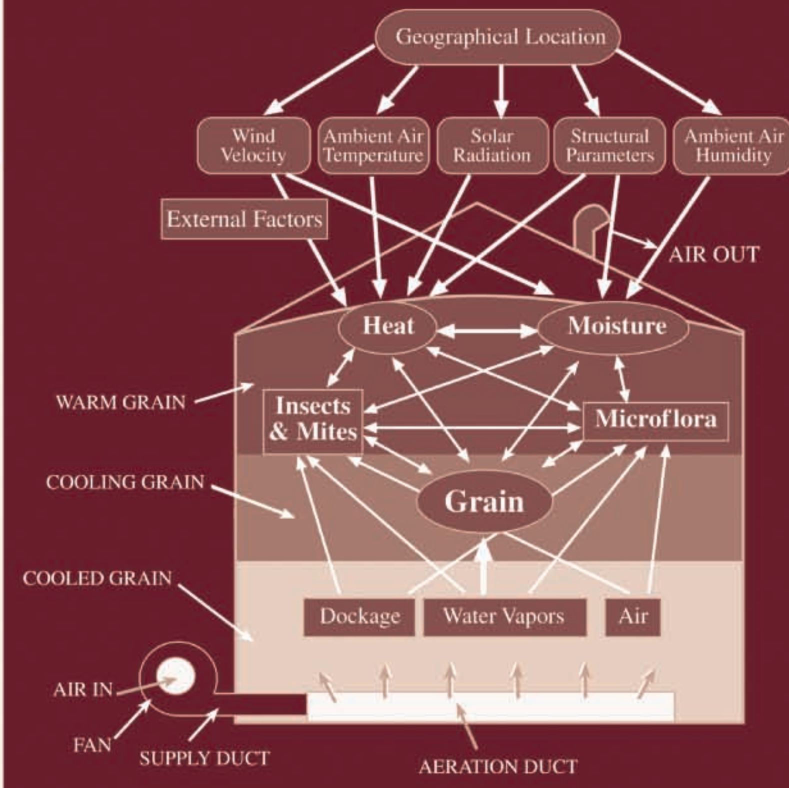
The MECHANICS and PHYSICS of MODERN GRAIN AERATION MANAGEMENT



Edited by

Shlomo Navarro

Ronald Noyes

CRC PRESS

The MECHANICS and PHYSICS of MODERN GRAIN AERATION MANAGEMENT

The MECHANICS and PHYSICS of MODERN GRAIN AERATION MANAGEMENT

Edited by
Shlomo Navarro
Ronald Noyes

CRC PRESS
Boca Raton London New York Washington, D.C.

Library of Congress Cataloging-in-Publication Data

The mechanics and physics of modern grain aeration management / Shlomo Navarro and Ronald Noyes, editors.
p. cm.
Includes bibliographical references and index.
ISBN 0-8493-1355-4 (alk. paper)
1. Grain aeration—Management. I. Navarro, Shlomo. II. Noyes, Ronald T.

SB190 .M42 2001
633.1′0468—dc21 2001035405

International Standard Book Number 0-8493-1355-4
Library of Congress Card Number 2001035405
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0
Printed on acid-free paper

Dedication

This book is dedicated to Juliet Navarro and Zona Noyes, who provided much-needed support throughout the years of development and strongly encouraged us to complete this book. Without their continued patience and understanding, this project would not have been possible.

Foreword

The discontinuation of registration of many highly toxic pesticides used until recently and the ban on methyl bromide (associated with the depletion of atmospheric ozone) have generated an immediate worldwide need for alternative technologies to solve grain storage problems. This manual presents the most advanced theoretical concepts and practical solutions to grain management through the effective use of various forms of aeration as they affect grain storage science and technology. This book describes and illustrates the many variations in aeration practice that are required for effectively cooling grain, for controlling storage insects, and for improving the storability of grain commodities while minimizing residual pesticides and molds.

The beginning of this collaborative writing partnership between Shlomo Navarro and Ronald Noyes began in 1991 to 1992, when Navarro submitted the original outline for the handbook to CRC Press. CRC asked Noyes to review the outline, and Noyes suggested the need for more applied chapters in the book. The authors communicated on a series of ideas related to grain storage technologies, including aeration, and on the need for this aeration handbook. An expanded outline of the handbook developed during subsequent meetings in 1993 and 1994. After the beginning of preparatory collaborations by the two authors in 1997, additional topics of major importance with other collaborating authors were identified and incorporated to make this a more complete coverage of the many aspects of forced air and gas movement that collectively fall within the scope of aeration.

The expanded coverage of all aspects of aeration contained in this manual is deemed necessary to provide guidance for practicing and future grain storage engineers, grain technologists, and entomologists, their technicians, and bulk grain managers, who are destined to bear responsibility for the quality of cereals and their products throughout the world.

Because the scientific community uses the metric system, metric units are employed predominantly throughout the book. However, because of its expected extensive use in the U.S., we have adopted American English as the language of the book and have periodically incorporated dual units of measure. Thus, metric units are primary; and English units are secondary in some sections (especially in the "practical" handbook core Chapters 5, 6, 7 and 8) to make working examples more user friendly to U.S. engineers, grain storage manufacturers, and commercial grain industry personnel. Dual units (metric/English) are also used where data tables were abstracted from other English unit sources such as dissertations, research reports, and technical papers.

In addition to the conversion of English to metric units, another difficulty that remained was to bridge between the various units used to describe airflow, even within the metric system. As an example of dual units, we cite the conventionally accepted pressure units, inches water column (in w.c.) used by past generations of engineers, and the new generation that uses only Pascal (Pa) units. To conform to the internationally accepted SI units system, we have elected to use Pa for pressure systems. For airflow rates we used three principal units of airflow — cfm/bu, (m^3/h)/tonne for practical discussions of airflow, and L/s.m^3 for theoretical scientific discussion of research data and practices.

Although the units cfm/bu and L/s.m^3 reflect accurate definitions of airflow rates, the unit (m^3/h)/tonne was included because it reflects a more meaningful unit used in daily practice in grain storage technology worldwide. This approach was adopted primarily because the grain storage manager usually knows the weight (mass) of grain in the bins but not the volume of grain. He requires additional calculations to convert weight to volume. We believe the readers will find these conversions useful in using the recommendations of the text for local use when converted to the units adopted by the reader.

The editors and co-authors are convinced that this book has provided us with a unique opportunity to collectively summarize the state of the art of grain storage technology throughout the world.

The book is arranged to provide the reader with an Introduction that includes a general background of grain storage technology. Chapter 1 reviews the objectives and describes what is expected by the application of the various forms of aeration. Chapter 2 includes basic approaches adopted toward the effects of aeration on the stored grain ecosystem, then describes the physical process that occurs during heat and mass transfer in non-aerated grain bulks.

Chapters 3 and 4 deal with air properties (psychrometrics) and grain bulk properties, respectively. To enhance the description and design applications of aeration systems in Chapter 5, appendices include physical design considerations that help the practicing engineer to apply his knowledge to the design and operation of a wide range of aeration systems.

Chapters 6, 7, and 8 deal with experimental aeration systems, the operation of aeration systems, and specialized supplementary aeration systems. The potential importance to the grain industry of chilling grain with refrigerated air is considered separately in Chapter 9. Special attention is also given to evaluating aeration system efficiency in Chapter 10. Finally, because of the special design requirements involved, Chapter 11 is dedicated to modeling of air distribution in aeration.

Preface

The preparation and release of this publication is timely because it details the most practical available technology that is designed to cope with environmental pollution resulting from historic and traditional conservation practices in grain storage facilities. Its release at the beginning of the 21st century coincides with the preferences of many consumers for grains and seeds that are free of pesticide residue.

This handbook focuses on the protection of grain and other bulk products from deterioration by insects and molds through diligent sanitation and temperature management practices. It includes contributions by distinguished researchers currently active in the field of grain storage with particular expertise in aeration and cooling technologies of grain stored in bulk. Their joint experience is derived from research work on four continents and from travels and field experience throughout the world.

The original impetus for the preparation of this volume was a modest, state-of-the-art publication prepared for the FAO (Food and Agriculture Organization) of the United Nations entitled *Aeration of Grain in Subtropical Climates,* FAO Agricultural Services Bulletin No. 52 (Navarro and Calderon, 1982). This FAO publication documented the current information on aeration technology available at that time. Particular emphasis was placed on the inherent advantages of using aeration in subtropical climates.

The outline of the 1982 publication was prepared during an FAO mission by Shlomo Navarro to Cyprus to assist the Cyprus Grain Commission and the Cyprus Ministry of Agriculture. The objective of the mission was to disseminate the grain storage management technology to strengthen the existing infrastructure in Cyprus in the use of aeration and chilling of grain by refrigerated air. Dr. Navarro remains indebted to the late Geoff G. Corbett, senior officer, Storage of Food Crops and Inputs, FAO Agricultural Research Service, for his encouragement in the preparation of the FAO publication. Geoff Corbett will always be remembered for his contribution to disseminating advanced grain storage technologies throughout the world, particularly in developing countries.

Acknowledgments

We especially thank our colleague Dr. Ezra Donahaye, Department of Stored Products, Israel Agricultural Research Organization (ARO), for his careful reading and accurate review of this publication. His excellent comments have resulted in significant improvements in the scientific accuracy and functional application of aeration throughout this book.

The excellent staff of CRC Press LLC, particularly John Sulzycki, senior editor, Sara Seltzer, production manager, and Madeline Leigh, project editor, are to be commended for their diligence and painstaking attention to detail that has provided technical continuity of thought and consistency in reading style throughout the text. CRC has indeed homogenized the writings of authors from four continents to the great benefit of and better understanding by the reader. CRC has been most supportive of the authors during the duration of the writing and review phases of preparation of this progressively enlarging work in progress.

We are extremely grateful to Dr. Guray Ahmet Ferizli, visiting scientist from the University of Ankara, Turkey, who contributed to the understanding of the text through his illustrative work. Dr. Ferizli prepared many figures for Chapters 1, 5, 6, 7, and 9. We also thank Dr. Sam Angel of the ARO for his invaluable help in reviewing drafts of various chapters, improving style, and retrieving literature. We are also grateful to Dr. Simcha Finkelman for helping to finalize the chapters and for annotating lists of references. Miriam Rindner, Avi Azrieli, Rafael Dias, and Dr. David Hovevey-Sion of the Department of Stored Products, ARO, were of tremendous help during the different phases of the preparation of this publication by preparing new graphs and providing literature and data.

Our special thanks particularly are extended to Dr. Svetlana Fishman, mathematician at the Department of Statistics, Israel ARO, for her patience and competence in reviewing the many mathematical equations for technical accuracy and application in various chapters. We also profoundly thank all contributing authors and reviewers of this book. Without their enthusiasm, perseverance, loyal support, and dedication to the vision of this new stand-alone worldwide handbook of aeration, this volume could not have been written.

About the Authors

Dr. Shlomo Navarro, Ph.D., is a principal scientist in the Agricultural Research Organization (ARO), Volcani Center, Bet Dagan, Israel. Dr. Navarro was instrumental in organizing the Department of Stored Products and has served as head of the department. He has chaired numerous professional and scientific committees at the ARO, including the Research Projects Evaluation Committee on Food Technology and the Stored Products Advisory Board of the Ministry of Agriculture. He has held numerous positions, among them director for academic affairs and director for international cooperation at the ARO. Currently he serves as chairman of the Committee for Promoting Commercialization of R&D Applications and deputy director for international relations, ARO. He has conducted postharvest research in tropical and subtropical countries of the world.

In 1972, Dr. Navarro cofounded the Permanent Working Committee for the International Conference on Controlled Atmosphere and Fumigation (CAF). He has been Secretary of CAF since its inception. He has edited two books of proceedings of the CAF Conferences and one book of the International Conference on Stored Product Protection. His *Handbook of Aeration of Grain in Subtropical Climates* for the FAO was the leading authority for aeration in tropical and subtropical grain stores and was the forerunner of this book. He has authored or coauthored 287 technical articles in scientific journals, conference proceedings, and books. He holds five patents on developing storage structures and technologies. Dr. Navarro is the leading authority on hermetic storage in semi-permanent plastic storage structures for use with grains, seeds, dried fruits, and other stable bulk products.

Dr. Ronald Noyes, P.E., Ph.D., is professor, Stored Product Management, BioSystems and Agricultural Engineering Department, Oklahoma State University, Stillwater, OK. Since 1985 he has developed advanced grain storage automatic aeration controls and recirculation fumigation systems for grain elevators in Oklahoma and throughout the U.S. His work in adapting recirculation fumigation to steel bins and concrete silos in the U.S. has improved fumigation efficacy while minimizing required dosages. During his tenure on the faculty of Purdue University in the mid 1960s, Dr. Noyes conducted the first field research of *Dryeration,* a high-speed aeration process used to improve drying efficiency while maintaining higher grain quality from high-temperature grain dryers. From 1968 to 1985, Dr. Noyes was chief engineer and vice president, engineering for a U.S. grain dryer manufacturer, where he invented and patented an energy-saving process that reduced fuel consumption of continuous flow column type grain dryers by 40 to 50%. He holds six U.S. patents on grain dryers. Dr. Noyes is a member of the Permanent Working Committee of the International Conference on Controlled Atmosphere and Fumigation (CAF) and consults internationally on grain storage aeration and fumigation system design and management.

Mr. David Armitage C. Biol., M.I. Biol., is a senior scientific officer and contract manager with the Ministry of Agriculture, Fisheries and Food's Central Science Laboratory in York, where he leads a small sub-team on integrated commodity management. He has worked on aeration since 1971, initially with Mr. Norman Burrell, the pioneer of the technology in the U.K. Mr. Armitage has contributed over 60 papers on storage technology, specializing in effects of control measures on insects, mites, and fungi. He is a principal author of the U.K.'s primary advisory sources on storage, *The Grain Storage Guide,* and the integrated grain storage manager software. Currently he is on the organizing committee of the 8th International Working Conference on Stored Product Protection to be held in 2002 in York, U.K. He is also known as an aquarist, specializing in a family of air-breathing fish that he has studied in their natural habitats in Africa and Asia.

Dr. Digvir S. Jayas, P. Eng., P. Ag., is associate dean for research, Faculty of Agricultural and Food Sciences, University of Manitoba, Winnipeg, Manitoba, Canada. Dr. Jayas joined the University of Manitoba in 1985 as a member in the Department of Agricultural Engineering (now Biosystems Engineering), serving from 1997 to 1999 as department head. His research objective is to reduce qualitative and quantitative losses of stored grain. As an interdisciplinary research leader, he coordinates work of entomologists, agricultural engineers, and mathematicians into new methods of measuring, analyzing, and modeling grain properties, and heat and mass transfer in stored grain — the basis for non-chemical insect control methods. His physical process research has led to a better understanding of biotic and abiotic variable interactions. Dr. Jayas has made important progress in the use of digital image processing for grain type classification. He has authored or coauthored over 300 technical articles in scientific journals, conference proceedings, and books. He is co-editor of the book *Stored-Grain Ecosystems* and coauthor of *Grain Drying: Theory and Practice*. He has received awards from the Canadian Society of Agricultural Engineering, the American Society of Agricultural Engineers, and the Association of Professional Engineers of Manitoba.

Dr. Dirk E. Maier, Ph.D., P.E., is associate professor and extension agricultural engineer in the Agricultural and Biological Engineering Department, Purdue University, West Lafayette, Indiana. In addition to maintaining an active technology transfer and continuing education program, Dr. Maier conducts research on postharvest engineering and value-added processing of agricultural crops and biological products. His research also includes ecosystem modeling, stored products protection (IPM), alternative crop storage systems, dehydration of biological products, bulk material (grain, feed) handling, facilities design and simulation, and feed manufacturing. Dr. Maier is co-founder of the Purdue Grain Quality Team and is director of Purdue University's Postharvest Education and Research Center and Grain Quality Laboratory. He is a member of the Editorial Board of the *Journal of Stored Products Research*.

Dr. William E. Muir, P. Eng., is a professor in the Department of Biosystems Engineering, University of Manitoba, Winnipeg, Canada. He has been teaching and conducting grain storage research at the university since 1967. Dr. Muir provided the engineering input to the grain storage ecosystem studies initiated at the Canada Department of Agriculture Research Station and at the University of Manitoba. His research led to analysis of the stored grain bulk as a man-made ecosystem impacted by several biotic variables (the living grain, several species of insects, mites, and microorganisms) and abiotic variables (time, temperature, moisture content, carbon dioxide, oxygen, aeration, etc.). He has carried out many studies on the effect of aeration on the storability of grain, on in-bin drying systems, on modeling temperature distribution in grain bulks, on the influence of ambient temperature on the successful operation of aeration systems, and on heat transfer models. His multidisciplinary approach was first presented in an international symposium in 1971 and the resulting co-edited book, *Grain Storage: Part of a System.*

Dr. Graham Thorpe, Ph.D, D.Eng., obtained his bachelor's degree in chemical engineering from the University of Nottingham, U.K. After working one year as a process engineer, he completed his Ph.D. at the University of Nottingham on mathematical modeling of pneumatic conveyor dryers. After obtaining his Ph.D., he held the position of research scientist at CSIRO, Division of Mechanical Engineering, Melbourne, Australia, where he designed and tested refrigerated grain storage systems with storage capacities up to 15,000 tonnes. He also designed and evaluated the performance of a fluidized bed grain dissinfestation unit that treated over 100 tonnes of grain per hour.

Professor Thorpe contributed to theoretical development of stored grains engineering with Professor Stephen Whitaker at the University of California, Davis. He applied the "volume averaging" theorem to derive from first principles the rate at which moisture diffuses through bulk stored grains and the constraints that must be satisfied for grains and intergranular air in thermodynamic equilibrium. Professor Thorpe has also developed complex mathematical models of bulk stored grains, including the effects of natural convection on moisture migration.

Professor Thorpe is employed by Victoria University, Melbourne, where he is developing a novel open cycle desiccant bed grain cooling system and applying the computational fluid dynamics methods to grain storage systems designs. The new cooling system is predicted to cool one tonne of grain per 0.5 kW of energy. In 1998 the University of Melbourne awarded Professor Thorpe the Doctor of Engineering in recognition of his distinguished works in postharvest technology.

Technical Reviewers of Book Chapters

We are especially grateful for the excellent technical reviews of the chapters of this book by the scientists listed below. Each of the reviewers is a highly recognized professional in grain and seed drying and handling, storage research, teaching, and extension programs in their states or regions at leading universities and government research stations in the U.S. and Israel.

Without their diligent and thorough reading, their in-depth insight and understanding of grain and seed storage systems, and numerous valuable suggestions for improving the clarity of the ideas and illustrations, numerous important ideas and concepts in the book would not have been as well defined or clearly understandable.

We very much appreciate the great contribution in time and energy devoted to this text by Dr. Jonathan Donahaye, which required an effort far beyond his heavy research workload at the Volcani Center.

A special and significant contribution was provided by the mathematical review by Dr. Svetlana Fishman, a scientist with the ARO Department of Statistics, Volcani Center. Her review of formulae and mathematical modeling equations was essential to confirming the validity and technical soundness of the text.

We recognize that there are many demands on the time of these busy, well-known professionals. This section is to publicly acknowledge their sacrifices of time and willingness to assist in this important work with only the satisfaction of making a contribution to the improvement of grain storage worldwide through improved aeration systems as their primary reward.

Dr. Shlomo Navarro, Editor and Author
Dr. Ronald Noyes, Co-Editor and Author
Mr. David Armitage, Author
Dr. Digvir Jayas, Author
Dr. Dirk A. Meier, Author
Dr. William. E. Muir, Author
Dr. Graham Thorpe, Author

Technical Reviewers and Their Chapters

General Technical Review

General Editorial Review of Chapters 3 to 9

Dr. E. Jonathan Donahaye (Emeritus)
Department of Stored Products
Agricultural Research Organization
The Volcani Center
P. O. Box 6
Bet Dagan, 50 250
Israel

Specific Technical Review

Chapters 3, 4, and 11

Dr. Svetlana Fishman
Department of Statistics
Agricultural Research Organization
The Volcani Center
P. O. Box 6
Bet Dagan, 50 250
Israel

Individual Chapter Reviews

Chapters 1 and 2

Dr. James L. Steele (Retired)
USDA Agricultural Research Service
U.S. Grain Marketing and Production Research Center
1515 College Avenue
Manhattan, KS 66502
U.S.A.

Chapter 5

Dr. Kenneth J. Hellevang, Professor
Agricultural and Biosystems Engineering Department
P.O. Box 5626
Fargo, ND 58105
U.S.A.

Chapter 6
Dr. Carl J. Bern, Professor
Agricultural and Biological Engineering
Department
217 Davidson Hall
Iowa State University
Ames, IA 50011
U.S.A.

Chapter 7
Dr. Joseph P. Harner, Professor
Department of Biological and Agricultural
Engineering
Seaton Hall
Kansas State University
Manhattan, KS 66506
U.S.A.

Chapter 8
Dr. William F. Wilcke, Professor
Biosystems and Agricultural Engineering
Department
1390 Eckles Avenue
University of Minnesota
St. Paul, MN 55108
U.S.A.

Chapter 9
Dr. Fred Bakker-Arkema, Professor Emeritus
Agricultural Engineering
Department
Michigan State University
211 Farrall Hall
East Lansing, MI 48824
U.S.A.

Chapter 10
Dr. Christopher L. Butts
USDA Agricultural Research Service
National Peanut Research Laboratory
1011 Forrester Drive, S.E.
Dawson, GA 31742
U.S.A.

Shlomo Navarro and Ronald Noyes, Editors

Introduction

Shlomo Navarro and Ronald Noyes

1. INTRODUCTION

Aeration is the most widely used and one of the safest technologies for preserving grain without the use of chemicals. However, unless the necessary knowledge is available on planning and operating grain aeration systems, this technology cannot be successfully implemented. Although aeration is widely applied, its use is often misinterpreted and the objectives of aeration are not achieved.

