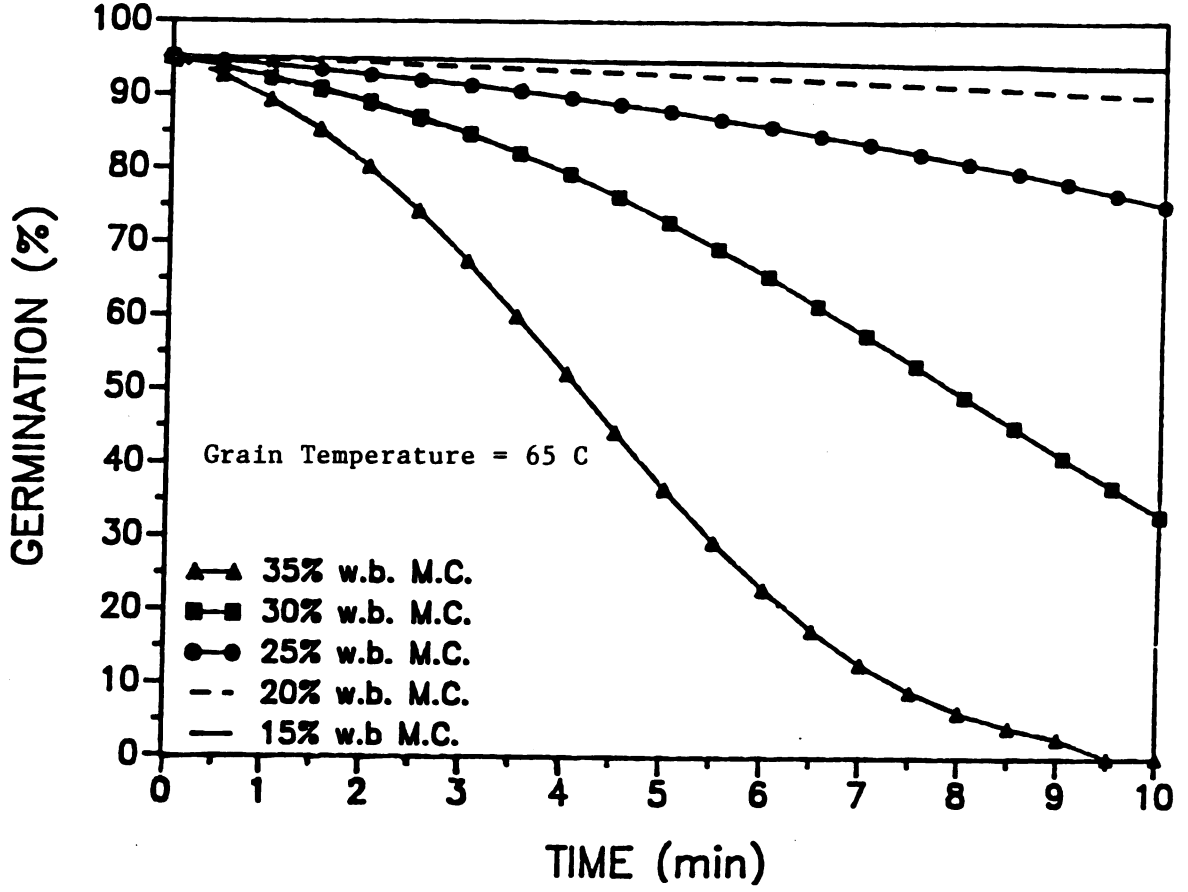


Figure 7.6 Simulated Germination Decrease During 10-minutes Heating of Corn Seed at 65 °C Temperature at Five Initial Moisture Contents (15, 20, 25, 30, and 35% w.b.)

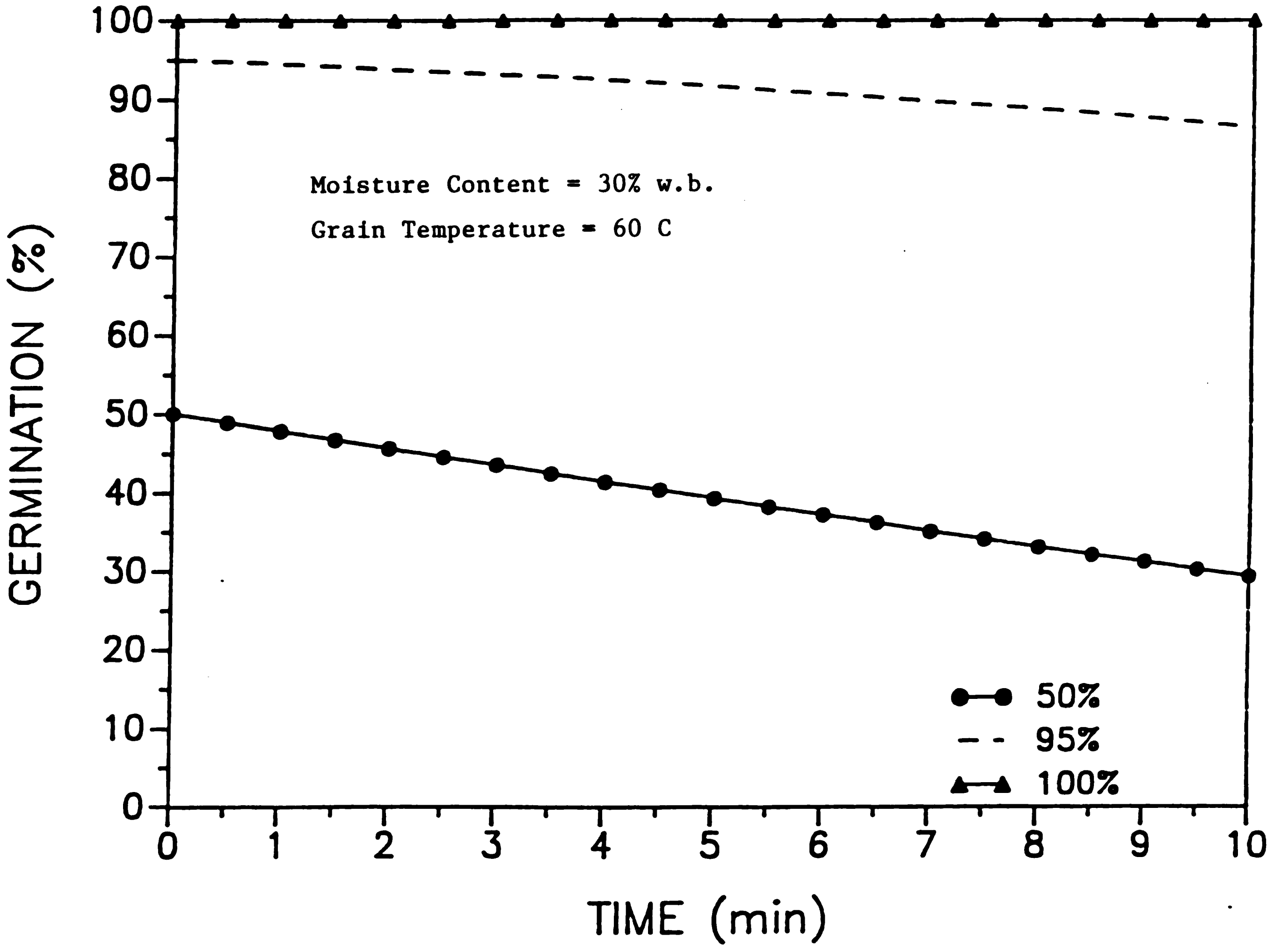


Figure 7.7 Simulated Germination Decrease During Ten-minute Heating of Corn Seed at 60 C Temperature and 30% (w.b.) Moisture Content at Three Initial Viabilities (50, 95, and 100%).

7.2.2 The NDD Model Attached to the Concurrentflow Drying Simulator

In concurrentflow drying, as in any other drying process, the seed germination is affected by the seed temperature and moisture content and the time of exposure to the drying air. Temperature and moisture content history of the seed in the dryer are determined by the rate of heat and mass transfer.

A germination model allows evaluation of the influence on the seed deterioration of the physical conditions during drying. The operating conditions of the concurrentflow dryer can be controlled to maintain a minimum for the calculated germination.

The usefulness of the germination model in assessing the effect of concurrentflow drying parameters on seed germination is illustrated by three examples. The influence of five initial moisture contents (16, 19, 22, 25, and 30%) on the germination of seed corn dried in a one-stage concurrentflow dryer will be analyzed. The drying conditions are shown in Table 7.1

Figures 7.8, 7.9, and 7.10 show the seed temperature, the moisture content, and the germination on the dryer. Since the seed temperature and moisture content determine the germination, the three graphs are closely related.

Figure 7.8 shows that at 30% moisture content the initial germination is preserved during drying. However,

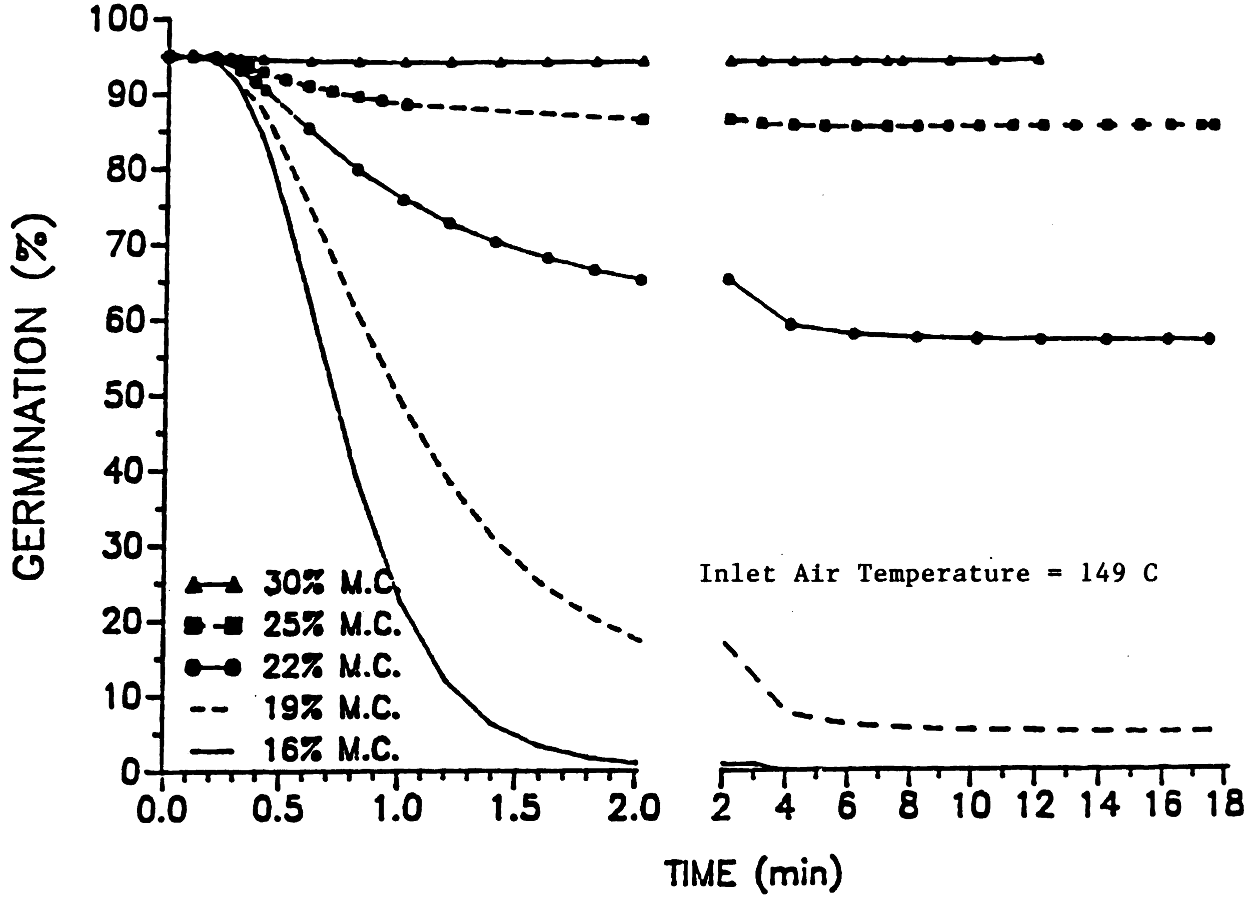


Figure 7.8 Influence of Corn Seed Initial Moisture Content on Viability During One Stage CCF Drying.

