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*APPLICATION OF MICROPROCESSOR TECHNOLOGY
FOR THE CONTROL OF CONTINUOUS FLOW
COMMERCIAL GRAIN DRYERS*

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James Carl Borsum

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James F. Steffe
Major professor (For F.W.B.A.)

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APPLICATION OF MICROPROCESSOR TECHNOLOGY FOR THE CONTROL
OF CONTINUOUS FLOW COMMERCIAL GRAIN DRYERS

By

James Carl Borsum

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ABSTRACT

APPLICATION OF MICROPROCESSOR TECHNOLOGY FOR THE CONTROL OF CONTINUOUS FLOW COMMERCIAL GRAIN DRYERS

By

James Carl Borsum

The feasibility of utilizing microprocessor-based technology for the automated control of continuous flow commercial grain dryers has been investigated. An indirect method of maintaining a desired outlet grain moisture content for a single concurrent flow drying stage, based on outlet air and grain kernel temperatures, is presented. The microcomputer control system was tested on a pilot-scale concurrent flow corn dryer.

The microcomputer controller implements a modified Proportional-Integral (PI) control algorithm which adjusts the grainflow rate to maintain a pre-selected outlet grain temperature (moisture content). To compensate for a variable deadtime element, the microcomputer calculates a new set of PI controller constants whenever a correction in the grainflow rate is initiated. During limited concurrent flow corn drying tests the control system maintained the average outlet corn temperature within 0.5 C of the set-point value (corresponding to a simulated average outlet corn moisture content within 0.2 % w.b. of a set-point value).

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TABLE OF CONTENTS

	Page
LIST OF TABLES	v
LIST OF FIGURES	vii
 Chapter	
1 INTRODUCTION	1
2 OBJECTIVES	6
3 BACKGROUND INFORMATION	8
3.1 Continuous Flow Grain Dryers	8
3.2 Process Control Fundamentals	12
3.3 Digital Control Systems	13
3.4 Microcomputers: A Brief Overview	15
3.4.1 Information Transfer	15
3.4.2 Memory	16
3.4.3 Buses	17
3.4.4 Input/Output Circuitry	18
3.4.5 Programming	20
4 LITERATURE REVIEW	22
5 DRYER CONTROL PARAMETERS	31
5.1 Time	31
5.2 Temperature	33
5.2.1 Air Temperature	34
5.2.2 Grain Temperature	35
5.3 Airflow Rate	37
5.4 Grain Moisture Content	38
5.4.1 On-Line Grain Moisture Measurement	38
5.4.2 Indirect Moisture Monitoring	42
5.5 Computer Simulation Analysis	44
5.5.1 Grainflow	44
5.5.1.1 Concurrent Flow Dryers	45
5.5.1.2 Crossflow Dryers	52
5.5.2 Airflow Rate	54
5.6 Multi-stage Dryer Control	58

6	EXPERIMENTAL INVESTIGATION	61
6.1	The Control System	61
6.1.1	The Drying Plant	61
6.1.2	Microcomputer Controller	64
6.1.3	Temperature Measurement	66
6.1.4	Grainflow Rate	69
6.1.4.1	Motor Speed Control	69
6.2	Dryer Control Algorithm	72
6.2.1	System Analysis	77
6.2.2	Controller Implementation and Testing ...	86
6.3	Airflow Rate	101
7	CONCLUSIONS	105
8	SUGGESTIONS FOR FUTURE STUDY	107
	APPENDIX A - Circuit Diagrams and Specifications for Equipment Used in the Experimental Investigation.	109
	APPENDIX B - ZIBL Code Implementing the Dryer Control Algorithm.	113
	LIST OF REFERENCES	117

LIST OF TABLES

Table	Page
1.1 Data from a typical 12-hr run of a Ferrell-Ross 3-stage concurrent flow grain dryer at Saginaw, MI during November 1980.	3
3.1 Microcomputer language levels.	20
5.1 Concurrent flow dryer simulation, Input conditions.	46
5.2 Outlet grain moisture content when maintaining three different outlet grain temperatures within a concurrent flow dryer.	49
5.3 Outlet grain moisture content when maintaining a constant outlet grain temperature at three different inlet air temperatures within a concurrent flow dryer.	51
5.4 Crossflow dryer, simulation, Input conditions. ..	54
6.1 Input conditions and calculated controller settings for grainflow stepchange test from 4.0 to 2.4 (tonne/hr/sq m)	82
6.2 Input conditions and calculated controller settings for grainflow stepchange test from 2.4 to 1.3 (tonne/hr/sq m).	84
6.3 Input conditions and calculated controller settings for grainflow stepchange test from 2.4 to 4.0 (tonne/hr/sq m).	86
6.4 Input conditions and calculated controller settings for grainflow stepchange test from 1.4 to 2.4 (tonne/hr/sq m).	88
6.5 Input conditions and controller constants for testing of the outlet grain temperature control system.	93

6.6	Input conditions and controller constants for testing of the final outlet grain temperature control system.	99
6.7	Input conditions for airflow step change tests.	104

LIST OF FIGURES

Figure	Page
3.1 Air and grain temperature distribution in crossflow dryers.	9
3.2 Air and product temperatures versus depth for a single-stage concurrent flow dryer (Brook, 1977).	11
3.3 Control system block diagram (Bibbero, 1977). ..	13
5.1 Grainflow versus outlet grain temperature for a single-stage concurrent dryer (MSU computer simulation).	47
5.2 Grain required to maintain a constant outlet grain temperature with a varying inlet moisture content in a single-stage concurrent flow dryer (MSU computer simulation).	48
5.3 Grainflow required to maintain a constant outlet grain temperature with a varying inlet grain moisture content at three different inlet air temperatures in a single-stage concurrent flow dryer (MSU computer simulation).	50
5.4 Grainflow required to maintain a constant outlet grain moisture content with a varying inlet grain ,cr moisture content at two inlet air temps in a single- stage crossflow dryer (MSU computer simulation). ..	53
5.5 Average product and exhaust air temperatures when maintaining a constant outlet grain moisture in a single-stage crossflow dryer (MSU) computer simulation).	55
5.6 Effect of airflow rate on outlet grain moisture for a single-stage concurrent flow dryer (MSU computer simulation).	56
5.7 Effect of airflow rate on outlet moisture for a crossflow dryer (MSU computer simulation). ..	57

6.1	Schematic of the MSU pilot-scale concurrent flow grain dryer (Dalpasquale, 1981).	62
6.2	Flowchart TEMPOUT - Program to read and convert thermocouple voltage signals.	68
6.3	Flowchart RPMSET - Program which controls the discharge auger motor speed.	71
6.4	Single-stage concurrent flow grain dryer control system - Block Diagram.	73
6.5	Determination of Ziegler-Nichols PI controller constants (Smith, 1979).	78
6.6	Outlet grain temperature response to a step change in grainflow rate from 4.0 to 2.4 (tonne/hr/sq m) for a single stage concurrent flow corn dryer. .	81
6.7	Outlet grain temperature response to a step change in grainflow rate from 2.4 to 1.3 (tonne/hr/sq m) for a single stage concurrent flow corn dryer. .	83
6.8	Outlet grain temperature response to a step change in grainflow rate from 2.4 to 4.0 (tonne/hr/sq m) for a single stage concurrent flow corn dryer. .	85
6.9	Outlet grain temperature response to a step change in grainflow rate from 1.4 to 2.4 (tonne/hr/sq m) for a single stage concurrent flow corn dryer. .	87
6.10	Flowchart DRYERPI - Program which controls the outlet grain temperature.	93
6.11	Experimental test results for the outlet grain temperature controller.	96
6.12	Experimental test results for the final outlet grain temperature controller.	98
6.13	Outlet grain temperature response to a positive step change in airflow rate.	102
6.14	Outlet grain temperature response to a negative step change in airflow rate.	103

CHAPTER 1

I N T R O D U C T I O N

Recent advances in microelectronics have made it possible to put all of the elements of a conventional computer central processing unit into a single integrated circuit package known as a microprocessor. This study deals with the application of microprocessor technology to the control of continuous flow commercial grain dryers. Very little automatic control, of any type, is presently being utilized in the operation of such dryers.

Continuous flow grain dryers provide an excellent opportunity for the application of microprocessor-based control. Much experience is necessary to correctly interpret and adjust the dryer parameters (such as grainflow rate, airflow rate and temperature) for optimum performance. An operator is required to determine the entering grainflow rate, the heating and cooling rates, etc. All this information needs to be blended together and used to modify the dryer parameters sometime in the future.

Table 1.1 summarizes the operation of a continuous-flow three-stage concurrent flow dryer during a 12 hour period. An experienced operator was on duty at all times. The test was conducted during the 1980 fall drying season in Saginaw, MI [Bakker-Arkema et al., 1981]. Note that even an experienced operator has difficulty maintaining the desired outlet conditions.

A microcomputer control system, while probably not completely replacing the operator, has the potential to maintain dryer parameters close to optimum values and to free the operator for other duties.

Energy can be saved by operating dryers at higher inlet air temperatures or lower airflow rates. The source of the savings is the greatly increased ability of air to hold moisture at higher temperatures. When optimizing the design of corn dryers Brook and Bakker-Arkema [1980] placed primary importance on setting the air temperature in each stage of a concurrent flow dryer to the maximum value allowed. Minimal values of airflow and dryer length were then found which met moisture content and grain quality constraints.

Grain quality constraints include limits on the kernel temperature at the end of each stage [Westelaken, 1981]. The closer a dryer is operated to the product temperature limit, the more important is an accurate control of the drying conditions.

Table 1.1: Data from a typical 12-hr run of a Ferrell-Ross CCF 3-stage concurrent flow grain dryer at Saginaw, MI during November 1980.

TIME	M.C. in* [% wb]	AIR TEMPS			AIRFLOW ** (static pres.) [in. H2O]			GRAINFLOW (feedroll)
		[F]						[RPM]
		top	mid	bot	top	mid	bot	
8:00 pm	24.9	500	398	300	13.5	16.0	17.5	50
9:00	23.8	500	400	305	14.0	16.0	17.0	50
10:00	28.5	0	310	255	12.0	15.5	17.0	45
11:00	29.0	490	390	295	14.5	14.5	17.0	45
12:00	29.0	505	380	280	15.0	15.0	15.0	40
1:00 am	26.2	500	380	290	15.0	15.0	15.0	40
2:00	25.4	500	400	290	15.0	16.0	17.0	40
3:00	28.8	500	400	300	12.5	15.0	17.0	50
4:00	22.3	495	340	260	14.0	14.5	16.0	44
5:00	26.1	500	340	265	13.5	15.0	16.5	50
6:00	26.7	500	340	265	14.0	15.0	16.5	50
7:00	27.5	495	340	265	13.0	14.5	16.5	50
8:00	24.7	490	340	265	13.0	14.0	16.5	50

	OUTLET GRAIN TEMP			M.C. out
	[F]			[% wb]
	top	mid	bot	(SP=16.5%)
8:00 pm	138	129	102	15.6
9:00	139	134	87	19.7
10:00	138	139	87	17.6
11:00	129	130	93	17.4
12:00	134	100	79	19.2
1:00 am	112	136	71	22.0
2:00	133	123	76	20.6
3:00	147	128	77	20.7
4:00	119	151	70	19.0
5:00	141	138	102	11.9
6:00	130	132	86	15.5
7:00	133	124	85	16.3
8:00	114	124	80	19.8
				AVG= 18.1

* Commercial corn, available at the terminal, was used in the test

** Static pressure is an indicator of the airflow rate

As a result of inadequate control, elevator managers commonly underdry or overdry grain. Underdried grain can spoil and if maximum moisture content values are exceeded, a heavy penalty (dockage) results (e.g. for #2 yellow corn the shipping limit is 15.5% moisture or less; higher moisture contents place corn in the #3 or #4 category).

Overdrying of grain is expensive. The costs involved include fuel costs, investment costs, maintenance costs, labor costs, "handle" losses[1] and shrinkage losses. The cost of a microcomputer control system and its sensors can easily be recovered in less than one year by significantly reducing overdrying.

Drying is an inherently stable process. If the feed to the dryer and its ambient surroundings do not change, there is no need for automatic control once the machine is properly adjusted. This is important to

[1] The "handle" refers to the profit per bushel of grain handled. During the season elevators are restricted to the amount of grain taken in and by the limitations on drying, (wet grain can not be stored). The more grain an elevator handles in one season the more profit it can generate.

consider for a responsible analysis of just how much control is actually justified. With microprocessor technology it is possible for a dryer to be overcontrolled [Zagorzycki, 1979].

CHAPTER 2

O B J E C T I V E S

The objectives of this study include:

1. to ascertain the parameters which can best be controlled in commercial grain dryers, in particular in concurrent flow dryers;
2. to investigate the requirements for implementation of microprocessor based controllers for single and multi-stage continuous flow commercial grain dryers;
3. to investigate the differences for controlling dryers of crossflow and concurrent flow design; and,
4. to develop and test a microprocessor-based control

system for a pilot-scale, single stage concurrent
flow grain dryer.