This book deals with mechanical and physical aspects of aerating grain. But if the biological factors and the ecosystems of the grain bulk are not understood, the information on the physical design and operation of aeration presented in the book would not be complete. Therefore, this introduction presents a short overview of the grain bulk ecosystem, with particular emphasis on the biological agents — namely, insects, mites, and microflora — and how they interact with the dormant yet living grain kernels during storage.

2. HOW AERATION FITS IN THE GRAIN BULK ECOSYSTEM

In the context of the grain bulk ecosystem, grain is considered as a living organism even though its biological activity is extremely low. This low level of activity is due to the prerequisite for conservation of grain in storage — that it should be stored at low moisture contents. Grain that is termed *dry* has moisture at a level that is safe for storage and, in consequence, it remains in a *dormant* condition. Although such grain may not always possess all the viable characteristics of seeds, it is still considered part of the living composition of the grain bulk ecosystem. With respect to its interaction with other biotic agents, particularly insects and microflora, it serves as a host for the development of these noxious organisms.

Rodents, although part of this ecosystem, cause very little damage in modern structures with well-designed grain storage facilities. In practice, most structures exclude rodents from the ecosystem since they cannot reside within the depth of the grain bulk or survive the extreme dryness prevailing in the grain mass without a supply of water. However, for grain stored in bags, rodents do pose a serious problem, especially in inadequately constructed or poorly maintained storage facilities. Although bag storage is still the prevalent method of storing grain in developing countries, only the bulk storage of grain is considered here.

In contrast to rodents, insects and mites are considered natural residents of the ecosystem because of their abilities to enter most storages easily and reproduce within the range of low humidities characteristic of the grain bulk. Most insect species can survive very low humidity conditions; and at temperatures that enable reproduction, they can become the predominant organisms of the grain bulk ecosystem. Their metabolisms are adapted to generate metabolic water, and they can live and reproduce without the assistance of an external water supply.

Mites favor more humid conditions and prefer grain bulks in which the humidity of the intergranular air is close to or equivalent to the critical grain moisture content. Although similar to insects in that they can survive and reproduce freely within the grain bulk, their occurrence and economic importance is limited to countries where storage of grain is carried out at higher levels of moisture — though often below the critical moisture content. Microflora will develop only when the water activity (a_w) in the grain mass is sufficiently high. An equivalent relative humidity of

70% in air is considered as a critical humidity for the development of xerophytic microorganisms in the grain. Thus, grain moisture contents that are in equilibrium with the surrounding air containing a lower relative humidity than 70% are considered safe for each grain variety.

Development of microorganisms is a factor in the ecosystem that arises only when adverse storage conditions permit excessive moisture accumulation in the grain bulk or when grain is stored initially above permissible safe moisture contents required for its preservation. Consequently, the main reason for drying or reducing the moisture content of grain is to prevent the activity of the microflora. These organisms consist of fungi, yeasts, and bacteria. Fungi live and reproduce best at medium a_w levels (70 to 80% relative humidity), whereas yeast and bacterial development require humidities higher than 85% in the intergranular air.

Most grain insects and mites are of tropical or subtropical origin and favor the prevailing temperatures of warm climates. Therefore, a relatively rapid reduction in temperature of the immediate environment is an important intervention that tends to inhibit their biological activities. Thus, the primary objective of aeration is to alter the microclimate of the ecosystem by reducing its temperature, thereby creating micro-environmental conditions unfavorable to the development of all organisms that are noxious to grain stored in bulk.

The general information that follows will help readers to understand the principles of grain storage, the background of modern storage technologies, and the different aspects of grain conservation.

3. BACKGROUND ON STORAGE OF CROPS, FOOD, AND FOODSTUFFS

Growing crops and protecting them until ready for consumption have been major preoccupations of mankind since the inception of agriculture. Storage is an essential interim operation in the food pipeline that moves crops from producer to processor and processed foodstuffs from processor to consumer. It equilibrates the quantitative fluctuations or surges in supply between harvests that create the imbalance of supply and demand.

As the major consumer of cereal food and pulse crops, the human population was estimated to be about 5.3 billion in 1990; and projections indicate growth to 8.1 billion in 2025. Dependence on cereals for food energy has decreased in developed countries. However, 53 developing countries still derive 40% of all food energy from cereals. The present demand has caused a serious reduction in world cereal stocks, especially in the major export countries.

With the steady world population growth, global food production has scarcely kept pace with increased demand. Surpluses in industrialized countries are in striking contrast to the food shortages in many developing countries. There are still threats of famine in countries where natural disaster and internal strife combine to destroy the agricultural infrastructure. Today, hunger threatens the lives of about 800 million people in the developing world, with approximately 60% of them living in Asia. People suffer from food shortage or malnutrition — especially in the poorest countries, where agricultural production is never in surplus, where suitable grain storage facilities are inadequate or nonexistent, and in regions subject to extreme climatic fluctuations from one year to the next.

Durable foodstuffs with low moisture content form the bases for most human diets precisely because these commodities can be stored for extended periods and are continuously available, provided there is no serious insect infestation or moisture damage losses. However, losses occur at every stage of food handling and storage. These losses may be quantitative, qualitative, or both. The magnitude of losses is highly variable; in severe cases they may even reach 100%. Qualitative losses are more difficult to evaluate than quantitative ones. Qualitative losses may consist of changes in physical appearance, nutritional degradation, loss of germination, insect infestation, presence of insect fragments or filth, contamination by mold, or development of mycotoxins. Some of these factors are difficult to detect visually.

In developed countries, qualitative aspects of food loss are of greater importance than the quantitative ones. In these countries cereal grains are stored in large centralized bulk storage facilities or on-farm in bulk. Under these conditions quantitative losses are generally at low levels so that further loss prevention measures are not cost effective. Losses of biological origin, such as grain or insect respiration or limited drying due to insufficient aeration of grain, are common in storage. Quantitative losses on an annual basis are usually less than 1% in developed countries.

Developing countries are characterized by small-scale farming, where deficiencies in handling and storage methods and warm and humid climatic conditions often promote rapid deterioration of the stored foodstuffs. In developing countries the major portion of grain and pulses (sometimes up to 80% of the national production) is kept on the farms for home consumption. Post-harvest losses of food grain in developing countries have been conservatively estimated during the 1980s at 10 to 15% by the FAO's Special Action Programme for the Prevention of Food Losses. For example, losses of corn due only to insects in farmers' stores in Nigeria, Swaziland, and Kenya were in the order of 6 to 10%.

In recent decades, major efforts have been devoted to improving storage conditions of cereal and pulse crops and reducing losses in tropical countries. Past attempts at introducing state-of-the-art storage structures into several developing countries for this purpose have failed. Many such "white-elephants" stand empty, deteriorated and abandoned. However, storage systems that are more suitable for local climatic and farming conditions have also been widely introduced, which has enabled the successful transfer and updating of modern conservation and control technologies with consequent reduction in storage losses.

Reduction of storage losses at the small-scale and subsistence farmer levels has proved to be far more difficult than in the commercial or public sectors because the available storage conservation technologies are costly and not applicable to most of the traditional storage methods unless radical changes are made. Also, it is difficult to educate and transfer new storage technology information to large numbers of farmers in remote farming districts. Therefore, new solutions must be found that are appropriate to the local conditions and acceptable to the societies into which they are to be introduced. These new storage technologies must be demonstrated to be physically and economically practical, and a means for transferring the storage methodology to users at the local level must be developed.

In spite of the advances recorded in many fields of modern agriculture and particularly a changing approach to pest control, fumigation has remained a mainstay for control of stored product insects. However, it is worth noting that of the 14 fumigants listed some 20 years ago, only two remain in regular worldwide use today — namely, phosphine and methyl bromide. Methyl bromide (MB) is characterized by its lethal effect within very short exposure times, such as 4 h to 24 h. Insect resistance to this fumigant has not been recorded in the field.

In contrast, phosphine is a relatively new fumigant that is extremely widespread and popular, particularly in developing countries, because of its ease of application in comparison with MB. Phosphine has the distinct disadvantage of requiring long periods of exposure, with a minimum of 5 days now recommended. A serious threat to this fumigant is the increasing number of reports of insects that have developed resistance over the last decade.

MB is regarded as the main anthropogenic compound that is depleting the ozone layer. It is widely used as a fumigant in agriculture, for pest control in structures, stored commodities, and quarantine treatments. Its main uses are for soil sterilization (about 72% of total usage), disinfestation of perishables (9%), disinfestation of durables (14%), and against pests in structural fumigations (5%). Presently there is no available alternative to MB for short-exposure fumigations.

Development of alternatives to MB is likely to be costly, and many developing countries will not be able to afford evaluations of these alternatives without assistance. Regulatory actions to reduce and eliminate the use of MB have been taken recently by the United Nations Environment Program (Montreal Protocol) and by the U.S. Environmental Protection Agency (EPA). In October 1998, the U.S. Congress made specific changes to the Clean Air Act to "harmonize" the U.S. phase-out of MB with the Montreal Protocol schedule for developed countries. The EPA has taken the necessary regulatory steps to implement these changes.

The new MB schedules include a 25% reduction from the 1991 baseline in 1999, a 50% reduction in 2001, a 70% reduction in 2003, and a 100% reduction in 2005. For developing countries, the agreed schedule is reduction in consumption by 20% by 2005 with total phase-out by 2015. Under present agreements, there are exemptions for all countries from controls on MB when used for quarantine, pre-shipment fumigations, and for some critical agricultural uses yet to be defined.

Contact insecticides may provide persistent protection against reinfestation. They can be applied directly to grain, but they are not normally registered for use on processed foodstuffs. Contact insecticides include synthetic chemicals, insect growth regulators, plant extracts (botanicals), and inert dusts. One major constraint associated with their use is the presence of chemical residues in the treated commodities. Resistance also is a major problem, while the high cost of registration is a constraint to the development of new products.

Among the non-chemical alternatives of physical control methods, aeration of bulk grain plays an important role. Other non-chemical alternatives include the use of modified atmospheres, heat, irradiation, and physical removal of insects. Treatment with controlled or modified atmospheres based on carbon dioxide and nitrogen offers a potential alternative to fumigation with toxic gases for insect control in all durable commodities. However, these intensive control methods are not suitable to a large percentage of existing bulk storages because of relatively high application costs and lack of sealed storages.

As a general rule, except aeration and chilling by refrigerated air, cold treatments are not used for disinfestation of large masses of durables. A major problem encountered with cooling or chilling is the time needed to cool such masses. For this reason, cooling is generally used to prevent reproduction and reinvasion of pests in grain bulks by applying aeration and refrigerated aeration for cooling, rather than as a disinfestant. Heat treatment is one of the very few pest control options for grain that is capable of matching the speed of treatment afforded by MB. Fluid bed heating systems for bulk grain have been developed to a commercial prototype stage. But heat treatment is also quite expensive to apply to large bulks of relatively low value grain.

The electromagnetic spectrum also offers a series of possibilities for processed foods. The two extreme ranges — longwave radio frequencies and ionizing irradiation — have detrimental effects on insects, whereas medium wavelengths, especially in the range of visible light, are used for insect monitoring purposes. Irradiation is already in use commercially for shelf-life extension of some fresh commodities and for disinfestation. The food industry is concerned about consumer acceptance of irradiated food products. The large initial capital expenditure for plant construction also poses a serious constraint.

Physical removal of insects, sanitation, and improved packaging methods should all be regarded as means to assist pest control in stored commodities. Biological methods, including the use of microbiological control agents and pheromones, are at an early stage of implementation. Although pheromones are used increasingly for monitoring purposes, their widespread application as control measures is not expected in the near future.

4. THE BENEFITS OF AERATION IN PRESERVATION OF STORED GRAIN AND SEEDS

The world grain industry, particularly the storage sector, is undergoing constant changes and adaptations to rapidly evolving agricultural practices as well as technological and administrative developments. Many countries have adopted deregulation processes that have significantly influenced the attitudes and decision making of grain growers regarding the subsequent handling and destinations of their newly harvested crops. In some countries, growers choose to deliver their harvests directly to the grain cooperatives or grain growers associations, centrally or regionally. In other countries, on-farm storage and direct delivery to consumers or merchants are the preferred options. Globally, the process of grain production and storage management is under the influence of these changing realities. The endeavor to provide "food security" for all is dependent upon improved storage technologies at all levels that enable the reduction of both the quantitative and qualitative losses of grain in storage.

A significant development over the past 10 years is the fast-approaching phase-out of MB. This has resulted in a significant increase in the number of publications dealing with its alternatives. In particular, the search for non-chemical methods of insect control has increased in intensity. Additionally, a public awareness has arisen with respect to pesticide residues in food and their harmful influence on the environment.

Public pressure is increasing to encourage legislators to close every loophole that might enable the contamination of food with toxic materials. Consequently, future prospects for using new fumigants on stored food products remain very limited.

Many research groups are now in a "rethink" mode as a direct result of pressure from national and international legislative bodies and import country grain purchase contract restrictions. These authorities are rapidly reducing the range of existing chemical options, while the development of new, friendly chemicals specifically for the stored product market has become prohibitively expensive. These constraints have led to a realization that prevention is better than cure. The emphasis is rapidly shifting to integrated pest management (IPM) or integrated commodity management (ICM), with chemical means of control as a last resort. However, in practice, chemical control still plays a dominant role, with phosphine fumigation as the mainstay of the grain storage industry — even though, as with methyl bromide, its use may also become increasingly more restricted in the future.

Grain aeration technology provides many advantages and benefits when applied appropriately and when its qualifying factors are recognized in comparison to conventional chemical treatments. One of the aims of this book is to disclose all of the advantages that the aeration technology can offer. On one hand, aeration has limitations with regard to killing insects in a short time — while on the other hand, for the range of temperatures obtainable by aeration, it is possible to arrest insect development and even prevent oviposition.

Widespread experience has proven that insects can develop resistance to chemicals applied at commercial levels. In addition, and contrary to the general understanding and consensus, we must question the belief that fumigation provides a complete kill. Although it is feasible to obtain complete mortality under laboratory conditions, we question the chances of undertaking a commercial fumigation that can guarantee that *all* life stages of all insects have been killed.

Adequate sealing is essential for successful fumigation. The question then arises as to how many of the storage structures are seal-tested before phosphine is applied? The objective difficulties in achieving adequate sealing of large commercial storages for a successful fumigation must be recognized. Many bins that are sealed for fumigation purposes fail sealing pressure tests. Only a few of these failed tests in unsealed or partially sealed storages are reported, and literature on fumigation usually claims successful treatments. These partial fumigation failures undoubtedly provide the selection pressure that generates insect resistance to phosphine.

The wisdom of relying upon a single chemical such as phosphine, with the hope that resistance does not develop, has been invalidated. Furthermore, improvements in aeration technologies for grain cooling provide an alternative that is becoming progressively cheaper. When properly applied, aeration cooling by itself can meet the nil tolerance for infestation in certain circumstances, and it can be selectively combined with a number of other treatments if required.

In aerated storages, insects are not evenly distributed throughout the bulk; they tend to concentrate on or near the surface. Such high infestations are susceptible to other control measures. For example, it has been shown that surface infestations in bins declined to zero after an application of pirimiphos-methyl was raked into the surface. Thus, aeration plus a surface application can meet industry standards. However, it is important that the material applied to the surface has some degree of persistence and that it is applied at an early stage of storage. A number of trials were conducted in Australia under an aeration program named Smart Aeration. In both farm bins and in commercial bins, the technique of surface application plus good aeration met commercial requirements.

In comparing the benefits and advantages of aeration with alternative methods, the costs of different procedures depend on a range of factors, including inputs (wet or dry grain), facilities (sealed or unsealed storage), desired results, and market preferences. Since cooling by aeration has several advantages in addition to controlling insects that cannot be achieved using chemicals, it is clearly easier to compare fumigants with protectants than to compare chemicals with aeration.

For control of insects, where a quick kill is required, chemicals and fumigants are superior to aeration. However, when a reduction in dependence on chemicals is the objective, cooling by aeration should be regarded as the primary complementary technique. In the modern technological trends of grain storage, two areas of major importance where chemicals and aeration are complementary are in the management of resistance and the implementation of IPM. Aeration is superior and without competition for the short-term storage of wet grain, for preventing moisture migration in large bulks, for suppressing insect development, and for preservation of quality in grain, in seeds, and in oilseeds.

Aeration is the most widely applied and environmentally user-friendly technology in the grain industry. Its proper implementation has a significant impact on the reduction of chemical pollution and on prevention of contamination by pesticide residues of the food and feed products in daily use. The use of aeration should be maximized in the application of modern grain storage technology. This will increase our contribution toward a better and safer environment by reducing chemical residues in food and feed, and reducing the risk of development of resistance by insects.

The objective of this book is to provide the relevant information to enable the reader to take full advantage of the benefits of aeration. Whoever is involved — old or new generations of grain storage managers, farmers and commercial grain facility operators, silo or warehouse engineers, grain storage systems designers, sanitation specialists, or food technologists — aeration must be the leading grain storage management tool of the future.

Contents

CHAPTER 1

Objectives of Aeration

Shlomo Navarro, Ronald Noyes, David Armitage, and Dirk E. Maier

CONTENTS

0-8493-1355-4/02/$0.00+$1.50

1.1 EFFECTS OF FORCED AERATION ON THE PRESERVATION OF STORED GRAIN

Aeration can be defined as the forced movement of ambient air of suitable quality or of suitably conditioned air through a grain bulk for improvement of grain storability (Calderon, 1972). Aeration is also called *active, mechanical, low-volume,* or *forced* ventilation, since fan power is used to deliver ambient air.

Aeration should be distinguished from *passive* or *natural* ventilation due to natural or convective air currents, which take place in grain bins with open manholes or in granaries with open doors or windows. Passive aeration also takes place in corn cribs, used traditionally in tropical and subtropical climates. Wind forces ambient air to flow through corn (maize) cribs, causing slow drying of damp unshelled corn and other grains.

Aeration is a widely used method for the preservation of stored grain. This technology is used to modify the grain bulk microclimate; to create unfavorable conditions for the development of harmful or damaging organisms in the grain; and to create favorable conditions for the sustained preservation of grain quality.

The effects of aeration on stored grain are better demonstrated by viewing the grain bulk as an *ecosystem* in which grain, microflora, and insects are biotic components. Substantial storage losses are often caused by microflora due to favorable moisture conditions, and insect infestation can be destructive if preventative control measures are not taken. Monetary losses of grain in storage have been estimated to range from 1 to 50% (Sinha and Muir, 1973) and in some instances can render the grain worthless or costly for proper disposition. These losses should be considered a result of interactions among the components of the ecosystem as affected by the grain and ambient conditions.

The interactions between the biotic and abiotic components of the system are in a dynamic state, with each component continuously affecting the others. The role of aeration in this ecosystem is to "condition" the stored grain to improve existing conditions in the grain bulk by moving air of suitable quality through the grain mass (Figure 1.1).

Moving air of suitable quality through the system (air properties of low temperature and humidity) can create conditions that suppress the development and growth of insects and microflora and sustain quality preservation and safe storage of grain. Forced aeration is an effectively applied method in commercial-scale bulk storage of grain and takes advantage of two important physical properties of the grain bulk:

1. Porosity of the grain bulk: for most cereal grain, the intergranular void volume is 35 to 55% of the grain bulk volume. The porous nature of bulk grain permits forced air to contact almost all grain kernels.
2. Thermal insulation property of the grain bulk: due to low thermal conductivity, the grain mass is self-insulating. This enables maintenance of a *modified microclimate* long after the grain bulk is aerated.

To summarize, aeration is possible because air can be forced through the grain bulk to impart desirable properties to the grain; and these properties are maintained (for prolonged storage) due to the thermal insulative nature of the bulk.

Although the role of temperature has long been recognized as an important regulator of biological processes, manipulation of temperature by aeration techniques was first brought into focus in the early 1950s. Since then several authors have reported their findings on aeration carried out in temperate climates, forming the basis of present-day aeration technology (Bewer, 1957; Burges and Burrell, 1964; Holman, 1966; Hukill, 1953; Johnson, 1957; Jouin, 1963; Kreyger et al., 1960; Shedd, 1953; Shibaev and Karpov, 1969; Williamson, 1961).

Understandably, grain aeration technology was developed and has been used mostly in temperate climates, primarily as a result of need and the availability of selected air of desired properties — namely, low temperature and humidity in these regions. However, from the mid 1960s, experimental

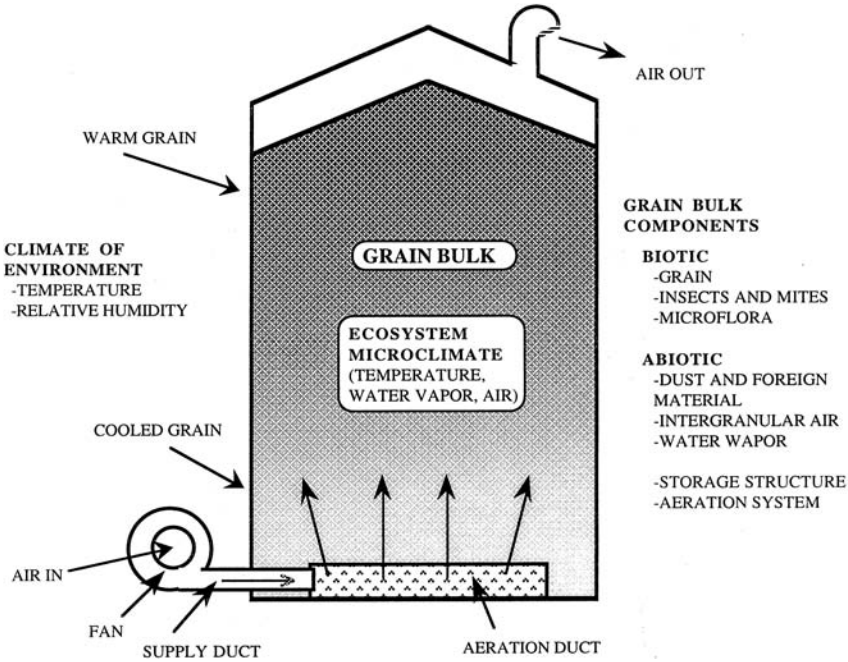


Figure 1.1 Biotic and abiotic components of the grain bulk ecosystem and the ecosystem microclimate changes resulting from aeration.

work was also conducted in warm climates such as Australia (Griffiths, 1967; Elder, 1969), Brazil (Sartori et al., 1976), India (Bhatnagar and Bakshi, 1975), and Israel (Calderon, 1974; Navarro et al., 1969). In some of these countries, aeration technology has been put into routine practice (Elder, 1969; Navarro, 1976). The use of effective aeration can be advantageous, especially in subtropical regions that have reasonably cool winters and cool nights. Experience has shown that grain bulks cooled during winter maintained the acquired low grain temperatures for many months, continuing into the following summer (Navarro et al., 1969).