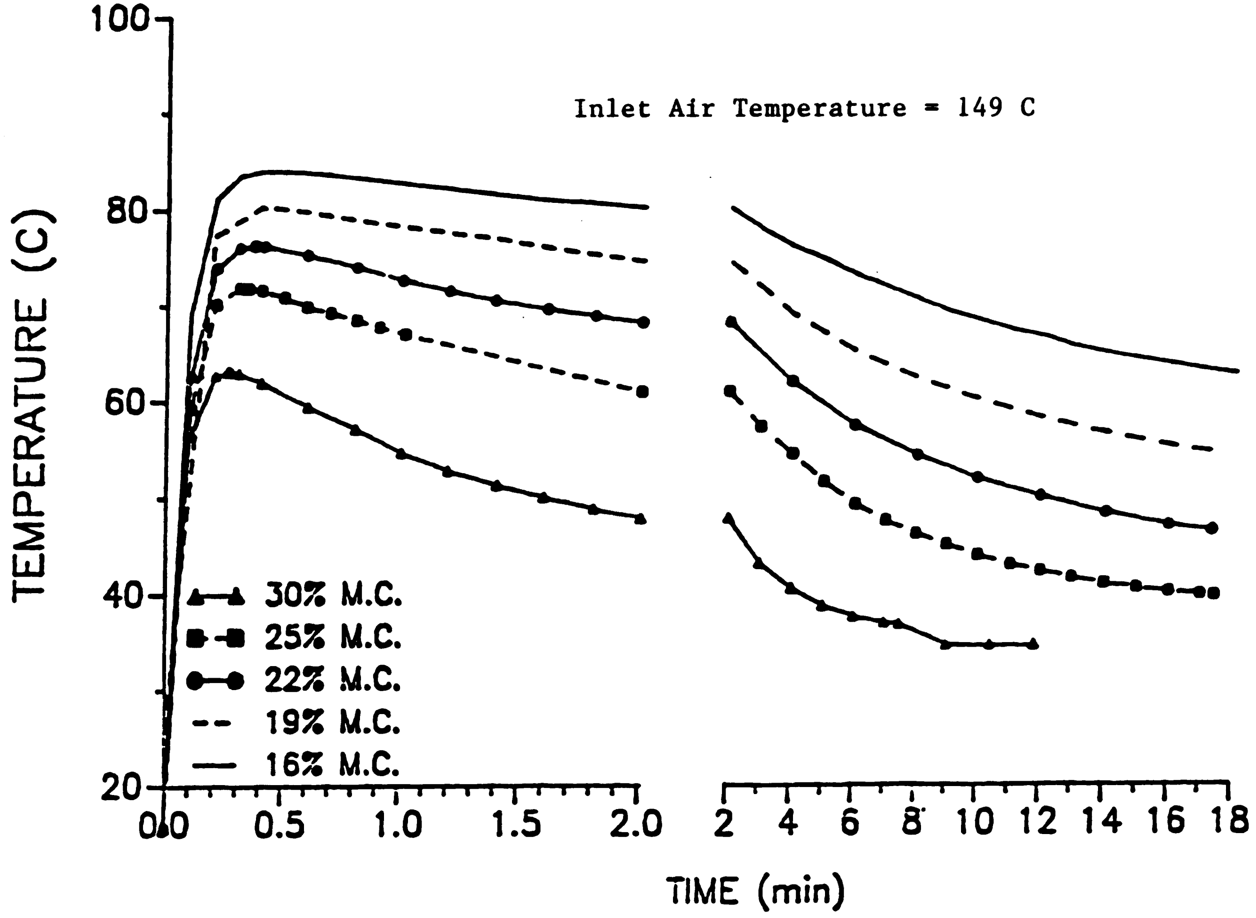


Figure 7.9 Influence of Corn Seed Initial Moisture Content on Grain Temperature During One Stage CCF Drying.

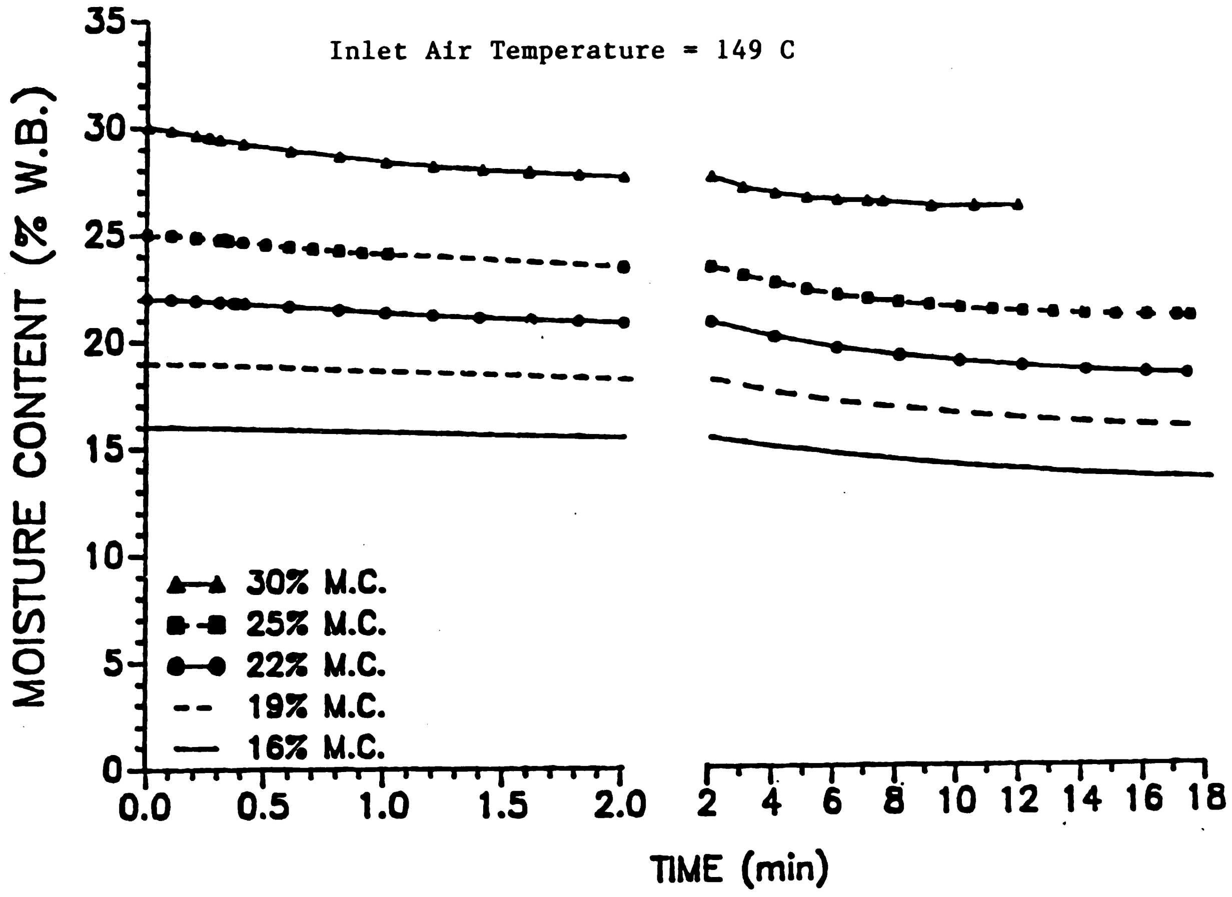


Figure 7.10 Influence of Corn Seed Initial Moisture Content on Grain Moisture During One Stage CCF Drying.

Table 7.1 One-stage Concurrentflow Drying Parameters Used in in the Simulation of the Influence of Initial Grain Moisture Content on Seed Corn Germination.

Initial grain temperature, (C)	15.6
Initial grain viability, (%)	95.0
Ambient air temperature, (C)	15.6
Inlet drying air temperature, (C)	149.0
Inlet drying air absolute humidity,(kg/kg d. air)	0.006
Airflow rate, (m3/s-m2)	0.66
Grain velocity (m/h)	2.2

the germination decreases for the lower moisture contents due to the higher seed temperatures. At 16% moisture content the germination is essentially zero after 2 minutes of drying because the grain temperature is above 80 C for more than one and a half minute. Note that, at 30% initial moisture content, the grain temperature is above 60 C for less than 30 seconds. In the case considered, the grain moisture content during drying is not as important in the germination decrease as the grain temperature. The decreasing moisture content (Figure 7.8), theoretically, should favor a higher germination retention but the corresponding increase in grain temperature, and therefore in damaging effects, overshadows the beneficial effects. An important trade-off between grain temperature and moisture content is noted; the trend may be reversed, however, in other dryer designs.

It is a common practice to assess the appropriateness of a concurrentflow drying process with respect to grain quality by the value of the outlet air temperature which is approximately equal to the outlet grain. As Figures 7.7 and 7.8 indicate, the lowest grain outlet temperature, indeed represents the process with the best germination retention.

Figures 7.8 and 7.10 also show that the optimum drying temperature, which corresponds to the highest moisture content profile, causes a limited decrease in moisture content (less than three points) during drying. This fact seems to indicate that a drying process to preserve germination of corn seeds at high initial moisture content (about 30% for this study) requires more than three stages or passes. Thus, for any set of drying parameters, there is a maximum initial drying temperature that provides a maximum germination retention and a maximum moisture content decrease.

An important application of the germination loss equation is in the design of concurrentflow dryers. For example, corn seed at 18, 20, and 25% moisture is dried at the conditions given in Table 7.2 and three cases are considered. To meet the required final conditions of 90% viability and 14% moisture content at the outlet of the dryer (cooling step is not considered) a series of trial and error designs is evaluated. The results are presented in Table 7.3.

Table 7.2 Multiple-stage Concurrentflow Dryer Parameters Used in the Drying Simulation of 18, 20, and 25% Moisture Corn Seed.

Initial grain temperature, (C)	15.6
Final grain moisture content, (% w.b.)	14.0
Initial grain viability, (%)	95.0
Minimum viability after drying, (%)	90.0
Ambient air temperature, (C)	15.6
Inlet drying air absolute humidity,(kg/kg d.air)	0.006
Airflow rate, (m3/s-m2)	0.66
Depth of drying bed, (m)	0.76
Depth of tempering zone, (m)	3.0

Table 7.3 Concurrentflow Drying Conditions for 95% Initial Viability Corn Seed at 18, 20, and 25% Moisture Content, and a Quality Criterion of 5% Viability Decrease.

	Grain velocity (m/h)	Inlet air temp. (C)	Exit air temp. (C)	Outlet grain M.C. (% w.b.)
A) INITIAL MOISTURE CONTENT: 18%				
Stage 1	2.4	121.1	51.1	15.66
Stage 2	2.4	76.7	51.1	14.01
B) INITIAL MOISTURE CONTENT: 20%				
Stage 1	2.8	123.9	45.3	17.70
Stage 2	2.8	93.3	50.6	15.69
Stage 3	2.8	82.2	52.1	14.08
C) INITIAL MOISTURE CONTENT: 25%				
Stage 1	2.3	121.1	36.1	21.44
Stage 2	2.3	100.0.	42.3	18.23
Stage 3	2.3	82.2	44.6	15.89
Stage 4	2.3	76.7	46.9	14.00

Table 7.3 shows that concurrentflow drying of corn seed at 18, 20, and 25% moisture content requires two, three and four stages, respectively. The maximum inlet drying air temperature, as expected, corresponds to the wettest grain. The grainflows are 1.5, 1.75, and 1.42 MT/hr-m2 for the 18% (2 hours of total drying time), 20% (3.5 hours of total drying time), and 25% (5.0 hours of total drying time), respectively. As was discussed previously, the oulet air temperature

gives in general a reasonable approximation of the quality of the drying process. However, at low moisture contents the outlet temperature tends to increase to about 50 C, which results in an improved efficiency of the drying process without affecting the quality of the grain.