CHAPTER 3

B A C K G R O U N D I N F O R M A T I O N

3.1 Continuous Flow Grain Dryers

Continuous flow grain dryers are generally of crossflow design. In a crossflow dryer, grain and airflow in perpendicular directions. The temperature of grain on the air inlet side of a crossflow dryer will approach or equal the maximum temperature of the heating air (see Figure 3.1) Overdrying and underdrying of the grain column occurs but mixing is used to eliminate wet grain pockets

Continuous, concurrent flow grain dryers have recently become commercially available. In a concurrent flow dryer, grain and air both flow in the same direction. High rates of evaporation occur at the inlet of each drying stage where the hottest air encounters the wettest grain. The grain temperature remains considerably below the air

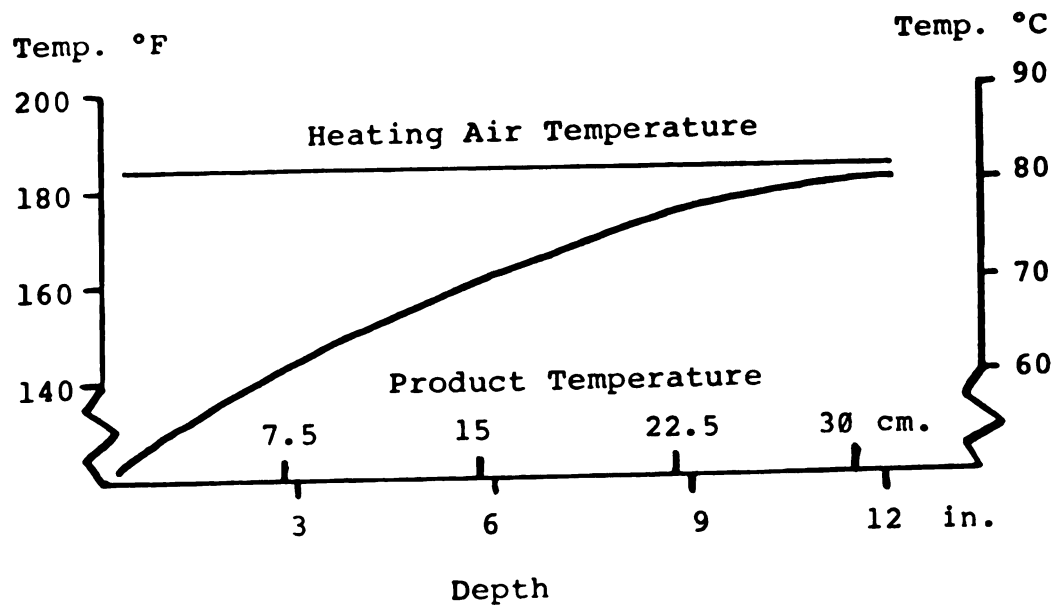


Figure 3.1 Air and grain temperature distribution in crossflow dryers.

temperature in this region and thus exceptionally high drying air temperatures can be used. As the air and grain move through the dryer their temperatures equilibrate. As shown in Figure 3.2 the air and grain temperatures normally become equal within the first few inches of a concurrent flow drying section [Brook, 1977].

The concurrent flow dryer has advantages over the crossflow dryer because of its favorable energy efficiency, grain quality characteristics, and pollution qualities. The high inlet air temperatures used in concurrent flow dryers result in high energy efficiencies. Energy efficiencies between 4185-5120 kJ/kg of water removed are common for concurrent flow dryers while crossflow dryers average about 7500 kJ/kg of water removed [Muhlbauer and Isaacs, 1975].

There is no moisture gradient among the grain kernels in a concurrent flow dryer and the continuous gradual decrease of the product temperature through the last portion of the drying section reduces drying stresses and helps lessen stress cracking and mechanical damage during subsequent handling.

The amount of pollution given off by a grain dryer is a function of the quantity of air discharged to the atmosphere. The volume of air exhausted from a crossflow dryer is eight to ten times larger than from a comparable concurrent flow dryer [Bakker-Arkema et al., 1972].

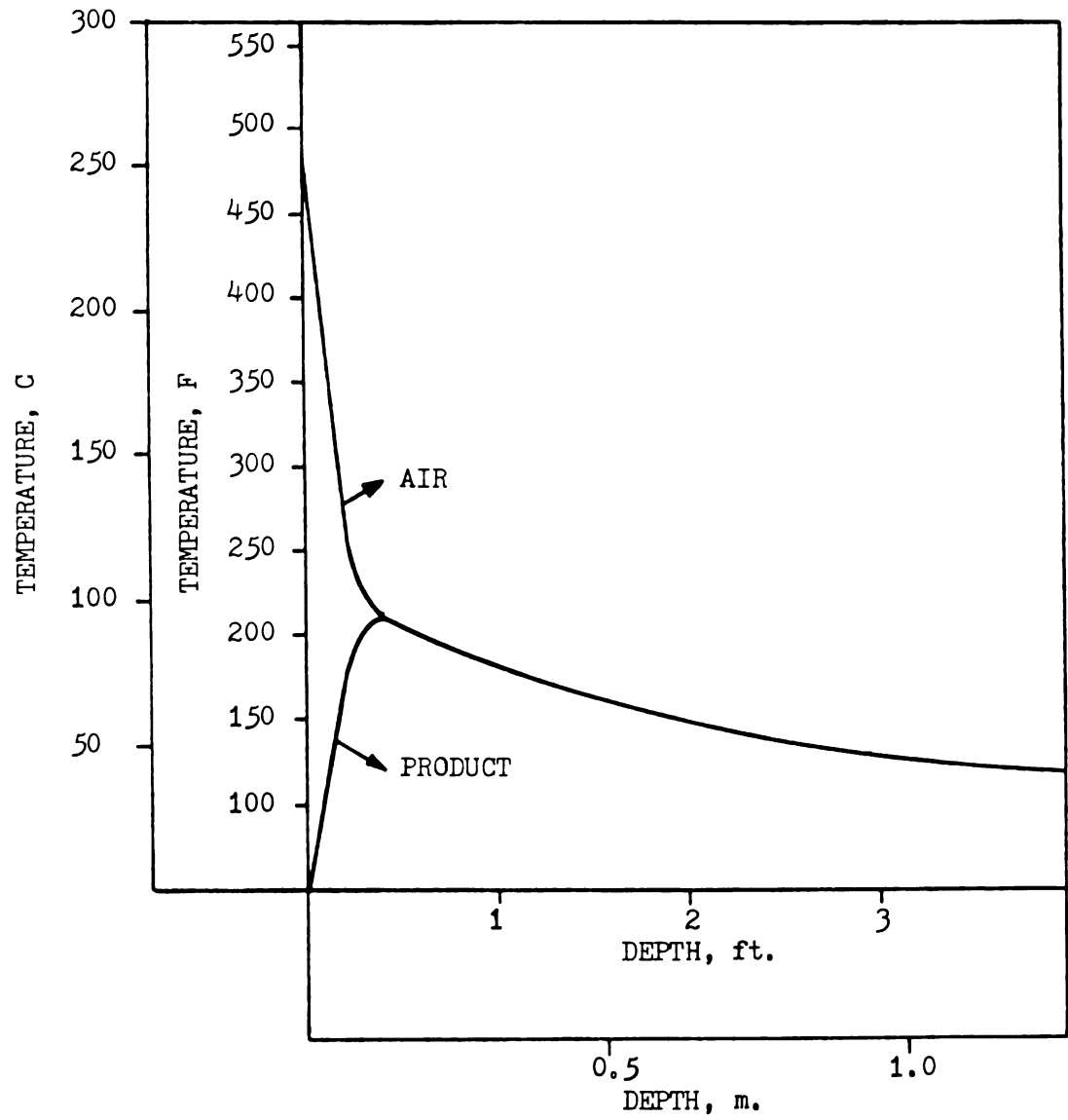


Figure 3.2 Air and product temperatures versus depth for a single-stage concurrent flow dryer (Brook, 1977).

3.2 Process Control Fundamentals

In control theory, the physical hardware that is associated with the process being controlled is referred to as the "plant". Elements that are added to effect control are designated as the "controller". The task of a controller is to adjust the state of a process as measured by some variable - the process variable (PV) - to conform to a particular standard value termed the set-point (SP).[1] The difference between the SP and the PV is called the error(E). With knowledge of the error the controller acts on the process through a final control element to change the process variable in the desired direction. The way the controller responds to the error is called its "control algorithm" [Bibbero, 1977]. The plant and the controller taken together constitute a control system (see Figure 3.3).

The input-output relationship of a control system element can often be represented by a transfer function. The "transfer function" of an element is defined as the

[1] The state of a process can usually be described by several process variables which may interact with each other. Although this study is only considering the case of independent process variable control, it should be pointed out that digital processors are particularly suited for interactive "multivariable" control.

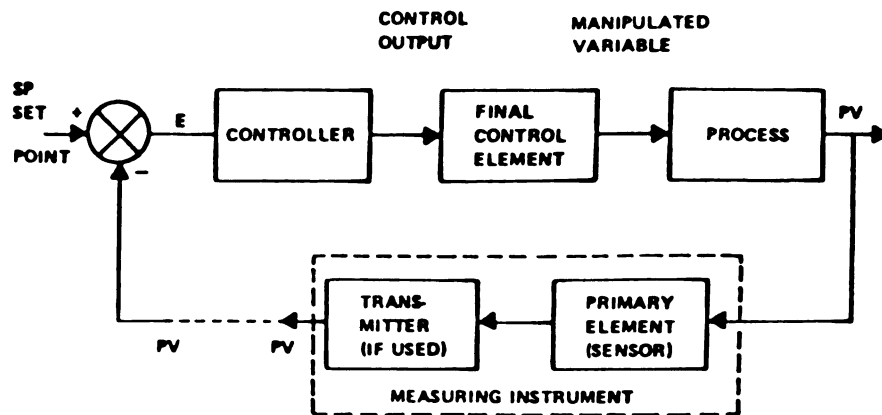


Figure 3.3 Control system block diagram (Bibbero, 1977).

ratio of the transform of its output to the transform of its input. Laplace transforms are used for continuous systems analysis while the z-transform has the same role in discrete systems [Franklin and Powell, 1980].

3.3 Digital Control Systems

The control of physical systems with digital techniques is becoming more common [U.S. Dept. of Energy, 1979]. Traditional controllers have been of analog design

and variables such as temperature, pressure, and flow vary in a continuous analog fashion. Digital controllers (e.g. microcomputers) compute the correct output for a discrete instant in time. Therefore a digital control algorithm must be repeated periodically at a rate sufficient to make the control system behave as if it were under the influence of a continuous controller.

Bibbero [1977] listed the following advantages of using digital control systems:

1. lower cost per function than analog control systems;
2. flexibility;
3. security (accuracy and stability);
4. human factors (digital control systems are easier to operate and maintain than analog control systems); and,
5. advanced control capability.

Digital controllers allow a sampled data input. A sampled data input offers the greatest flexibility in compensating difficult plant processes, especially where the plant has considerable inherent deadtime.[1]

[1] "Deadtime", also known as reaction lag, is the time required for a change in controller output to be sensed as a change in the measured process variable.

3.4 Microcomputers: A Brief Overview

The single most significant development in digital systems design in recent years has been the advent of the microprocessor [Short, 1981]. A "microprocessor" includes all the elements of a conventional computer central processing unit (specifically arithmetic, logic, and control) implemented on a single silicon chip. When coupled with the other major components of a digital computer (i.e., memory and input/output circuits), it forms a "microcomputer". A microcomputer is generally implemented as a collection of chips on a printed circuit board although single chip microcomputers have recently been introduced [Wise, K.D. et al., 1980].

3.4.1 Information Transfer

The basic memory element for digital systems is the "bit". A bit can exist at one of two logic levels, represented by the binary digits "0" and "1". A "word" consists of N bits which can be stored, transferred, and manipulated by the microprocessor as a unit. If a word is divided into units of eight bits, these are usually termed "bytes". The "word length" of a microprocessor is the amount of information that can be manipulated at one time.

Word length determines the accuracy of data, the speed of calculation, and the cost of memory (or the trade-off between these factors) for a particular microprocessor.

An "instruction" is a unit of information that is used to indicate to the microprocessor which operation it is to perform. A set of instructions that are used together to accomplish a complete computational task is called a "program". A program or a collection of programs is, in general, called "software." Strictly speaking, a microprocessor contains no software. All programs are located in memory and therefore enter the picture only in the discussion of microcomputers.

3.4.2 Memory

Basically two types of memory are used in a microcomputer system, read-only memory (ROM) and random-access memory (RAM). ROM, as its name implies, can only be read. Once its contents are set, they can be changed only by special equipment (e.g. ultraviolet erasers). ROMs are used to store sets of instructions and/or constants that need not be altered after the computer is installed.

RAM is the name commonly used for memory that can be both read from and written into (read/write). RAM is used for working storage, insertion of problem constants and program options, and as a data base. RAM is almost always volatile, i.e. with power cut off, the contents of the memory are lost.

3.4.3 Buses

One or more electrical connections, known as "buses", are usually used to transfer information within a microprocessor system. The bus is designed to be N bits wide (N is the word length of the microprocessor) to facilitate high-speed data transfer, so that information can be transferred in parallel (e.g. one byte at a time). Typically, all data transferred within the chip and between the microprocessor and external input/output devices is passed on the "data bus", and addresses of external-memory locations are passed on the "address bus". Since addresses are generally two words long, the address bus is usually two words wide. A third bus for control signals is sometimes employed, but more frequently these signals are sent serially over 1-bit-wide paths [U.S. Dept. of Energy, 1979].