The relative suitability of aeration techniques for subtropical climates and limitations for use in tropical climates will become more evident in the following chapters. However, though aeration is not widely practiced in tropical climates, two potential aspects deserve mention: use of aeration with dehumidified air, and use of refrigerated air.

Trials on the use of aeration with dehumidified air have yielded promising results in warm and humid areas (Odigboh, 1976). Ambient air was forced through a sorbent bed (containing $CaCl_2$) where the exhausting air for aeration of grain was much lower in relative humidity. This method of air dehumidification by desiccants has been developed and used for many years in seed storage practice (Justice and Bass, 1978).

Refrigerated aeration involves cooling ambient air with a refrigeration unit before using it to aerate a grain bulk. Refrigerated aeration has been used for cooling dry grain in subtropical climates when ambient temperatures are too high for successful insect control by aeration with untreated air (Hunter and Taylor, 1980; Navarro et al., 1973). Refrigeration involves considerable investment; but together with the dehumidified air method, it could answer questions about the practicability of aeration for safe commercial storage in tropical climates.

At present, forced aeration of grain is one of the most effective non-chemical methods in use for control of stored grain conditions, biological activity, and grain quality losses. Nevertheless, forced aeration is not the sole remedy for prevention of stored grain losses. Efforts should continue to integrate other methods with this technology, including alternative methods for control of aeration air qualities. However, the main contribution of aeration, in the environment-minded world of today, is the reduction in use of controversial pesticide chemicals in grain storage. Therefore, the extension and promotion of appropriate aeration technologies is recommended.

The many aspects elaborated in this book should be considered during the planning stage of aeration systems to be added to existing storages or when erecting new storage installations. The aim of this book is to gather the available knowledge on grain aeration in countries with temperate and warm climates and to present a document for practical and beneficial promotion of this technology.

1.2 OBJECTIVES OF AERATION

The purpose of aeration is to improve and sustain the condition of bulk grain in storage. Aeration is achieved by moving air of desired or selected properties through a grain bulk until a new microclimate is produced that will keep the stored grain from deteriorating. Although aeration is aimed at improving storage conditions, it is not generally aimed at improving the intrinsic quality attributes of the grain but rather at maintaining those quality attributes.

Since aeration with air of different characteristics has different effects on the stored grain, storage conditions may be improved in various ways. The improvement depends on the properties of the air used for aeration and on the existing condition or properties of the grain. Therefore, before operating an aeration system, it is essential to understand the effect aeration will have on the grain. Without prior knowledge of the process, the benefits in improved storage conditions cannot be anticipated. The specific objectives of operating any aeration system should be clear in advance of operation.

These objectives may be defined according to the effects of aeration on a grain bulk as follows:

- Cooling the grain bulk
- Equalizing temperature throughout the grain bulk
- Preventing biological heating in damp grain
- Limiting drying
- Introducing and recirculating fumigant gases
- Removing odors and fumigant residues

1.2.1 Cooling the Grain Bulk

Cooling grain is the most frequently applied objective of grain aeration. If cold air is available (during fall or winter seasons, on cold nights), introducing and moving this air throughout the grain mass gradually lowers the grain temperature. Thus, a new environment is created for all biological components of the grain bulk ecosystem. The biological component responses are reviewed in the following sections.

1.2.1.1 Suppression of Insect Development

Freshly harvested grain is often at a temperature favorable to the development of the common stored-product insects. These are generally of tropical or subtropical origin and require fairly high temperatures (in the range of 27 to 34°C) for development. These insects thrive at about 29 to 30°C. After several months of storage at or above 27°C, any lot of grain would probably be infected with insects if protective measures were not taken. Grain-infesting insects are sensitive to temperature. Insect development is slowed or frequently stopped below 16°C, with little survival of stored-product insects above 42°C. In the southwestern U.S., wheat, rice, and sorghum have grain temperatures up to 40°C at harvest. During the fall harvest in the northern U.S., grain temperatures around 15 to 17°C are typical.

Table 1.1 Optimum Temperature for Rapid Insect Growth; the Temperature at which the Development Cycle Takes 100 Days on One of the Best Foods for Each Species; and Minimum Humidity Requirements of Some Stored-Product Insects

Cold Hardiness	Response to Humidity	Species	Optimum Temperature (°C)	Minimum Relative Humidity (%)	Safe Temperature (°C) (Oviposition to the Change to Adult in a Mean of 100 Days)
		Species Needing High Temperature			
Cold hardy	Tolerant of low RH	Khapra beetle *Trogoderma granarium*	33–37	1	22
		Rust-red grain beetle *Cryptolestes ferrugineus*	32–35	10	20
		Saw-toothed grain beetle *Oryzaephilus surinamensis*	31–34	10	19
Moderately cold hardy	Tolerant of low RH	Confused flour beetle *Tribolium confusum*	30–33	1	21
Cold susceptible	Tolerant of low RH	Rust-red flour beetle *Tribolium castaneum*	32–35	1	22
Moderately cold hardy	Need moderate RH	Lesser grain borer *Rhyzopertha dominica*	32–35	30	21
Cold susceptible	Need high RH	Flat grain beetle *Cryptolestes pusillus*	28–33	60	19
		Species Thriving at Moderate Temperatures			
Cold hardy	Need high RH	Grain weevil *Sitophilus granarius*	26–30	50	17
Moderately cold hardy	Need high RH	Rice weevil *Sitophilus oryzae*	27–31	60	18

From Burges, H.D. and Burrell, N.J. (1964). Cooling bulk grain in the British climate to control storage insects and improve keeping quality, *J. Sci. Food Agric.,* 15, 32–50; and Howe, R.W. (1965). A summary of optimal and minimal conditions for population increase of some stored-product insects, *J. Stored Prod. Res.,* 1, 177–184.

A summary of the optimum and safe temperatures for insect growth for a 100-day development cycle for several major grain pests is listed in Table 1.1. The temperatures given are transferable to microclimate and grain temperatures for stored grain.

At temperatures lower than 20°C, population growth of most storage insects is significantly suppressed. This is clearly shown in Table 1.1 (Burges and Burrell, 1964). According to Table 1.1, grain and microclimate temperatures in the range of 17 to 22°C are considered "safe" for insect management, since completion of their life cycles at those temperatures takes about 3 months or more. At low temperatures, oviposition and fecundity of these insects are also much lower so that, over time, their population growth remains insignificant. Consequently, insect damage caused under these low temperature conditions is negligible.

The optimum temperature and relative humidity conditions for stored-grain insects vary by species. Storage insects can develop at relative humidities below 70%, but some species reproduce successfully at relative humidity levels below 30% (Table 1.1). However, for dry grain, the equilibrium relative humidity (ERH) of the grain bulk is usually higher than 30% but does not exceed 70%. Therefore, stored-grain insects must tolerate the microclimate's relative humidities in dry grain bulks.

In most grain storages without cooling, the number of insects rapidly increases, rendering the commodity unsaleable since there is a low tolerance of live pests in grain trades of most countries. The aim of cooling is therefore twofold: to reduce the grain temperature below the development temperature of insects, and to cool the grain quickly enough so that an egg laid by a wandering female insect on the first day of storage will not develop to adulthood. The quoted recommendation of Burges and Burrell (1964) was that the grain should be cooled to below 17°C based on the fact that *S. granarius* would take more than 100 days to complete a life cycle. The researchers also recommended temperatures as low as 5°C if the stored bulk is infested. Today, quality demands and longer periods of storage dictate the need for faster cooling.

The extent to which this objective can be achieved by ambient aeration only depends on the climate immediately after harvest and the airflow rate chosen. If cooling is considered as a series of discrete "fronts," then the first target is to cool the grain to below 15°C to prevent the fastest developing insect, usually *O. surinamensis*, from completing a life cycle. This assumes that a life cycle would have been completed under the initial grain storage conditions, which allows only 17 days to cool the grain. The next aim is to lower the temperature to below 10°C. This should prevent breeding of the most cold hardy insect, usually, *S. granarius*, which takes 26 days at optimum temperature and 144 days at 15°C. Howe (1965) summarized the minimal temperatures for development of many stored-product pests.

A rule of thumb for aeration is that about 1000 volumes of air are required to cool one volume of grain (Burrell and Laundon, 1967; Poichotte, 1977). This yields results similar to calculations based on the ratio of air to cooling front velocity (McLean, 1980). Based on airflow rate, the hours of aeration required to pass a cooling front through grain can be determined. A study of meteorological records reveals the average number of days after harvest before the total number of hours below a given temperature can be accumulated. This will determine whether sufficient cooling can be achieved in time to prevent insect development. Based on this principle, Armitage et al. (1991) showed that an airflow of 10 (m^3/h)/tonne was the minimum rate to achieve satisfactory aeration during the warmest years in the U.K.

In many climates, cool air is not available in sufficient quantity after harvest; and higher airflow rates may be required for timely aeration. For example, Harner and Hagstrum (1990) showed that airflow rates greater than 1.5 cfm/bu (90 (m^3/h)/tonne) were required in Kansas in July and August to complete one cooling cycle based on limited hours of sufficiently cool air. However, this theoretical level of airflow is not considered economically feasible. Arthur et al. (1998) calculated the numbers of *S. zeamais* occurring in unaerated maize and maize cooled at 3 different airflow rates in 11 southern U.S. states. They recommended an airflow rate of 0.1 cfm/bu (6 (m^3/h)/tonne). The researchers indicated that, while aeration reduced populations dramatically, it was not sufficient to completely prevent moderate insect population increases.

Where sufficient cool air is not available immediately after harvest, fumigation may have to be applied before cooler weather arrives. Hagstrum and Flinn (1990), and Longstaff (1986) have modeled strategies based on this principle. Airflow rates of 0.1 cfm/bu are considered standard, but airflows greater than about 0.2 cfm/bu would not be considered in the realm of standard aeration — based on the original purpose of aeration of controlling moisture movement (moisture migration) in grain masses. This natural moisture movement results from convection currents caused by grain temperature differentials between cold grain along outside walls and warm grain in the center of the mass.

Aeration immediately after harvest may have to be delayed for reasons other than climate. In the northern hemisphere, many malting barleys have dormancy problems and are often stored at high temperatures in order to break dormancy. This delay at high temperatures obviously makes the grain vulnerable to insect attack. Armitage and Woods (1997) and Armitage and Cook (1997) suggested dormancy should be broken below 20°C or above 40°C to discourage infestation by five species of insects, including *Trogoderma granarium* Everts.

In colder climates, ambient aeration is used to cool grain to low temperatures — not just to prevent insect increase but also to kill the insect during prolonged storage. Fields (1992) summarized survival times of many stored-product insects at low temperatures. The lower temperature range could be divided into three bands. Between the chill coma and minimum breeding temperatures, the insects are able to sustain a low metabolic rate but are unable to repair accumulating physical damage. Between the chill coma temperature and the super-cooled point, insects are unable to feed and therefore slowly starve. At and below super-cooled temperature, death occurs when the water in body fluids freezes (see Chapter 2, Table 2.2).

Evans (1983) determined that the median chill coma temperature for *S. granarius* is between 2.7 and 5.6°C; for *C. ferrugineus* at 4.4 to 6.4°C; and for *O. surinamensis* at 5.6 to 10.0°C. Reducing grain temperatures to these values is desirable to prevent damage by the insects, which may live for extended periods at temperatures above chill coma temperatures. Smith (1970) found the super-cooled point of *C. ferrugineus* to be –17°C without acclimation at an unspecified RH, while Robinson (1926) found that between 12 and 16% mc, the super-cooled point of *S. granarius,* is from –9 to –10°C. Fields (1992) gave the super-cooled point of *O. surinamensis* as –16°C. These temperatures are unlikely to be achieved by aeration within the mass of British grain stores or in many other locations; however, these temperatures may be achieved in climates of Scandinavia and Canada. Death by starvation at low temperatures can be retarded by increased availability of water and acclimation (Ushatiskaya, 1948, 1950; Evans, 1983). The species of insect also determines survival rates at low temperatures (David et al., 1977). Although grain beetles do not hibernate, Evans (1979) has noted how some strains lower their oxygen consumption with exposure to cold, an apparent adaptation.

Thorpe and Elder (1980) incorporated the decay of chemical pesticides into a heat and mass transfer simulation model. Their objective was to determine the potential of reducing insecticide usage and delaying insect resistance by chilling bulk stored grain. They found an optimum airflow rate for chilling the grain, which slowed chemical breakdown and extended efficacy of pesticides to their maximum level. The decay rates of malathion and methacrifos were insensitive to the initial grain temperature and moisture content when the bulks were chilled quickly after the pesticide application during bin filling.

As malathion was phased out in the Australian grain industry in 1977, it was replaced by other chemicals (Longstaff, 1988a). However, resistance continued to develop with time against the newer and more expensive insecticides. A major factor in reducing insect population growth rate is prolongation of the development period at lower temperatures. Longstaff (1988a) investigated the effect of temperature manipulation upon the spread of a resistant gene in an infested grain stored under Australian ambient weather conditions. Cooling of the grain had a pronounced effect upon the generation time of the insects and thus on the rate of spread of the resistant gene. He concluded that "combining grain cooling and insecticide treatments slowed the rate of development and/or spread of pesticide resistance."

In a related study, Longstaff (1988b) determined that cooling grain to 15°C was not sufficient to prevent population growth. However, aeration immediately after fumigation gave some long-term insect protection when grain was cooled quickly. The benefit of cooling depended on the type of insecticide. With pyrethroids, a beneficial effect and reduced application rate were noted. Organophosphorous insecticides, on the other hand, showed a positive temperature-toxicity relationship.

Hagstrum and Flinn (1995) described the integrated pest management (IPM) approach to pest control that involves insect sampling, risk/benefit analysis, and use of multiple control tactics. IPM is a concept that is well established in crop protection and one that must be more widely understood and used by stored-grain managers. In their approach, the economic injury level (EIL) is defined as the insect density that causes reductions in market value greater than the cost of the control. A critical concept in IPM is the economic threshold (ET), an insect density at which control measures should be applied to prevent insect populations from exceeding the EIL (Hagstrum and Flinn, 1995). The ET approach to control insect populations in stored grain is illustrated in Figure 1.2. Onstad (1987) provides a detailed discussion of the economic threshold.

Stored-grain IPM programs would be improved by the development of better insect sampling programs. Sampling of insect populations is critical to an IPM program, because without it the manager would not know if the population were approaching or exceeding the economic threshold. IPM programs use risk/benefit analyses to maximize profit and reduce economic losses. IPM

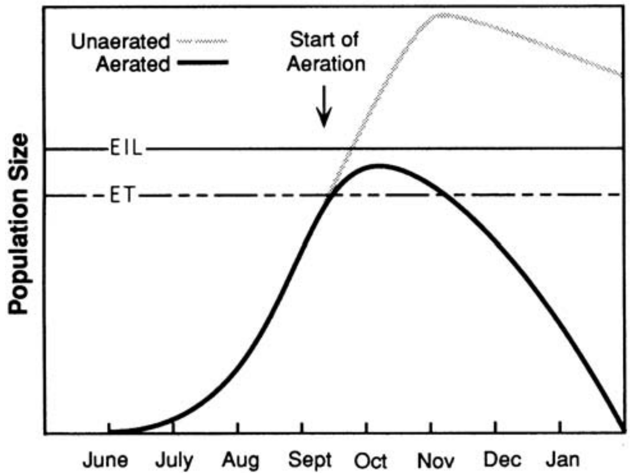


Figure 1.2 Economic threshold (ET) and the economic injury level (EIL) concept, demonstrating the population dynamics of insects over time in aerated and un-aerated stored grain. (From Hagstrum, D.W. and Flinn, P.W. [1995]. IPM in grain storage and bulk commodities, in *Stored Product Management,* Krischik, V., Cuperus, G., and Galliart, D., Eds., Oklahoma State University, Stillwater, OK, pp. 201–205. With permission.)

programs are based on an understanding of the ecology of insect pests and allow for a variety of control measures, such as sanitation, parasites, and aeration, to be substituted for some or all insecticide applications (Hagstrum and Flinn, 1995).

1.2.1.2 Suppression of Mite Development

Mites are important pests of stored products, particularly in damper, cooler, or maritime climates. Mites can hollow out the germ of cereals or reduce oilseeds to empty shells. They can also contaminate the products with feces and impart an offensive odor. Feeding mite-infested food to animals may cause nutritional problems; handling infested grain may cause allergies in humans, and ingestion may cause clinical symptoms. In comparison with stored-grain insects, control of mites has received little attention — although mites are usually omnipresent and easier to detect than insects.

Geographic variations occur, but the most common mites encountered include *Acarus siro* L., *Lepidoglyphus destructor* Schrank and *Tyrophagus putrescentiae* Schrank (which live off the grain and associated fungi) and predatory *Cheyletus eruditus* Schrank. As an example, *A. siro*, perhaps the most widespread species, can develop between 7 and 30°C, unless RH is below 60 to 65% (Cunnington, 1984). From this data, the crucial control parameter for these pests is not temperature, but establishing an equilibrium relative humidity (ERH) below about 65% RH (about 12.5% moisture content for wheat at 25°C), which suppresses mite development. Weekly rates of mite increases at optimum conditions of 20 to 25°C and 80 to 90% RH are about sixfold, emphasizing an ability to quickly increase and the need to surpress population dynamics. Data for *L. destructor* is given by Stratil et al. (1980).

Although temperatures required to suppress development of mites in damp grain (14 to 16% mc wet basis) are obtainable in temperate climates, maintenance is too expensive at the bulk periphery when mean ambient temperatures are favorable for mite development (Burrell, 1974). Burrell and Havers (1976) concluded that, although cooling by aeration is unlikely to prevent moderate mite infestation, aeration may be expected to reduce the incidence of hot spots, and the heavy populations of mites associated with hot spots. The authors also recommended drying grain for prevention of mite infestations rather than cooling moist grain.

Table 1.2 Approximate Minimum and Optimum Temperatures at which Storage Mites Breed

Species	Temperature (°C)	
	Minimum	Optimum
Tyrophagus putrescentiae	9–10	23–28
Glycyphagus destructor	10–15	15–25
Cheyletus eruditus	12	25–27
Carpoglyphus lactis	15	25–28
Aleuroglyphus ovatus	22	23–25
Rhizoglyphus echinopus	6–10	23–27
Caloglyphus berlesei	16.5	22–30
Acarus siro	7	23–30

From Sinha, R.N. (1968). Climate and potential range of distribution of stored-product mites in Japan, *J. Econ. Entomol.,* 61, 70–75.

Mite infestations in grain are more common in temperate climates than in subtropical climates. Aeration cooling in both of these regions should be aimed mainly at prevention of insect damage.

In contrast, the predator, *C. eruditus*, requires a temperature minimum of about 12°C (Boczek, 1959) and rarely establishes itself in cool grain until the summer. Unfortunately mites are not very susceptible to organo-phosphate pesticides; so physical control measures — drying and cooling — must be relied upon for control.

Continuous or high-temperature drying techniques are processes that are completed too quickly to permit mite development in grain. Ambient-air, slow-drying techniques may take several weeks, even with airflow rates several times those required for cooling. During slow drying, mites may develop to significant populations before reducing their development at a rate dependent on the final moisture content achieved by drying (Armitage et al., 1982).

Mites favor conditions of moderately low temperatures and high relative humidities. The temperatures that prevent growth of mites vary from species to species but are generally in the range of 0 to 10°C (Smith, 1974). Most mite species found in stored grain reproduce very rapidly between 20 to 30°C (Table 1.2). However, mite survival is seriously limited at relative humidities below 60% (equivalent to about 12% moisture content for cereal grains). When moisture contents of cereal grains are higher than 14%, conditions are favorable for mite development. Therefore, for grain stored with initial moisture contents lower than 14%, mite infestation is negligible.

1.2.1.3 Suppression of Microfloral Growth

The fungi that grow in the field such as *Fusarium*, *Cladosporium,* and *Alternaria* are replaced in store by species adapted to more xerophilic conditions, such as *Penicillium* and *Aspergillus* spp. (Christensen and Kaufmann, 1969). Some species, such as members of the *Aspergillus flavus* group, which produce aflatoxins, and *Penicillium verrucosum,* which produces ochratoxin A, create metabolites containing mycotoxins that are injurious to human, fowl, fish, and animal health. Fungi may also reduce the viability of grain as well as cause discoloration and taints.

To remove moisture effectively by natural air drying, at least 10 times and preferably 20 to 30 times as much airflow should be used than airflows required for cooling grain. Unless higher than normal aeration rates (0.2 to 0.3 cfm/bu) are used, temporary storage of damp grain with normal airflow rates (0.1 cfm/bu) for cooling will lead to undesirable fungal as well as mite activity. Attention has been given to modeling strategies for cost-effective optimum drying of grain to avoid over- or under-drying (Nellist, 1988). Unfortunately, these studies neglect adequate analyses of spoilage avoidance.