The last example of usefulness of the germination deterioration model is as a general quality index for the corn milling industry. An inlet air temperature of 260 C (not uncommon in the concurrentflow drying of corn) has been selected to illustrate the effects of grain temperature, moisture content and exposure time (Table 7.4 and Figure 7.11). Two initial viability levels (100 and 50%) are considered. At the initial germination of 100%, the viability of the seed does not change during the drying process. In contrast, the 50% viability seed loses germination in the drying process to 10%.

A 50% initial viability is not uncommon for grain received at elevators. After the drying process in a one-stage concurrentflow dryer the viability is lowered but the drying process is so gentle that some seeds still remain alive. What happens to the other processing quality

Table 7.4 One-stage Concurrentflow Drying Parameters Used in the Simulation of Corn Seed Drying at Two Initial Viabilities: 50 and 100%.

Initial grain temperature, (C)	15.6
Initial grain moisture content, (% w.b.)	25.0
Ambient air temperature, (C)	15.6
Inlet drying air temperature, (C)	260.0
Inlet drying air absolute humidity, (kg/kg d.air)	0.005
Airflow rate, (m3/s-m2)	0.66
Grain velocity (m/h)	4.9

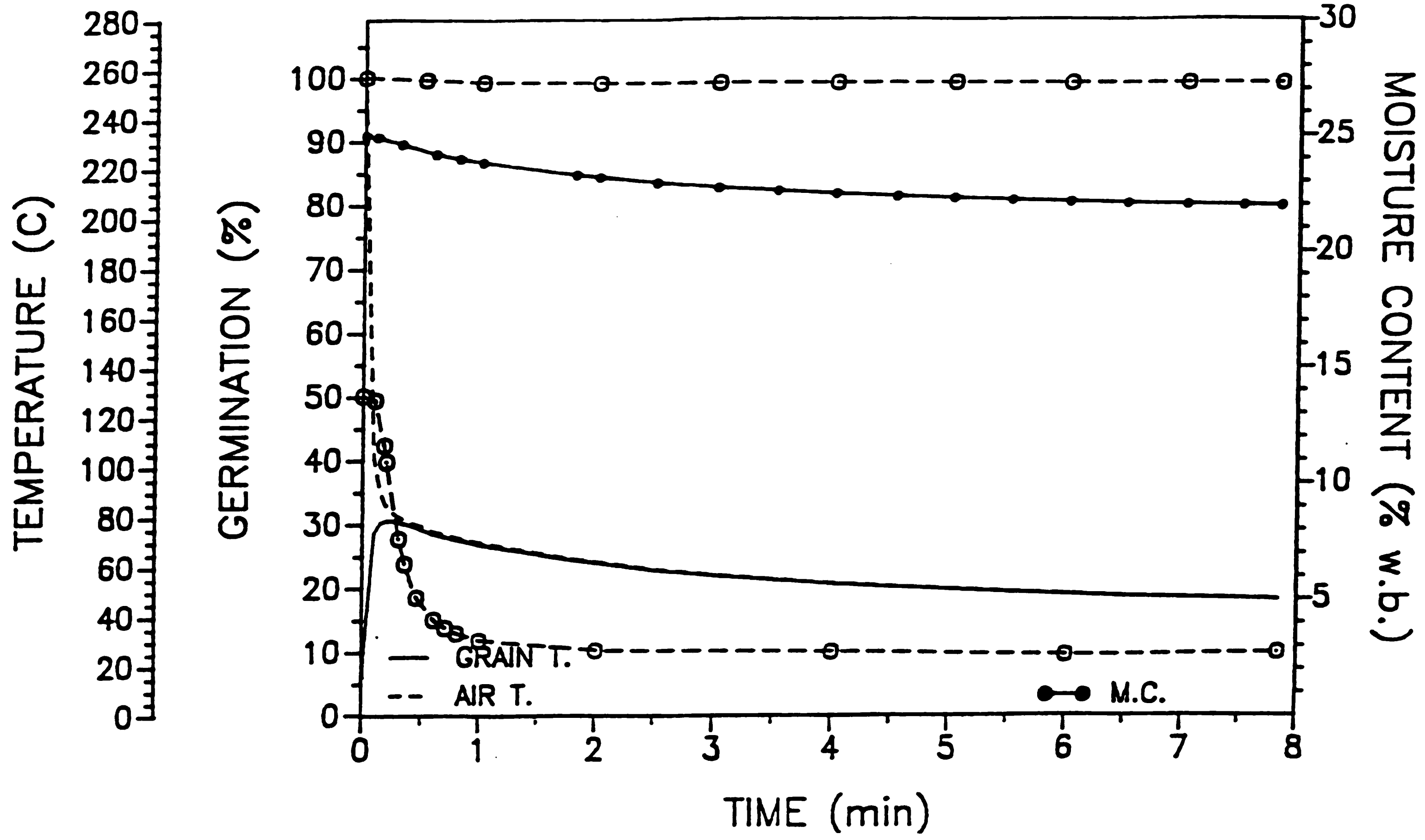


Figure 7.11 Corn Seed NDD Deterioration Model: Germination Retention and Simulated Physical Conditions During One-stage CCF Drying at 260 C Air Temperature and 25% (w.b.) Initial Moisture Content at Two Initial Viabilities (50 and 100%).

criteria can not be answered, but, at the present, the model demonstrates itself to be versatile enough to detect as a viability value, any physical condition of corn in the drying process.

As the examples presented in this section indicate, the germination model in conjuntion with a dryer model provides a convenient and efficient way of assessing the influence of drying parameters on the final grain quality. This is of utmost importance to the processors, designers, manufacturers, researchers, and operators of grain/seed drying equipment.

8. CONCLUSIONS

1. A laboratory thin-layer dryer was successfully designed and tested in the collection of germination and moisture content loss data for shelled corn at different temperatures and drying times.
2. Thin-layer drying germination and moisture content data were recorded for shelled corn seeds with moisture content ranging between 15.18 to 32.43% (w.b.), temperature from 40 to 75 C and exposure time from 1 to 180 minutes.
3. Changes in viability of corn seeds during thin-layer drying are accurately predicted by the normal distribution of deaths theory (NDD) along with an empirical equation for the spread of death rate with time as affected by moisture content and temperature. The NDD model with three parameters predicts with acceptable agreement the seed viability decrease of corn seeds during drying. Increases of viability at the beginning of the drying process, found in several tests, were not predicted by the model developed.
4. The NDD germination model in conjunction with a concurrentflow dryer model does predict the trend of the viability decrease of seed corn during commercial drying in a two-stage dryer.
5. Germination losses during long- and short-time storage/ tempering periods were predicted for different initial

moisture contents, different temperatures and different time periods using the NDD model.

6. The NDD germination model in conjunction with a concurrentlow dryer model is a powerful tool in providing a better understanding of the concurrentflow drying process with respect to quality. Dryer design and the influence of the drying parameters in the loss of viability were analyzed with the aid of the model.
7. Simulation runs showed that 25% shelled corn required four-stage concurrentflow drying; corn seed of 20% and 18% moisture content needed three-stage and four-stage concurrentflow drying, respectively.

9. SUGGESTIONS FOR FUTURE RESEARCH

1. The validity of the normal distribution of deaths theory for other varieties and types of corn should be further investigated. Similar research is recommended for other seed types.
2. The relationship between the total viability and quality factors of corn intended for milling should be studied, with special emphasis on the lower-range values of germination. These studies are important to the quest for the single quality factor.
3. The application of shelled corn drying techniques in the seed industry merits more consideration. This research indicates that the concurrentflow drying of shelled corn seeds appears to be possible if no damage occurs during field drying, harvesting and post-harvesting operations. The best conditions for minimum mechanical damage and viability retention should be investigated.
4. The observed increase of viability during the initial phase of the drying processes, demands more study.
5. The effects of a temperature gradient in the kernel in the moisture content prediction and germination retention during concurrentflow drying needs investigation.

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APENDIX A

Table A.1 Germination and Thin-layer Drying of Corn Seeds: Experimental Results.

Test No	Case No	Temperature	Moisture Content % w.b.	Time min	Germination %
1	1	40	32.00	0	95.0
	2	40	31.60	5	94.0
	3	40	30.55	5	92.0
	4	40	30.65	10	92.0
	5	40	30.99	10	95.0
	6	40	30.78	15	95.5
	7	40	30.78	15	90.0
	8	40	31.23	20	91.0
	9	40	31.40	20	96.5
	10	40	31.14	25	93.0
	11	40	31.08	25	95.0
	12	40	31.15	30	94.0
	13	40	31.24	30	95.5
	14	40	29.60	45	95.0
2	15	50	32.00	0	95.0
	16	50	31.17	5	93.5
	17	50	29.36	5	94.5
	18	50	29.38	10	95.5
	19	50	29.17	10	91.0
	20	50	29.28	15	91.5
	21	50	28.80	15	93.5
	22	50	29.43	20	93.0
	23	50	30.40	20	91.5
	24	50	29.18	25	94.5
	25	50	29.60	25	93.5
	26	50	28.26	30	88.5
	27	50	28.23	30	93.5
3	28	65	32.00	0	95.0
	29	65	31.83	3	93.0
	30	65	31.68	3	92.0
	31	65	31.63	5	89.5
	32	65	31.77	5	88.0
	33	65	30.96	7	75.0
	34	65	30.55	7	33.0

Table A.1 (Cont'd.)

Test No	Case No	Temperature C	Moisture Content % w.b.	Time min	Germination %
	35	65	30.33	9	23.0
	36	65	30.27	9	22.0
	37	65	29.89	12	13.5
	38	65	30.17	12	19.5
	39	65	29.29	15	18.0
	40	65	29.24	15	5.5
	41	65	28.95	20	11.5
	42	65	28.02	20	5.0
	43	65	27.94	25	25.0
	44	65	27.59	25	6.5
	45	65	26.45	30	4.0
	46	65	27.05	30	2.5
4	47	70	32.00	0	95.0
	48	70	30.94	3	81.0
	49	70	31.49	3	82.0
	50	70	30.14	5	7.0
	51	70	29.66	5	2.5
	52	70	31.50	7	65.5
	53	70	31.84	7	80.0
	54	70	28.48	9	8.0
	55	70	29.05	9	6.5
	56	70	29.34	12	5.0
	57	70	28.96	12	3.0
	58	70	28.72	15	3.0
	59	70	28.52	15	0.5
	60	70	25.56	20	4.0
	61	70	26.77	20	0.0
	62	70	26.30	25	0.5
	63	70	26.74	25	0.0
	64	70	26.10	30	1.0
	65	70	26.54	30	0.0
	66	70	23.35	45	0.0
5	67	75	32.43	0	95.0
	68	75	31.57	3	39.5
	69	75	32.04	3	33.0
	70	75	27.89	5	4.0
	71	75	28.11	5	5.0
	72	75	30.19	7	2.0
	73	75	30.38	7	0.5
	74	75	29.78	9	0.0
	75	75	30.39	9	0.0
	76	75	28.10	12	0.0
	77	75	28.62	12	0.0

Table A.1 (Cont'd.)