3.4.4 Input/Output Circuitry

Input/output (I/O) circuitry allows a microcomputer to communicate directly with its surrounding environment. I/O devices can be connected to a microcomputer through either a serial or a parallel interface known as a port. A parallel interface moves information one word at a time, whereas a serial interface moves the information one bit at a time. A "port" is nothing more than an integrated circuit that physically connects the device to each of the system's buses (data, address, and control).

Each port is responsible for handling a number of complex tasks associated with the movement of data between the microcomputer and the I/O device. These tasks include error checking, parallel-to-serial conversion and formatting.

There are three basic techniques used to accomplish the actual movement of information between the microcomputer system and an I/O device. The first technique, termed "programmed I/O", is normally used when a program in execution needs to read or write data. In programmed I/O the external logic responds to the microcomputer. If a data transfer is requested during execution of a program, the program code initiates the transfer by identifying the appropriate memory address or I/O port then through a series of microcoded instructions,

the microprocessor executes the transfer of data. The second method, "interrupt I/O", allows external logic to initiate a request for data transfer. Essentially, an interrupt is a subroutine call initialized by external hardware. Whenever a byte of data is ready for transfer, the I/O device sends an interrupt signal which causes the microprocessor to temporarily leave the program which is being executed in order to service the device. Once the microprocessor has completed the data transfer it resumes execution of the program where the interrupt occurred.

The third method of executing an I/O transfer is called "direct-memory-access" (DMA). DMA differs from the other two methods because information can be transferred between memory and the external device without involving the microprocessor in the data-transfer logic. The current operation of the microprocessor is not interrupted. Of the three methods, DMA is the fastest, but it also is the most expensive to implement since the microcomputer logic requires a DMA controller (usually incorporating an additional microprocessor) for servicing the DMA requests.

3.4.5 Programming

Programs can be written at any one of three language levels: machine language, assembly language, or high level language (see Table 3.1 for examples of each type). Only machine language is directly executable by a microprocessor. Programs written in assembly or high level languages must be translated to machine language for execution. Machine code is usually represented in

Table 3.1: Microcomputer language levels.

High Level Language	Assembly Language	Machine Language	
		hexadecimal	binary
I = J+K	LDA AUGND	3A	00111010
		0C	00001100
		00	00000000
	MOV B, A	47	01000111
	LDA ADDND	3A	00111010
		0D	00001101
		00	00000000
	ADD B	80	10000000
	STA SUM	32	00110010
		0E	00001110
		00	00000000
	HLT	76	01110110

The above program adds two numbers obtained from memory, stores the results in memory, and then halts. The instruction set is for the Intel 8085A microprocessor [Short, 1981].

hexadecimal notation for conciseness. However, it must be converted to binary to be loaded into memory. Programs of any appreciable length are not written directly in machine language because they are difficult to read and write.

Assembly language uses mnemonic representations for operation codes, data, and addresses. These mnemonics are abbreviations of the names or descriptions of the instructions, addresses, or data and are used to aid the programmer's memory. Assembly language programs are more understandable than corresponding machine language programs, which makes writing and modification of the programs easier.

Programming ease is further enhanced by a high level language, where a single instruction is equivalent to several machine language instructions. The high level languages now available for use with microprocessors include BASIC, FORTH, PASCAL, and FORTRAN [Short, 1981]. The question of whether a particular high level language is available for a specific microprocessor is actually a question of whether there is a compiler to translate the language to the microprocessor's machine code.

CHAPTER 4

L I T E R A T U R E R E V I E W

The following section summarizes the literature on grain dryer control pertinent to this study.

Cloud [1957] listed three main objectives for automatic controls on crop drying equipment:

1. to provide or to utilize the best possible drying conditions consistent with the drying system;
2. to eliminate the human element and to reduce labor; and,
3. to provide safety in case of failure of the system.

Matthews [1963a] developed a means for automatically controlling the moisture content of dried grain at the outlet of a continuous flow dryer. An

electronic controller unit adjusted the grain throughput rate in response to the signal from a capacitance-type moisture monitor. The monitoring system consisted of a permittivity sensing [1] electrode placed in the grain mass at the outlet of the dryer. A capacitive-sensitive bridge circuit was used to condition the signal from the sensor.

An experimental low capacity cross flow dryer was used to determine the optimum dryer control action. The object in optimizing the action of the controller was to minimize the duration and extent of the outlet moisture content error when input moisture content variations were encountered. Proportional control action with automatic reset was found to give near optimum performance when drying both freshly harvested and artificially wetted wheat.

The prototype control system was fitted to a tower-type farm grain dryer [Matthews, 1964]. Barley, wheat and oats were dried during the trial. The moisture content regulation over approximately 400 hours drying was shown to be generally satisfactory. The control system was not tested on a large scale commercial dryer.

[1] Permittivity is also called the "dielectric constant".

Matthews noted that the sensing electrode introduced an obstruction to the moving grain, liable to collect straws, etc. with the subsequent possibility of partial blockage. The electrodes also caused considerable disturbance to the flow of drying air. Problems were encountered with calibration of the equipment. Initial settings had to be obtained using a sample-type moisture meter for reference. High temperature rises in the commercial control unit caused the variable-speed drive, used to regulate the grain discharge rate, to malfunction. For these reasons the unit was not commercialized.

Aguilar and Boyce [1966] stated that the control system developed by Matthews [1964] was also prohibitively expensive. They investigated various ratios, developed from the dry bulb and wet bulb temperatures of the drying and exhaust air, in order to determine whether such ratios could be used as a means of controlling grain drying processes. Specifically they investigated whether a drying process could be terminated when the average moisture content had reached some predetermined level.

Aguilar and Boyce proposed the use of a ratio termed the Effective Heat Efficiency (EHE) defined as:

$$\text{EHE} = (T_i - T_o) / (T_i - T_{iw}) \quad (4.1)$$

where: T_i = dry bulb temperature of the drying air

T_o = dry bulb temperature of the exit air

T_{iw} = wet bulb temperature of the drying air

The EHE ratio considers the sensible heat in the drying air as being the effective heat for drying. It was stated that EHE should always have the same value at a given average grain moisture content and grain depth, as long as the exit air is not saturated.

Tests were conducted using a static bed dryer to dry barley. An EHE chart was developed for different airflows and temperatures using relatively simple instrumentation. It was concluded that development of an electronic device utilizing the EHE ratio was possible and that the device could be used to control the flow rate through a continuous flow dryer. As far as the author knows, the EHE has not been commercially adopted for control purposes.

Zachariah and Isaacs [1966] described a simulation procedure used in the development of an automatic moisture control system for a continuous flow grain dryer. The control system regulated the flow rate of grain through the dryer. The principal objective of the control-system simulation was to select an optimum set of controller constants. It was established that a direct analytical approach to the synthesis of an optimal dryer-control system was not feasible.

Utilizing a mathematical model for the drying process based on the drying equation developed by Hukill [1954], Zachariah and Isaacs [1966] presented a means of simulating various control systems to select an optimum set of controller constants. Four different control systems were investigated including one based on the proportional-reset control algorithm which will be considered in detail in this thesis.

A prototype proportional-reset control system was constructed and tested on a full scale dryer as a check of the simulation procedure. A modified capacitance grain moisture meter was used to monitor the moisture content of the grain leaving the dryer. The monitoring unit required periodic sampling resulting in a sampled-data system with zero-order hold. Thus, the electric signal representing the moisture content was established at the time of sampling and held constant until the subsequent sampling period.

Several limitations of this study can be pointed out. The testing of the control system did not provide conclusive evidence of the accuracy of the simulation model. Difficulties were reported in achieving the required slow reset rate - in the order of one repeat per hour - using commercially available controllers (this problem can now be overcome by using a microprocessor-based controller). Perhaps the greatest limitation of

Zachariah-Isaacs' approach is that it requires a direct measurement of the grain moisture content. As will be discussed in a later section, on-line moisture measurement of grain, which is both relatively inexpensive and sufficiently accurate for control, is not commercially available.

Holtman and Zachariah [1969a] used computer simulation to design and evaluate optimal controls for a continuous cross flow grain dryer. Utilizing a model which assumes moisture content is a linear function of time, computational methods for deriving the discharge pattern for any input-moisture pattern were developed. Performance indices for evaluation of the controls were based on the deviation from set-point (moisture content) of grain being discharged.

A simulation of the process under control was used to obtain typical response data for the optimal controllers. The simulation requires as input the initial moisture of the grain flowing into the drier. Test results showed that the average error increased significantly with dryer size. A larger dryer size implies a higher discharge rate in bushels per hour. Thus when an error occurs in a larger dryer, more off-specification grain is discharged.

Holtman and Zachariah did not test their controller on an actual dryer. They based their results on the assumption that a continuous grain moisture measurement

could be made. This assumption combined with the fact that a large time-shared computer is needed to implement the optimal control strategy casts doubt upon the usefulness of the approach for an on-line control situation.

Harrell et al. [1979] presented a design for a microprocessor-based control system for a solar assisted grain drying facility. The control system implements an optimization procedure utilizing a modified form of the critical path method of optimization [Colliver et al., 1979] and the logarithmic model of grain drying [Sabbah et al., 1977] to determine the optimum drying air temperature. The control network is configured around a Motorola M68MM01A single-board microcomputer which utilizes the M6800 microprocessor.

The microcomputer is to monitor the grain moisture content and air temperatures (dry bulb and wet bulb) to determine whether the current moisture content is equal to or less than the desired final moisture content. If so, the drying is complete and the system is shut down. If not, the drying process is simulated for a one-hour interval with current temperatures and airflow rate. After the simulation is complete the moisture removal rate is computed and the microcomputer executes the optimization routine to determine the optimum drying air temperature. If more heat is needed a heater is turned on and the whole operation is repeated.

The control system has not been implemented. The major obstacle to be overcome is the measurement of the grain moisture content. An indirect method to determine the moisture content, based on dry and wet bulb temperatures, is being considered by Harrell et al.

Another limitation of this study is that the optimization process must continually update itself, leaving very little computer time for heater control. Significantly more computer time must be available for monitoring and control of the variables in a multi-stage continuous flow grain dryer.

Hinkle (1980) demonstrated the potential for microcomputer control of grain dryers. An Intel 8085-based microcomputer replaced the existing, electromechanical controls of an automatic batch grain dryer. Loading, purging, drying, cooling, and unloading functions were successfully scheduled by the microcomputer. An automatic batch dryer continues to cycle through the above five stages as long as wet grain is available. The drying cycle is terminated when the temperature of the grain reaches a preset level which is indicative of the desired final moisture content.

Hinkle noted that 98% of the computer operating time was spent in wait cycles. This point is particularly important when considering the implementation of a microcomputer to control the outlet moisture content of

continuous flow dryers because these control tasks are much more complex and may need considerably more computing time.

Hinkle did not actually utilize the computational power of the microprocessor, but he did demonstrate that a microcomputer can replace existing dryer controls with the potential for implementing future complex control strategies.

CHAPTER 5

DRYER CONTROL PARAMETERS

The primary objective of grain drying is to bring the moisture of the grain down to a particular level (set-point). Time, temperature, and airflow rate are the three primary variables that determine the moisture content of a particular grain discharged from each drying stage [Zachariah and Isaacs, 1966]. Measurement and control of each of these parameters is considered separately.

5.1 Time

The drying time in continuous flow dryers is determined by the rate at which grain is discharged from the dryer. Continuous flow dryers require a grain metering device so that the grainflow rate can be regulated and controlled. The metering device used on most continuous flow dryers is a feed-roll auger powered by an electric

motor. The grainflow rate can be considered constant at a given auger speed. In multi-stage dryers the grain metering device is located at the outlet of the last stage and thus the grainflow rate (in terms of dry bushels) is the same throughout the dryer.

Auger speed can be regulated by controlling the velocity of the drive motor. A microcomputer can be programmed to put out a digital signal to a digital-to-analog (D/A) converter which in turn provides the input voltage to an electronic motor speed controller (usually replacing a manually operated potentiometer). This control strategy has been utilized successfully in the experimental investigation which is presented in Section 6.1.4 of this thesis. When interfacing a microcomputer to a motor speed controller, care must be taken to completely isolate the microcomputer from the current surges which occur in the controller during motor startup and when making abrupt changes in motor speed (the current surges are a result of back EMF generated by the motor at these times). This can be accomplished using optical or transformer isolation techniques [Burton and Dexter, 1977; Sheingold, 1981; and Morrison, 1977].

There are normally practical limits within which the grainflow rate can be controlled. Dryer capacity is decreased as the grainflow rate is lowered. When the grainflow rate is decreased to a certain point, rather than

further decrease the dryer capacity, an operator will adjust the inlet air temperatures and/or airflow rates to increase the drying rate. Also, when relatively dry grain is introduced into the dryer, an operator will increase the grainflow rate only to a certain point before adjusting the inlet air conditions. These practical limits should be incorporated into the dryer control algorithm.