Table 1.3 Temperature and Relative Humidity Conditions of Fungi on Stored Grain

Fungus	Minimum % ERH for Germination[a]	% EMC[b]	Growth Temp °C Min. °C	Opt. °C	Max. °C
Alternaria	91[b]	19	–3	20	36–40
Aspergillus candidus	75	15	10	28	44
A. flavus	82	16–17	6–8	36–38	44–46
A. fumigatus	82	16–17	12	37–40	50
A. glaucus **(blue eye mold)**	72	13.5–14.0	8	25	38
A. restrictus	71–72	13.5	—	—	—
Cephalosporium acremonium	97	22	8	25	40
Epicoccum	91	19	–3	25	28
Fusarium moniliforme	91	19	4	28	36
F. graminearum (G. zeae)	94	20.5	4	25	32
Mucor	91	19	–3	28	36
Nigrospora oryzae	91	19	4	28	32
Penicillium funiculosum	91	19	8	30	36
P. oxalicum	86	17	8	30	36
P. brevicompactum	81	16	–2	23	30
P. cyclopium	81	16	–2	23	30
P. viridicatum	81	16	–2	23	36

Note: **= Low to moderate moisture storage fungi**
= High moisture storage fungi

[a] Approximately 5% or more of the spore population can germinate at this relative humidity.
[b] Approximate equilibrium moisture content at 25.5°C equal to minimum percent relative humidity in which fungus can germinate, but probably takes a higher moisture content for fungus to grow and compete on cereal grain (average values for wheat and corn).

From Purdue University (1988). Plant Pathology Department Publications, Purdue University, Lafayette, IN; and Lacey, J., Hill, S.T., and Edwards, M.A. (1980). Microorganisms in stored grains: their enumeration and significance, *Trop. Stored Prod. Inform.,* 38, 19–32.

As with fast cooling models, the aim in this case is to model a drying front moving through the grain before spoilage levels (primarily fungal deterioration) become significant and detrimental. Grain should be dried fast enough so that fungi development in the slowest drying areas does not exceed acceptable levels. Although there is no definition of acceptable fungal contamination, numbers of storage fungi in grain dried with ambient air frequently exceed 100,000 colonies per gram (Armitage et al., 1982). Like mites, the equilibrium relative humidity (ERH), which constitutes the lower limit for most fungi development, is in the region of 65 to 70% (Ayerst, 1969).

Low temperatures are required to prevent microfloral damage in damp grain. Table 1.3 shows that temperatures lower than 5°C (and for *Penicillia* molds, below 0°C) are needed for the suppression of mold development.

Most fungi do not grow at relative humidities below 70%, which is equivalent to about 13% mc for cereal grains. Therefore, microfloral growth is dependent mainly upon the ambient humidity, and cooling the grain does not seem to be an efficient method for arresting development. Nevertheless, the lower the temperature, the more limited the microfloral damage. Therefore, grain with slightly high moisture content can be stored without being seriously damaged if the ambient temperature is sufficiently low. Christensen and Kaufmann (1974) reported the possibility of storing sound, in-good-condition grain of 15% moisture content for 9 to 12 months, without damage, when the grain temperature is maintained between 8 and 10°C. However, these low temperatures are difficult to attain by aeration in subtropical climates.

Very often grain must be harvested under unfavorable weather conditions with a moisture content too high for safe storage. Sometimes this is a result of cold, cloudy, or rainy weather at harvest, when field crops do not receive adequate solar radiation and wind to finish field drying. Even in regions where the relative humidity is high at night, with or without the deposition of dew, grain harvested in early morning may have a moisture content 3 to 5% above that harvested in midafternoon.

Differences were greater than that in sorghum seeds collected from different parts of the same heads. Sorghum kernels collected at about 8 a.m. from the top of the heads of several plants had an average moisture content of 16.3%, whereas kernels from the bottom of the same heads had an average moisture content of 35.0% — a difference of almost 20% (Christensen and Kaufmann, 1969). Few people seem to be aware of this wide variation in moisture content, although at times wide-spread moistures at the beginning of harvest can have a great influence on the storability of some types of grain.

Most of the maize (corn) produced and marketed in the U.S. is harvested with cylinder-concave or rotary self-propelled harvesters or combines. For best shelling results, maize is harvested at a moisture content of about 23 to 26%. Unfavorable weather at harvest time, delayed maturity, or other factors may result in maize harvested at moisture contents of 27 to 35% or more. In much of the U.S. corn belt, daytime temperatures and the resulting grain temperatures are within a range that permits rapid microbial growth, especially if the moisture content of the harvested grain is above 22%. This biological activity and favorable conditions combine to form a significant grain storage hazard.

Several approaches and combinations of approaches have been developed to improve storability and maintain marketable qualities in corn and other grains harvested at susceptible temperature and moisture conditions. The principal approaches are (1) drying to a moisture content safe for storage; (2) aeration with ambient air that maintains a low, uniform temperature to prevent migration of moisture; and (3) aeration with pre-conditioned air, generally artificially cooled with refrigerant-based systems.

Grain system operators must take into account the moisture content of the grain when received. In addition, they must assess grain conditions such as how long the grain can be kept before drying without losing grade or quality. Also they must determine the temperature and moisture conditions at which the grain should be conditioned to maintain quality for the required long- or short-term storage period or for immediate market. The uses of the grain, shifts in market prices and demands, plus storage and marketing costs are also important considerations.

Short-term holding of grain at higher than "safe" storage moisture levels is often economically beneficial. Grain marketing systems in all countries are based on wet-basis moisture contents that are part of the grading system. For example, No. 2 commercial maize in the U.S. is based on 15.0% moisture content (wet basis). Farmers or commercial elevator operators who market No. 2 maize at moisture levels below 15.0% lose a significant amount of profit from grain moisture weight loss from overdrying. Commercial elevators often blend drier maize with wet maize to ship at the allowable 15.0% moisture, profiting from combining over- and underdried grain.

Overdrying increases fuel costs; but if grain is underdried or delivered to a grain elevator without drying, drying and/or shrinkage penalties are assessed. When maize is delivered to a U.S. grain elevator at moisture levels at 15.1% or higher, grain elevator managers typically assess a drying expense discount of $0.01/bu and a moisture shrinkage factor of 0.7% weight for each 0.5% moisture above 15.0%. If maize is stored for farmers by the elevator, discounts and shrinkage start at 14.6%. Between 20.1 and 20.5% moisture, maize discounts range from about $3.98 to 4.73 per tonne ($0.10 to 0.12 per bushel), and shrinkage for moisture ranges from about 7.7 to 9.1% (Assumption Coop Grain Company, 1997).

Some grain milling processes — such as wheat flour milling or wheat, oats, or maize processing for cereals — require specific moisture levels of 15 to 17% to obtain optimum milling or processing yields. The closer wheat, oats, maize, or other food grains are to the desired processing moisture level, the more efficient and profitable the milling process becomes.

In summary, grain cooling by forced aeration is beneficial in preventing fungal damage through both temperature and moisture control. However, attaining effective low grain temperatures and moistures by using aeration may be difficult in subtropical warm climates. In most cases, microfloral damage should be prevented by storing dry (or dried) grain rather than by aeration cooling. However, there are cases where an acceptable reduction in deterioration rate can be more easily achieved by lowering grain temperature rather than drying or artificially drying the grain.

1.2.1.3.1 Wet Grain Storage and the Influence of Fungi

Field grain carries many mold spores or fungi. Field fungi are invariably present on cereal grains at harvest either under the epidermis or on the surface of the seeds (Christensen and Kaufmann, 1974). At low temperatures, below about 5°C, the original field fungi may survive for long periods of time in both damp and dry grain. At higher temperatures, these field organisms die out; if the grain is damp, field fungi are rapidly replaced by storage molds.

Mold spores can germinate and damage grain at above a minimum grain equilibrium moisture content and temperature. Several common storage fungi are listed in Table 1.3. Grain with moisture levels that result in ERH values above 80% RH may have several common field fungi, such as *Aspergillus flavus* and *Penicillium funiculosum*, which may germinate even at minimum temperatures of 6 to 8°C. The concept of "safe grain" moisture levels that sustains an ERH of 65 to 70% or less are illustrated by *A. candidus, A. glaucus* (blue eye mold) and *A. restrictus*, which have a minimum of about 72% ERH.

Of these common grain fungi, several are only active at relatively high moisture levels, while others are considered "low to moderate moisture level fungi." The low to moderate moisture storage fungi are the most dangerous to stored grain. This is because of the possibility of developing just above the critical moisture content that may be created due to uneven drying moisture, condensate moisture, or moisture migration that can result in moisture buildup in dry stored grains. These mold species that germinate in the range of 71 to 82% ERH are listed in **bold type** in Table 1.3. A higher grain moisture level may be required to sustain the growth of these fungi.

In ventilated or refrigerated grain, odors in the air leaving the grain bulk are useful guides to its condition. A faint mustiness in the normally fresh smell of the expelled air is an indication of the beginning of fungal attack (Burrell, 1974). Such odors should be taken as a danger sign and indicate the need for remedial action. The presence of the odor in the air above a bin of unventilated grain indicates that fungi have proliferated to a considerable extent.

Such activity occurs in bulk drying systems where drying is too prolonged. At a later stage of fungal growth, visible colonies of fungi may appear on isolated kernels in cold grain. Fungal growth occurs more rapidly with increasing moisture. To prevent this, knowledge of conditions that lead to fungal growth is essential. Most common storage fungi only become visible to the naked eye at counts in excess of five hundred thousand viable particles per gram of grain, but mycotoxin production may occur at levels below this.

Visible growth is usually first seen on broken seeds where the endosperm or germ is exposed, but sound seed may also be attacked. Dead seeds, lacking natural defenses, are expected to succumb first to fungal attack; but seeds attacked by fungi are not necessarily dead. Tests on moldy seeds taken from damp bulks of grain demonstrate that they will often germinate. Rapeseeds, for example, may be covered with fungal colonies for weeks before they die (Burrell et al., 1980).

Once fungal growth has preferentially attacked isolated individual seeds in a layer of damp grain, it then spreads to adjacent seeds until the damp layer is completely caked. During the process, the seeds are invaded by a succession of different fungi that consume dry matter, increase the moisture content, and produce carbon dioxide and heat. In caked grain, dry matter losses of 10 to 30% are common; and in extreme cases the seeds disintegrate when disturbed.

Fungal growth and the production of fungal spores create a variety of problems; the product becomes musty, unpalatable, or unstable — but above all, fungi or fungal metabolites may be harmful to men and animals. For example, many fungi produce toxins that may adversely affect animals and, through animal products, gain access to the human food chain (MAFF, 1980; WHO,

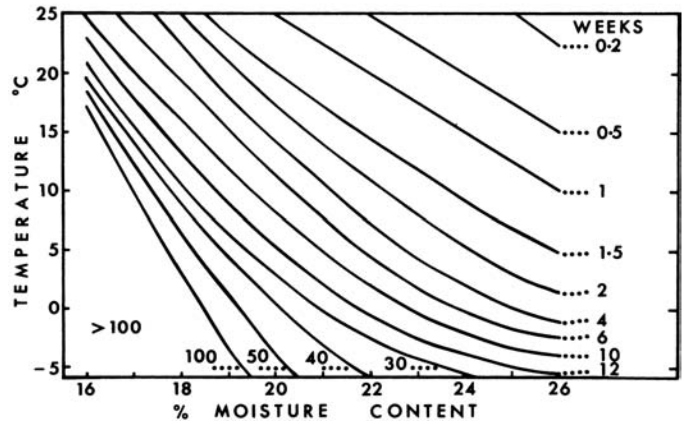


Figure 1.3 Estimated number of weeks of freedom from visible molding for barley at a range of temperatures and moisture contents. (From Burrell, N.J. [1982]. Refrigeration, in Christensen, C.M. (Ed.), *Storage of Cereal Grains and their Products,* based on data by Kreyger [1972] and Burrell [1966], St. Paul, MN, pp. 407–441. With permission.)

1979). Another type of harmful effect is caused by spores and other dusts released into the air when moldy grain is disturbed by handling. Such dusts may sensitize workers and animals, causing allergies to specific fungi.

Temperatures well below 0°C are needed to prevent fungal activity during sustained storage of grain above 23% moisture content. For short-term storage, particularly for moistures up to about 22%, temperatures just above freezing are adequate. The limitations of low-temperature storage are illustrated for barley in Figure 1.3; but at the same relative humidity, wheat, rye, and oats are more readily attacked by fungi than barley (Kreyger, 1972).

1.2.1.3.2 Control of Respiration and Fungi

The losses of cereal grains, from the time of maturity in the field to time of consumption, vary from 5 to 50% of the production depending on the type of cereal grain, variety, geographic region, and climate (Brooker et al., 1974). Field losses tend to increase as grain moisture decreases due to shatter losses during delayed harvest. Rain on mature grain decreases grain quality; and storms cause lodging of grain, increasing harvesting field losses. Losses and loss rates during slow drying and storing generally increase with an increase in moisture.

Respiration of carbohydrates, the primary constituent of grain kernel dry matter, is a process that produces heat, water, and carbon dioxide. The combustion of a simple sugar follows the following molecular equation (Brooker et al. 1974):

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 677.2\ kcal/mole \tag{1.1}$$

One percent dry matter loss is accompanied by the production of 14.7 grams of carbon dioxide per kg of dry matter, causing an equivalent heat production of 157.2 kJ/kg grain (Steele et al., 1969). In the U.S., much of the work on grain deterioration has focused on the dry matter loss of maize during natural and low-temperature drying operations and subsequent storage periods. In Europe, much of the work on grain deterioration has focused on the small grains such as wheat, rye, and barley.

In the 1950s grain spoilage due to respiration and molding became a concern in many on-farm grain storage installations (Hall, 1980). Large-scale farm storage systems that approach the size of small country grain elevators are usually managed more like commercial elevators. These operations are frequently more technically advanced than most small farm operations. Operators of large farms have more investment at risk and typically keep more up to date on grain storage technology than smaller farmers. Often, during adverse weather conditions, small farm in-bin drying systems are not capable of drying high-moisture maize rapidly enough; and serious spoilage occurs in the undried grain.

Foster (1953) did early studies on the development of the design parameters for ambient- and low-temperature drying. He pointed to the deterioration of grain in the top 0.3 m (meters) of the grain pile, which dried last. He used a weighted deterioration index, which increased with time, to estimate grain spoilage.

Saul and Lind (1958) and Steele (1963) developed the deterioration concept further by relating the production of CO_2 to the dry matter loss of maize due to respiration and mold development. Steele and Saul (1962) proposed a relationship between the effect of temperature and moisture content. Later Steele et al. (1969) reformulated the proposed multiplicative relationship to also include mechanical damage effects on the rate of dry matter loss. The proposed relationship was given by Steele et al. (1969) as:

$$AST = T_R \, m_T \, m_M \, m_D \tag{1.2}$$

The allowable storage time, *AST,* is in hours. The reference time, T_R, is defined as 230 hours for a 0.5% dry matter loss when maize is held at a constant temperature of 15.6°C and 25% moisture content. The reference grain condition was field-shelled maize that was visually assessed to contain 30% mechanical damage based on weight at the time of assessment. The relationships of the dimensionless multipliers, m_T, m_M, and m_D, were given in graphical form. A reference time of 58 hours was determined for a 0.1% dry matter loss, and 536 hours for a 1.0% loss. Saul (1970) reported on more studies for grain temperatures below 15.6°C. This extended the range for the temperature multiplier and lengthened the *AST* at grain temperatures significantly below 15.6°C.

Thompson (1972) investigated the temporary storage of high-moisture shelled maize under continuous aeration and used a computer simulation to predict moisture content, temperature, and grain quality. Grain quality was calculated using the dry matter loss equation of Steele et al. (1969) and Saul (1970). Saul concluded that deterioration was minimized with higher airflow rates, later harvest dates, and lower moisture contents. Although deterioration was slowed at lower initial grain temperatures, the total deterioration was about the same over the length of storage. The quality index varied by as much as twofold depending upon the local yearly weather pattern.

1.2.1.3.3 Aeration to Suppress Mold Activity

The three possibilities for suppressing mold development with aeration are:

1. Remove the heat generated due to spontaneous heating of wet grain. In such a case, moisture and temperature of grain may remain unchanged; but further heating within the grain mass may be reduced to that in line with the present grain condition, temperature, and moisture.
2. Cool the grain mass for this purpose; high cooling rates are necessary. To hold wet grain in temporary storage for an extended period of time, the grain must be cooled quickly to a temperature that will minimize mold development. The grain temperature must be maintained uniformly at or below that level.
3. Dry the grain. Airflow rates lower than typical for drying grain are applicable and can effectively reduce grain moisture to safe storage levels.

According to Lacey et al. (1980), the number of field microorganisms found in stored grain depends largely on conditions prior to harvest but also on the conditions of storage. In wet weather, field fungi may develop abundantly and then be carried in to store.

If the grain is sufficiently dried and then stored well, the field microorganisms may survive for long periods. Otherwise they die out rapidly. Thus, field microorganisms found in stored grain may indicate that storage has been good although pre-harvest conditions may have been poor. In contrast, in the presence of many intermediate fungi, high water activity may indicate low temperature deterioration. If *Fusarium* species are present, there is a possibility of toxin production.

The particular microorganisms that grow in stored grain are determined by the interaction of many factors. These include the water activity of the product, temperature of storage (including any spontaneous heating), aeration, period of storage, chemical composition of the product, presence of foreign material, insect and mite infestation, and the use of chemical preservatives.

Water activity (a_w) is the ratio of the vapor pressure of water in a product or solution to that of pure water at the same temperature. Water activity and ERH are numerically equivalent, but ERH is expressed as a percentage; thus, a_w 0.8 = 80% ERH. At a_w 1.00 free water is available in the substrate. Water activity (or ERH) is a more useful parameter than water content since it reflects the availability of water for metabolic processes. Different products with the same water activity may have very different water contents. For example, oilseeds have a higher water activity at a given water content than starchy cereal seeds (Lacey et al., 1980).

Microorganisms have characteristic optimum and limiting water activities and temperatures. These are interrelated. For a given microorganism, the lowest minimum water activity for growth occurs at or slightly above the optimum temperature, while the maximum temperature for growth may be highest at rather low water activity (Ayerst, 1966). This interaction of water activity and temperature determines the ability of microorganisms to germinate as well as their rate of growth. There is a continuous spectrum of species growing in grain from –8º to 70°C and from a_w 1.0 down to about 0.65, but groups with similar requirements can be recognized (Lacey et al., 1980).

Water activity largely determines the amount of microbiological heating in a stored crop. The minimum for fungal growth is about 0.6 a_w. At water activities slightly above 0.65, *Aspergillus restrictus* and species of the *A. glaucus* group grow slowly without increasing the grain temperature. If the water activity is somewhat higher, then growth is more rapid and the temperature soon rises, since the grain, being an insulator, cannot conduct metabolic heat away faster than it is produced. Metabolism also produces water, increasing the water activity further.

Microbiological heating is thus a self-accelerating process up to a peak temperature. Nevertheless, the initial water activity largely determines the maximum temperature reached (Lacey et al., 1980), and different combinations of water activity and peak temperature produce characteristic associations of microorganisms. The conditions under which the different species predominate are not necessarily their optimum for growth in pure culture but are those at which the species compete most effectively in a mixed population (Lacey et al., 1980).

Table 1.4 summarizes the limiting water activities for mold growth in relation to temperature. Since mold activity is dependent on temperature, molds appear to tolerate lower temperatures at higher water activities. Table 1.4 is based on approximate equilibrium moisture content values at 25.5°C equal to the minimum percent relative humidity in which fungus can germinate, but fungi seem to require higher moisture content to grow and compete with grain. Water activity appears to be a more accurate approach to express the humidity values in terms of water activity (decimal of relative humidity) and dependence on temperature (Lacey et al., 1980).

1.2.1.3.4 Cooling Wet Grain

Moist or wet grain is characterized as being above 70% ERH, which usually places cereal grains in a moisture range of 13 to 14% moisure content (mc) in ambient temperature ranges. Regardless of geographic region, terrain elevation, latitude, or prevailing weather patterns, designing an aeration system to keep moist grain from spontaneous biological heating due to sustained mold growth requires much higher aeration airflow rates than dry grain. This requires installing higher

Table 1.4 Limiting Water Activity (a_w) for Mold Growth[a]

Temperature T_{ab} (°C)	Experimental Data a_w	Polynomial Values a_w
–5	0.953	0.943
0	0.910	0.903
5	0.882	0.843
10	0.782	0.779
20	0.698	0.683
27.5	0.673	0.666
30.0	0.678	0.672
35.0	0.703	0.702
40.0	0.765	0.750
45.0	0.828	0.808

[a] At water activity levels below the limiting experimental values, molds do not grow, or grow very slowly. Above the limiting values, mold growth is possible.

From Lacey, J., Hill S.T., and Edwards M.A. (1980). Microorganisms in stored grains: their enumeration and significance, *Trop. Stored Prod. Inform.,* 38, 19–32.

capacity blowers, ducts, and vents than those used for aeration of dry grain in order to provide fast cooling while gradually drying the grain to safe moisture levels.

Regardless of ambient temperatures, aeration systems should be started as soon as moist grain is placed in holding tanks to keep fresh air moving through the moist grain. Aeration should be operated as the tank is being filled and run continuously until the grain is removed or the moisture reaches a safe storage level. If aeration is stopped, the interstice air RH will increase to equilibrium, which may cause germination of fungi, mold growth, and spontaneous heating. Although low humidity air will quickly become saturated, continuous airflow will minimize spontaneous heating.

While aeration of dry grain typically removes from ¼ to ½ percentage point moisture for each complete cooling cycle, aeration of wet grain may remove as much as ¾ to 1 percentage point or more during the time required to complete a cooling cycle. The wet grain aeration process operates much like low-speed natural air drying. Aeration is not considered a drying process, but continuous high aeration airflow rates used for wet grain cooling slowly lower grain moisture toward safer levels while keeping fresh air moving across each kernel.

Depending on mc, even in cool or cold regions, wet grain can develop spontaneous heating even at relatively low grain storage temperatures of zero to 10°C, causing mold odor, germ damage, and discoloration and resulting in a severe loss of grain quality. A review of Table 1.5 indicates that grain above 20% moisture levels is unsafe unless uniform bulk grain temperatures of at least 0°C are maintained until the grain is dried or processed.