Test No	Case No	Temperature C	Moisture Content % w. b.	Time min	Germination %
	78	75	27.84	15	0.0
	79	75	27.77	15	0.0
	80	75	25.77	20	0.0
	81	75	26.50	20	0.0
	82	75	25.55	25	0.0
	83	75	25.35	25	0.0
	84	75	24.05	30	0.0
	85	75	24.59	30	0.0
	86	75	21.49	45	0.0
6	87	40	27.22	0	88.0
	88	40	27.79	0	86.0
	89	40	26.40	5	89.0
	90	40	26.57	5	89.5
	91	40	25.98	10	88.5
	92	40	25.90	10	87.0
	93	40	25.36	15	89.0
	94	40	25.06	15	91.5
	95	40	24.81	20	89.0
	96	40	24.47	20	88.0
	97	40	24.49	30	92.0
	98	40	24.19	30	92.5
	99	40	23.86	45	89.0
	100	40	23.72	45	92.0
7	101	50	27.08	0	90.0
	102	50	27.14	0	90.0
	103	50	24.74	5	94.0
	104	50	25.05	5	92.5
	105	50	25.91	10	93.5
	106	50	25.76	10	91.5
	107	50	24.59	15	91.0
	108	50	24.48	15	93.5
	109	50	24.17	20	96.0
	110	50	24.22	20	91.5
	111	50	23.52	30	94.5
	112	50	23.07	30	95.5
	113	50	22.48	45	86.5
	114	50	22.36	45	96.0
8	115	60	26.96	0	92.5
	116	60	26.94	0	90.0
	117	60	25.14	3	94.5
	118	60	24.84	3	94.5

Table A.1 (Cont'd.)

Test No	Case No	Temperature C	Moisture Content % w. b.	Time min	Germination %
	119	60	24.74	6	96.0
	120	60	24.26	6	95.0
	121	60	24.11	9	94.0
	122	60	24.82	9	95.0
	123	60	24.31	12	95.0
	124	60	24.39	12	95.0
	125	60	24.31	15	92.5
	126	60	23.67	15	93.0
9	127	70	26.03	0	88.0
	128	70	27.04	0	90.0
	129	70	23.53	3	95.0
	130	70	24.74	3	67.5
	131	70	24.51	6	12.0
	132	70	23.52	6	3.5
	133	70	24.83	9	5.5
	134	70	24.63	9	8.5
	135	70	24.31	12	4.0
	136	70	24.22	12	5.0
	137	70	23.47	15	2.0
	138	70	23.22	15	0.0
10	139	55	25.21	0	86.5
	140	55	21.51	30	94.5
	141	55	20.43	45	92.0
	142	55	19.64	60	90.5
	143	55	17.97	90	91.5
	144	55	17.00	120	95.0
11	145	60	25.21	0	86.5
	146	60	27.77	10	91.5
	147	60	21.74	20	95.0
	148	60	19.88	40	95.5
	149	60	18.71	60	94.0
12	150	65	25.21	0	86.5
	151	65	23.80	4	95.0
	152	65	22.95	8	84.0
	153	65	22.59	12	68.5
	154	65	21.99	15	68.5
	155	65	21.15	30	48.0
13	156	70	25.21	0	86.5
	157	70	23.98	2	92.5

Table A.1 (Cont'd.)

Test No	Case No	Temperature C	Moisture Content % w. b.	Time min	Germination %
	158	70	23.55	4	75.0
	159	70	22.93	6	64.5
	160	70	22.64	8	31.5
	161	70	22.15	10	29.0
14	162	60	22.04	0	95.0
	163	60	18.05	30	91.0
	164	60	17.00	60	93.0
	165	60	15.80	90	94.0
	166	60	14.98	120	94.5
	167	60	13.82	150	90.0
	168	60	13.50	180	90.0
15	169	65	21.80	0	95.0
	170	65	19.73	10	93.5
	171	65	18.70	20	89.0
	172	65	18.01	30	92.5
	173	65	17.24	40	94.5
	174	65	16.55	50	91.5
	175	65	16.36	60	91.5
	176	65	15.68	70	89.5
	177	65	15.20	80	87.5
	178	65	15.00	90	68.5
16	179	70	21.95	0	91.5
	180	70	20.55	5	94.5
	181	70	19.73	10	72.5
	182	70	19.01	15	67.5
	183	70	18.59	20	57.0
	184	70	18.07	25	13.5
	185	70	17.65	30	21.5
17	186	75	21.87	0	92.0
	187	75	21.32	2	94.5
	188	75	20.49	4	41.5
	189	75	19.97	6	9.0
	190	75	19.79	8	17.5
	191	75	19.30	10	17.0
	192	75	19.07	12	4.5
	193	75	18.78	14	5.0
	194	75	18.62	16	8.0
	195	75	18.20	18	0.5
	196	75	18.09	20	2.0
18	197	75	21.08	0	91.5
	198	75	20.55	1	90.5

Table A.1 (Cont'd.)

Test No	Case No	Temperature C	Moisture Content % w. b.	Time min	Germination %
	199	75	20.05	2	86.0
	200	75	19.96	3	66.5
	201	75	19.63	4	64.5
	202	75	19.55	5	37.5
	203	75	19.23	6	17.5
19	204	75	15.56	0	91.0
	205	75	15.38	1	89.5
	206	75	15.54	2	84.0
	207	75	14.98	3	87.5
	208	75	14.83	4	77.5
	209	75	14.85	5	72.0
	210	75	14.63	6	65.5
20	211	70	15.54	0	92.5
	212	70	14.86	5	94.0
	213	70	14.16	10	89.0
	214	70	13.84	15	88.0
	215	70	13.72	20	81.5
	216	70	13.61	25	82.0
	217	70	13.50	30	74.5
	218	70	13.47	35	80.0
	219	70	13.24	40	82.0
	220	70	12.98	45	67.0
	221	70	12.96	50	73.5
	222	70	12.78	55	75.0
	223	70	12.69	60	57.5
21	224	75	15.51	0	92.5
	225	75	15.51	1	88.5
	226	75	15.23	2	93.0
	227	75	15.13	3	82.5
	228	75	15.09	4	86.0
	229	75	14.78	5	84.5
	230	75	14.98	6	68.0
	231	75	14.81	7	54.0
	232	75	14.79	8	65.0
	233	75	14.77	9	50.5
	234	75	14.28	10	38.5
22	235	65	15.24	0	94.5
	236	65	13.68	30	88.5
	237	65	12.80	60	90.0
	238	65	12.41	90	89.5

Table A.1 Cont'd.

Test No	Case No	Temperature C	Moisture Content % w. b.	Time min	Germination %
	239	65	12.20	105	88.5
	240	65	11.91	120	86.5
	241	65	11.13	135	83.0
	242	65	11.17	150	83.5
	243	65	11.17	165	88.0
	244	65	10.92	180	84.0
23	245	75	15.18	0	91.5
	246	75	14.80	1	88.0
	247	75	14.76	2	89.0
	248	75	14.80	3	87.5
	249	75	14.44	4	83.0
	250	75	14.65	5	74.0
	251	75	14.19	6	68.5

APPENDIX B : COMPUTER PROGRAMS

1) SUBROUTINE GERMI

PROGRAMMER : CARLOS EDUARDO LESCANO (10-10-1986)