Controlling grain moisture by regulating the grainflow rate introduces a variable deadtime element into the control system. Also, because the grain velocity is the same throughout a continuous flow dryer, varying the grainflow rate to control the drying time for a changing inlet grain moisture content, also changes the drying time for grain which is already in the drying stage(s). These two consequences of utilizing grainflow rate as a controlled variable severely complicate the grain dryer control problem.

5.2 Temperature

Drying efficiency is maximized by setting inlet air temperatures to the maximum value allowed [Brook and Bakker-Arkema, 1980]. Restrictions on grain temperature levels are imposed on the drying process in order to maintain the quality of the product [Westelaken, 1981].

Both drying air and grain temperatures are important parameters when considering automatic control of commercial continuous flow grain dryers.

5.2.1 Air Temperature

The heat input for the drying air of commercial grain dryers in the United States is usually supplied by direct-fired burners. Drying air temperature is controlled by regulating the fuel flow to the burners. Fuel flow is regulated using a throttling valve which is normally positioned by a modulating motor. Modulating motors are actuated via a potentiometer. A controller utilizing the signal from a temperature probe for a feedback signal may be used to regulate the fuel flow in order to maintain the drying air temperature at a particular set-point.

A microcomputer based control loop can be used in place of the temperature controller on commercial dryers. The manual potentiometer used to control the modulating motor would be replaced with a digitally controlled potentiometer or a D/A converter operated by a microcomputer. The drying air temperature could thus be controlled in accordance with the overall grain dryer control software implemented in a microcomputer.

Accurate exhaust air temperature measurements are difficult to obtain in concurrent flow grain dryers [Bakker-Arkema, 1981]. Temperature measurements of exhaust air are difficult because of severe turbulence and mixing with ambient air in the proximity of the dryer exhaust vents. As shown in Figure 3.2 the air and grain temperatures at the exit of a concurrent flow drying stage are approximately equal. Thus, the grain kernel temperature at the exit of a concurrent flow drying stage may be monitored in lieu of the more elusive exhaust air temperature. Measurements of exhaust air temperatures from a crossflow dryer may entail calculating the average reading of a number of temperature probes (e.g. a thermopile) placed uniformly across the entire exhaust air vent.

5.2.2 Grain Temperature

Grain kernel temperatures can be monitored using Type-T (copper-constantan) thermocouples. Type-T thermocouples are recommended for use in a moist, low temperature (less than 350.0 C) environment as found in a grain dryer. Accuracies of ± 0.5 C are possible with Type-T thermocouples which meet ANSI "special limits of error" [Omega Engineering Inc. 1981]. The thermocouples should

be placed in sheaths directly in the grain mass. Aluminum sheaths are recommended for temperatures less than 350.0 C.

Thermocouple signals must be amplified, compensated for ambient temperature, and converted to a digital value before being put into a microcomputer. The microcomputer converts the digital value to the corresponding temperature. There are several commercially available circuits which perform the required thermocouple signal conditioning. One such unit was used in the experimental investigation and is presented in Section 6.1.3 of this thesis.

Copper-constantan extension wires should be used between the thermocouple leads and the signal conditioning circuitry to eliminate errors due to extraneous thermocouples along the signal transmission lines. Copper-constantan extension wire has a resistance of 2.46 ohms/m (0.75 ohms/ft), however voltage drops along the transmission lines are minimal because very little, if any, current is developed at the input of the signal conditioning circuitry [Sheingold, 1981]. Shielded thermocouple extension wire should be used to minimize the pickup of external noise along the transmission lines.

5.3 Airflow Rate

Ambient (and recycled) air is supplied to the burners in a commercial flow dryer by fans (usually of centrifugal design) powered by electric motors. The fans are normally operated at a constant speed. If a means for controlling the airflow rate is provided, it is usually a manually operated control damper located in the air duct between the fan inlet or outlet and the burner inlet. Airflow rate is normally determined indirectly by monitoring the static pressure in the air duct.

Automatic control of the airflow could be accomplished by installing control dampers adjustable via a modulating motor. The modulating motor can be adjusted from the microcomputer as previously described in the discussion of fuel flow regulation.

Using airflow rate as a controlled variable introduces a variable deadtime element into the control system, similar to that found with grainflow regulation [Shinskey, 1978]. Power requirements impose a practical limit on the maximum airflow rate obtainable and fans operate efficiently only over a small airflow range.

5.4 Grain Moisture Content

Optimal control of a drying process requires knowledge of the product moisture content. The operator of a continuous flow grain dryer will typically conduct off-line moisture measurements of representative grain samples. These measurements are usually conducted with some type of electronic moisture analyzer, (the Motomco Moisture Meter has been accepted by the Standardization and Testing Branch of the Grain Division, U.S. Dept. of Agriculture [Henry, 1975]).

5.4.1 On-Line Grain Moisture Measurement

An on-line method of monitoring grain moisture content would be useful for automatic control of the drying process. However, currently available continuous moisture-sensing instrument systems have proven to have serious limitations [Bakker-Arkema, 1981; Sen, 1981]. The following short-comings of currently available commercial moisture measurement systems are largely responsible for their limited use for control of drying processes [Yang, 1981]:

1. EXPENSE: High cost prevents wide use of moisture

sensor systems. Advanced systems cost from \$5,000 to \$20,000.

2. LACK OF AUTOMATED READOUT: The popular dewpoint instruments commonly produce a temperature reading from which the relative humidity must be calculated by using a psychrometric table. This type of instrument does not generate a direct electrical command for automated process control. Other moisture sensors based on mechanical principals also lack an electrical signal output.
3. NONLINEAR RESPONSE: A large class of instruments (e.g., hygroscopic chemical-electrical resistant-type sensors) produce a nonlinear response. Sophisticated electronics are required to compensate for the effects of nonlinearity in order to achieve a linear readout, (this is not a serious limitation when utilizing a microcomputer controller).
4. SLOW RESPONSE: It is not uncommon for a moisture-sensing system to require a stabilization time in excess of 30 seconds (up to several minutes).

5. LARGE SIZE: The main disadvantages of a large probe are inconvenience of installation and interference with the product flow.
6. ENVIRONMENTAL INSTABILITY: Certain types of probes deteriorate with time when exposed to contaminants such as smoke and chemicals or when subjected to an abrasive environment, such as rice. This can change the sensitivity factor, and requires frequent probe recalibration or replacement.
7. INCONVENIENT CALIBRATION PROCEDURES: The repeatability and the calibration factors of most sensors change with time, therefore periodic calibration is necessary. For the majority of exposed sensors, the calibration requires removing the probes and placing them in humidity-controlled chambers that can maintain a standard humidity.

Several manufacturers have marketed systems for continuous measurement of grain moisture content. The DICKEY-john Corporation (Auburn, IL) manufactures the CFMM-A Continuous Flow Moisture Monitor which is intended to provide continuous moisture monitoring of grainflow for grain handling operations. A capacitance-type detector senses dielectric properties of the flowing grain and

transmits an electrical signal back to a moisture display unit [DICKEY-john, 1980; Matthews, 1963b]. The system has been tested in the commercial drying of corn and soybeans. The performance of the system has been found to be unsatisfactory [Bakker-Arkema, 1981]. The limitations of the system which make it unsatisfactory for control purposes are:

1. detector plugging: although a scalper is used to deflect foreign debris from the detector, frequent plugging occurs due to the accumulation of wet grain, cobs, etc., this causes a wrong moisture reading and severely limits the system's use for control purposes;
2. initial cost: The initial cost of a CFMM system is in excess of \$10,000.

Diversified Engineering, Inc. (Richmond, VA.) manufactures the DM6 Digital Moisture Meter. The system consists of a probe head which utilizes a highly stabilized RF signal to detect product moisture. The signal from the probe is transmitted to a separate unit where it is amplified and converted to a digital moisture display. The DM6 system is intended for sensing moisture in agricultural or cellulose products. The DM6 system has been tested in

grain drying processes [Sen, 1981]. The unit was found to be unsatisfactory for grain dryer control purposes because the probe's surface was worn down due to the abrasiveness of the grain. The worn probe heads had to be replaced at frequent intervals. The cost of the DM6 monitoring system is approximately \$5,000.

5.4.2 Indirect Moisture Monitoring

Indirect means of determining product moisture, based on ratios of inlet and exhaust air temperatures, have been presented by Aguilar and Boyce [1966] (see Literature Review) and Fadum and Shinskey [1980].

Fadum and Shinskey presented a moisture control system embodying the technique of variable driving force. On-line measurement of product moisture or feed moisture is not required. The control strategy has not been implemented on a commercial grain dryer. To control moisture in a dryer, the driving force ratio at input and output must be kept constant by varying both input and output temperatures as the load varies, according to the equation:

$$X_p = k * \ln(T_i - T_w / T_o - T_w) \quad (5.1)$$

where: X_p = product moisture

T_i = inlet air temperature

T_o = outlet air temperature

T_w = wet bulb temperature

k = a constant for a particular dryer
and product.

The equation assumes that the product dries solely in the falling drying rate region. Control algorithms based on the equation have been successfully implemented for steam-tube and direct fired dryers.

As previously mentioned, the temperatures of exhaust air in commercial grain dryers are difficult to measure accurately. Also, wet bulb temperatures are difficult to obtain, especially at the high inlet air temperatures utilized in concurrent flow dryers [Shinskey, 1978]. The derivation of the equation assumes that product temperatures are limited to the wet-bulb temperature of the drying air. This assumption is not valid for continuous flow grain dryers [Bakker-Arkema, 1981]. For these reasons Equation (5.1) has limited use for control of continuous flow commercial grain dryers.

5.5 Computer Simulation Analysis

Modified versions of the Michigan State University (MSU) crossflow grain dryer computer simulation and the MSU concurrent flow grain dryer computer simulation were used to assist in the analysis of the dryer control parameters. The accuracy of the simulation models has been verified [Dalpasquale, 1981; Brook, 1977]. The grain dryer simulations were treated as the objective function of a golden section search routine (modified Fibonacci search) [Beveridge and Schechter, 1970]. Given a set of input conditions, one parameter (e.g. grainflow, inlet temperature, or airflow rate) was searched until a prespecified outlet condition had been reached. The results of these simulations are presented in this section.

5.5.1 Grainflow

Grainflow is the parameter most easily and often adjusted by commercial grain dryer operators attempting to maintain acceptable outlet grain moisture content-quality characteristics [Cloud, 1957; Zachariah and Isaacs, 1966; Hinkle, 1980]. In this study the MSU grain dryer computer simulations were utilized to evaluate the effect of variations in grainflow rate on the grain condition at the

outlet of a drying stage in a one-stage concurrent flow corn dryer.

5.5.1.1 Concurrent Flow Dryers

Experience has shown that corn at the outlet of a concurrent flow drying stage which is maintained in the temperature range from 54.4 to 60.0 C (130.0 to 140.0 F) will have acceptable moisture content-quality characteristics [Westlaken, 1981; Bakker-Arkema, 1981]. Modified versions of the MSU concurrent flow computer simulation were used to obtain the results shown in Figures 5.1 - 5.4. These results are for steady-state conditions (i.e. transient responses to changes in dryer parameters were not simulated). Corn was used for all simulations. Bakker-Arkema et al. [1973] proposed the standard conditions listed in Table 5.1 for the drying of shelled corn. Table 5.1 also lists the input conditions used in the concurrent flow dryer analysis. These conditions (unless otherwise noted) are used in obtaining the results in the following sections.

Figure 5.1 shows the steady-state grainflow vs outlet grain temperature relationship for a 3.0 ft (0.914 m) concurrent flow drying section for both 25% wb and 30% wb inlet grain moisture contents. Note that the

Table 5.1: Concurrent flow dryer simulation,
Input conditions.

<u>Standard conditions for corn drying simulation</u>	
Inlet Corn Moisture Content, % wb	25.0
Ambient Air Temperature, C	15.0
Ambient Air Humidity Ratio, decimal db	0.0065
Inlet Corn Temperature, C	15.0
Inlet Corn Foreign Material, %	3.0
Inlet Corn Breakage, %	10.0
<u>Additional Dryer Input Conditions</u>	
Inlet Air Temp., C	200
Airflow Rate, cu m/min-sq m @ Tamb	60
Dryer Length, m	0.914

relationship is approximately linear in both cases over the range shown.

Figure 5.2 shows the grainflow rates required to maintain grain outlet temperatures of 54.4, 57.2 and 60.0 C (130, 135, 140 F) over the inlet grain moisture content range of 20-35% wb with an inlet air temperature of 200 C (392 F). The outlet grain moisture content for each of these outlet temperatures was found to be essentially constant at the values shown in Table 5.2.