Table 1.5 lists wet holding time vs. grain temperatures during which stored maize at a range of moisture contents is known to sustain dry matter losses that will cause the grain to lose one grade level in U.S. grain markets. This chart is used by U.S. producers and elevator managers in the U.S. corn belt and other grain regions as a guide for cooling and holding high-moisture maize while it is dried to safe storage levels. For storage at high moisture, maize should be cooled to sufficiently low temperatures or should be dried to safe storage moisture levels well in advance of the time listed. Variables such as uneven cooling, high moisture zones, and condensate drainage that creates wet grain under fill spouts require that a margin of safety be applied to Table 1.5.

Kuppinger et al. (1977) compared the low temperature drying of maize in Germany at field moisture contents of 35% and maize at moisture contents of 20 to 25% after pre-drying in a high-temperature dryer. Germination, dry matter loss, and spore count of microorganisms were determined to evaluate the quality of the maize. Germination was not found to be a good quality indicator because of high values even after molding was already visually detected. Dry matter loss varied from 0.6 to 3.0% for

Table 1.5 Approximate Allowable Storage Time (Days) for Cereal Grains

Moisture Content (& wet basis)	Temperature (°C) –1	4	10	16	21	27
14	*	*	*	*	200	140
15	*	*	*	240	125	70
16	*	*	230	120	70	40
17	*	280	130	75	45	20
18	*	200	90	50	30	15
19	*	140	70	35	20	10
20	*	90	50	25	14	7
22	190	60	30	15	8	3
24	130	40	15	10	6	2
26	90	35	12	8	5	2
28	70	30	10	7	4	2
30	60	25	5	5	3	1

* Approximate allowable storage time exceeds 300 days.

Compiled from *ASHRAE (1995).*

Based on composite of 0.5% maximum dry matter loss calculated on the basis of USDA research; *Transactions of ASAE 333-337, (1972)*; Unheated Air Drying, Manitoba Agriculture Agdex 732-1, rev. 1986.

Table 1.6 Spore Count (Number of Spores per Gram of Dry Matter) for Bacteria, Yeast, and Molds in Harvest–Wet and Pre-Dried Maize

Microorganism	Harvest–Wet at 35% wb	Pre-dried to 19% wb
Bacteria	0.2106–4.3106	1.5103
Yeast	0.3105–1.3105	2.1100
Molds	3.9103–6.5104	3.2102

From Kuppinger, H.V., Muller, H.M., and Muhlbauer, W. (1977). Die beluftungstrocknung vonerntefrischem und vorgetrocknetem kornermais unter thermodynamischem undmikrobiologischem aspekt, *Grundl. Landtechnik Bd.,* 27, 119–132.

maize dried from 35% moisture, while the dry matter loss of pre-dried maize was only 0.04%. The spore count for the microorganism groups of harvest-wet and pre-dried maize is listed in Table 1.6.

Grain deterioration, associated largely with fungal growth, is the principal constraint on the allowable length of time to complete drying. The maximum permissible storage time in low temperature drying systems depends on grain type and physical condition, moisture content, and temperature. Saul and Lind (1958) and later Steele et al. (1969) monitored CO_2 production to indicate the amount of dry matter loss incident to microbial growth in shelled corn.

From these studies, the allowable storage time was established based on a dry matter loss of less than 1% (Figure 1.4). Steele et al. (1969) calculated the permissible storage time for field-shelled corn with 30% mechanical damage with temperature and moisture content. Storage time was determined based on 0.5% dry matter loss (Figure 1.5). Thompson (1972) incorporated these data into a deterioration index and adopted a dry matter loss of 0.5% as the major constraint in establishing minimum airflow requirements for drying grain with unheated air.

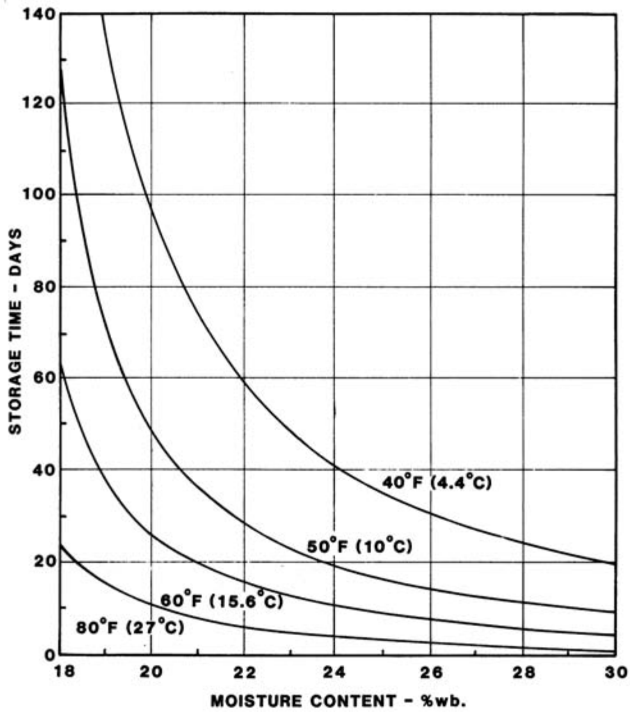


Figure 1.4 Permissible storage time for corn based on a dry matter loss of less than 1%. (From Foster, G.H. [1982]. Drying cereal grains, in *Storage of Cereal Grains and their Products,* Christensen, C.M., Ed., American Association of Cereal Chemists, St. Paul, MN, pp. 79–116. With permission.)

1.2.1.4 Maintenance of Seed and Grain Quality

Historically, research has demonstrated that low kernel temperatures are desirable for better maintenance of seed and grain quality. Storage of seeds at low temperatures (cold storage) is in widespread practice today, and studies have shown that the lower the temperature (within certain limits), the longer the seeds maintain their full viability. A rule of thumb was proposed (Harrington, 1973) where the relationship between seed longevity and the seed temperature and moisture is expressed arithmetically. This rule states that a seed's lifespan in storage is doubled for each 5°C decrease in temperature (within the range of 0 to 50°C) and for each 1% decrease in seed moisture (within the range of 5 to 14%).

Hukill (1963) approached the problem of defining the relationship between viability and environmental factors in a different way. He used the data of Toole and Toole (1946; 1954) on the viability of soya beans to develop the concept of an "age index." Roberts (1974) summarized the attempts to define quantitatively the relationship between temperature, moisture content, and period of viability. This dependence of seed life on storage temperature (and humidity) was expressed mathematically in a formula by Roberts (1974), where the seed lifespan can be predicted according to data on seed temperature and moisture.

Roberts (1974) determined a series of viability constants that make possible the prediction of the time needed for viability to drop to any given level of germination and that enable the equation to be applied to many different seeds. From this work he derived many convenient nomograms. A simplified version, based on work by Linko (1960) for estimating the half viability period for wheat under a wide range of conditions, is shown in Figure 1.6. It demonstrates the extent to which low temperatures may be used to prolong storage life. Another convenient form for expressing loss of viability at higher (Kreyger, 1967) and lower (Burrell, 1966) temperatures is illustrated in Figure 1.7.

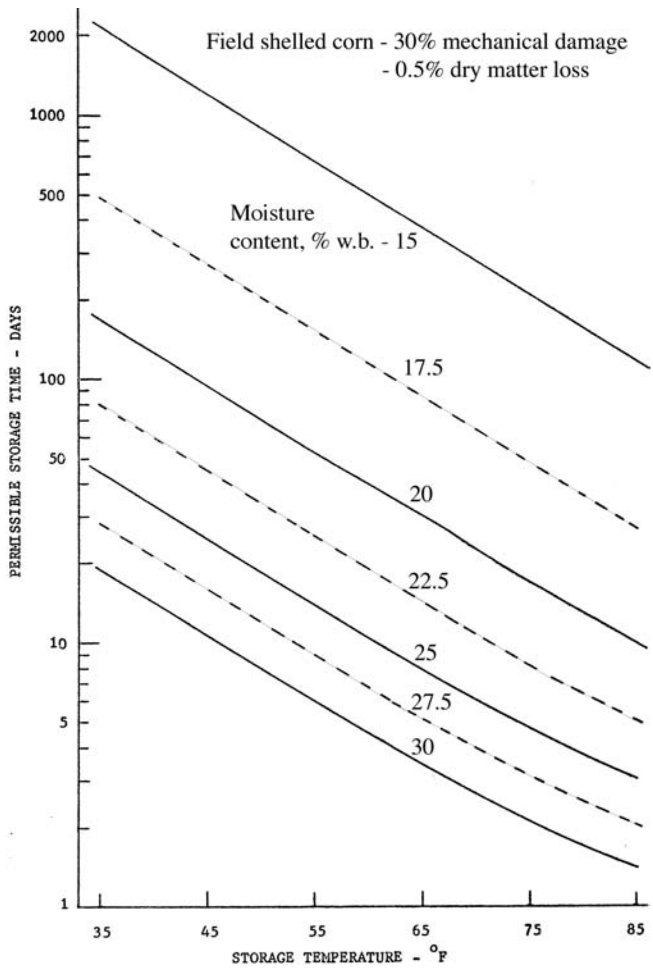


Figure 1.5 Permissible storage time for field-shelled corn with 30% mechanical damage with temperature and moisture content. Storage time was determined based on 0.5% dry matter loss. (From Steele, J.L., Saul, R.A., and Hukill, W.V. [1969]. Deterioration of shelled corn as measured by carbon dioxide production, *Trans. ASAE,* 12, 685–689. With permission.)

Germination tests as a measure of stored grain viability are important in the evaluation of grain quality in storage. Grain with reduced viability reportedly becomes vulnerable to mold attack and is more susceptible to deterioration. Consequently, seed storability (period over which seeds can be safely stored at specified references or standard conditions) becomes greatly reduced.

1.2.1.4.1 Maintenance of Germination

The terms *germination* and *viability* are often used interchangeably. The Association of Official Seed Analysts defines *seed germination* as "the emergence and development from the seed embryo of those essential structures which, for the kind of seed in question, are indicative of the ability to produce a normal plant under favorable conditions" (Copeland and McDonald, 1985). *Viability,* on the other hand, refers more directly to the ability of seeds "to survive as viable regenerative organisms" until the time and place are right for the beginning of a new generation. "Like other forms of life, seeds cannot retain their viability indefinitely and eventually deteriorate and die." (Copeland and McDonald, 1985). Germination is important in cooling by aeration or in chilled storage — not only because the germ viability is crucial to the reproductive cycle of seed grain,

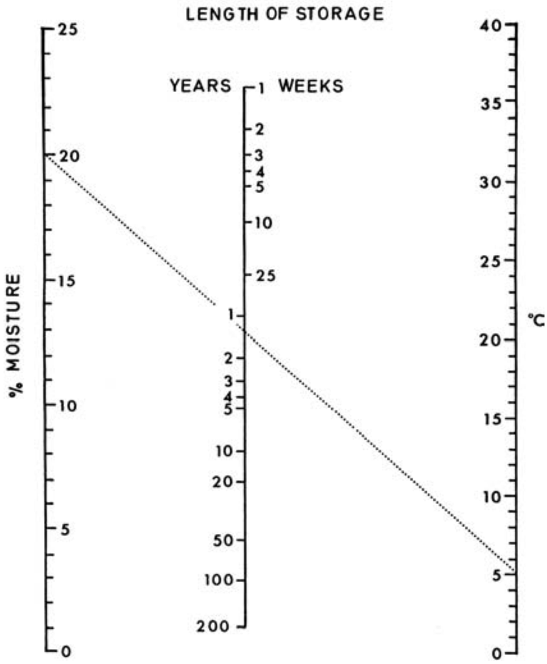


Figure 1.6 Estimated half-life for wheat (time taken for germination to fall to 50%) under a wide range of storage conditions. Dotted line shows half-life for wheat stored at 5°C and 20% moisture. (From Burrell, N.J. [1982]. Refrigeration, in *Storage of Cereal Grains and their Products,* Christensen, C.M., [Ed.], St. Paul, MN, pp. 407–441, based on Linko [1960] and Roberts [1974]. With permission.)

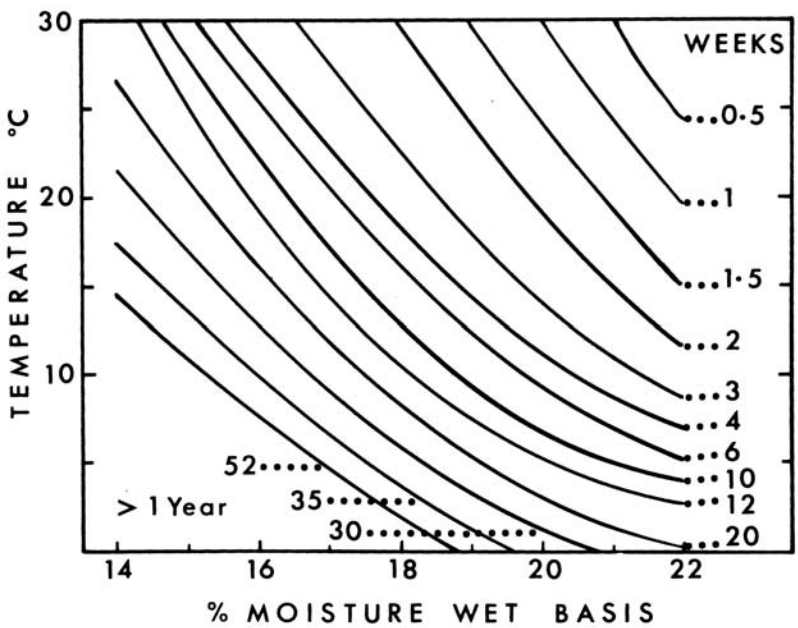


Figure 1.7 Estimated time for the viability of malting barley to fall by 5% at a wide range of temperatures and moisture contents. Note that at temperatures below about 10ºC, damp seed may remain dormant for many months and may also become water sensitive. (From Burrell, N.J. [1982]. Refrigeration, in *Storage of Cereal Grains and their Products,* Christensen, C.M. [Ed.], St. Paul, MN, pp. 407–441, based on Burrell [1966] and Kreyger [1967]. With permission.)

Table 1.7 Allowable Storage Time (in Days) of Seed Grain as a Function of Moisture Content (% wb) and Temperature (°C)

Moisture Content (% wb)	5°C	10°C	15°C	20°C
18%	80	33	25	13
20%	42	20	15	9
26%	15	8	6	4

From Bewer, H.E. (1957). Getreidekonservierung mit kalter Nachtluft. München Wolfrathausen, Ber. Inst. Landtechnik No. 47, Bonn.

but the germ is essential in several end uses of cereal grain, such as malting and brewing, distilling, and sprouting (Christensen, 1982).

In 1927, Reimann noted that grain storage in Germany was worry-free between November and March. However, in April and May problems arose as the ambient temperatures surrounding the grain storage increased. He stated that minimal quality losses (i.e., germination) in the storage of bread grains could be achieved when moisture contents were below 14% wet basis (wb) and grain temperatures less than 10°C. No decrease in the viability or damage to milling and baking qualities were found in wheat samples stored at 5°C and moisture contents of 10 to 20% (wb) were reported by Swanson (1941). Carter and Young (1945) investigated the effect of moisture content, temperature, and storage time on the development of "sick" wheat (i.e., brown germs). The proportion of "sick" wheat increased with higher moisture content, temperature of the grain, and longer storage times. Only a small percentage of "sick" wheat developed over 32 days in wheat at 18.6% moisture stored at 5°C.

The initial conditions of different batches of grain vary considerably. Shands et al. (1967) have shown that the weather before harvest can seriously affect the germination potential of cereal grains. Cool storage also may reduce the germination of grain, particularly if it has been damaged by combining during harvest (Arnold, 1963). Blum and Gilbert (1957) have suggested that inhibition of germination can result from fungal activity at high moisture content.

Cooling of wet grains to subzero temperatures can be detrimental, however. For example, Agena (1961) measured the effect of refrigeration on the germination of cereals at temperatures between 6 and –24°C and at moisture contents of 20 to 26%. He found that for wheat, barley, and rye, temperatures below –6°C damaged the seed in 24 hours and that germination failure increased as the temperature was progressively reduced and as moisture contents were increased.

Research has now fully established that the dormancy of some grains, particularly some varieties of barley, is maintained for long periods unless the grain is thoroughly dried and stored warm for a period of 2 to 3 weeks. Exposure of moist grain to cool storage, such as that experienced in chilling, prolongs natural dormancy. It may, however, also impose a secondary dormancy or "water sensitivity" that prevents barley from germinating after it is steeped in water during the malting process. Malting and seed barley should, therefore, be dried normally because cool, moist storage conditions adversely affect germination.

Bewer (1957) stored the seeds of primary bread grains (wheat, oats, barley, and rye) at moisture contents ranging from 18 to 26% and temperatures of 5 to 20°C. The seed quality was evaluated by testing germination. He concluded that the higher the moisture content and temperature in the ranges studied, the sooner spoilage would occur. His results are summarized in Table 1.7.

Papavizas and Christensen (1958) evaluated viability, brown germs, and percentage of seeds invaded by fungi. They concluded, "Evidence suggests that wheat with a moisture content up to 16% may be stored without obvious deterioration for a year at a temperature of 10°C or below." Agena (1961) investigated the effect of storing higher moisture grain at temperatures of –24 to 6°C on the viability of grain and mold development. At 0°C he recommended maximum storage times of 40 days at 26%, 60 days at 22%, and 170 days at 18% moisture content. No reduction in baking quality was observed.

Christensen and Kaufmann (1969) reported that fungi-free maize stored for two years at 18% moisture and 15°C had a germination rate of 96%; but when stored at 15.6 to 15.8% moisture at 5, 10, and 15°C for two years, the germination rate was 100%. However, No. 2 maize stored at 12°C decreased in germination from 60% at the beginning of the test to 42% after 6 months, to 36% after 12 months, and to 1% after 18 months. When maize was inoculated with a mixture of *Aspergillus* species and stored at 15.9% moisture content and 15°C, germination was only 48% after 2 years. The germination of 18% moisture maize inoculated with *A. flavus* stored at 15°C over 4.5 months was 62%. Come (1982) noted that seeds of tropical and subtropical origin retained high viability when stored in bulk silos in a dry 5°C atmosphere.

Burrell (1974) noted that the conditions stated by various researchers on the safe storage with respect to seed germination varied considerably. Apparently, different batches of grain behave differently when exposed to the same set of storage conditions. He stated, "For the preservation of high germinability, drying is preferable to chilled storage" in cool and moist conditions. The estimated safe storage time to preserve the viability of barley at a 95% germination rate was determined to be a function of temperature and moisture content.

Generally, the lower the moisture content and the lower the temperature, the longer the seed can be stored (Copeland and McDonald, 1985). The knowledge of the appropriate limits is the basis for the proper engineering design of a grain cooling and seed storage system.

1.2.1.4.2 Maintenance of Grain Quality by Cooling

Rates of chemical deterioration such as oxidation of fats and vitamin loss occurring in grain during storage are very slow and sometimes insignificant at low temperatures. The rate of chemical reaction taking place in stored food is halved with each decrease of 10°C in temperature. Therefore, cool storage is important for the prevention of deteriorative changes in stored grain.

Converse et al. (1977) reported on changes in quality of wheat stored with and without aeration in concrete silos. Aeration of wheat significantly reduced losses in germination and development of free fatty acids. Wheat from aerated silos had a better physical appearance and a more desirable aroma than wheat from non-aerated silos.

Grain in storage, even though a living component of the grain bulk ecosystem (Figure 1.1), is actually in a dormant state in which all biotic activities of the grain are imperceptibly slow. This state of inactivity should be maintained for as long a period as possible, since activation of life processes in grain leads to loss of viability, followed by deterioration in quality. Thus, low ambient temperatures, introduced into the grain bulk by aeration, are very beneficial in keeping the grain in the state of quiescence needed to maintain grain quality over long periods of storage.

By the 1970s considerable practical experience with grain chilling had been obtained, and earlier recommendations were refined. A summary of current grain chilling and storage recommendations is listed in Table 1.8. The data on the relationships between moisture content, temperature, and allowable storage time of small grains are based on the research work of Bewer (1957), Agena (1961), Kosmina (1956), Scholz (1962), and Jouin (1965). The chilled storage of grains above 22% moisture was recommended in 1972, but this practice was no longer considered practical by 1989 because drying was more economical.

Chilling maize proved to be more complicated than chilling small grains (Sulzer-Escher Wyss, 1980). According to research recommendations, maize above 21% moisture content should only be stored short-term under continuous chilling at 3 to 5°C without reheat. Maize at 19 to 21% moisture can be stored 3 to 6 weeks by chilling once to 8 to 10°C. By the end of the storage period, the maize needs to be dried to a safe level. Maize at 17 to 18% moisture chilled to less than 10°C

Table 1.8 Moisture Content Ranges (mc), Grain Temperatures (°C), and Allowable Storage Times (AST) of Grains with Different End Uses under Chilled Storage Conditions

	Seed Grain and Malting Barley		Bread Grains		Feed Grains	
MC (%)	°C	AST	°C	AST	°C	AST
12–15[a]	9–12	1.5 y<	10–12	1.5 y<	10–14	1.5 y<
15–16.5[a]	8–10	1–1.5 y	9–10	1.5 y<	10–12	1.5 y<
16.5–18[a]	5–7	4–6 m	8–10	5–10 m	8–10	6–13 m
18–20[a]	5	2–3 m	8–10	2–7 m	8–10	3–9 m
20–22[a]	5	3–4 w	6–8	4–16 w	8–10	5–20 w
22–25[b]	5	1–2 w	5–7	3–8 w	5–8	10–25 w
25–30[b]	4–5	2–3 d	4–5	5–10 d	4–5	14–30 d
>30[b]	—	—	—	—	4–5	<5 d

Note: y = years, m = months, w = weeks, and d = days.

[a] Sulzer-Escher Wyss (1989). Sales brochure, *Granifrigor Grain Cooling Systems,* Sulzer-Escher Wyss, Lindau, Germany.

[b] Sulzer-Escher Wyss (1972). Sales brochure, *Granifrigor Grain Cooling Conservation* (in German), Sulzer-Escher Wyss, Lindau, Germany.

can be stored safely if the moisture content is reduced to 16% or less during chilling. Maize below 16% moisture can be safely stored several months if properly managed.