FOR REFERENCES AND DETAILS SEE PHD THESIS (1986) MSU-AE
VIABILITY CONSTANTS (3) ARE FOR CORN SEED (GL-579)

```
      SUBROUTINE GERMI(DB,TAIR,T,DY,GVEL,GERM)
      REAL NMLVAL(21),NMLVL2(27),XNMLVL1(96),XNMLVL2(26)
      DATA JPC,TTIME,TPRRT/0,0.,0.010/
      WB= 100.*DB/(1.+DB)
      DTIME = 60.*DY/GVEL
      IF(JPC.GT.0)GO TO 31
      X1 = GERM/100.
      Y=X1
      IF(X1.LT.0.5)X1=1.0-X1
      IF(X1.GE.0.975)GO TO 27
      Y1=XINVNR1(XNMLVL1,X1)
      GO TO 30
   27 Y1=XINVNR2(XNMLVL2,X1)
30    IF(Y.LT.0.5)Y1=-Y1
      XI = Y1
      GO TO 32
31    XI=YY
32    CONTINUE
      IF(TTIME.LT.TPRRT)GO TO 998
995   PRINT 999,GERM,WB,TAIR,T,DTIME,DY,GVEL,TTIME
      TPRRT=TPRRT+0.010
998   TTIME=TTIME+DTIME
999   FORMAT(//, 15H  GERM.,PERC. =,F6.2,3(F7.2,1X),3E9.2,F7.3)
C****
C         CORN SEED VIABILITY CONSTANTS (THREE).... CHANGE FOR OTHER SEED
C****
      SIGMA = (1./WB**4.198)*EXP(33.20 - 0.267*T)
      DX = (1./SIGMA)*DTIME
      X = XI - DX
      YY = X
      IF(X.LT.0.)X =-X
      IF(X.GT.1.96)GO TO 127
      G=PNOR1(NMLVAL,X)
      GO TO 128
  127 G=PNOR2(NMLVL2,X)
128   IF(YY.LT.0.0)G=1.-G
      GERM=G*100.
      JPC=JPC+1
      GERZERO=GERM
      RETURN
      END
      FUNCTION PNOR1(NMLVAL,X1)
      REAL NMLVAL(21)
C         VALUES OF THE CUMULATIVE NORMAL DISTRIBUTION FUNCTION
C     USED BY FUNCTION PNOR1 TO TRANSFORM X VALUES  INTO PROBABILITY
C               VALUES, USING EQUAL SPACE INTERPOLATION
```

```
C                    X.GE.0.0   AND X.LT.1.96
C **
      NMLVAL(1)  =0.5000  $ NMLVAL(2)  =0.5390  $ NMLVAL(3)  =0.5777
      NMLVAL(4)  =0.6156  $ NMLVAL(5)  =0.6525  $ NMLVAL(6)  =0.6879
      NMLVAL(7)  =0.7217  $ NMLVAL(8)  =0.7536  $ NMLVAL(9)  =0.7835
      NMLVAL(10)=0.8111   $ NMLVAL(11)=0.8365   $ NMLVAL(12)=0.8595
      NMLVAL(13)=0.8802   $ NMLVAL(14)=0.8987   $ NMLVAL(15)=0.9150
      NMLVAL(16)=0.9292   $ NMLVAL(17)=0.9416   $ NMLVAL(18)=0.9521
      NMLVAL(19)=0.9611   $ NMLVAL(20)=0.9687   $ NMLVAL(21)=0.9750
      XS1 = 0.0
      DX1 = 0.098
      N1  = 20
      IF(X1 - XS1)3,3,2
    2 IF(X1 - XS1 - N1*DX1)7,5,5
    3 PNOR1 = NMLVAL(1)
      GO TO 10
    5 PNOR1 = NMLVAL(N1 + 1)
      GO TO 10
    7 XD1 = X1 - XS1
      I1 = 1.0 + XD1/DX1
      A=NMLVAL(I1)
      PNOR1=(XD1-FLOAT(I1-1)*DX1)*(NMLVAL(I1+1)-NMLVAL(I1))/DX1+A
   10 RETURN
      END
      FUNCTION PNOR2(NMLVL2,DUMMY)
      REAL NMLVL2(27),ARG2(27)
C           VALUES OF THE CUMULATIVE NORMAL DISTRIBUTION FUNCTION
C        USED BY FUNCTION PNOR1 TO TRANSFORM X VALUES  INTO PROBABILITY
C                 VALUES, USING UNEQUAL SPACE INTERPOLATION
C                             X VALUES.GE.1.96
C **
      NMLVL2(1)  =0.9750  $ NMLVL2(2)  =0.9760  $ NMLVL2(3)  =0.9770
      NMLVL2(4)  =0.9780  $ NMLVL2(5)  =0.9790  $ NMLVL2(6)  =0.9800
      NMLVL2(7)  =0.9810  $ NMLVL2(8)  =0.9820  $ NMLVL2(9)  =0.9830
      NMLVL2(10)=0.9840   $ NMLVL2(11)=0.9850   $ NMLVL2(12)=0.9860
      NMLVL2(13)=0.9870   $ NMLVL2(14)=0.9880   $ NMLVL2(15)=0.9890
      NMLVL2(16)=0.9900   $ NMLVL2(17)=0.9910   $ NMLVL2(18)=0.9920
      NMLVL2(19)=0.9930   $ NMLVL2(20)=0.9940   $ NMLVL2(21)=0.9950
      NMLVL2(22)=0.9960   $ NMLVL2(23)=0.9970   $ NMLVL2(24)=0.9980
      NMLVL2(25)=0.9990   $ NMLVL2(26)=0.9999   $ NMLVL2(27)=1.0000

C*    TABLE OF ARGUMENTS WHICH CORRESPOND TO EACH OF THE VALUES GIVEN BY
C*                              THE ARRAY NMLVL2
      ARG2(1)  =1.9600  $ ARG2(2)=1.9774     $ ARG2(3)  =1.9954
      ARG2(4)  =2.0141  $ ARG2(5)=2.0354     $ ARG2(6)  =2.0537
      ARG2(7)  =2.0749  $ ARG2(8)=2.0969     $ ARG2(9)  =2.1201
      ARG2(10)=2.1444   $ ARG2(11)=2.1701    $ ARG2(12)=2.1973
      ARG2(13)=2.2262   $ ARG2(14)=2.2571    $ ARG2(15)=2.2904
      ARG2(16)=2.3263   $ ARG2(17)=2.3656    $ ARG2(18)=2.4089
      ARG2(19)=2.4573   $ ARG2(20)=2.5121    $ ARG2(21)=2.5758
      ARG2(22)=2.6521   $ ARG2(23)=2.7478    $ ARG2(24)=2.8782
      ARG2(25)=3.0902   $ ARG2(26)=3.6160    $ ARG2(27)=3.8910
      N1 = 27
      DUM= AMAX1(AMIN1(DUMMY,ARG2(N1)),ARG2(1))
      DO 1 I = 2,N1
      IF(DUM.GT.ARG2(I))GO TO 1
      PNOR2 = (DUM-ARG2(I-1))*(NMLVL2(I)-NMLVL2(I-1))/
     +(ARG2(I)-ARG2(I-1)) + NMLVL2(I-1)
      RETURN
1     CONTINUE
      END
```

```
      FUNCTION XINVNR1(XNMLVL1,X)
      REAL XNMLVL1(96)
C         VALUES OF THE INVERSE CUMULATIVE NORMAL DISTRIBUTION FUNCTION
C       USED BY FUNCTION XINVNR1 TO TRANSFORM PROBABILITY DECIMAL VALUES
C                    TO INVERSE (ARGUMENT) VALUES.
                             G.LT.0.975
C **
      XNMLVL1(1)  =0.0000  $ XNMLVL1(2)  =0.0125  $XNMLVL1(3)  =0.0251
      XNMLVL1(4)  =0.0376  $ XNMLVL1(5)  =0.0502  $XNMLVL1(6)  =0.0627
      XNMLVL1(7)  =0.0753  $ XNMLVL1(8)  =0.0878  $XNMLVL1(9)  =0.1004
      XNMLVL1(10)=0.1130  $ XNMLVL1(11)=0.1257  $XNMLVL1(12)=0.1383
      XNMLVL1(13)=0.1510  $ XNMLVL1(14)=0.1637  $XNMLVL1(15)=0.1764
      XNMLVL1(16)=0.1891  $ XNMLVL1(17)=0.2019  $XNMLVL1(18)=0.2147
      XNMLVL1(19)=0.2275  $ XNMLVL1(20)=0.2404  $XNMLVL1(21)=0.2533
      XNMLVL1(22)=0.2663  $ XNMLVL1(23)=0.2793  $XNMLVL1(24)=0.2924
      XNMLVL1(25)=0.3055  $ XNMLVL1(26)=0.3186  $XNMLVL1(27)=0.3319
      XNMLVL1(28)=0.3451  $ XNMLVL1(29)=0.3585  $XNMLVL1(30)=0.3719
      XNMLVL1(31)=0.3853  $ XNMLVL1(32)=0.3989  $XNMLVL1(33)=0.4125
      XNMLVL1(34)=0.4261  $ XNMLVL1(35)=0.4399  $XNMLVL1(36)=0.4538
      XNMLVL1(37)=0.4677  $ XNMLVL1(38)=0.4817  $XNMLVL1(39)=0.4959
      XNMLVL1(40)=0.5101  $ XNMLVL1(41)=0.5244  $XNMLVL1(42)=0.5388
      XNMLVL1(43)=0.5534  $ XNMLVL1(44)=0.5681  $XNMLVL1(45)=0.5828
      XNMLVL1(46)=0.5978  $ XNMLVL1(47)=0.6128  $XNMLVL1(48)=0.6280
      XNMLVL1(49)=0.6433  $ XNMLVL1(50)=0.6588  $XNMLVL1(51)=0.6745
      XNMLVL1(52)=0.6903  $ XNMLVL1(53)=0.7063  $XNMLVL1(54)=0.7225
      XNMLVL1(55)=0.7388  $ XNMLVL1(56)=0.7554  $XNMLVL1(57)=0.7722
      XNMLVL1(58)=0.7892  $ XNMLVL1(59)=0.8064  $XNMLVL1(60)=0.8239
      XNMLVL1(61)=0.8416  $ XNMLVL1(62)=0.8596  $XNMLVL1(63)=0.8779
      XNMLVL1(64)=0.8965  $ XNMLVL1(65)=0.9154  $XNMLVL1(66)=0.9346
      XNMLVL1(67)=0.9542  $ XNMLVL1(68)=0.9741  $XNMLVL1(69)=0.9945
      XNMLVL1(70)=1.0152  $ XNMLVL1(71)=1.0364  $XNMLVL1(72)=1.0581
      XNMLVL1(73)=1.0803  $ XNMLVL1(74)=1.1031  $XNMLVL1(75)=1.1264
      XNMLVL1(76)=1.1503  $ XNMLVL1(77)=1.1750  $XNMLVL1(78)=1.2004
      XNMLVL1(79)=1.2265  $ XNMLVL1(80)=1.2536  $XNMLVL1(81)=1.2816
      XNMLVL1(82)=1.3106  $ XNMLVL1(83)=1.3409  $XNMLVL1(84)=1.3722
      XNMLVL1(85)=1.4051  $ XNMLVL1(86)=1.4395  $XNMLVL1(87)=1.4758
      XNMLVL1(88)=1.5141  $ XNMLVL1(89)=1.5548  $XNMLVL1(90)=1.5982
      XNMLVL1(91)=1.6449  $ XNMLVL1(92)=1.6954  $XNMLVL1(93)=1.7507
      XNMLVL1(94)=1.8119  $ XNMLVL1(95)=1.8808  $XNMLVL1(96)=1.9600
      XS1 = 0.500
      DX1 = 0.005
      N1  = 95
      IF(X - XS1)3,3,2
    2 IF(X - XS1- N1*DX1)7,5,5
    3 XINVNR1 = XNMLVL1(1)
      GO TO 10
    5 XINVNR1 = XNMLVL1(N1 + 1)
      GO TO 10
    7 XD1 = X  - XS1
      I1 = 1.0 + XD1/DX1
      A=XNMLVL1(I1)
      XINVNR1=(XD1-FLOAT(I1-1)*DX1)*(XNMLVL1(I1+1)-XNMLVL1(I1))/DX1+A
   10 RETURN
      END
      FUNCTION XINVNR2(XNMLVL2,X)
      REAL XNMLVL2(26)
C        VALUES OF THE INVERSE CUMULATIVE NORMAL DISTRIBUTION FUNCTION
C       USED BY FUNCTION XINVNR2 TO TRANSFORM PROBABILITY DECIMAL VALUES
C                     TO INVERSE (ARGUMENT) VALUES.
C                               G.GE.0.975
C **
```

```
      XNMLVL2(1)  =1.9600  $ XNMLVL2(2)  =1.9774  $XNMLVL2(3)  =1.9954
      XNMLVL2(4)  =2.0141  $ XNMLVL2(5)  =2.0335  $XNMLVL2(6)  =2.0537
      XNMLVL2(7)  =2.0749  $ XNMLVL2(8)  =2.0969  $XNMLVL2(9)  =2.1201
      XNMLVL2(10)=2.1444   $ XNMLVL2(11)=2.1701   $XNMLVL2(12)=2.1973
      XNMLVL2(13)=2.2262   $ XNMLVL2(14)=2.2571   $XNMLVL2(15)=2.2904
      XNMLVL2(16)=2.3263   $ XNMLVL2(17)=2.3656   $XNMLVL2(18)=2.4089
      XNMLVL2(19)=2.4573   $ XNMLVL2(20)=2.5121   $XNMLVL2(21)=2.5758
      XNMLVL2(22)=2.6521   $ XNMLVL2(23)=2.7478   $XNMLVL2(24)=2.8782
      XNMLVL2(25)=3.0902   $ XNMLVL2(26)=3.6160
      XS  = 0.975
      DX  = 0.001
      N   = 25
      IF(X - XS)3,3,2
    2 IF(X - XS - N*DX)7,5,5
    3 XINVNR2 = XNMLVL2(1)
      GO TO 10
    5 XINVNR2 = XNMLVL2(N + 1)
      GO TO 10
    7 XD  = X  - XS
      I1 = 1.0 + XD /DX
      A=XNMLVL2(I1)
      XINVNR2=(XD -FLOAT(I1-1)*DX)*(XNMLVL2(I1+1)-XNMLVL2(I1))/DX+A
   10 RETURN
      END
```

```
C                2)  CONCURRENTFLOW MSU MODEL


      PROGRAM CONCUR (INPUT,OUTPUT)