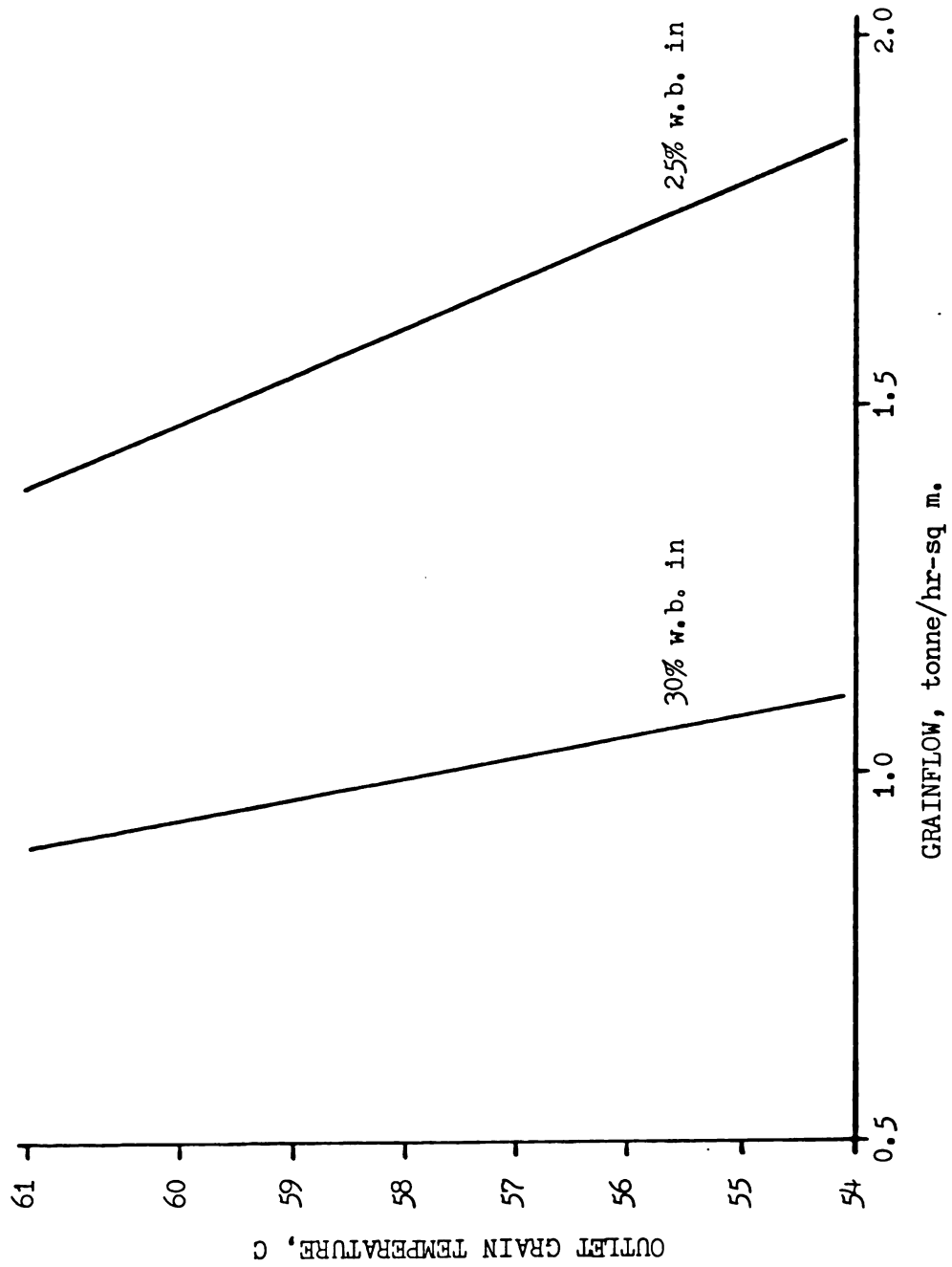


Figure 5.1 Grainflow versus outlet grain temperature for a single-stage concurrent flow dryer (MSU computer simulation).

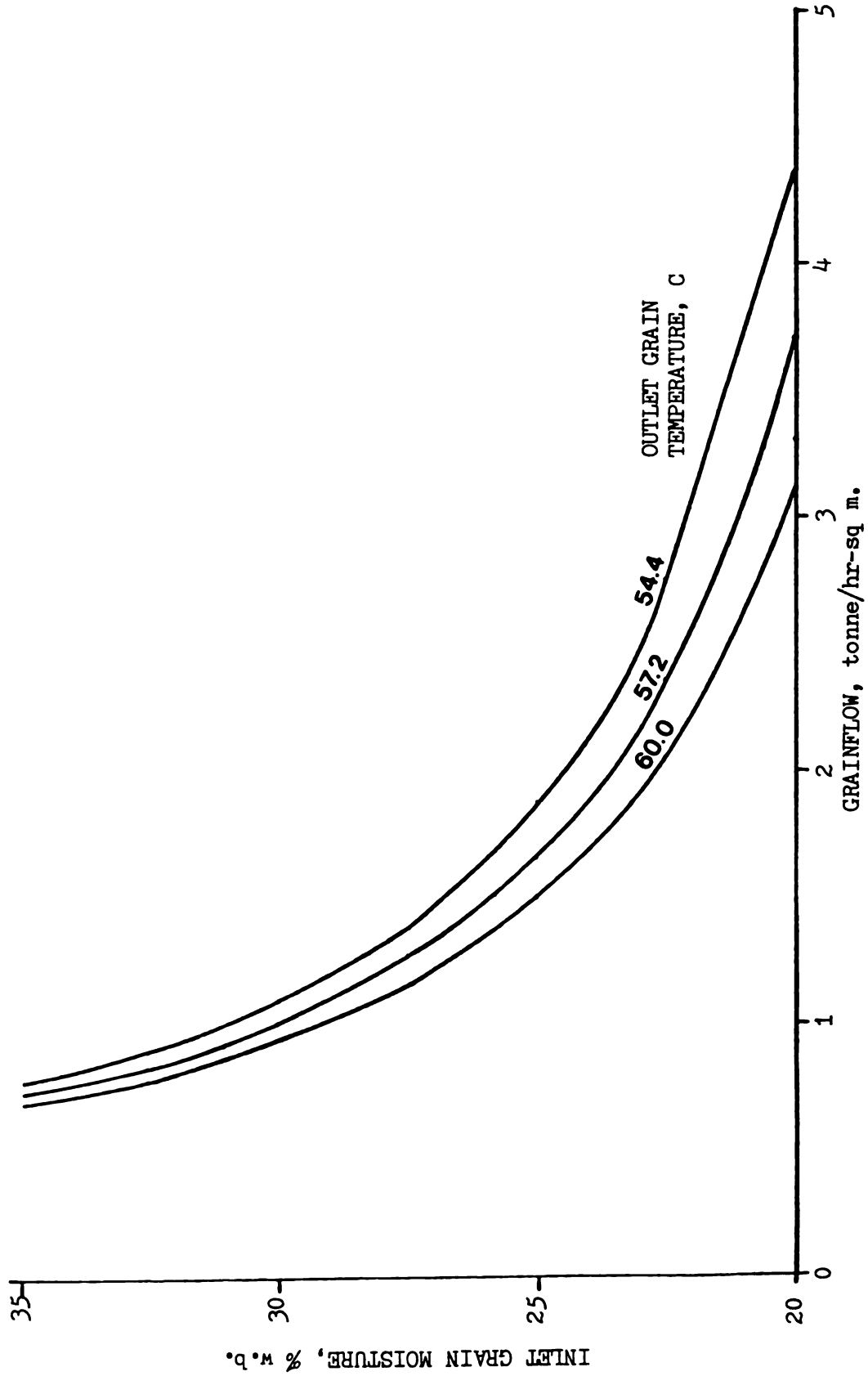


Figure 5.2 Grainflow required to maintain a constant outlet grain temperature with a varying inlet grain moisture content in a single-stage concurrent flow dryer (MSU computer simulation).

Table 5.2: Outlet grain moisture content when maintaining three different outlet grain temperatures within a concurrent flow dryer.

Outlet Grain Temp. [C]	Outlet Grain Moisture [% wb]
54.4	18.8
57.2	18.0
60.0	17.2

Figure 5.3 shows the grainflow rates required to maintain an outlet temperature of 57.2 C (135 F) at inlet air temperatures of 250, 200 and 150 C (482, 392, and 302 F) over the inlet grain moisture content range of 20-35% wb. The outlet grain moisture content for each of the inlet air temperatures was found to be essentially constant at the values shown in Table 5.3. Note that using a higher inlet air temperature results in a higher outlet grain moisture content for a given outlet grain temperature set-point. As the inlet air temperature is increased, the grain must be transported through the dryer at a faster rate in order to maintain the same outlet grain temperature. Because the drying time is reduced at the faster grainflow rate, the moisture content of the grain at

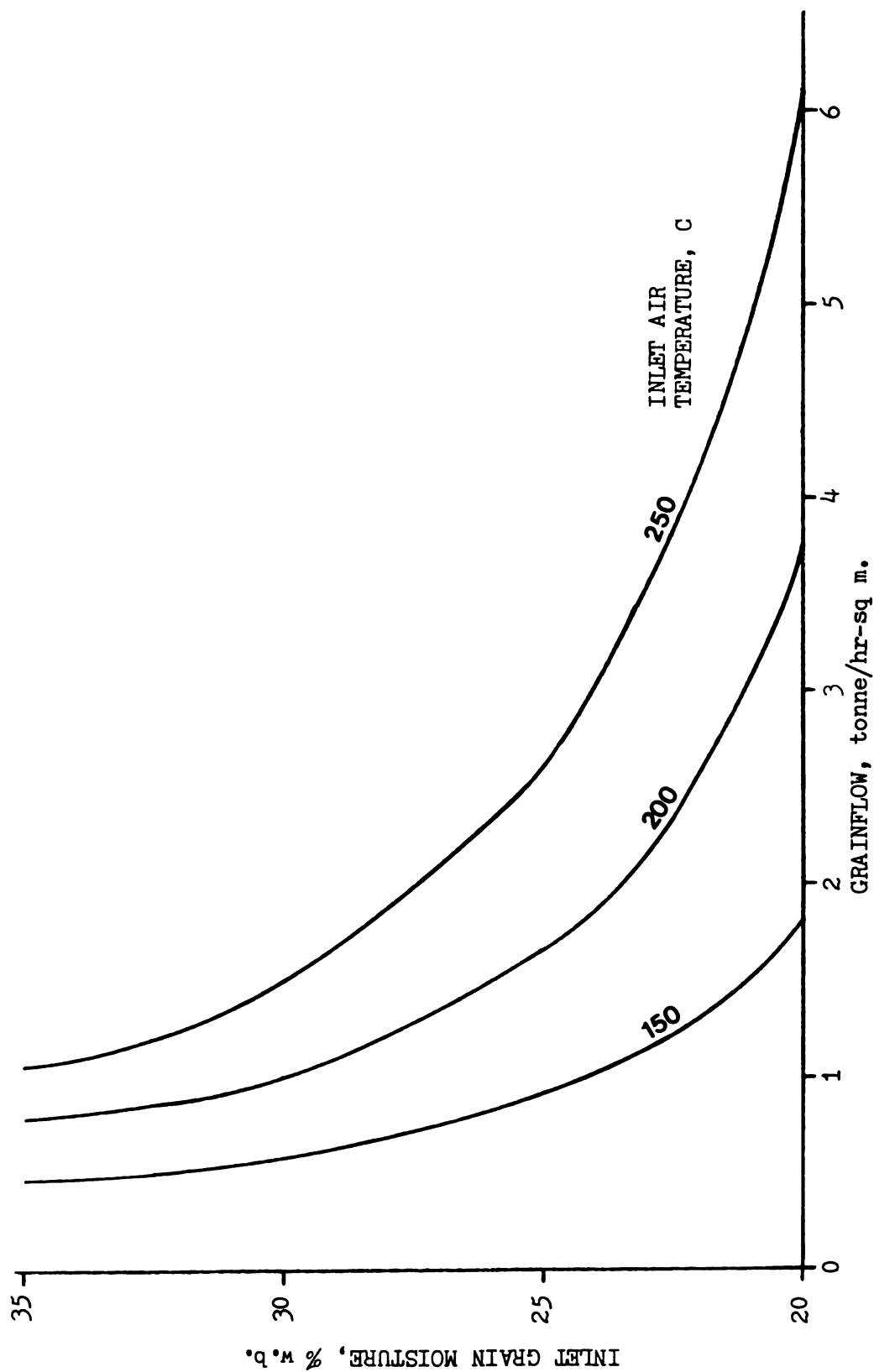


Figure 5.3 Grainflow required to maintain a constant outlet grain temperature with a varying inlet grain moisture content at three inlet air temperatures in a single-stage concurrent flow dryer (MSU computer simulation).

Table 5.3: Outlet grain moisture content when maintaining a constant outlet grain temperature at three different inlet air temperatures within a concurrent flow dryer.

Inlet Air Temp. [C]	Outlet Grain Moisture [% wb]
150	16.2
200	18.0
250	19.4

the outlet of the drying stage increases.

Changes in ambient conditions and inlet grain temperature do affect the grainflow rates required to maintain a constant outlet grain temperature. Also, the moisture content of grain at a given outlet temperature will change slightly with varying ambient and inlet air temperatures. However, the computer simulation did verify that for a given inlet drying air temperature, constant inlet grain temperature and constant ambient conditions, it is possible to maintain a fairly constant outlet grain moisture content by varying the grainflow rate to maintain a constant outlet grain temperature. An experimental, microcomputer based control system which automatically adjusts the grainflow rate to maintain a set-point outlet

grain temperature in a concurrent flow dryer is presented in Chapter 6.