Maize chilling following high-temperature drying provides major economic and grain quality benefits. Less stress cracking of kernels is observed when maize is first dried to 19 to 20% and then chilled in-bin, while the maize is still hot. The evaporative cooling process theoretically has enough stored heat energy to remove an additional 2.5 to 3.5% moisture. However, because of grain temperature losses during the transfer process from dryer to cooling bin, the grain cools. Realistic values of moisture removal are about 1.5 to 2.0%, depending on tempering time and cooling airflow rate. This in-bin cooling reduces the grain temperature to a safe storage level (less than 10°C) according to Sulzer-Escher Wyss (1980). This combined drying/cooling process is a modified version of *Dryeration,* a very powerful and economical drying process discussed in detail in Chapter 8.

Maize should be thoroughly cleaned before filling and chilling the storage bin. A grain spreader should be used to distribute trash and fines (which constitute small particles of grain or foreign material) to improve air distribution and uniformity of chilling. Komba et al. (1987) investigated the airflow through maize with and without a spreader. Without a spreader, the airflow through the maize ranged from 0.15 m/s in the center of the bin to 1.2 m/s at the 7.5 m radius. The silo filled with a grain spreader showed an airflow rate of 0.6 to 0.87 m/s over the entire radius of the bulk.

Christensen and Kaufmann (1969) stated that grains and seeds are exceptionally durable but are also highly perishable, depending on the environmental and seed maturity and moisture conditions. Seeds that are harvested sound and kept at a low moisture content and low temperature will retain a high proportion of their original processing quality and germination for several years or decades. Although deterioration of grain generally begins with harvest, damage can begin even before harvest. After harvest, the rate of quality loss depends on the subsequent handling, drying, and storage conditions (Bailey, 1982). The parameters that govern the rate of deterioration of grain in storage include the initial condition of the grain, moisture content, and temperature. The initial condition of the grain encompasses many biological parameters such as germination, respiration, fungal contamination, and insect infestations.

The primary goal of cooling is to slow the rate of losses by lowering the grain temperature after bin filling and maintaining uniform low temperatures during storage. The effects of grain temperature as a function of moisture content and storage time on the biological parameters have been the subject of numerous investigations.

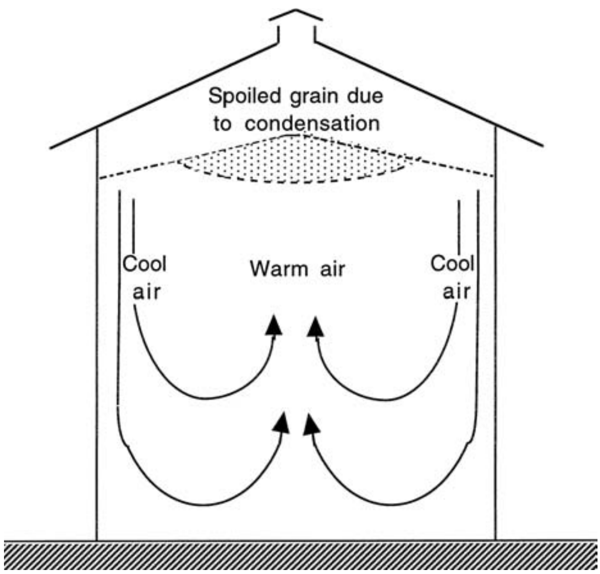


Figure 1.8 Mold-damaged surface layer of wheat due to moisture migration in a non-aerated bulk.

1.2.2 Equalization of Temperature throughout the Grain Bulk

Because of its self-insulating properties, grain loaded into storage during summer harvest retains the initial harvest temperatures for several weeks into cool weather in the fall. For safe storage through winter and spring months, grain temperatures must be lowered during the summer and fall and maintained at low levels which will suppress insect and mold reproduction and growth.

1.2.2.1 Prevention of Moisture Migration in the Grain Bulk

As the ambient temperature drops during the cool season, the surface (and peripheral) layers of the grain become considerably cooler than the internal grain mass. Temperature gradients are established in the grain bulk which create convection currents that circulate air through the intergranular spaces. The cold dense air settles along the outer walls, and the warmer air (which contains more moisture than cool air) moves upward toward the colder upper surface of the grain bulk. In this way, moisture carried by warm air may "migrate" to cooler surface grain — where the air cools to "dew point" and deposits excess moisture, slowly increasing the grain moisture content in the upper parts of the grain bulk.

Moisture migration is a slow convection air movement process that occurs in a grain mass when sufficient temperature differentials exist between the outside and middle of a grain mass, which occurs during a period of several weeks or months. Slow-moving convection air causes moisture to slowly accumulate in the coldest grain layers. In extreme cases, condensation of water may occur on the grain, causing rapid mold (and sometimes bacterial) spoilage. One of the typical symptoms of this phenomenon is the "crusting" of the grain surface (Figure 1.8). Surface crusting should be taken as a warning sign indicating that action must be taken to prevent further damage. The more damaging aspect of moisture migration is not the amount of damaged grain, which is usually small in proportion to the grain bulk, but mixing damaged with undamaged grain during bin unloading. Mixing may reduce the quality of a significant part of the entire grain volume.

In addition to discoloration, mustiness, and decreases in germination, the potential for production of mycotoxins in microflora-damaged grain should also be considered. This is the most significant aspect of microfloral damage that has received worldwide attention by mycologists and nutritionists since the mid 1960s.

An important objective of grain aeration, especially in subtropical and temperate climates in which diurnal or seasonal temperature fluctuations occur, is to maintain uniform grain temperatures. Thus, a major purpose of aeration is not only cooling grain to lower temperatures but also the prevention of moisture migration by maintaining uniform temperatures throughout the grain mass.

Moisture migration occurs in warm, subtropical climates as well as in cooler, temperate climates in which ambient temperatures may fluctuate widely between day and night and may be much colder than the stored grain during winters. Moisture migration can be prevented by the elimination of temperature gradients throughout the grain bulk by aeration with ambient air during cool weather at low aeration rates. Grain temperatures should be measured throughout the aerated bulk at frequent intervals (bi-weekly or monthly) to check grain temperature uniformity.

1.2.2.2 Prevention of Head-Space Water Condensation

Under-roof condensation is a different natural process than moisture migration within the grain bulk. Condensate that drips on the grain involves moisture in humid air that accumulates in the head-space above the grain bulk, condensing on the undersurface of the bin roof. This natural condition, which is acute in hot climates, is the primary factor limiting the introduction of bulk handling technology in tropical countries.

For example, there have been several attempts to adopt metal silos or bins for storage of paddy (rice) in the Philippines. However, head-space moisture condensation caused grain spoilage accompanied by insect infestation and hot spots, even during short storage durations of 3 months (de Padua, 1974). Similar occurrences of head-space moisture condensation in metal silos have been reported in other ASEAN countries (Abdulkadir and Joyosuparto, 1979; Shamsuddin, 1979). Experimental work carried out on the storage of paddy in the Philippines demonstrated that moisture condensation in metal silos could be significantly reduced by using aeration systems to maintain uniform grain temperatures and ventilate bin head-spaces (NAPHIRE, 1990). By using aeration-equipped bins, low-moisture paddy could be successfully stored for one year without significant loss in quality.

Roof head-space exhaust fans operated by humidistat control would be desirable for controlling head-space humidity in steel bins or silos in tropical or subtropical climates. Repeat 24-hour cycle timers may be a simple alternative to humidistat control. The timer could be set to turn roof exhaust fans *on* and *off* at the times each day when bin roofs normally cool and head-space relative humidity rises.

In subtropical and temperate climates, if grain bulks are stored at high temperatures and are not cooled before cold weather, moisture may condense on the underside of the bin roof. Warm grain stored in metal bins can cause condensation during the night, even in relatively warm weather in subtropical and temperate climates. This condition occurs when heat from the roof radiates to the cold night sky, chilling the roof metal until head-space air reaches dew point or below, causing moisture to condense on the metal roof panels and drip on surface grain. Proper aeration can minimize the risk of head-space moisture condensation. Cooling the surface grain by aeration tends to lower head-space dew point temperatures, reducing condensation.

1.2.3 Prevention of Biological Heating

Biological heating of dry grain is caused by moisture increases from insect population growth in localized areas of a grain mass. In moist grain, spontaneous heating can be triggered by mold development. These two phenomena are discussed in the following sections.

1.2.3.1 Ecological Aspects of Heating of Grain

1.2.3.1.1 Heating in Heavily Infested Grain

Howe (1962) noted that most of the heating caused by *S. granarius* was due to the last instar larvae. For example, these larvae produce about 10 times the gaseous exchange of half-grown larvae and 5 times that of adults. *R. dominica* last instar larvae also produce about 10 times the heat of half-grown larvae, but only about 1.5 times that of the adults. From the standpoint of heat generation, most stored-grain insects resemble *R. dominica* rather than *S. granarius*. Heating of grain by insects thus depends on the age or life-cycle stage of the insect. Very high densities of infestation are necessary to cause even small increases in grain temperature. However, temperature rises of 10°C in two weeks are possible; and thousand-fold increases in population in 16 weeks are possible even at low initial temperatures of 23°C. The spread of the hot spot is due to insects migrating from high densities in small pockets of grain. Grain as near as 50 cm to the hot spot can remain cool since steep temperature gradients occur between the heating pocket and the uninfested grain nearby. Most heat is produced near the edge of the small grain volume hot spot.

Hot spots caused by insects can develop at low temperatures (e.g., *S. granarius*) and can attract more infestation. More active insects that require higher temperatures, such as *O. surinamensis* and *C. ferrugineus*, can increase dramatically in a short time. As hot air rises from these hot spots and moisture condenses on cool grain surfaces, mold growth may accelerate, allowing thermophilic fungi to eventually push grain temperatures to 50°C — well beyond the lethal high threshold of insects.

Heat generated by insect metabolism in heavily infested grain causes a chain reaction of moisture increase followed by mold development in the grain bulk. In grain bulks where infestation is localized, insect populations develop in small pockets of grain. *R. dominica* and *Sitophilus* are characteristic species that develop hot spots. Temperatures of heavily infested grain undergoing widespread heating are typically about 38 to 42°C. This can create enough of a temperature differential to develop convection currents in cooler grain (a 5 to 10°C difference is sufficient), causing moisture migration.

When such heavy infestations are discovered, the grain should be fumigated immediately to control insect activity. Then aeration should be used to cool the grain bulk. For grain stored in large bulks in temperate and subtropical climates, it is advisable to fumigate first in order to arrest the spontaneous heating and then aerate to reduce the grain bulk temperature to prevent further damage. Fumigations are more effective at higher temperatures.

1.2.3.1.2 Heating in Moist Grain

Aeration is often applied to freshly harvested, high-moisture grain prior to artificial drying, especially when drying capacity is insufficient. Wet grain aeration is mainly used in temperate climates and is intended to enable grain with excessive moisture content to be "held" temporarily in storage for several days, until the grain can be dried. In Europe, this aeration is called "maintenance of condition" or "ventilation de maintien" (Baudet, 1976; Poichotte, 1977) and is aimed solely at maintaining grain quality and preventing spoilage. Maintaining high-moisture grain in good condition can extend the drying season by several weeks — reducing the need to buy more grain dryer capacity, which is much more expensive than grain aeration equipment and temporary holding facilities.

In damp grain bulks, respiration is very intensive, due partly to the grain but mainly to microfloral metabolism. Respiration results in some loss of dry weight and produces a phenomenon termed *spontaneous heating*. Heat accumulating in the grain bulk has a detrimental effect on grain quality. These high temperatures (up to about 60°C) create steep temperature gradients between the heated grain and the cool surroundings. Moisture migration, brought about by non-uniform temperatures in the grain mass, causes molds that attract insects, adding to the progressive deterioration of storage conditions.

1.2.3.2 Means of Arresting Heating in Grain

In order to prevent heating in damp grain, an aeration system that delivers higher than the generally recommended airflow rates of 6 (m^3/h)/tonne (0.1 cfm/bu) must be put into continuous operation. Specific recommendations for holding moist grain are provided in Chapter 7.

The flow of air through the grain bulk prevents the formation of heating foci and also eliminates differences in grain temperatures throughout the bulk. High-airflow forced aeration maintains the stored grain in a condition that prevents immediate damage, and it normally contributes to improved storability. Storage time is lengthened, and further loss in storability status is reduced.

When cool ambient air is used for moist grain aeration, some decrease of grain moisture content is gradually obtained. However, to achieve faster moisture removal, higher than normal aeration airflow rates and higher total air volumes are needed. High-flow aeration is preferably done in hopper tanks or flat-bottomed steel silos that are equipped for continuous transfer of moist grain to dryers. Holding damp grain in flat storages (in relatively shallow layers of grain) is also practiced in some climates, but aeration must be continuous until the grain is cooled and moisture is gradually reduced to levels suitable for safe storage. This practice of high-airflow aeration is practical in temperate climates, when suitable cool air is available in these regions after summer harvest and following fall harvest.

Storage of damp grain in warm climates poses a much greater problem since respiration, mold growth, and grain deterioration are accelerated at higher temperatures. Aeration for "maintenance of condition" would only be practical in these regions during cool nights or during the cool season. Even then, the aerated grain should not be too moist (13.5 to 15% for most cereals).

In conclusion, storage of damp grain in warm climates is very risky. Aeration to hold moist grain should be carried out with great care, at the highest possible airflow rates per unit volume of grain allowable. Where aeration airflow cannot be increased satisfactorily or is limited, moist grain should be held in as shallow as possible a grain bulk, utilizing air temperatures lower than those of the grain.

1.2.4 Limited Grain Drying by High-Airflow Aeration

In general, aeration systems are not designed for grain drying. However, in temperate climates, damp grain (about 20% mc) can be dried by natural air using high air volumes and continuous fan operation.

The recommended minimum airflow rates for natural air drying of grain depend upon the environmental conditions but are typically 15 to 25 times greater than airflow rates used for cooling grain (Brooker et al., 1974; McLean, 1980). This method of in-bin drying should be distinguished from aeration for grain cooling. It falls within the customary and historical definition of *slow drying* or *in-storage drying*. Chapter 7, Section 7.2.4 contains more detailed discussions of wet grain aeration.

A small but significant drying effect (up to 2% moisture removal) may be obtained during long-term aeration (multiple cooling cycles) to cool large grain bulks (Navarro et al., 1979). This water loss is reflected in a corresponding weight loss in the grain bulk and is of concern in the marketing of grain when records of receipt and delivery from storage facilities or sites do not tally.

1.2.5 Use of Aeration Systems in Fumigation Processes

1.2.5.1 Recirculation to Obtain Adequate Distribution

Recirculation is an effective method of application and distribution of fumigant compounds for the treatment of insects in grain stored in bulk. Gaseous-type fumigants may be recirculated through the grain bulk to obtain a uniform concentration and exposure time that will effectively control insect infestations. The most important advantage of this method is that, because the gas is distributed more quickly throughout the structures and tighter sealing is normally used in the structures, recirculation fumigation usually allows shorter fumigation exposure periods (Bond, 1984). Recirculation is an effective method of returning the air-fumigant mixture that has passed through the grain bulk back into a fan so that continuous circulation is achieved (Brown and Heseltine, 1949; Howe and Klepser, 1958). Although the laws of partial pressures are at work with or without recirculation, the forced circulation accelerates the movement of the gas to all parts of the grain mass, greatly enhancing the natural expansion of the gas.

Although the airflow rate is a basic factor in the design of a fumigant recirculation system, leaks and permeability of the structural materials are also an important concern. Using the existing knowledge for the design of aeration systems, the resistance to airflow through the commodity can be determined. The friction loss in ducts, elbows, and air distribution systems can be used to determine the fan capacity required in a given grain bin (Holman, 1966; Shedd, 1953; Navarro and Calderon, 1982). The existence of an aeration system in a silo is conducive to designing and incorporating a recirculation system.

The airflow in recirculation systems is usually only 5 to 10% of the airflow capacity needed for aeration. The specific design airflow rate is not as critical as in aeration since gas distribution throughout the grain mass is the objective, not cooling of the grain mass. The number of gas or air changes required to reach a relatively uniform distribution of the gas depends on the type and structural shape and the airflow distribution method (aeration duct vs. false floor) of the storage unit.

Tall, slender silos usually reach uniformity with fewer gas exchanges than wide, shallow, flat storage strucutures. Recirculation in tall silos may be stopped after three to four air changes. Large-diameter, shallow grain bins and wide, shallow, flat storages may require eight to twelve air changes for uniform gas distribution.

1.2.5.2 Removal of Fumigant Residues and Odors

After successful fumigation, the resulting residues in the grain must be within tolerable limits. Fumigant sorption and desorption play an important role in determining whether the treatment is successful. The initial phase in a fumigation treatment is the sorption of the fumigant by the commodity. This initial rapid uptake of gas is recognized as a diffusion process. Although sorption curves for widely used fumigants such as MB, phosphine, and CO_2 exist, desorption phenomena have not been studied in as much detail.

These processes need to be recognized and understood for successful removal of residual fumigants from grain. For some fumigants the sorption time is relatively long, while for others the time is much less. For instance, carbon dioxide sorption takes several days, whereas MB is sorbed in a matter of hours. On the other hand, desorption of MB can take several days — just as long as for carbon dioxide desorption. Therefore, release of fumigants using aeration systems requires advance knowledge of the fumigant. Since release of the fumigant is slow as a result of resistance to movement of gas molecules out of each individual kernel, the release of or desorption of fumigants can be achieved with relatively low airflow rates by using the fumigation recirculation blower.

If the aeration system is used to ventilate the structure, to minimize the cost of operating the aeration system to remove fumigants that are slow in desorbing, the grain manager can operate the aeration system intermittently, or in "pulses," to flush gas vapors from the storage. Operate the fan about 10 to 20% of the time, such as 15 minutes every 2 to 3 hours. Allow the interstitial air space to reach equilibrium with the concentration of the fumigant in the grain, and then activate the aeration system several times. After several cycles of fan operation, check the gas level with a gas monitoring instrument after the aeration fan has been shut off for 2 to 3 hours to see if the gas level is below the threshold limit allowed for human entry. In the U.S., phosphine gas concentrations must be below 0.3 ppm before workers can enter without a gas mask and canister or self-contained breathing apparatus.

Field studies on the subject of aeration following fumigation are lacking in the literature. Following fumigation, aeration is routinely recommended. A fumigant gas detector must be used to determine that residual vapors are below the threshold limit for human entry before allowing the grain storage facility to be opened or grain to be removed after in-bin fumigation treatment.

Similar to fumigants, chemicals with aromatic properties can be sorbed by grain. Often these chemicals are unintentionally introduced with a fumigant during a treatment. The presence of odors different from the characteristic grain odor may be an indication that the condition of the grain is changing. Odor is an indicator of grain soundness.

Storage odors can also develop in a grain bulk due to hot spots containing deteriorating grain. These could mix with the grain and affect a larger mass. Sour odors result from anaerobic activity in the process of fermentation at very high moisture contents (above 18% mc for cereals). At moderately high mc (14 to 18% mc for cereals), musty odors in grain are usually caused by the growth of certain molds. While these odors may appear in the early stages of deterioration, they usually occur during the fairly advanced stages of deterioration (Pomeranz, 1974). Other odors occasionally found in grain are considered “commercially objectionable foreign odors” (COFOs) because they are odors that are foreign to grain and render it unfit for normal commercial usage. Examples of odors that fall into this category are odors from fertilizers, oil products, smoke, decaying animal and vegetable matter, fumigants/insecticides, and skunk. Grain that contains an off odor, regardless of its origin, cannot receive any grade higher than U.S. Sample grade, which is the lowest of the quality grade designations (Giler, 1995).

The determination of off odors may be made on the basis of a representative sample of the grain before or after mechanical cleaning. Due to the subjectivity involved in making odor determinations, a consensus of experienced inspectors is used to determine marginal odors. Samples containing fumigant or insecticide odors are permitted to air for 4 hours to determine if the fumigant odor persists. Fumigant/insecticide odors that persist after aeration are considered COFOs (Giler, 1995).

Most of these odors can be reduced using aeration; however, residual odors may linger after repeated aeration cycles. Musty odors in grain are best avoided by prevention and operations that prevent grain deterioration. Other similarly undesirable odors that may be present in stored grain may also be partially removed by repeated aeration cycles.

REFERENCES

Abdulkadir, A. and Joyosuparto, S. (1979). A study on the performance of silo in RPC Tambun, *Proceedings of Workshop on Grains Postharvest Technology,* January 16–19, 1979, Jakarta, 342–353.

Agena, M.U. (1961). Untersuchungen uber Kälteeinwirkungen auf lagernde Getreidefrüchte mit verschiedenem Wassergehalte, Dissertation for D. Agr., University of Bonn.

Armitage, D.M. and Cook, D.A. (1997). Laboratory experiments to compare the development of populations of five species of insects during dormancy break and subsequent cool storage of malting barley, *J. Inst. Brew.,* 103, 245–249.

Armitage, D.M. and Woods, J.L. (1997). The development of an integrated storage strategy for malting barley, HGCA Research Rep., 138, Home-Grown Cereals Authority, London.

Armitage, D.M., Burrell, N.J., and Llewellin, B.E. (1982). Changes in fungal and mite populations in grain during prolonged drying and subsequent storage, *Proc. 3rd Drying Symp.,* 2, 193–201 (J.C. Ashworth, Ed.), Publication Drying Research Ltd., Wolverhampton, U.K.

Armitage, D.M., Wilkin, D.R., and Cogan, P.M. (1991). The cost and effectiveness of aeration in the British climate. *Proc. 5th Int. Working Conf. on Stored Prod. Prot.,* Bordeaux, September 1990 (F. Fleurat-Lessard and P. Ducom, Eds.), 1925–1933.

Arnold, R.E. (1963). Effects of harvest damage on the rate of fall in viability of wheat stored at a range of moisture levels, *J. Agric. Eng. Res.,* 8, 7–16.

Arthur, F.H., Throne, J.E., Maier, D.E., and Montross, M.D. (1998). Feasibility of aeration for management of maize weevil populations in corn stored in the southern United States; model simulations based on recorded weather data, *Am. Entomologist,* Summer, 118–123.