C*****   SUBROUTINES USED
C*****        DATA      -GRAIN PROPERTY VALUES
C*****        DERFUN    -DIFFERENTIAL EQUATIONS FOR RKAMSUB
C*****        QUAL      -GRAIN QUALITY CALCULATIONS
C*****        RKAMSUB   -LASTMAN,G.J. COOP ID  D2 UTEX RKAMSUB (1964)
C*****        START     -LASTMAN,G.J. COOP ID  D2 UTEX RKAMSUB (1964)
C*****   FUNCTION SUBPROGRAMS USED
C*****        EMC       -EQUILIBRIUM MOISTURE CONTENT FOR GRAIN
C*****        FDIFF     -DIFFUSION EQUATION FOR GRAIN MOISTURE
C*****        FHFG      -HEAT OF VAPORIZATION OF WATER FROM GRAIN
C*****        SYCHART PACKAGE
      COMMON /CONSTNT/ CONA(12),CONB(12),CONC,COND,CONE(12),CON1,CON2,CO
     1N3,CON4,CON5,CON6
      COMMON /CNODE/ NODE,NP1,NP2,NP3,NP4,NTOT,ND,NDP1,NDTOT,NTMPR
      COMMON /CDIFF/ XME,RH,XMIN,CFM,GVEL,IFLOW
      COMMON /CHC/ HCA,HCB
      COMMON /CUNT/IUNT,UNT(2,15),CNV(2,16),UNTTYP(2)
      COMMON /PRPRTY/ SA,CA,CP,CV,CW,RHOP,HFG
      COMMON /DIMEN/ ITYPE,FN,DELR,RO,V(10),VP
      COMMON /SPFAC/ SPKA,SPKB
      COMMON /PRESS/ PATM
      COMMON /NAME/ INAME,IPROD
      COMMON /RKAM/ Y(202)
      DATA UNTTYP/7HSI     ,7HENGLISH/
      DATA UNT/1HC,1HF,9HM3/M2/MIN,9HCFM/FT2  ,10HMTON/HR/M2,10HBU/HR/FT
     12 ,2HM ,2HFT,8HKJ/KG/C ,8HBTU/LB/F,7HM2/M3  ,7HFT2/FT3,6HKG/M3 ,6H
     2LB/FT3,6HKJ/KG ,6HBTU/LB,4HN/M2,4HPSI ,9HKG/HR/M2 ,9HLB/HR/FT2,10H
     3KJ/HR/M2/C,10HBTU/HRFT2F,5HM/HR ,5HFT/HR,2HCM,2HIN,6HHP/M2 ,6HHP/F
     4T2,5HKG/KG,5HLB/LB/
      DATA CNV/1.,1.8,0.,32.,1.,3.281,1.,3.6576,1.,3.281,1.,.23886,1.,.3
     1048,1.,.06243,1.,.4299,1.,1.45E-4,1.,.2048,1.,.0489,1.,3.281,1.,.3
     2937,1.,.0929,1.,1./
      FT(T)=5.*(T-32.)/9.
      F(T)=T+273.13
C*****   INPUT CONDITIONS OF DRYER TO BE SIMULATED
      PRINT 340
      READ 280, IUNT
 5    PRINT 310
      READ 280, ITYPE
      IF(ITYPE.LE.0) STOP
      CALL DATA
      PRINT 270,INAME,IPROD,UNTTYP(IUNT)
      SUMBTU=0.0
      XTMPR=0.0
      QUALITY=0.0
      ISTG=0
      PRINT 260, UNT(IUNT,1)
      READ 130, TAMB
      PRINT 170
      READ 130, XMOW
      WB=XMOW
      PRINT 320, UNT(IUNT,1)
      READ 130, THIN
```

```
C*****   CONVERT XMO TO DECIMAL DRY BASIS
      XMO=WB/(100.-WB)
      NTP1=NTOT+1
C*****   INITIALIZE Y-ARRAY VALUES FOR TIME = 0.
      IF (IUNT.EQ.1) GO TO 10
      TAMB=FT(TAMB)
      THIN=FT(THIN)
   10 DO 20 IN=1,NP2
   20 Y(IN)=XMO
      Y(NP4)=THIN
C*****   BEGIN LOOP FOR NSTG STAGES
    8 ISTG=ISTG+1
C*****   INITIALIZE CONTROLS FOR STAGE ISTG
      IEXIT=0
      HFG=FHFG(XMO,THIN)
      Y(NTP1)=0.0
      XMIN=Y(NP2)
C*****   READ INPUTS FOR STAGE ISTG
      PRINT 140, ISTG
      READ 280,IFLOW
      IF(IFLOW.LE.0.) GOTO 5
      IF(IFLOW.EQ.1) IFLOW=-1
      IF(IFLOW.EQ.2) IFLOW=+1
      PRINT 145,UNT(IUNT,1)
      READ 130, TIN
      PRINT 150
      READ 130, HIN
      PRINT 160, UNT(IUNT,2)
      READ 130, CFM
      PRINT 180, UNT(IUNT,3)
      READ 130, BPH
      PRINT 190, UNT(IUNT,4)
      IF(IFLOW.GT.0.) GOTO 30
      READ 130, XLENG
      PRINT 200, UNT(IUNT,4)
      READ 130, DBTPR
C*****   SKIP TEMPERING AFTER LAST STAGE
      PRINT 290, UNT(IUNT,4)
      READ 130, XTMPR
   30 IF(IFLOW.LT.0.) GOTO 35
      XLENG=1.
      DBTPR=1.
      XTMPR=0.
      GOTO 40
   35 IF (IUNT.EQ.1) GO TO 40
      TIN=FT(TIN)
      CFM=CFM*.3048
      BPH=BPH*.2734
      XLENG=XLENG*.3048
      DBTPR=DBTPR*.3048
      XTMPR=XTMPR*.3048
C****   COMPUTE INLET RH
   40 RHIN=RHDBHA(F(TIN),HIN)
      RH=RHIN
C*****   CONVERT AIRFLOW TO KG/HR AND COMPUTE CONVECTIVE HEAT TRANS-
C*****   FER COEFFICIENT AND EQUILIBRIUM MOISTURE CONTENT
      GA=60.*CFM/VSDBHA(F(TAMB),HIN)
      HC=.047*HCA*((2.*GA*RO/.0675)**HCB)/RO
      XME=EMC(RHIN,TIN)
C*****   CONVERT GRAIN FLOW TO KG/HR AND COMPUTE GRAIN
C*****                 VELOCITY (M/HR)
```

```
      GP=1000.*BPH
      GVEL=GP/RHOP
      CALL STAGE(TIN,HIN,GA,HC,GP,XLENG,DBTPR,XTMPR)
C*****   MAKE END OF STAGE CALCULATIONS AND PRINT
      SP=((CFM/SPKA)**SPKB)*XLENG*2.54
      EAIR=GA*(CA+CV*HIN)*(TIN-TAMB)/GP
      HP=2.*CFM*SP/456.72
      EFAN=.746*HP*3413./GP
      EAUG=0.0
      ENERGY=EAIR+EFAN+EAUG
      SUMBTU=SUMBTU+ENERGY
      WATER=(XMO-Y(NP2))
      BTUH2O=SUMBTU/WATER
      PRINT 250, UNT(IUNT,13),SP*CNV(IUNT,14),UNT(IUNT,14),HP*CNV(IUNT,1
   15),UNT(IUNT,8),EFAN*CNV(IUNT,9),EAIR*CNV(IUNT,9),EAUG*CNV(IUNT,9),
   2SUMBTU*CNV(IUNT,9),UNT(IUNT,15),WATER,UNT(IUNT,8),BTUH2O*CNV(IUNT,
   39)
      DELM=XMIN-Y(NP2)
      CALL QUAL (DELQUL,DELM,Y(NP4),BPH)
      QUALITY=QUALITY+DELQUL
      PRINT 330, DELQUL,QUALITY
      GOTO 8
C*****   ESTIMATED QUALITY CHANGE FOR DRYING IN STAGE ISTG
C*****
C*****   FORMAT STATEMENTS
C*****
C
  130 FORMAT (F10.0)
  140 FORMAT (/, 7H STAGE ,I1, 18H INPUT CONDITIONS:,/
     15X,*STAGE TYPE (0=NEW ANALYSIS,1=CONCURRENT,2=COUNTER)*)
  145 FORMAT(5X, 16HINLET AIR TEMP, , A1)
  150 FORMAT (5X, 22HINLET ABS HUM RATIO   )
  160 FORMAT (5X, 14HAIRFLOW RATE, ,A9, 26H(AT AMBIENT CONDITIONS)    )
  170 FORMAT (5X, 44HINLET MOISTURE CONTENT, WET BASIS PERCENT    )
  180 FORMAT (5X, 17HGRAIN FLOW RATE, ,A10)
  190 FORMAT (5X, 14HDRYER LENGTH, ,A2)
  200 FORMAT (5X, 17HOUTPUT INTERVAL, ,A2)
  250 FORMAT (//18H STATIC PRESSURE, ,A2,7H OF H20,F12.2/
    +13H HORSEPOWER, ,A6,F6.2//
     116H ENERGY INPUTS, ,A6/10X,12HFAN (.5 EFF)F7.0/10X,8HHEAT AIR,4X
     2F7.0/10X,10HMOVE GRAIN2XF7.0/10X,5HTOTAL7XF7.0//
     316H WATER REMOVED, ,A5,F10.4//1X,A6,  4H H20,F9.2)
  260 FORMAT (5X, 14HAMBIENT TEMP, ,A1)
  270 FORMAT(///41H SIMULATE A CONCURRENT/COUNTER FLOW DRYER/
     111H USING THE ,A10,24H DIFFUSION EQUATION FOR ,A10/
     215H WITH INPUT IN ,A7,6H UNITS,//18H INPUT CONDITIONS: )
  280 FORMAT (I1)
  290 FORMAT (5X, 18HTEMPERING LENGTH, ,A2)
  300 FORMAT (/, 46H ESTIMATE OF THE EFFECT OF COUNTERFLOW COOLING,/5X,
     126HOUTLET GRAIN TEMPERATURE, ,A1,F9.2/5X, 34HFINAL MOISTURE CONTEN
     2T, WET BASIS ,F9.2)
  310 FORMAT (* GRAIN TYPE (0=STOP,1=BEANS,2=CORN)*)
  320 FORMAT (5X, 19HGRAIN TEMPERATURE, ,A1)
  330 FORMAT (//, 25H QUALITY CHANGE, PERCENT ,F6.2,5X, 13HTOTAL CHANGE
     1,F6.2)
  340 FORMAT ( 25H UNIT TYPE(1=SI,2=ENGLISH)
C
      END
      SUBROUTINE DERFUN
C****    SUBROUTINE FOR CALCULATING DERIVATIVES
C****          R.C. BROOK, PROGRAMMER
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```
      COMMON /PRPRTY/ SA,CA,CP,CV,CW,RHOP,HFG
      COMMON /CONSTNT/ CONA(12),CONB(12),CONC,COND,CONE(12),CON1,CON2,CO
     1N3,CON4,CON5,CON6
      COMMON /CNODE/ NODE,NP1,NP2,NP3,NP4,NTOT,ND,NDP1,NDTOT,NTMPR
      COMMON /CDIFF/ XME,RH,XMIN,CFM,GVEL,IFLOW
      COMMON /DIMEN/ ITYPE,FN,DELR,RO,V(10),VP
      COMMON /RKAM/ Y(202)
C*****   DERIVATIVE FOR MOISTURE AT CENTER NODE
      Y(ND)=6.*CON1*(Y(2)-Y(1))
C*****   DERIVATIVE FOR MOISTURE AT INTERIOR NODES
      IN=ND
      DO 10 INY=2,NODE
      IN=IN+1
   10 Y(IN)=CON1*(CONA(INY)*Y(INY+1)-2.*Y(INY)+CONB(INY)*Y(INY-1))
      IF (NTMPR.GT.0) GO TO 20
      Y(NDTOT)=CON1*(CONA(NP1)*XME-2.*Y(NP1)+CONB(NP1)*Y(NODE))
C*****   DERIVATIVE FOR GRAIN SURFACE MOISTURE (ASSUMED AVERAGE)
      Y(NDTOT+1)=Y(NDTOT)
C*****   DERIVATIVE FOR AIR HUMIDITY
   15 Y(NDTOT+2)=IFLOW*Y(NDTOT+1)/COND
C*****   DERIVATIVE FOR GRAIN TEMPERATURE
      Y(NDTOT+3)=(CON4*(Y(NTOT)-Y(NP4))-(HFG+CV*(Y(NTOT)-Y(NP4)))
     +*COND*Y(NDTOT+2)))/(CP+CW*Y(NP2))
C*****   DERIVATIVE FOR AIR TEMPERATURE
      Y(NDTOT+4)=IFLOW*CON5*(Y(NTOT)-Y(NP4))/(CA+CV*Y(NP3))
      GO TO 30
C*****   DERIVATIVES CONSTANT AIR/GRAIN TEMPERATURES (TEMPERING)
   20 Y(NDTOT)=-Y(NDTOT-1)
      Y(NDTOT+1)=0.
      Y(NDTOT+2)=0.
      Y(NDTOT+3)=0.
      Y(NDTOT+4)=0.
   30 RETURN
      END
      SUBROUTINE DATA
      COMMON /CNODE/ NODE,NP1,NP2,NP3,NP4,NTOT,ND,NDP1,NDTOT,NTMPR
      COMMON /PRPRTY/ SA,CA,CP,CV,CW,RHOP,HFG
      COMMON /DIMEN/ ITYPE,FN,DELR,RO,V(10),VP
      COMMON /CHC/ HCA,HCB
      COMMON /SPFAC/ SPKA,SPKB
      COMMON /CEMC/ EA,EB,EC
      COMMON /PRESS/ PATM
      COMMON /CONSTNT/ CONA(12),CONB(12),CONC,COND,CONE(12),CON(6)
      COMMON /NAME/ INAME,IPROD
      COMMON /CHFG/ HA,HB
      DATA CA,CV,CW,HFG/1.013,1.884,4.187,2326./
      DATA NODE,PATM/4,98599.0/
C*****   COMPUTE CONSTANTS FOR DERFUN
      NP1=NODE+1
      NP2=NODE+2
      NP3=NODE+3
      NP4=NODE+4
      NTOT=NODE+5
      ND=NODE+8
      NDP1=ND+1
      NDTOT=ND+NODE
      FN=2.*FLOAT(NP1)**3
      DO 10 IN=2,NP2
      CONA(IN)=FLOAT(IN)/FLOAT(IN-1)
      CONB(IN)=FLOAT(IN-2)/FLOAT(IN-1)
   10 CONE(IN)=(FLOAT(IN-1)**3-FLOAT(IN-2)**3)/FN
```