5.5.1.2 Crossflow Dryers

As shown in Figure 3.1, there is a temperature (and corresponding moisture content) gradient across the drying column of a crossflow dryer. Therefore average outlet moisture content and temperature values are used for this analysis. A modified version of the MSU crossflow grain dryer simulation was used to determine the relationship between inlet grain moisture content and the grainflow rate needed to maintain an average outlet grain moisture of 16.5% wb at inlet air temperatures of 93.3 and 104.4 C (200.0 and 220.0 F). Figure 5.4 shows the results of this simulation given the input conditions of Table 5.4. Note that the two curves are approximately parallel.

Figure 5.5 shows the average outlet grain and exhaust air temperatures for the grainflow rates depicted in Figure 5.4. Note that the exhaust air temperatures are approximately equal for the two inlet air temperatures simulated. The product temperature curves are parallel.

The correlation between outlet grain temperature and moisture content found with the concurrent flow dryer simulation is not evident in the crossflow dryer simulation

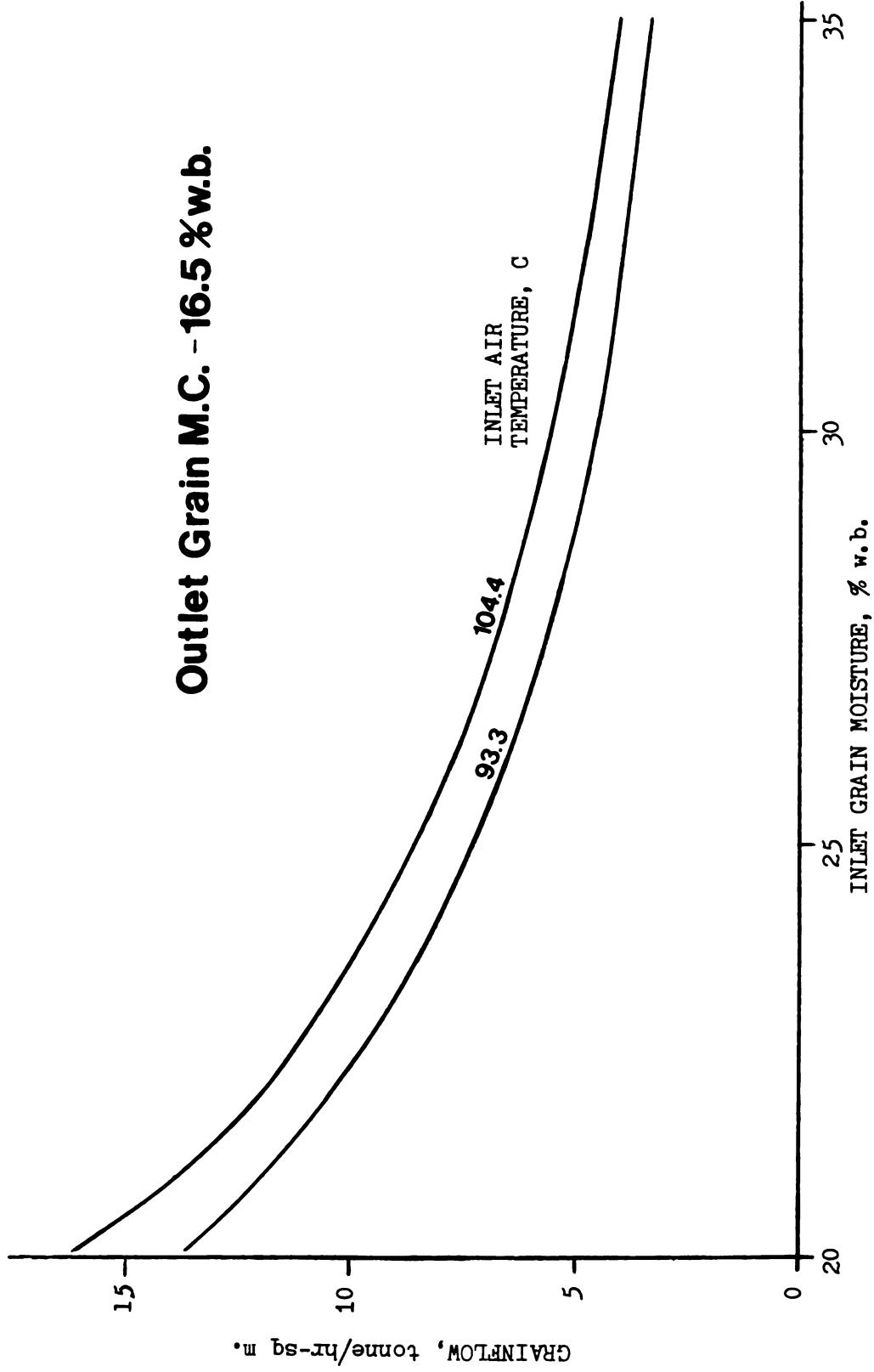


Figure 5.4 Grainflow required to maintain a constant outlet grain moisture content with a varying inlet grain moisture content at two inlet air temperatures in a single-stage crossflow dryer (MSU computer simulation).

Table 5.4: Crossflow dryer simulation, Input Conditions.

Inlet Grain Moisture, % wb	20-35
Inlet Grain Temp, C	14.9
Ambient Temp, C	15.6
Ambient RH, %	50
Inlet Air Temp, C	93.3 and 104.4
Airflow Rate, cu m/min/bu @ Tamb	2.32
Dryer Length, m (ft)	14.3 (47.0)
Column Width, m (ft)	0.305 (1.0)
Grainflow, tonne/hr/sq m	variable

results. Further research into the temperature-moisture content relationships for crossflow dryers should be conducted.

5.5.2 Airflow Rate

Figure 5.6 shows the simulated relationship between the airflow rate and the outlet grain moisture content for the second stage of a concurrent flow dryer. The grainflow rate and inlet grain moisture content are held constant. The relationship is linear over the range simulated. Figure 5.7 shows that the airflow versus outlet moisture content relationship is also linear for a crossflow dryer. Figures 5.6 and 5.7 show that outlet moisture content can be regulated by controlling the airflow rate. However, over the normal ranges of control, variations in grainflow rate have more effect on the grain outlet conditions than

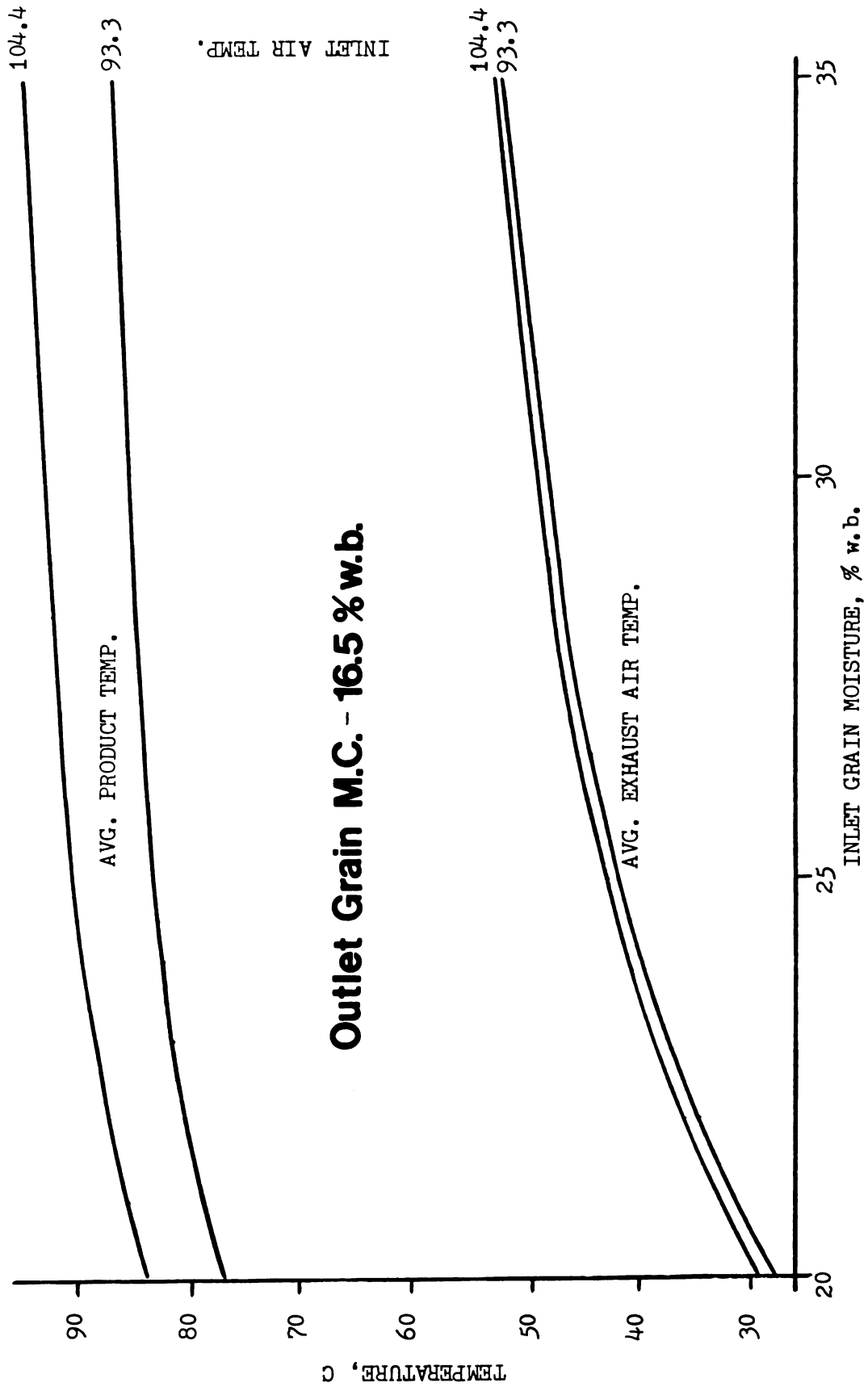


Figure 5.5 Average product and exhaust air temperatures when maintaining a constant outlet grain moisture content in a single-stage crossflow dryer (MSU computer simulation).

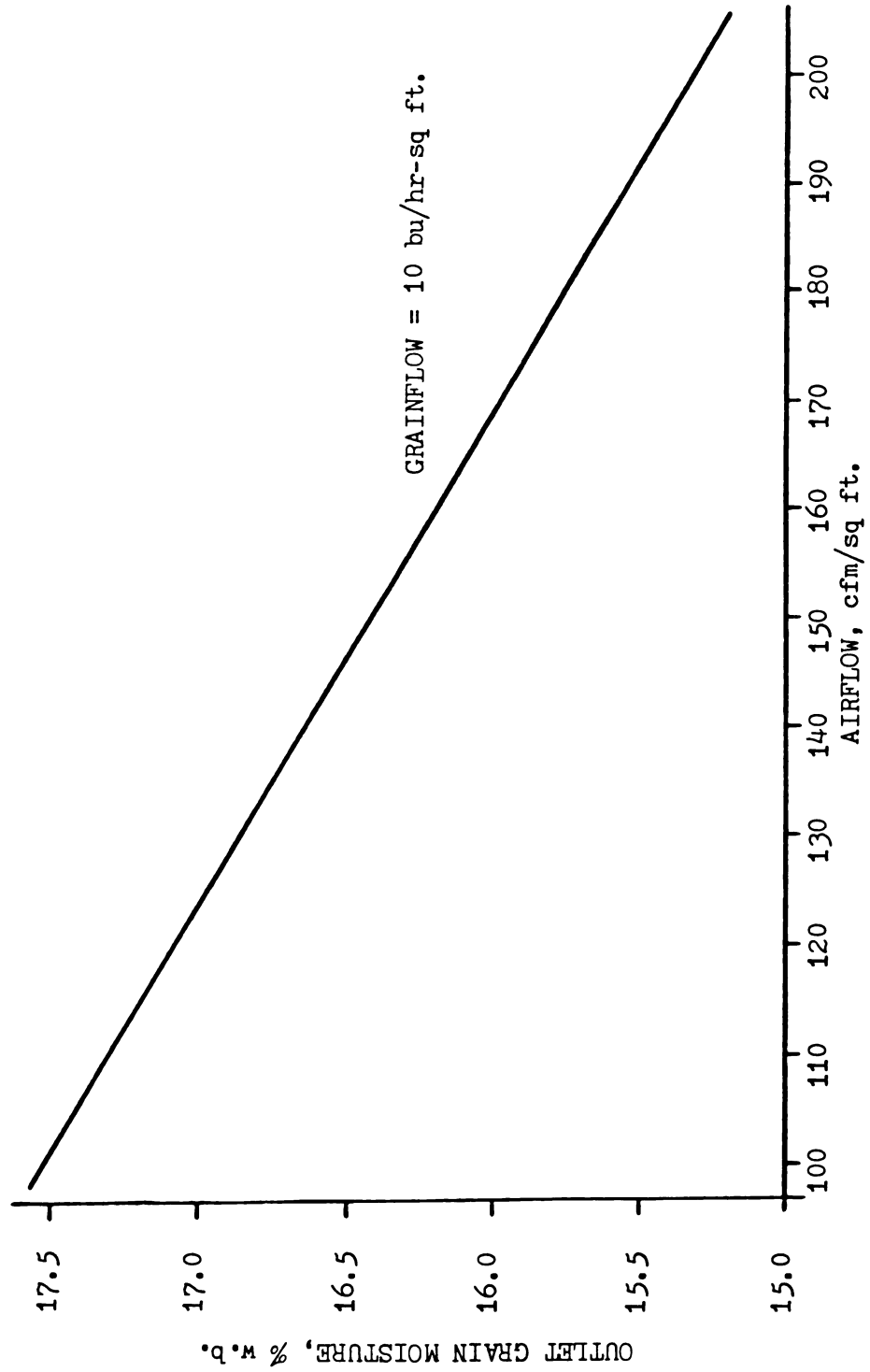


Figure 5.6 Effect of air flow rate on outlet grain moisture content for a single-stage concurrent flow dryer (MSU computer simulation).