ASHRAE (1995). Drying and Storing Farm Crops. Chapter 21, *ASHRAE Applications Handbook,* American Society of Heating, Refrigeration Air Conditioning Engineers, Inc., New York.

Assumption, (1997). Coop Grain Co., personal communication, Assumption, IL.

Ayerst, G. (1966). The influence of physical factors on deterioration by moulds, in Microbiological deterioration in the Tropics, *Society of Chemical Industry Monogr.,* No. 23, 14–20.

Ayerst, G. (1969). The effects of moisture and temperature on growth and spore germination of some fungi, *J. Stored Prod. Res.,* 5, 127–141.

Bailey, J.E. (1982). Whole grain storage, in *Storage of Cereal Grains and their Products,* (Christensen, C.M., Ed.), St. Paul, MN, pp. 53–78.

Baudet, J.J. (1976). La ventilation des grains, *Bull. CETIOM,* 63, 3–16.

Bewer, H.E. (1957). Getreidekonservierung mit kalter Nachtluft. München Wolfrathausen, Ber. Inst. Landtechnik No. 47, Bonn.

Bhatnagar, A.P. and Bakshi, A.S. (1975). Aeration studies on the storage of wheat grains, *J. Res. Pujap Agric. Univ.* 12, 189–199.

Blum, P.H. and Gilbert S.G. (1957). Mechanism of water sensitivity, *Am. Soc. Brew. Chem. Proc.* 1957, p. 22.

Boczek, J. (1959). Biology and ecology of Cheyletus eruditus (Schrank, 1781) (*Acarina, Cheyletidae*) Prace, Naukowe IOR, *Poznan,* 12, 175–230 (in Polish).

Bond, E.J. (1984). Manual of fumigation for insect control, FAO Plant Production and Protection Paper No. 54.

Brooker, D.B., Bakker-Arkema, F.W., and Hall, C.W. (1974). *Drying Cereal Grains,* AVI Publishing, Westport, CT.

Brown, W.B. and Heseltine, H.K. (1949). Fumigation of grain in silo bins: the provision of circulating systems, *Milling* 112, 229–230, 233.

Burges, H.D. and Burrell, N.J. (1964). Cooling bulk grain in the British climate to control storage insects and improve keeping quality, *J. Sci. Food Agric.* 15, 32–50

Burrell, N.J. (1966). Refrigerated damp grain storage, *Pest Infestation Res. Rep.,* 1965, 17–19.

Burrell, N.J. (1974). Aeration, p. 454, in *Storage of Cereal Grains and their Products,* 2nd ed. (C.M. Christensen, Ed.), American Association of Cereal Chemists, St. Paul, MN.

Burrell, N.J. (1982). Refrigeration. pp. 407–441, in *Storage of Cereal Grains and their Products,* (Christensen, C.M., Ed.), American Association of Cereal Chemists, St. Paul, MN.

Burrell, N.J. and Havers, S.J. (1976). The effects of cooling on mite infestations in bulk grain, *Ann. Appl. Biol.,* 82, 192–197.

Burrell, N.J., Knight, G.P., Armitage, D.M., and Hill, S.T. (1980). Determination of the time available for drying rapeseed before the appearance of surface moulds, *J. Stored Prod. Res.,* 16, 115–118.

Burrell, N.J. and Laundon, J.H.J. (1967). Grain cooling studies, I: Observations during a large-scale refrigeration test on damp grain, *J. Stored Prod. Res.* 1, 125–144.

Calderon, M. (1972). Aeration of grain — benefits and limitations. *EPPO Bull.,* 6, 83–94.

Calderon, M. (1974). The possible role of aeration in the control of stored product insects in warm climates, *Proc. First Int. Working Conf. Stored Prod. Entomol.,* Savannah, GA, pp. 77–84.

Carter, E.P. and Young G.Y. (1945). Effect of moisture content, temperature, and length of storage on the development of “sick” wheat in sealed containers, *Cereal Chem.,* 22, 418–428.

Christensen C.M. (1982). *Storage of Cereal Grains and their Products,* Vol. 5, 3rd ed., American Association of Cereal Chemists, St. Paul, MN.

Christensen, C.M. and Kaufmann, H.H. (1969). *Grain Storage: the Role of Fungi in Quality Loss,* University of Minnesota Press, Minneapolis, MN.

Christensen, C.M. and Kaufmann, H.H. (1974). Microflora, in *Storage of Cereal Grains and their Products,* (Christensen, C.M., Ed.), American Association of Cereal Chemists, St. Paul, MN, pp. 158–192.

Come, D. (1982). Seeds, organs of survival, in *Preservation and Storage of Grains, Seeds, and their By-Products,* (Multon, J., Ed.), Lavoisier Publishing, New York, pp. 205–225.

Converse, H.H., Miller, B.S., and Graves, A.H. (1977). Quality changes of hard red winter wheat in concrete silos. Agriculture Research Services, ARS-NC-58, U.S. Department of Agriculture, Washington, D.C.

Copeland, L.O. and McDonald, M.B. (1985). *Principles of Seed Science and Technology,* 2nd ed., Burgess Publishing, Minneapolis, MN.

Cunnington, A.M. (1984). Resistance of the grain mite, *Acarus siro* L. (Acarina, Acaridae) to unfavourable physical conditions beyond the limit of its development, *Agric. Ecosystems Environ.,* 11, 319–339.

David, M.H., Mills, R.B., and White, C.D. (1977). Effects of low temperature acclimation on developmental stages of stored product insects, *Environ. Entomol.,* 6, 181–184.

De Padua, D.B. (1974). *Postharvest Rice Technology in Indonesia, Malaysia, Philippines and Thailand — A State of the Art Survey,* International Development Research Center, Ottowa.

Elder, W.B. (1969). Aeration and cooling of stored grain, *Power Farming Better Farming Dig.,* 75, 10–13.

Evans, D.E. (1979). The effect of thermal acclimation and relative humidity on the oxygen consumption of three *Sitophilus* species, *J. Stored Prod. Res.,* 15, 87–93.

Evans, D.E. (1983). The influence of relative humidity and thermal acclimation on the survival of adult grain beetles in cooled grain, *J. Stored Prod. Res.,* 19, 173–180.

Fields, P.G. (1992). The control of stored-product insects and mites with extreme temperatures, *J. Stored Prod. Res.,* 28, 89–118.

Foster, G.H. (1982). Drying cereal grains, in *Storage of Cereal Grains and their Products,* (Christensen, C.M., Ed.), American Association of Cereal Chemists, St. Paul, MN, pp. 79–116.

Foster, G.H. (1953). Minimum airflow requirements for drying grain with unheated air, *Agric. Eng.,* 34, 681–684.

Friday, D., Tuite, J., and Stroshine, R. (1989). Effect of hybrid and physical damage on mould development and carbon dioxide production during storage of high-moisture shelled corn, *Cereal Chemistry,* 66, 422–426.

Giler, J. (1995). The FGIS' role in grain inspection, in *Stored Product Management,* (Kirschik, V., Cuperus, G., and Galliart, D., Eds.), Agricultural Communications, Oklahoma State University, Stillwater, OK, pp. 35–43.

Griffiths, H.J. (1967). Wet-bulb control of grain aeration systems, Division of Mechanical Engineering, Circular Number 3, CSIRO.

Hagstrum, D.W. and Flinn, P.W. (1990). Simulations comparing insect specie differences in response to wheat storage conditions and management practices, *J. Econ. Ent.,* 83, 2469–2475.

Hagstrum, D.W. and Flinn, P.W. (1995). IPM in grain storage and bulk commodities, in *Stored Product Management,* (Krischik, V., Cuperus, G., and Galliart, D., Eds.), Oklahoma State University, Stillwater, OK, pp. 201–205.

Hall, C.W. (1980). *Drying and Storage of Agricultural Crops*, AVI Publishing, Westport, CT.

Harner, J.P. and Hagstrum, D.W. (1990). Utilizing high airflow rates for aerating wheat, *Appl. Eng. Agric.,* 6, 315–321.

Harrington, J.F. (1973). Problems of seed storage, in *Seed Ecology,* (Heydecker, W., Ed.), Pennsylvania State University Press, University Park, PA, pp. 251–263.

Holman, L.E. (1966). Aeration of grain in commercial storages, Marketing Research Report No. 178. Agricultural Marketing Service, Research Division, U.S. Department of Agriculture, Washington, D.C.

Howe, R.G. and Klepser, G.E. (1958). Forced recirculation, control of stored grain insects, *Down to Earth,* 14, 6–9.

Howe, R.W. (1962). A study of the heating of stored grain caused by insects, *Ann. Appl. Biol.,* 50, 137–158.

Howe, R.W. (1965). A summary of optimal and minimal conditions for population increase of some stored product insects, *J. Stored Prod. Res.,* 1, 177–184.

Hukill, W.V. (1963). Storage of seeds, *Proc. Int. Seed Test. Assoc.,* 28, 871–873.

Hukill, W.V. (1953). Grain cooling by air. *Agric. Eng.,* 34, 456–458.

Hunter, A.J. and Taylor, P.A. (1980). Refrigerated aeration for the preservation of bulk grain, *J. Stored Prod. Res.,* 16, 123–131.

Johnson, H.K. (1957). Cooling stored grain by aeration, *Agric. Eng.,* 38, 238–241, 244–246.

Jouin, C. (1965). Le froid et la conservation des cereales, *Bull. Anciens Eleves Ecole Fr. Meun.,* 205, 9–13.

Jouin, C. (1963). La ventilation et le problème de la conservation des grains, *Journée d'Etudes sur la conservation des grains.* CERDIA, CNEEMA, 41–48.

Justice, O.L. and Bass, L.N. (1978). Principles and practices of seed storage, *Agriculture Handbook No. 506,* U.S. Department of Agriculture, Washington, D.C.

Komba, G., Bellus, Z., and Csermely, J. (1987). Findings concerning the cooled storage of grain in Hungary, *Rio. di Ing. Agric.,* 3, 150–156.

Kosmina, N.P. (1956). *Organisation und Technik der Getreidelagerung* (In German; *Organization and Technology of Grain Storage*), Deutscher Bauernverlag, Berlin.

Kreyger, J. (1967). Drogestoffverliezen en Verandering van de Gebruikswaarde van tarwe bij Geventjleerde Bewaring, *Jaarb. Inst. Bewar. Verwerk. Landb. Prod.* I.B.V.L. 1966, 1967, 33–34.

Kreyger, J. (1972). Drying and storing grains, seeds and pulses in temperate climates, Publikatie 205, Inst. Bewar. Verwek Landb. Prod. I.B.V.L.

Kreyger, J., Van Bastelaere, G.R., and Jansen, J. (1960). Investigations into ventilated storage and slow drying of malting barley, *Petit J. Brass.,* 68, 238–241.

Kuppinger, H.V., Muller, H.M., and Muhlbauer, W. (1977). Die beluftungstrocknung vonerntefrischem und vorgetrocknetem kornermais unter thermodynamischem undmikrobiologischem aspekt, *Grundl. Landtechnik Bd.,* 27, 119–132.

Lacey, J., Hill S.T., and Edwards M.A. (1980). Microorganisms in stored grains: their enumeration and significance, *Trop. Stored Prod. Inform.,* 38, 19–32.

Linko, P. (1960). The biochemistry of grain storage, *Cereal Sci. Today,* 5, 302–306.

Longstaff, B.C. (1988a). A modelling study of the effects of temperature manipulation upon the control of *Sitophilus oryzae* (Coleoptera curculionidae) by insecticide, *J. Appl. Ecol.,* 25, 163–175.

Longstaff, B.C. (1988b). Temperature manipulation and the management of insecticide resistance in stored grain pests: a simulation study for the rice weevil, *Sitophilus oryzae, Ecol. Modelling,* 43, 303–313.

Longstaff, B.C. (1986). Environmental manipulation as a physiological control measure, *Proc. 4th Int. Working Conf., Stored Prod. Prot.,* Tel Aviv (Donahaye, E. and Navarro, S., Eds.), p. 47–61.

MAFF. (1980). Survey of mycotoxins in the United Kingdom, Food Surveillance Paper No. 4, Ministry of Agriculture, Fisheries, and Food. Her Majesty's Stationery Office, London.

McLean, K.A. (1980). *Drying and Storing Combinable, Crops,* Farming Press Limited, Ipswich, Suffolk, England.

NAPHIRE, (1990). Study of the Physics of Bulk Storage for Paddy: Terminal Report. National Postharvest Institute for Research and Extension (NAPHIRE), Philippines.

Navarro, S. and Calderon, M. (1982). Aeration of grain in subtropical climates, FAO Agricultural Services Bulletin No. 52, Rome.

Navarro, S. (1976). Aeration of bulk-stored grain in commercial facilities, Israel Agricultural Research Organization, Special Publication No. 56. (Hebrew, with English summary.)

Navarro, S., Donahaye, E., and Calderon, M. (1969). Observations on prolonged grain storage with forced aeration in Israel, *J. Stored Prod. Res.,* 5, 73–81.

Navarro, S., Donahaye, E., and Calderon, M. (1973). Studies on aeration with refrigerated air. I. Chilling of wheat in a concrete elevator, *J. Stored Prod. Res.,* 9, 253–259.

Navarro, S., Kashanchi, Y., and Frandji, H. (1979). Physical and biological causes of loss in stored grain in Israel, Israel Agricurtural Research Organization Progress Report 1978/9, Stored Prod. Div., Special Publication No. 140, 45–49. (Hebrew, with English summary.)

Nellist, M.E. (1988). Near-ambient grain drying, *Agric. Eng.,* Autumn, 93–101.

Odigboh, E.U. (1976). Dehumidified air from sorbent beds for aeration of food grains, *J. Agric. Eng. Res.,* 21, 273–280.

Onstad, D.W. (1987). Calculation of economic-injury levels and economic threshold for pest management, *J. Econ. Entomol.,* 80, 297–303.

Papavizas G.C. and Christensen C.M. (1957). Grain storage studies 25: effect of invasion by storage fungi upon germination of wheat seed upon development of sick wheat, *Cereal Chem.,* 34, 3–50.

Poichotte, J.L. (1977). La conservation des grains par la ventilation, *Fermes Mod.,* 51, 43–46.

Pomeranz, Y. (1974). Biochemical, functional, and nutritive changes during storage, in *Storage of Cereal Grains and their Products,* 2nd ed. (C.M. Christensen, Ed.), American Association of Cereal Chemists, St. Paul, MN, p. 100.

Purdue University, (1988). Plant pathology department publications, Purdue University, Lafayette, IN.

Reimann. E. (1927). The influence of temperature on grain storage, *Die Mühle,* 12, 367–368. (In German).

Roberts, E.H. (1974). Storage environment and the control of viability, in *Viability of Seeds,* (Roberts, E.H., Ed.), Chapman and Hall, London, pp. 14–58.

Robinson, W. (1926). Low temperature and moisture as factors in the ecology of the rice weevil, *Sitophilus oryzae* L. and the granary weevil, *Sitophilus granarius* L., Technical Bulletin of Minnesota Experimental Station.

Sartori, M.R., D'Amico, C.R., da Costa, S.I., Leitào, M.F.F., Jordào, B.A., and Ortolani, B.D. (1976). Preservaçào do soja armazenada a granel mediente emprego de aeraçào mecànica para melhoria das condiçoès de armacenamiento, *Boletin do Instituto de Tecnologia de Alimentos,* 46, 75–110.
Saul, R.A. (1970). Deterioration of moist shelled corn at low temperatures, American Society of Agricultural Engineers, St. Joseph, MI, Paper 70–302.
Saul, R.A. and Lind, E.E. (1958). Maximum time for safe drying of grain with unheated air, *Transactions of the ASAE,* 2, 29–33.
Scholz, B. (1962). Atmungsverluste bei Weizen in Abhängigkeit von Temperatur, Lagerzeit und Wassergehalt (In German; Dry matter loss of wheat due to respiration as a function of temperature, storage time and moisture content), *Landtechnische Forschung,* No. 2, 212, 48–52.
Shamsuddin, I. (1979). Bulk storage and handling of paddy in Malaysia, *Proceedings of Workshop on Grains Postharvest Technology,* January 16–19, 1979, Jakarta, 434–443.
Shands, H.L., Janisch, D.C., and Dickson, A.D. (1967). Germination response of barley following different harvesting conditions and storage treatments, *Crop Sci.,* 7, 444–446.
Shedd, C.K. (1953). Resistance of grain and seeds to airflow, *Trans. of the ASAE,* 34, 616–619.
Shibaev, P.N. and Karpov, R.A. (1969). Activnoe ventilerovanie semyan (Active ventilation of seeds), Rosselchozizdat, Moskva, URSS.
Sinha, R.N. (1968). Climate and potential range of distribution of stored-product mites in Japan, *J. Econ. Entomol.,* 61, 70–75.
Sinha, R.N. and Muir, W.E. (Eds.) (1973). *Grain Storage: Part of a System,* Avi Publishing, Westport, CT.
Smith, L.B. (1970). Effects of cold acclimation on supercooling and survival of the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Cucujidae) at subzero temperatures, *Can. J. Zool.,* 48, 853–858.
Smith, L.B. (1974). The role of low temperature to control stored food pests, *Proc. First Int. Working Conf. Stored Prod. Entomol.,* Savannah, GA, pp. 418–430.
Steele, J.L., Saul, R.A., and Hukill, W.V. (1968). Deterioration of shelled corn as measured by carbon dioxide production, American Society of Agricultural Engineers, Chicago, Paper No. 68-621.
Steele, J.L., Saul, R.A., and Hukill, W.V. (1969). Deterioration of shelled corn as measured by carbon dioxide production, *Trans. of the ASAE,* 12, 685–689.
Steele, J.L. (1963). Deterioration of shelled corn during drying as measured by carbon dioxide production, M.S. thesis, Iowa State University of Science and Technology, Ames, IA.
Steele, J.L. and Saul, R.A. (1962). Laboratory measurements of the rate of deterioration of grain during drying, Mid-Central Region Paper No. 68-621, ASAE, St. Joseph, MI. [Paper summarized and published in American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) *Guide and Data Book*, 1965, p. 133–135.
Stratil, H.V., Stratil, H.H., and Knulle, W. (1980). Untersuchungen uber die spezifische Vermehrungsrate von Populationen der in Lagergetreide lebende milbe Glycyphagus destructor (Schrank, 1781) bei verschidenen temperatur und Luftfeuchtebedingungen, *Z. Ang. Ent.,* 90, 209–220.
Sulzer-Escher Wyss. (1972). Granifrigor Getreidekühl-konservierung (In German; Granifrigor grain cooling conservation), Sales brochure, Sulzer-Escher Wyss, Lindau, Germany.
Sulzer-Escher Wyss. (1980). Kühlung von Körnermais (In German; Cooling of corn), Sulzer-Escher Wyss, Lindau, Germany.
Sulzer-Escher Wyss. (1989). Granifrigor Grain Cooling Systems, Sales brochure, Sulzer-Escher Wyss, Lindau, Germany.
Swanson, C.O. (1941). The effect of low temperature in preventing damage to wheat stored with high moisture content, *Cereal Chem.,* 18, 299–315.
Thompson, T.L. (1972). Temporary storage of high-moisture shelled corn using continuous aeration, *Trans. of the ASAE,* 15, 333–337.
Thorpe, G.R. and Elder, W.B. (1980). The use of mechanical refrigeration to improve the storage of pesticide treated grain, *Int. J. Refrig.,* 3, 99–106.
Toole, E.H. and Toole, V.K. (1946). Relation of temperature and seed moisture to the viability of stored soybean seed, Circular 753. U.S. Department of Agriculture, Washington, D.C.
Toole, E.H. and Toole, V.K. (1954). Relation of storage conditions to germination and to abnormal seedlings of beans, *Proc. Int. Seed Test. Assoc.,* 18, 123–129.

Ushatiskaya, R.S. (1948). The importance of sudden and gradual falls in temperature on the cold stability of the granary weevil (*Calandra granaria* L.) (in Russian.), *Zool. Zh.,* 27, 495–502.

Ushatiskaya, R.S. (1950). The influence of humidity of the surroundings and of food on the cold resistance of the granary weevil (*Calandra granaria* L.) (in Russian.), *Zool. Zh.,* 29, 341–349.

WHO. (1979). *Environmental Health Criteria,* No. II, World Health Organization, Geneva.

Williamson, W.F. (1961). Cooling grain in silos, *J. Agric. Eng. Res.,* 6, 51–58.

CHAPTER 2

Stored Grain Ecosystem and Heat, and Moisture Transfer in Grain Bulks

Shlomo Navarro, Ronald Noyes, and Digvir S. Jayas

CONTENTS

0-8493-1355-4/02/$0.00+$1.50

2.1 THE ECOSYSTEM APPROACH TO GRAIN STORAGE

The ability to store durable agricultural products depends on many interrelated factors. To better understand their interplay and the potential fields of intervention for improving traditional storage, the storage structure is considered as an ecosystem. The following are the components of the ecosystem and the interrelationships among them:

- *The stored grain* — the principal biotic factor
- *The storage structure* — abiotic factor
- *Temperature* — abiotic external and internal factor
- *Humidity* — abiotic external and internal factor
- *Storage atmosphere* — abiotic external and internal factor
- *Insects* — biotic external and internal factor
- *Microorganisms* — biotic external and internal factor
- *Foreign matter* — abiotic internal factor

The interaction of the above factors as they affect grain in the *traditional* storage structure should be carefully evaluated to form the overall perspective of managing the grain storage. Effective management of the stored grain ecosystem varies widely based on the external environment of the storage facility. It is also seriously affected by the influence of environmental and agricultural change in third-world countries, where available resources to support desirable storage units may be quite limited. Potential avenues of action to resolve these economic and environmental imbalances are discussed in the following sections.

The factors influencing the conservation of durable agricultural products during storage (mainly cereal grains and pulses) are numerous and interrelated. They are common to all storage situations, whether they are high-tech silos or home-stored grain in jute sacks. A convenient way to analyze the interactive relationships between these storage environment factors is by considering a storage structure as the boundary that defines the environment of a community of interacting living organisms, which can be termed an *ecological system* or *ecosystem* (Calderon, 1981).