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C*****   FOR REFERENCES SEE R.C.BROOK PHD THESIS, MSUAE-1,977
      IF (ITYPE.EQ.2) GO TO 20
C*****   INITIALIZE CONSTANTS FOR BEANS
      SA=880.
      CP=1.675
      RHOP=929.0
      SPKA=19.81
      SPKB=1.431
      EB=0.066826
      EA=0.48092
      EC=120.098
      HCA=0.992
      HCB=0.66
      HA=0.21624
      HB=-6.233
      RO=0.00457
      DELR=RO/FLOAT(NP1)
      INAME=10H SABBAH
      IPROD=10H BEANS
      GO TO 50
C*****   INITIALIZE CONSTANTS FOR CORN
   20 SA=784.1
      CP=1.122
      RHOP=620.1
      SPKA=17.68
      SPKB=1.528
      EB=0.05897
      EA=0.379212
      EC=30.205
      HCA=0.389
      HCB=0.850
      HA=4.349
      HB=-28.25
      RO=0.00484
      DELR=RO/FLOAT(NP1)
      INAME=10H HUSTRULID
      IPROD=10H CORN
50    CONTINUE
      RETURN
      END
C***
C
      FUNCTION EMC(RH,T)
C
C***
C**      COMPUTE EQUILIBRIUM MOISTURE USING CHUNG-PFOST EQU.
      COMMON /CEMC/ EA,EB,EC
      RHT=RH
      IF (RHT.GT.0.95) RHT=0.95
      IF (RHT.LT.0.01) RHT=0.01
      EM=EA-EB*ALOG(-1.987*(T+EC)*ALOG(RHT))
      IF(EM.LT.0.0001) EM=0.0001
      EMC=EM
      RETURN
      END
C
C***
      FUNCTION FHFG(XM,TH)
C***
C
C**      COMPUTE GRAIN LATENT HEAT OF VAPORIZATION
```

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      COMMON /CHFG/ HA,HB
      WHFG=2502.11-2.386*TH
      FHFG=WHFG*(1.+HA*EXP(HB*XM))
      RETURN
      END
C****
C****
      SUBROUTINE QUAL (DELQ,DELM,TH,BPH)
C****
C****
      COMMON /DIMEN/ ITYPE,FN,DELR,RO,V(10),VP
      IF (ITYPE.EQ.2) GO TO 10
      DELQ=.19868+5.55408*TH*DELM/BPH
      IF (DELQ.LT.0.0) DELQ=0.0
      RETURN
   10 DELQ=-8.39995+143.65433*DELM
      IF (DELQ.LT.0.0) DELQ=0.0
      RETURN
      END
C
C
      FUNCTION FDIFF(XM,TH)
C
C
      COMMON /DIMEN/ ITYPE,FN,DELR,RO,V(10),VP
      COMMON /CDIFF/ XME,RH,XMIN,CFM,GVEL,IFLOW
      IF (ITYPE.EQ.2) GO TO 10
C*****   COMPUTE DIFFUSION COEFFICIENT FOR BEANS
      FDIFF=0.04694372*EXP(-3437.16/(TH+273.13))
      RETURN
C*****   COMPUTE DIFFUSION COEFFICIENT FOR CORN (CHU-HUSTRULID)
   10 FDIFF=1.5134E-4*EXP((.045*TH+6.806)*XM-2513.0/(TH+273.13))
      RETURN
      END
C
C
      FUNCTION PSDB(DB)
C
C
      DATA R,A,B/.2210584739E08,-.274055258361E05,.9754129373E02/
      DATA C,D,E/-.1462440044,.1255753189E-03,-.4850171032E-07/
      DATA F,G/.434902897800E01,.3938107141E-02/
      IF (DB-273.16) 10,20,20
   10 PSDB=EXP(31.9602-6270.3605/DB-.46057*ALOG(DB))
      RETURN
   20 PSDB=R*EXP((A+DB*(B+DB*(C+DB*(D+DB*E))))/(DB*(F-G*DB)))
      RETURN
C
      END
      FUNCTION PVHA(HA)
      COMMON /PRESS/ PATM
      PVHA=HA*PATM/(.6219+HA)
      RETURN
C
      END
      FUNCTION HLDB(DB)
      IF (DB-273.16) 10,20,20
   10 HLDB=2839776.184-212.563836*(DB-255.38)
      RETURN
   20 IF (DB-338.72) 30,40,40
   30 HLDB=2502535.259-2385.764244*(DB-338.72)
```

```
      RETURN
   40 HLDB=SQRT(7329155978000.-15995964.08*DB*DB)
      RETURN
C
      END
      FUNCTION VSDBHA(DB,HA)
      COMMON /PRESS/ PATM
      VSDBHA=287.0*DB*(.6219+HA)/.6219/PATM
      RETURN
C
      END
      FUNCTION RHDBHA(D1,D2)
      A=PSDB(D1)
      B=PVHA(D2)
   10 RHDBHA=B/A
      RETURN
C
      END
      SUBROUTINE STAGE(TIN,HIN,GA,HC,GP,XLENG,DBTPR,XTMPR)
      COMMON /CONSTNT/ CONA(12),CONB(12),CONC,COND,CONE(12),CON1,CON2,CO
     1N3,CON4,CON5,CON6
      COMMON /CNODE/ NODE,NP1,NP2,NP3,NP4,NTOT,ND,NDP1,NDTOT,NTMPR
      COMMON /CDIFF/ XME,RH,XMIN,CFM,GVEL,IFLOW
      COMMON /CHC/ HCA,HCB
      COMMON /CUNT/IUNT,UNT(2,15),CNV(2,16),UNTTYP(2)
      COMMON /PRESS/PATM
      COMMON /PRPRTY/ SA,CA,CP,CV,CW,RHOP,HFG
      COMMON /DIMEN/ ITYPE,FN,DELR,RO,V(10),VP
      COMMON /RKAM/ Y(202)
      DIMENSION YSAVE(202)
      F(T)=T+273.13
      CFMHOT=GA*VSDBHA(F(TIN),HIN)/60.
      XMEW=100.*XME/(1.+XME)
C*****   PRINT HEADER PAGE OF CONDITIONS AND PROPERTIES
      PRINT 220, RH,UNT(IUNT,10),GA*CNV(IUNT,11),UNT(IUNT,2),CFMHOT*CNV(
     1IUNT,3),UNT(IUNT,11),HC*CNV(IUNT,12),XMEW,XME,Y(NP2),UNT(IUNT,12),
     2GVEL*CNV(IUNT,13),UNT(IUNT,10),GP*CNV(IUNT,11)
      PRINT 230, UNT(IUNT,4),UNT(IUNT,1),UNT(IUNT,15),UNT(IUNT,1)
      IF(IFLOW.LT.1) GOTO 40
C*****   COUNTERFLOW ESTIMATOR
      ICNT=0
      TOUT=TIN
      HOUT=HIN
      THOUT=Y(NP4)
      XMOUT=Y(NP2)
      CALL COOL(THOUT,XMOUT,GP,TOUT,HOUT,GA,HC,XLENG)
      WB=100.*XMOUT/(1.+XMOUT)
      RH=RHDBHA(F(TOUT),HOUT)
      PRINT 7,TOUT,HOUT,RH,THOUT,WB,XMOUT
    7 FORMAT(14H COOL ESTIMATE,2X,F8.1,2F8.4,F8.1,F8.2,F8.4)
      RETURN
   40 Y(NP3)=HIN
      Y(NTOT)=TIN
      RH=RHDBHA(F(Y(NTOT)),Y(NP3))
      XME=EMC(RH,Y(NTOT))
      CALL SOLVE(GA,HC,GP,XLENG,DBTPR,XTMPR)
      RETURN
  220 FORMAT(//30H PRELIMINARY CALCULATED VALUES//17H REL HUM, DECIMAL
     1F6.4/15H AIRFLOW RATE  A9,F8.1,3X,A9,7H AT TIN,F6.1/
     221H HEAT TRANSFER COEF, ,A10,F8.3/21H EQUIL MC, WB PERCENT,F6.2,
     320H  DRY BASIS, DECIMAL,F6.4/28H INLET MC, DRY BASIS DECIMAL,
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     4F6.4/17H GRAIN VELOCITY, ,A5,F6.2,  1H ,A9,F8.2)
  230 FORMAT (//3X,5HDEPTH4X,4HTIME5X,3HAIR5X,3HABS5X,3HREL3X,5HGRAIN6X,
     12HMC6X,2HMC/20X,4HTEMP5X,3HHUM5X,3HHUM4X,4HTEMP6X,2HWB6X,2HDB/7X,A
     22,5X,2HHR7X,A1,3X,A5,8H DECIMAL,7X,A1,16H PERCENT DECIMAL)
      END
      SUBROUTINE SOLVE(GA,HC,GP,XLENG,DBTPR,XTMPR)
      COMMON /CONSTNT/ CONA(12),CONB(12),CONC,COND,CONE(12),CON1,CON2,CO
     1N3,CON4,CON5,CON6
      COMMON /CNODE/ NODE,NP1,NP2,NP3,NP4,NTOT,ND,NDP1,NDTOT,NTMPR
      COMMON /CDIFF/ XME,RH,XMIN,CFM,GVEL,IFLOW
      COMMON /CUNT/IUNT,UNT(2,15),CNV(2,16),UNTTYP(2)
      COMMON /DIMEN/ ITYPE,FN,DELR,RO,V(10),VP
      COMMON /PRPRTY/ SA,CA,CP,CV,CW,RHOP,HFG
      COMMON /CHC/ HCA,HCB
      COMMON /RKAM/ Y(202)
      F(T)=T+273.13
      WB=100.*Y(NP2)/(1.+Y(NP2))
      RH=RHDBHA(F(Y(NTOT)),Y(NP3))
      PRINT 240,0.,0.,Y(NTOT)*CNV(IUNT,1)+CNV(IUNT,
     12),Y(NP3),RH,Y(NP4)*CNV(IUNT,1)+CNV(IUNT,2),WB,Y(NP2)
C*****   COMPUTE CONSTANTS USED BY EQUATIONS IN SUBROUTINE DERFUN
      NTP1=NTOT+1
      PRL=DBTPR
      DIFF=FDIFF(XMIN,Y(NP4))
      CONC=GVEL*DELR*DELR
      COND=GA/GP
      CONF=9.8696/RO/RO
      CON1=DIFF/CONC
      CON2=DIFF*CONF
      CON3=CW*CON1
      CON4=HC*SA/GP
      CON5=HC*SA/GA
      CON6=.6079*CON2/GVEL
C*****   CALL START TO INITIALIZE SOLUTION BY TAKING RUNGE-KUTTA STEPS
      NTMPR=0
      IEXIT=0
      CALL START (NTOT,3,1,1.E-4,1.E-4,1.E-8,.05,1.E-6,.5)
C*****   BEGINNING OF LOOP
   50 HFG=FHFG(Y(NP2),Y(NP4))
      XMB=Y(NP2)
C*****   CALL RKAMSUB TO TAKE NEXT STEP
      CALL RKAMSUB
C*****   COMPUTE AIR HUMIDITIES
      RH=RHDBHA(F(Y(NTOT)),Y(NP3))
      NTMPR=0
      IF (RH.LT.1.0) GOTO 55
      NTMPR=1
      RH=0.9999999999
   55 CONTINUE
      XME=EMC(RH,Y(NP4))
C*****   CALCULATE LENGTH VARIABLE CONSTANTS
      DIFF=FDIFF(Y(NP2),Y(NP4))
      CON1=DIFF/CONC
      CON2=DIFF*CONF
      CON3=CW*CON1
      CON6=.6079*CON2/GVEL
C*****   CHECK IF LONG ENOUGH, MOISTURE CONTENT LOW ENOUGH OR TIME TO