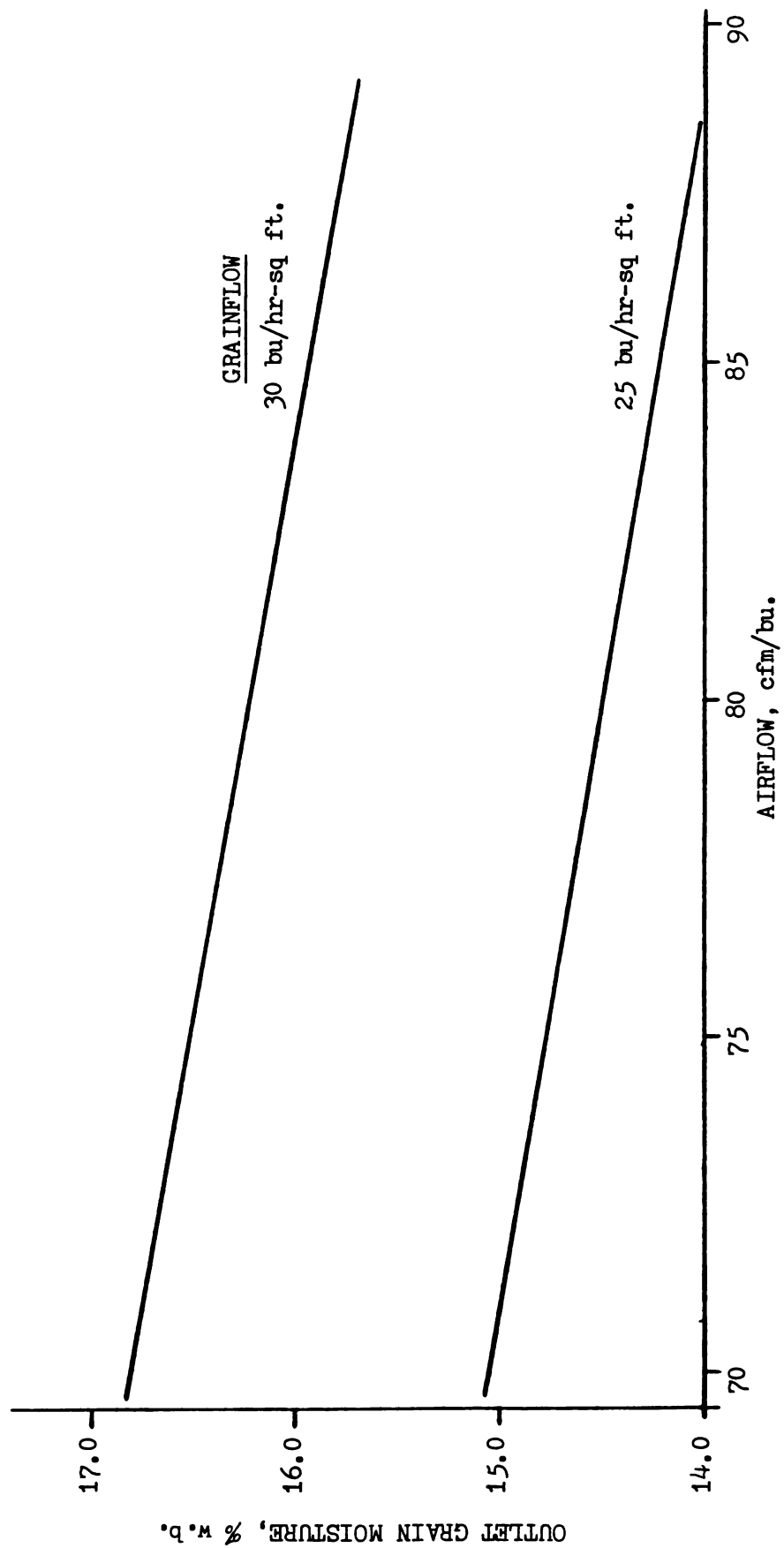


Figure 5.7 Effect of airflow rate on outlet grain moisture content for a single-stage crossflow dryer (MSU computer simulation).

do variations in airflow rate (given a constant inlet air temperature).

5.6 Multi-stage Dryer Control

As previously mentioned, the grainflow rate is the same throughout a multistage dryer. The control of grain moisture using grainflow regulation is only practical for a single stage of a multistage dryer. As the grain travels through the dryer it will be effected by changes in grainflow rate initiated to maintain the product moisture requirements in another stage.

This author proposes that grainflow regulation be used to maintain an outlet temperature setpoint in the first drying stage. Inlet air temperature and flowrate would be maintained at a constant value (maximum temperature, minimum airflow rate, for maximum efficiency) unless a grainflow limit had been reached, at which point these parameters could be adjusted accordingly (perhaps by the computer).

Because maintaining the highest possible inlet air temperature is essential for optimum dryer efficiency [Bakker-Arkema, 1981], airflow rate would be adjusted in the second stage (maintaining a constant inlet air temperature) as the grainflow rate and/or grain drying

requirements changed. Once again an outlet temperature set-point could be used. Should an airflow limit be reached (the limit could be due to fan output limitations or because of drying efficiency considerations) the inlet air temperature could be adjusted. Should a third drying stage be present the same control scheme could be implemented, perhaps using a different temperature set-point.

A microcomputer facilitates implementation of multi-stage control strategy by keeping track of a particular layer of grain as it travels through the dryer. Sen [1980] described a software-based digital dryer control system which divides a dryer into a pre-determined number of equal layers. Each layer is assigned a 1-byte block of computer memory. Software pointers identify the start and end of each drying zone. The discharge motor is equipped with a digital pickoff. When a pulse is received from the motor pickoff (to indicate that one layer of grain has passed into and out of the dryer) the memory is updated to reflect the current condition of the dryer. The pulse from the motor pickoff "keys" the start of a control algorithm which calculates the grainflow rate required to obtain a set-point outlet grain moisture content. The control algorithm constants are adjusted by the computer, based on the time-history of the dryer, such that at the end of several passes the computer is able to predict the

characteristics of each drying zone.

The strategy presented by Sen requires the direct monitoring of the grain moisture content and a predictive model for the dryer. However, in the absence of these capabilities, a similar approach based on the temperature of the product as it travels through the dryer may be possible. A series of thermocouples spread along the entire length of the dryer can be used to update the condition of the computer memory. The airflow rate and/or temperature of the second and third stages can be adjusted based on the average condition of grain within each stage. During the developmental stage of such an algorithm the microcomputer can be used for data-logging purposes to obtain information useful for design of future control systems.

CHAPTER 6

EXPERIMENTAL INVESTIGATION

A microprocessor based controller was utilized to control the outlet corn temperature of a one-stage concurrent flow grain dryer in the Processing Laboratory of the Agricultural Engineering Department at Michigan State University.

6.1 The Control System

The concurrent flow grain dryer control system is presented in this section.

6.1.1 The Drying Plant

The MSU pilot scale dryer (see Figure 6.1) consists of a single stage concurrent flow drying section and counterflow cooling section. Only the drying section was

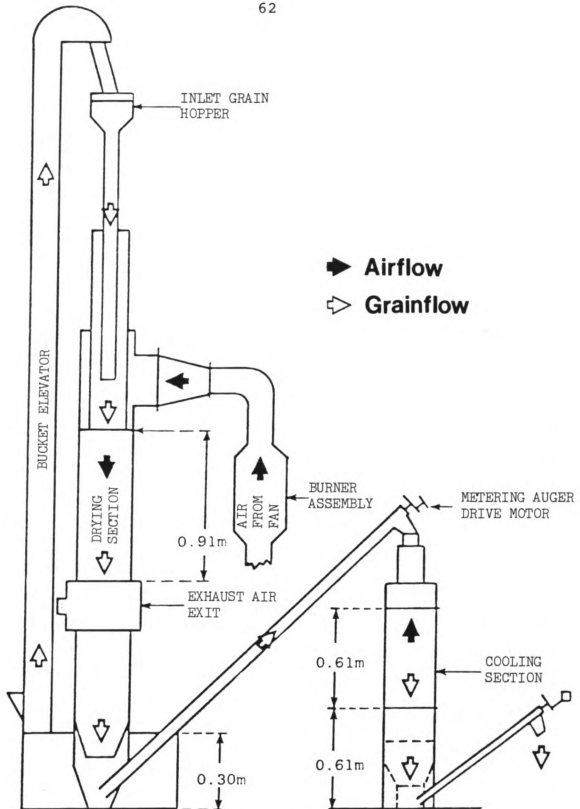


Figure 6.1 Schematic of the MSU pilot-scale concurrent flow grain dryer (Dalpasquale, 1981).

used during this investigation. The cross-sectional area of the dryer is 1.0 sq ft (0.09 sq m); the drying section has a length of 3.0 ft (0.91 m). 5.9 bushels (0.21 cu m) of grain are required to fill the dryer [Kalchik, 1977].

A bucket elevator is used to transport grain to the top of the dryer and load the material into a wet grain holding hopper. The elevator is powered by a 1/3 horsepower capacitor start motor. Grain flows through the dryer by gravity. A 4 inch (10.16 cm) diameter metering auger unloads the grain at the bottom of the drying column. The auger is powered by a 1/2 horsepower shunt wound D.C. electric motor. A gear reduction shaft and interchangeable pulleys are used to arrive at a proper range of discharge rates for the type of grain being dried.

Heating air is directed to the dryer via a tee section and elbow which connect to a propane burner. The burner temperature is adjusted manually by regulating the fuel flow using a series of throttling valves. The burner is equipped with an automatic shut-off valve to guard against burner malfunction. Inlet air is supplied by a 22 inch (56 cm) diameter forward inclined fan powered by a 3/4 horsepower motor, via a 4 inch (10.16 cm) diameter wire-reinforced air hose.

6.1.2 Microcomputer Controller

A Dynabyte, Inc. (Menlo Park, CA) model BC2, Basic Controller was used to implement the grain dryer control strategy. The Basic Controller is a self-contained, Z80-based microcomputer. All system components except the power supply and analog-to-digital conversion circuitry reside on a single 12.4 x 14.8 in (315 x 376 mm) printed circuit board. For developmental purposes, a CRT display and alpha-numeric keyboard for programming were added. A cassette tape deck was used to record process data and programs for future reference. A keyboard input port, a 16 line by 64 character composite video output port and a 300 baud cassette I/O port are provided to interface the peripherals. Specifications for the Basic Controller are presented in Appendix A.

A high-level programming language called Z80 Industrial Basic Language, or ZIBL, resides in 8K of on-board ROM. Many traditional features of BASIC are incorporated in ZIBL. Looping operations can be programmed using both DO-UNTIL and FOR-NEXT formats. The IF-THEN conditional command can be used to set up conditional branching and looping operations. Subroutining is supported by GOSUB and RETURN commands. Standard arithmetic operations, using 24-bit triple-precision integers, as well as value comparison functions are

provided and 26 global and 26 local arithmetic variables can be defined. Constants can be programmed in decimal or hexadecimal form. The logical operators AND, OR, and XOR can also be employed. A summary chart of ZIBL is provided in Appendix B. Application programs may reside in the 16K of on-board RAM or in the 4K of user programmable EPROM (there is an on-board EPROM programmer) [Manufacturing Engineering, 1980].

During initial testing of the control system the Basic Controller was placed directly next to the grain dryer. When the grain dryer is operating, temperatures in the Processing Laboratory may exceed 38 C (100 F). These high temperatures combined with RF interference from the spark ignition system of the propane burner caused the Basic Controller to malfunction. To alleviate these problems the Basic Controller was moved to an air conditioned room located 50 feet from the dryer. Shielded signal transmission lines were used to minimize problems due to electrical noise present in the Processing Laboratory. Power for the Basic Controller was taken from an isolated power line to protect it from noise present on the power lines supplying the grain dryer.

Texts by Morrison [1977], Ott [1976], and Sheingold [1981] are excellent references dealing with noise reduction techniques.

6.1.3 Temperature Measurement

Grain temperature at the outlet of the drying section was the process variable of interest for this investigation. A standard Type-T thermocouple with an aluminum sheath was mounted in the grain column at the outlet of the drying section (see section 5.2 for a discussion of grain temperature measurement). Copper-constantan extension wire was used to connect the thermocouple lead wires to the input terminal block of an Analog Devices (Norwood, MA.) AC-1215 mounting card for the Analog Devices 2B54-B four channel isolated thermocouple conditioner and 2B56 high accuracy cold junction compensator (see Appendix A for specifications).