The major components of the grain storage ecosystem and the interaction among them are discussed below. This is followed by an analysis of traditional storage systems to underline their vulnerability to various influences that cause storage losses.

2.1.1 Components of the Ecosystem

1. *The stored grain* — this is the component of principal interest to us and the one we wish to preserve. Consequently, we want to minimize the effect of any factor adversely affecting its conservation. Grain in itself is a biotic factor of the system and is a living organism in a state of dormancy that can remain unchanged for prolonged periods. High moisture permits the development of microorganisms that tend to kill the grain. At very high moisture contents and suitable

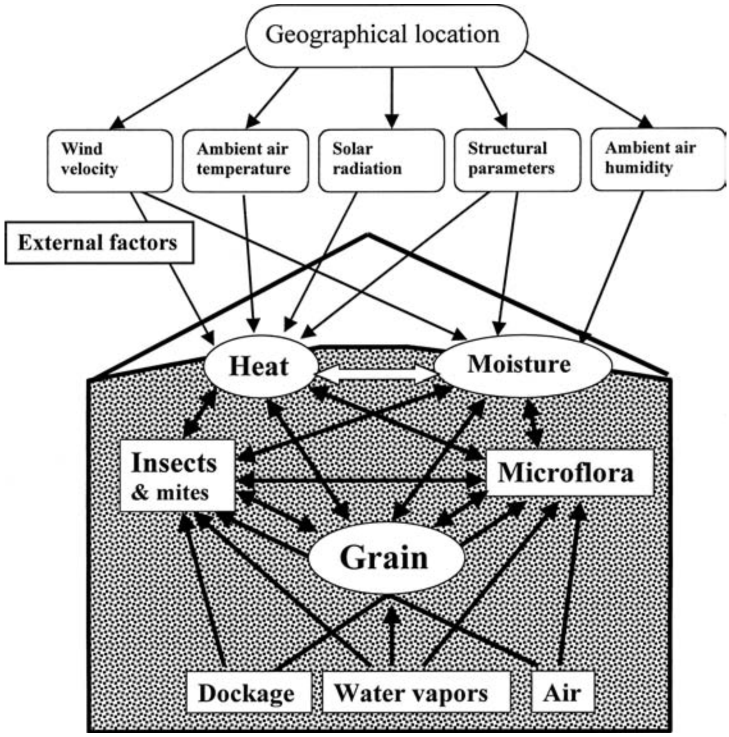


Figure 2.1 External factors and the interrelated grain bulk ecosystem components in non-aerated and unsealed bulks.

temperatures, the grain begins to germinate. Dead grain rapidly loses its nutritive value, while non-dormant (germinating) grain cannot be safely stored. Grain stored in dry conditions remains viable and dormant.

2. *The storage structure* — this component, which forms the boundaries of the ecosystem, is predetermined and fixed. The materials, the nature of its composition, and its placement are important in determining the extent to which external factors (both biotic and abiotic) affect the system. The structure is required to be mechanically designed to hold the grain. It should protect the grain from external environmental factors such as rain and ground water, minimize the influence of environmental temperature and humidity, and serve as a barrier to the ingress and contamination by insects, rodents, and birds.
3. *Temperature* — ambient temperature is an abiotic factor that has little direct influence on grain condition but greatly influences other biotic components (insects and microflora). It therefore indirectly affects conservation of grain quality. The grain temperature is only slowly influenced by environmental temperature due to its low thermal conductivity. Therefore, the main influence is due to seasonal fluctuations and is more pronounced in small rather than large storage structures exposed to the sun.
4. *Humidity* — ambient humidity is an abiotic factor of the air surrounding the grains. Within the confined storage space, the moisture of the grains — with which it reaches equilibrium — influences air humidity. Its greatest influence is on molds, which begin to develop at intergranular humidities above 70%. Humidity of the storage ecosystem is only influenced by the fluctuations in environmental humidity when a free exchange of air is possible through the storage structure fabric (cribs and open bins).
5. *Atmospheric composition* — air, the third abiotic factor, comprises about 50% of the volume of the storage structure since it is present in spaces between grain kernels and in the head-space above the grain. When there is free movement between air inside and outside the store, the composition of the atmosphere is relatively constant, containing about 21% oxygen and 0.03% carbon dioxide.

However, if the storage structure restricts or completely prevents movement of air between the grain bulk and the surrounding outside atmosphere, then the biotic factors (the grain, insects, and microorganisms) may strongly alter the atmospheric composition of the ecosystem, reducing the oxygen concentration and increasing the carbon dioxide concentration.

6. *Insects* — stored-product insects consist of a group of some 250 species (beetles and moths) characterized by their small size enabling them to penetrate the interstices of the grain bulk, their cosmopolitan distribution, and their catholic feeding habits. Some six species are the major pests and several of them attack crops in the field, thereby entering the ecosystem at the moment of loading the grain into storage. These insects are a major biotic factor, causing losses in both weight and quality. Their rates of development and population increase are strongly influenced by temperature of the grain bulk, and their metabolic activity produces heat and moisture — which in turn affects all biotic components of the ecosystem. Their development is suppressed and even controlled when the intergranular atmosphere is rich in carbon dioxide and is oxygen deficient.
7. *Microorganisms* — this biotic factor is composed of molds, yeasts, and bacteria. They are universally present on the grain but are inactive at humidities favorable to storage. Dry live grains have protective mechanisms against microorganisms; but when moisture of the grain rises above a critical level, molds begin to develop that can kill the grain and cause qualitative changes, including the production of mycotoxins under certain circumstances. Molds are strongly influenced by the abiotic components of the ecosystem. High temperatures and humidities favor their development, with different molds having different optima for activity.

   Since both molds and insects release heat and moisture by their metabolism, they may produce temperature and moisture gradients within the stored grain ecosystem. This in turn can create convection currents through the grain bulk, carrying warm moist air from the heating region to cooler regions, where the moisture is deposited as the air cools. Such areas of condensation favor the development of bacteria and may even cause the grain to germinate. As with insects, mold development is suppressed when the storage atmosphere is strongly modified, though this process cannot control all microflora, as some of the microorganisms develop under anaerobic conditions.
8. *Foreign matter* (*chaff, stalks, grain dust, sand, earth, stones, dockage, etc.*) — this is either an abiotic component of the ecosystem, or it can originate on dead parts of plants. Its effects on the ecosystem are many: chaff and grain dust tend to absorb moisture more rapidly than grain and present a more suitable substrate for mold development than whole grains. Many insects, which are unable to penetrate sound grain, are able to develop well on this material. All small particles of material tend to block the interstitial air spaces. Therefore, it may prevent the application of control measures that rely on the penetration of cool air to prevent the bulk from heating or the penetration of toxic gases throughout the grain bulk to kill insect populations.

2.1.2 The Ecosystem of Traditional Storage

1. *The stored grain* — in the past, only local grain varieties were stored. Today, many subsistence and small-scale farmers grow high-yielding hybrid varieties. These varieties are often harvested earlier and may enter storage at moisture contents above the safe level. Also, hybrids often do not have the natural resistance to insect pests that have developed over the course of time in many local varieties. A return to the cultivation of local varieties may not be a practical solution, but the influence of this change on the storage ecosystem does require review.
2. *The storage structure* — most traditional above-ground storage containers (mud, wicker and basket, wood, etc.) consist of a wooden platform on structural legs or columns to raise the structures and protect them from livestock, rodents, and floods. In areas subject to deforestation, there is evidence indicating that the lack of suitable wood may be a limiting factor. Most of the traditional systems are not insect-proof; and because they cannot be effectively cleaned and disinfested during periods between storage seasons, they may form a reservoir for residual insect infestations.
3. *Temperature* — most farmers who use traditional storage methods live in countries with tropical or subtropical climates. Ambient temperatures in these regions fall close to the optimal temperatures for development of dangerous stored-product pests. Regional temperature changes, and possibly global warming, may be increasing the rate at which insect infestations build up within traditional stores.

4. *Humidity* — in the humid tropics, the effective drying of harvested grain by sun drying and natural ventilation can be very difficult. Mold development poses a greater threat in these regions, particularly in light of our recently acquired knowledge of mycotoxin formation. Since the effects of these toxins are mainly chronic in nature, their past and present impact on regional health may not be known with certainty; but it is highly suspect. The early harvesting and double cropping of high-yielding varieties have also made the drying of harvested crops even more difficult for small-scale farmers.
5. *Atmospheric composition* — since traditional storage structures are extremely difficult to make airtight, the use of hermetic storage for controlling insect infestations and preventing mold development is not feasible except for underground storage. However, alternative storage structures — particularly made of flexible plastic if acceptable to the farmer — have the potential for providing an inexpensive method for controlling insects without the use of toxic chemicals. In this method, grain is stored undisturbed for an adequate period of time to reduce oxygen levels low enough to kill the insects.
6. *Insects* — insects in traditional stores have been the major factor that causes losses and the most difficult to combat. In traditional stores insects are almost always present, originating either from residual infestations hidden within the storage structural materials or from stored-product insects that lay their eggs on the ripening grain in the fields. In the past, insect control has relied heavily on insecticides (sprays, dusts, and fumigants). Direct and environmental health hazards, high prices, and resistance developed by the major pests all reduce the value of insecticides for use by the small-scale and subsistence farmer. Shifts in distribution of stored-product insects as a result of changes in climate and changing agro-practice are little known, but the spread of *Prostephanus truncatus* — a major pest — from America to Africa — and the spread of strains resistant to insecticides are both causes for concern.
7. *Microorganisms* — the threat of development of microorganisms in traditional storage is directly related to the climatic region and the time of harvest in relation to the rainy seasons. If grain is dry on entering storage (the case in many Sahelian and semi-arid climates), and the storage structure prevents the ingress of humidity or rainwater during the rainy season, microorganisms do not normally pose a problem. However, if grain is stored above a certain critical moisture content equivalent to about 70% relative humidity of the interstitial air, molds can develop; and these may be accompanied by the production of mycotoxins. Normally the small-scale farmer can tell the approximate dryness of his grain but does not have the means to accurately determine its moisture content to decide whether it is safe for storage. Therefore, if the grain cannot be quickly dried at harvest time, the farmer is often faced with the dilemma of risking storage at above safe moisture content or selling it at undesirably low prices.
8. *Foreign matter* — numerous traditional methods used in storage to protect the grain from losses consist of the addition of foreign matter to the grain. Although adding foreign material to grain would seem undesirable in developed countries, in traditional subsistence farming societies this practice has been developed based on experience through decades of practice. Upon close scrutiny these methods are found to be based on sound scientific principles (admixture of ash, sand, small grains, vegetable oils, and leaves and seeds of local plants containing anti-feedant or repellent properties). These methods should be studied in depth; and, where they have a broad-based potential, they should be encouraged to promote safe on-the-farm storage for the small-scale and subsistence farmer.

2.2 STORED-PRODUCT INSECTS AND MITES

The quality hazards to stored grain due to insects and mites are (1) devouring, perforation, or substantial damage of whole kernels; (2) consuming broken kernels and fines; (3) raising grain temperature and moisture content; (4) contamination of the grain; and (5) esthetic objections (Bailey, 1982).

Two aspects of insect production that need to be considered are the absolute temperatures that influence insect activity and the temperatures that affect rate of insect population growth. Suppression of insect activity will be discussed using these two parameters.

2.2.1 Insect Ecology

The insect pests of stored grain have environmental requirements that greatly affect their abundance and consequently their potential danger for causing damage. Of these, the most important factors are climate (temperature and moisture), food requirements, and competition with other living organisms.

2.2.1.1 Effects of Climate

For insects infesting crops in the field, climate plays a major role in determining geographical distribution of the insect species. However, for stored product pests the influence of climate is attenuated by the fact that the "climate" within a warehouse or grain storage silo may be very different from that outside. Thus, insects that are unable to withstand outdoor winter conditions in temperate climates may be able to survive and develop in relatively warm grain masses in storages or the heated buildings of food-processing factories, even in relatively cool or cold climates. In general, the influence of climate upon in-storage temperatures will affect the species composition of the insect populations in different regions of the world.

Beetles and moths comprise the majority of stored-grain insect pests. Ambient temperature and moisture content of the commodity have a major influence on the rate of insect development. The rate of beetle development is generally more affected by temperature than by grain moisture content (Hagstrum and Milliken, 1988). Moth development is more dependent on ambient humidity above the grain and moisture in the grain.

2.2.1.2 Temperature

Stored-product insects are mainly of tropical and subtropical origin that have spread to temperate areas via international trade. Because insects cannot control their body temperatures, their rates of development and reproduction increase with rising temperature. Consequently, most of them become inactive at low temperatures (10 to 15°C) and will die after prolonged periods at very low temperatures (0 to 5°C). Most species are unable to hibernate or enter an inactive phase termed *diapause* — though some, such as *Plodia interpunctella* and *Trogoderma granarium,* do hibernate.

For each insect species there is a minimum and maximum temperature at which they are able to develop (at certain low temperatures, oviposition and larval growth cease, and at specific high temperatures, egg sterility occurs and mortality increases). Conversely, there is a temperature range at which oviposition and insect development are optimal. The lower and upper limits and optimal temperatures of most of the important stored-product species have been studied and are well known. Table 2.1 (Howe, 1965) lists minimum and optimum critical temperature and humidity ranges for the major grain storage insects.

Survival of *Tribolium castaneum* from egg to adult is highest between 25°C and 27.5°C and decreases rapidly below and above this temperature (Howe, 1960) (Figure 2.2). According to Fields (1992), mortality at low temperatures is a function of cooling rate, exposure time, temperature, and intrinsic growth rate. Insects become better acclimatized and survive low temperatures if grain cooling rates are slow.

Egg production varies with insect species, temperature, grain moisture, and diet. In general beetles live longer than moths and produce eggs over a period of several months under favorable conditions. Egg production typically increases with increasing temperature, ambient humidity, and grain moisture.

Temperatures below 15°C generally arrest all insect development sufficiently to prevent damage, though not to cause mortality. For most insects, sustained temperatures above 40°C and below 5°C are lethal.

Table 2.1 Minimal and Optimal Conditions for Population Growth of Major Pest Species

Species	Minimum Temperature (°C)	Optimum Range (°C)	Minimum RH (%)	Rate of Increase per Month under Optimal Conditions
Trogoderma granarium	24	33–37	1	12.5
Oryzaephilis surinamensis	21	31–34	10	50
Plodia interpunctella	18	28–32	40	30
Ephestia cautella	17	28–32	25	50
Tribolium confusum	21	30–33	1	60
Tribolium castaneum	22	32–35	1	70
Rhyzopertha dominica	23	32–35	30	20
Lasioderma serricorne	22	32–35	30	20
Callosobruchus chinensis	19	28–32	30	30
Sitotroga cerealella	16	26–30	30	50
Ephestia elutella	10	25–28	30	15
Sitophilus granarius	15	26–30	50	15
Sitophilus oryzae	17	27–31	60	25

Adapted from Howe, R.W. (1965). A summary of estimates of optimal and minimal conditions for population increase of some stored product insects, *J. Stored Prod. Res.,* 1, 177–184.

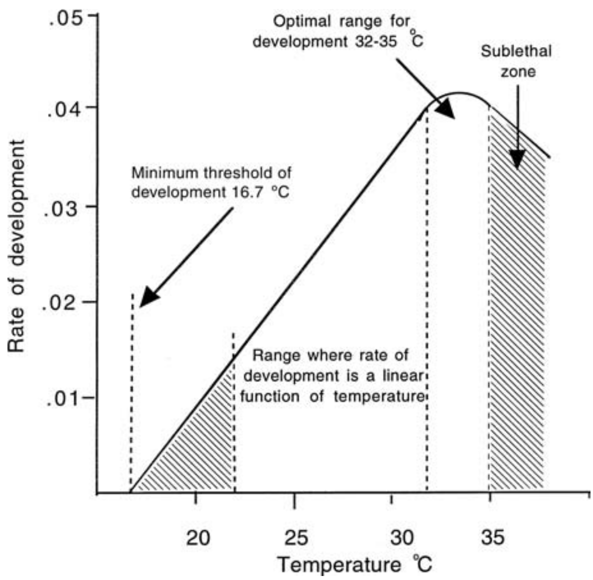


Figure 2.2 The influence of temperature on the rate of development of stored-product insects, exemplified by the flour beetle *Tribolium castaneum*. Shaded zones allow survival but are either too cool (left portion) or too warm (right portion) to allow rapid population growth. (Based on data from Howe, R.W. [1956]. The effects of temperature and humidity on the rate of development and the mortality of *Tribolium* Castaneum (Herbst) [Coleoptera, Tenebrionidae], *Ann. Appl. Biol.,* 44, 356–368.)

2.2.1.3 Moisture and Relative Humidity

Insect pests depend on their food supply to obtain the moisture they require for their life processes. Up to a certain point, the higher the mc of the grain, the higher the rate of increase of insect pests. Above *critical mc,* where molds are able to develop, there is a negative effect on the quality of the food supply that in turn affects insect development. Moisture requirements differ with different species of insects.

Rice weevils are unable to breed in grain with mc below 9%, and adults soon die in dry grain. However, temperature influences the ability of insects to breed in dry grain, and at high temperatures their ability to survive and reproduce is greater. *R. dominica* can breed in wheat at 8% mc at 35°C. *T. granarium* is capable of utilizing metabolic water and can survive on grain at 1% mc. *Tribolium* can survive on bran and wheat flour at very low moisture contents.

2.2.1.4 Food Supply

Each stored-product pest species has different food requirements. Studies have been made to identify the nutritional requirements of different species in order to breed them on artificial diets. Clearly these requirements affect the ability of insects to develop on different stored products and their ability to compete with other species. Consequently, for each stored product, there is a range of insect pests.

2.2.1.5 Insect Behavior

All stored-product insects are negatively phototrophic, which means that they stay away from sunlight. Because of their phototrophic behavior, they are generally not visible to the casual observer. The behavior of insects in grain bulks is not well understood.

The problems of insects mating in a grain bulk at low levels of infestation might appear to be based on random occurrence. However, the movement of insects through grain bulks has received limited attention, though it is known that insect dispersal is not random and that they tend to aggregate in areas favorable for their development. Movement along temperature gradients, along gas concentration gradients, the effects of attraction pheromones to enable sexual reproduction, aggregation pheromones, and oviposition behavior have all been studied to a limited extent. Mold-damaged grain is accompanied by temperature rise, which creates favorable conditions for insect development. This is a region in the grain bulk where insects develop most rapidly, and which serves as a source for additional mold and insect contamination as they disperse to infest other regions of the grain bulk.

Stored-product insects adapt to their environments to survive. The ecological conditions that prevail in stored grain is typically characterized by an environment of low relative humidities, below 70%. Environmental factors and food affect insect development times, survival, and egg production, resulting in insect proliferation. Under favorable conditions, development times shorten, survival rates increase, and egg production increases.

2.2.1.6 Heating of Grain by Insects

Grain stored at safe moisture contents (below the mc in equilibrium with 70% relative humidity intergranular air) and apparently in good condition except for the presence of an insect infestation can frequently develop hot spots. Metabolism of the grain and the microorganisms at this mc is not sufficient to account for the heating process. This phenomenon, which can only be attributed to heat released by metabolism of the insects, is termed *dry grain heating*.

In large grain bulks the heat-insulating properties of the grain prevent the heat from dissipating, and hot spots are formed with temperatures that can increase up to 42°C and then stabilize. As grain temperatures rise, conditions become unfavorable for insect development; and active forms of insects move away from the hot spot while sessile forms die.

In addition, metabolic water in the form of water vapor released from the developing population is carried upward through the bulk by convection currents caused by the hot air from the focus. It is deposited by condensation on cool grain layers higher in the mass or at the surface. Consequently, wet grain heating caused by molds as moisture is transferred from one part of the grain bulk to another often follows dry grain heating caused by insects.

The effects of the various factors influencing the development of insect populations (food supply, temperature, moisture, inter- and intra-specific competition between insects, predation, parasitization, and disease) are very complex. Unless the relationships from these interactive factors are carefully evaluated, the importance of insect infestations or the potential losses they may cause to the stored product is difficult to estimate. Methods for evaluating these effects on populations of insects have been developed. These population data are of great potential value for the development of computer-based predictive models that enable decisions about storage treatments on the basis of inspection procedures.

2.2.1.7 Population Dynamics of Stored Product Insects

The studies of population dynamics were developed originally from demographic studies on humans. Later the general application of these classic population dynamic model findings was modified for use in evaluating insect population development.

The simplest model of population growth assumes that there are no restrictions upon population growth (Southwood, 1968; Subramanyam et al., 1990). It is called the exponential model and is written:

$$N_t = N_o e^{rt} \tag{2.1}$$

where:
N_o = the population at time zero
N_t = the population at time t
r = the intrinsic rate of natural increase

The intrinsic rate of natural increase r describes the net effect of birth and death rates. The exponential model predicts an exponential trajectory for population growth.

The type of population growth described by this model occurs early in an infestation (Figure 2.3). The rate of population growth r is affected by environmental conditions, particularly grain temperature and moisture content. Under the same environmental conditions, each insect species has a different rate of population growth r depending upon the intrinsic factors listed below.

To derive the value of r, detailed data on age-specific mortality and reproductive rates are needed. These data must be obtained by laboratory studies under controlled environmental conditions.

2.2.1.8 Density Dependence

The above model reflects population growth where no limiting factor is taken into account. However, eventually populations reach densities at which reproduction and/or survival are adversely affected. At high densities, populations may decline due to egg cannibalism, interruption during mating, or oviposition. At very high population densities, the insects may also affect their own survival by cannibalism of eggs, larvae, pupae, and newly emerged adults.

Apart from the direct effects of insects upon themselves, populations may also affect the ecosystem conditions. Insects cause changes in temperature and moisture due to their metabolic activity, reduction in available food, contamination with their own excrement, and changes in the composition of the grain interstice atmosphere in well-sealed storage structures. All these factors have a negative effect on populations.