C*****   PRINT...IF NONE OF THESE GO TO BEGINNING OF LOOP
      IF (Y(NTP1).GE.XLENG) GO TO 60
      DELY=XLENG-Y(NTP1)
      IF (DELY.LT.Y(NTOT+2)) Y(NTOT+2)=DELY
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```
      IF (Y(NTP1)-PRL) 50,70,70
   60 IEXIT=1
   70 PRL=PRL+DBTPR
C*****   MAKE FINAL CALCULATIONS AND PRINT
      ETIME=Y(NTP1)/GVEL
      WB=100.*Y(NP2)/(Y(NP2)+1.)
      PRINT 240,Y(NTP1)*CNV(IUNT,5),ETIME,Y(NTOT)*CNV(IUNT,1)+CNV(IUNT,
     12),Y(NP3),RH,Y(NP4)*CNV(IUNT,1)+CNV(IUNT,2),WB,Y(NP2)
C*****   CHECK IF EXIT CONDITION HAS BEEN MET...IF NOT RETURN TO BEGIN
C*****   NING OF LOOP
   75 IF (IEXIT.EQ.0) GO TO 50
C*****   CALCULATE EFFECT OF TEMPERING ON MOISTURE PROFILE
C*****   SKIP IF ZERO TEMPERING LENGTH
      IF (XTMPR.LE.0.) GO TO 110
C*****   INITIALIZE CONTROLS FOR TEMPERING
      NTMPR=1
      Y(NTP1)=0.
      PRL=0.
      IEXIT=0
      HFG=FHFG(Y(NP2),Y(NP4))
C*****   CALL START TO INITIALIZE SOLUTION BY TAKING RUNGE-KUTTA STEPS
      CALL START (NTOT,3,1,1.E-2,1.E-4,1.E-8,.1,1.E-4,.5)
C*****   CALL RKAMSUB TO TAKE NEXT STEP
   80 CALL RKAMSUB
C*****   CHECK IF LONG ENOUGH, MOISTURE CONTENT LOW ENOUGH OR TIME TO
C*****   PRINT...IF NONE OF THESE GO TO BEGINNING OF LOOP
      IF (Y(NTP1).GE.XTMPR) GO TO 90
      DELY=XTMPR-Y(NTP1)
      IF (DELY.LT.Y(NTOT+2)) Y(NTOT+2)=DELY
      IF (Y(NTP1)-PRL) 80,100,100
C*****   SET FLAG IF EXIT CONDITION MET
   90 IEXIT=1
C*****   CHECK IF EXIT CONDITION HAS BEEN MET...IF NOT RETURN TO BEGIN
C*****   NING OF LOOP
  100 IF (IEXIT.EQ.0) GO TO 80
  110 RETURN
  240 FORMAT (2F8.2,F8.1,2F8.4,F8.1,F8.2,F8.4)
      END
      SUBROUTINE COOL (THIN,XMIN,GP,TAMB,HAMB,GA,HC,XLENG)
      COMMON /PRPRTY/ SA,CA,CP,CV,CW,RHOP,HFG
      C2=(GA*(CA+CV*HAMB)*TAMB+GA*HAMB*HFG)/TAMB
      C1=GP*(CP+CW*XMIN)
      HOUT=HAMB
      XMOUT=XMIN
      XM5=0.
      ICNT=0
   10 I=0
      ICNT=ICNT+1
      IF (C2.LT.C1) GO TO 20
   15 C3=C1
      C1=C2
      C2=C3
      I=1
   20 F=EXP((HC*SA*XLENG/C2)*((C2/C1)-1.))
      E=(1.-F)/(1.-(C2/C1)*F)
      IF (I.EQ.1) GO TO 30
      TOUT=TAMB+E*(THIN-TAMB)
      THOUT=THIN-(C2/C1)*E*(THIN-TAMB)
      GO TO 40
   30 CONTINUE
      THOUT=THIN-E*(THIN-TAMB)
```

```
      TOUT=TAMB+(C2/C1)*E*(THIN-TAMB)
   40 IF(TAMB.GT.THIN) GOTO 42
      A=GP*(CV*TOUT-CW*THIN+HFG)
      B=GA*(CA+CV*HOUT)*(TOUT-TAMB)-GA*HOUT*HFG
      C=GP*(CV*TOUT-CW*THOUT+HFG)
      GOTO 43
   42 A=GP*(CV*THOUT-CW*TAMB+HFG)
      B=GA*(CA+CV*HOUT)*(TAMB-TOUT)-GA*HOUT*HFG
      C=GP*(CV*THOUT-CW*TOUT+HFG)
   43 XMOUT=(A*XMIN-B)/C
      C1=GP*(CP+CW*(XMIN+XMOUT)/2.)
      HOUT=HAMB+GP*(XMIN-XMOUT)/GA
      C2=GA*(CA+CV*(HAMB+HOUT)/2.)+GA*HFG*(HAMB+HOUT)/(TAMB+TOUT)
      XM6=ABS(XMOUT-XM5)
      XM5=XMOUT
      IF(ICNT.GT.100) GOTO 99
      IF (XM6.GT.1.E-6) GO TO 10
45    XMIN=XMOUT
      THIN=THOUT
      TAMB=TOUT
      HAMB=HOUT
      RETURN
99    PRINT 50,ICNT,XM6
50    FORMAT(5X,*$$$$$$$$$$      STOP AFTER *,I3,* ITERATIONS*/
     +5X,*$$$$$$$$$$      XM6=*,F10.5)
      GOTO 45
      END
      SUBROUTINE RKAMSUB
      DIMENSION DELY(4,100),BET(4),XV(5),FV(4,100),YU(5,100)
      COMMON/SHARE/NN,SPACE ,MODE,KKA,E1MAX,E1MIN,E2MAX,E2MIN,FACT
      COMMON /RKAM/Y(202)
      TYPE DOUBLE YU
      IF (MODE .EQ. 1) 2, 4
C*****   RUNGE-KUTTA SOLVING ROUTINE
    1 LL = 1
    2 DO 103  K = 1, 4
        DO 101  I = 1, NN
          DELY(K,I) = Y(N2)*FV(MM,I)
          Z = YU(MM,I)
          Y(I) = Z + BET(K)*DELY(K,I)
  101   CONTINUE
        Y(NP1) = BET(K)*Y(N2) + XV(MM)
        CALL DERFUN
        DO 102  I = 1, NN
          FV(MM,I) = Y(I+N2)
  102   CONTINUE
  103 CONTINUE
      DO 104  I = 1, NN
        DEL = (DELY(1,I)+2.0*DELY(2,I)+2.0*DELY(3,I)+DELY(4,I))/6.0
        YU(MM+1,I) = YU(MM,I) + DEL
  104 CONTINUE
      MM = MM + 1
      XV(MM) = XV(MM-1) + Y(N2)
      DO 105  I = 1, NN
        Y(I) = YU(MM,I)
  105 CONTINUE
      Y(NP1) = XV(MM)
      CALL DERFUN
      IF (MODE .EQ. 1) 16, 3
    3 DO 106  I = 1, NN
        FV(MM,I) = Y(I+N2)
```

```
  106 CONTINUE
      GO TO (2,2,2,4), MM
C*****   ADAMS-MOULTON SOLVING ROUTINE
    4 DO 107  I = 1, NN
        DEL = Y(N2)*(55.0*FV(4,I)-59.0*FV(3,I)+37.0*FV(2,I)-9.0*FV(1,I))
     1  /24.
        Y(I) = YU(4,I) + DEL
        DELY(1,I) = Y(I)
  107 CONTINUE
      Y(NP1) = XV(4) + Y(N2)
      CALL DERFUN
      XV(5) = Y(NP1)
      DO 108  I = 1, NN
        DEL = Y(N2)*(9.0*Y(I+N2)+19.0*FV(4,I)-5.0*FV(3,I)+FV(2,I))/24.0
        YU(5,I) = YU(4,I) + DEL
        Y(I) = YU(5,I)
  108 CONTINUE
      CALL DERFUN
      IF (MODE .EQ. 3) 5, 16
C*****   ERROR ANALYSIS
    5 SSE = 0.0
      DO 109  I = 1, NN
        EPSIL = R*ABS(Y(I)-DELY(1,I))
        IF (MODE .EQ. 1) 6, 8
    6   IF (Y(I)) 7, 8, 7
    7   EPSIL = EPSIL/ABS(Y(I))
    8   IF (SSE-EPSIL) 9, 109, 109
    9   SSE = EPSIL
  109 CONTINUE
      IF (E1MAX-SSE) 10, 10, 11
   10 IF (ABS(Y(N2))-E2MIN) 16, 16, 13
   11 IF (SSE-E1MIN) 12, 16, 16
   12 IF (E2MAX-ABS(Y(N2))) 16, 16, 14
   13 LL = 1
      MM = 1
      Y(N2) = Y(N2)*FACT
      GO TO 2
   14 IF (LL .EQ. 1) 16, 15
   15 XV(2) = XV(3)
      XV(3) = XV(5)
      DO 110  I = 1, NN
        FV(2,I) = FV(3,I)
        FV(3,I) = Y(I+N2)
        YU(2,I) = YU(3,I)
        YU(3,I) = YU(5,I)
  110 CONTINUE
      Y(N2) = 2.0*Y(N2)
      LL = 2
      MM = 3
      GO TO 2
C*****   EXIT ROUTINE
   16 DO 112  K = 1, 3
        XV(K) = XV(K+1)
        DO 111  I = 1, NN
          FV(K,I) = FV(K+1,I)
          YU(K,I) = YU(K+1,I)
  111   CONTINUE
  112 CONTINUE
      LL = 2
      MM = 4
      XV(4) = XV(5)
```

```
      DO 113  I = 1, NN
        FV(4,I)  = Y(I+N2)
        YU(4,I)  = YU(5,I)
  113 CONTINUE
      IF (MODE .EQ. 3) 24, 26
C *****  ENTRY    STARTING RUNGE:KUTTA ROUTINE
      ENTRY RKSTART
      ALP = Y(NN+1)
      EPM = 0.0
      IF (MODE .EQ. 1) 17, 18
   17 MM = 4
      GO TO 19
   18 MM = 1
   19 BET(1)  = 0.5
      BET(2)  = 0.5
      BET(3)  = 1.0
      BET(4)  = 0.0
      N2 = NN + 2
      Y(N2)  = SPACE
      NP1 = NN + 1
      R = 19.0/270.0
      XV(MM)  = Y(NP1)
      IF (E1MIN) 20, 20, 21
   20 E1MIN = E1MAX/55.0
   21 IF (FACT) 22, 22, 23
   22 FACT = 1.0/2.0
   23 CALL DERFUN
      DO 114  I = 1, NN
        FV(MM,I)  = Y(I+N2)
        YU(MM,I)  = Y(I)
  114 CONTINUE
      N3 = N2 + NN + 1
      N4 = N3 + 1
      GO TO 1
   24 E = ABS(XV(4)-ALP)
      IF (E-EPM) 4, 4, 25
   25 EPM = E
   26 RETURN
      END
      SUBROUTINE START(M1,M2,M3,A1,A2,A3,A4,A5,A6)
      COMMON/SHARE/NN,SPACE ,MODE,KKA,E1MAX,E1MIN,E2MAX,E2MIN,FACT
C*****        START     -LASTMAN,G.J. COOP ID  D2 UTEX RKAMSUB (1964)
C START ARGUMENTS: 1) NUMBER EQUATIONS 2) INTEGRATOR RK,AM,AM:ERROR
C  3) ERORR RELATIVE OR ABSOLUTE 4) MESH INITIAL 5)MAX SINGLE STEP ERROR
C 6) MIN SINGLE STEP ERROR 7) MAX MESH SIZE 8) MIN MESH SIZE
C 9)REDUCTION FACTOR MESH :NOTE IF AM:ERROR CHECKING THEN NEED 5 THRU 9.
      NN = M1
      MODE = M2
      KKA = M3
      SPACE = A1
      E1MAX = A2
      E1MIN = A3
      E2MAX = A4
      E2MIN = A5
      FACT = A6
      CALL RKSTART
      RETURN
      END
```