The 2B54 provides input protection, isolation and common mode rejection, multiplexing, filtering, and amplification of the thermocouple signals. The 2B54 has a ± 5 v @ 5 ma output voltage swing which is transmitted to the input of the 2B56. The 2B56 operates with an external temperature sensor in thermal contact with the cold junction (a 2N2222 transistor is used as the cold junction sensor on the AC-1215). The 2B56 is calibrated to compensate the cold junction to a reference temperature of 0 C. The 2B56 may be digitally programmed to select compensation for seven types of thermocouples (including Type-T).

The AC-1215 uses a 74LS139 decoder for decoding digital signals from the computer. This allows the computer to read a particular channel of the 2B54 and assign the appropriate cold junction compensation. Power for the AC1215 (± 15 v) is supplied by an external power supply.

The inlet air temperature is not used in the control algorithm. However, it is monitored and displayed by the microcomputer to assist the operator in maintaining inlet air conditions. The inlet air temperature is measured with a Type-J (iron-constantan) thermocouple. All thermocouples were individually calibrated against a mercury bulb thermometer.

Up to 4 thermocouples can be monitored using the 2B54 multiplexing circuitry. Additional thermocouples can be used by installing a computer controlled multiplexing circuit ahead of the input to the AC-1215. Care is needed to insure that the multiplexing signal does not introduce any extraneous thermocouples into the measurement system.

Figure 6.2 shows the flowchart for program TEMPOUT which implements the temperature monitoring routine for the Basic Controller. Output flags are used to set the control bits on the AC-1215 for the appropriate thermocouple. The amplified and compensated thermocouple voltage is converted to the corresponding temperature using a linear approximation. Note that the integer value of the outlet

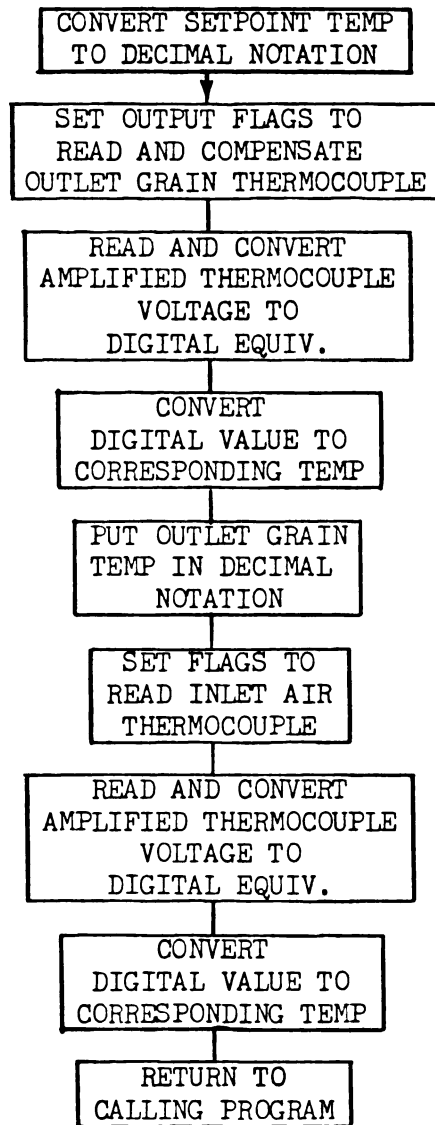


Figure 6.2 Flowchart TEMPOUT - Program to read and convert thermocouple voltage signals.

grain temperature is converted to decimal form for display and recording purposes.

6.1.4 Grainflow Rate

The grainflow rate through the dryer was correlated with the auger drive motor RPM. Test data showed a linear relationship described by:

$$\begin{aligned} \text{GRAINFLOW (tonne/hr/sq m)} \\ = 0.004699 * \text{RPM} + 0.032878 \end{aligned} \quad (6.1)$$

The 0.914 m by 0.093 sq m drying section has a volume 0.0849 cu m (3 cu ft) or 2.4 bu. The time for a kernel of grain to traverse the drying section (transportation time) can thus be related to the auger drive motor RPM by:

$$t \text{ (min)} = 2.4 * 60 * 0.2734 / \text{GRAINFLOW} \quad (6.2)$$

6.1.4.1 Motor Speed Control

An SCR-DC motor speed controller was constructed to control the auger drive motor [Jakeway, 1981]. Because of instability in the motor control circuitry a software feedback loop is implemented using the Basic Controller. A

DC generator coupled to the motor shaft was used to measure the speed of the motor (1 volt output/100 RPM). The generator's voltage signal is scaled down using a resistive voltage divider and fed through a 2nd-order Butterworth low-pass filter. The conditioned signal is converted to a digital value in the RTI-1220 A/D converter.

Figure 6.3 shows the flow chart for program RPMSET which implements a PI control algorithm (see Section 6.2 for a discussion of PI algorithms) to maintain a set-point motor speed. The set-point can be designated manually by the dryer operator or, when the controller is in automatic, by the dryer control software. The ZIBL code which implements the flowchart is shown in Appendix B.

There are several features of program RPMSET which show the versatility of a microprocessor-based controller. During tuning of the control algorithm it was found that even with a constant input voltage to the motor speed controller, the speed of the motor, as monitored by the DC generator, tends to fluctuate about a single RPM reading. The frequency and amplitude of the fluctuations vary with the speed of the motor. The low-pass filter (cutoff frequency of 1 Hz.) does not eliminate the wave pattern. It was found that by taking the average of ten successive RPM readings a fairly accurate speed measurement can be obtained. This type of signal correction is not possible with a continuous analog controller. It was also

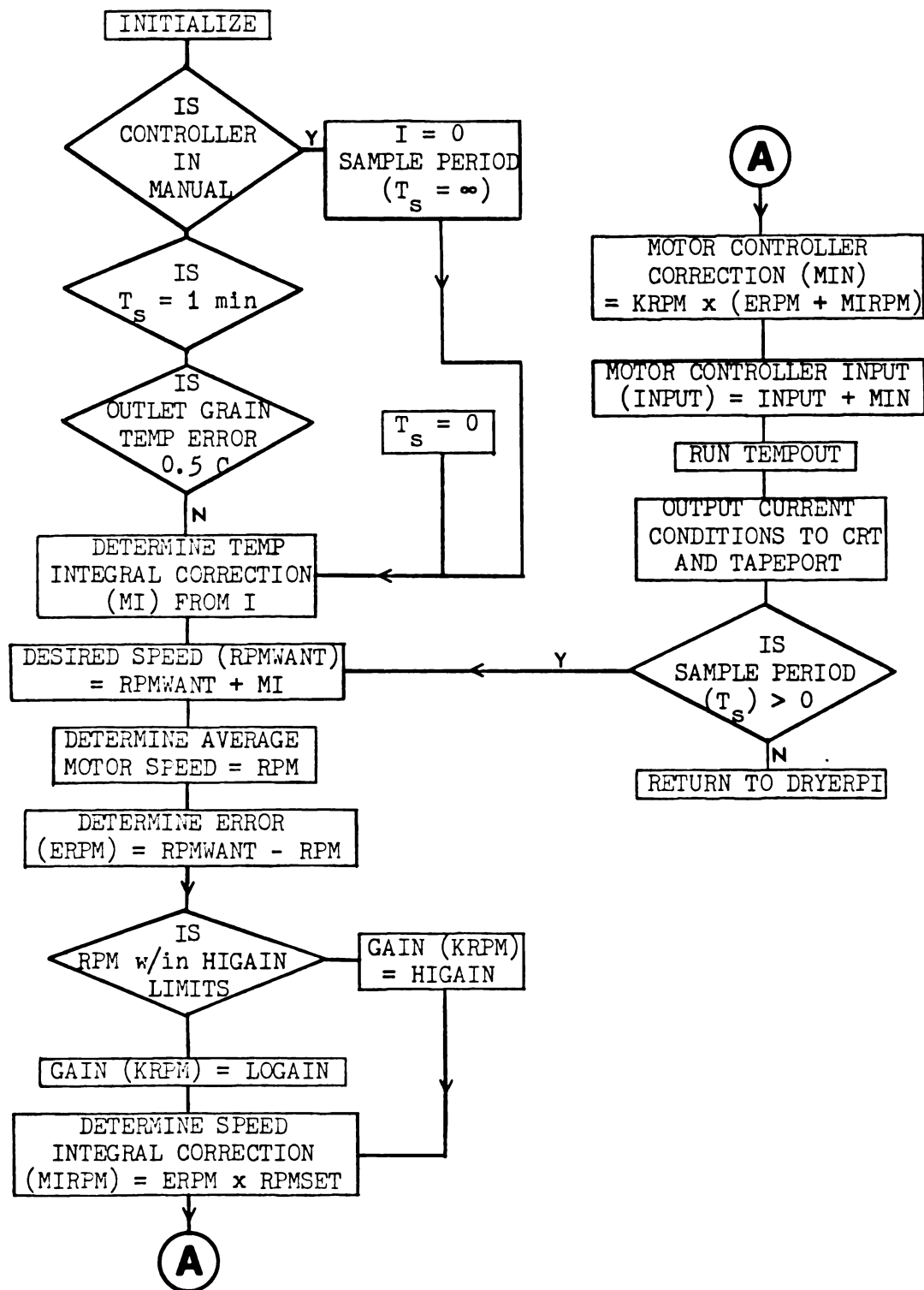


Figure 6.3 Flowchart RPMSET - Program which controls the discharge auger motor speed.

determined that within a certain error limit, a higher gain enables the controller to better maintain the motor speed at the RPM set-point. When changes in the set-point or load occur (putting the error outside the limits) a lower gain (resulting in a $1/4$ - decay ratio response [1]) is used in the control algorithm. This decision making capability is not possible with a conventional controller.

The digital signal output from the Basic Controller was converted to an analog voltage using an optically isolated D/A converter. The optocal isolation was needed to protect the microcomputer from current surges which occur in the motor controller circuitry during startup and during abrupt changes in motor speed.

Figure 6.4 gives the block diagram for the concurrent flow dryer outlet grain temperature control system.

6.2 Dryer Control Algorithm

The computer simulation results presented previously gave no information concerning the transient response of the dryer to changes in input conditions.

[1] A $1/4$ - decay ratio response is when the ratio of the second overshoot to the first is $1/4$.

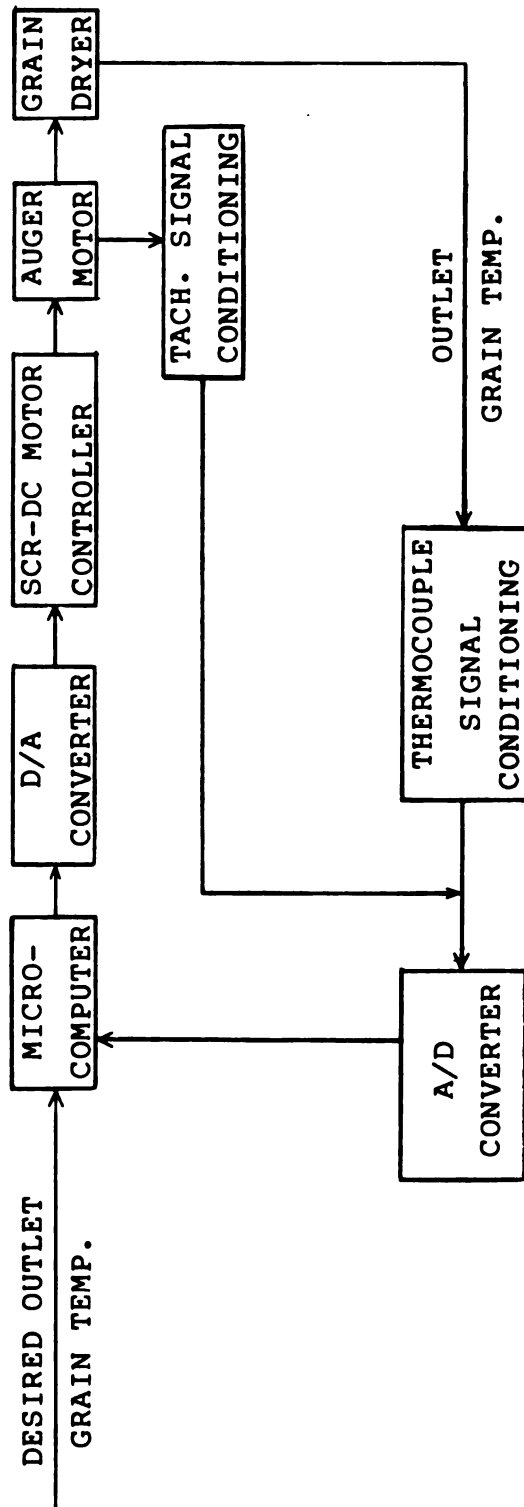


Figure 6.4 Single-stage concurrent flow grain dryer control, Block Diagram.

Transient response characteristics must be understood before developing a plant transfer function [Melsa and Schultz, 1969]. Most process control loops for which the plant transfer function has not been completely characterized, are controlled by the Proportional-Integral-Derivative (PID) algorithm or one of its variations. Ninety per cent of all controllers are said to be of the two-mode PI type [Bibbero, 1977]. A PI algorithm, implemented in microcomputer software, was used to control the MSU concurrent flow grain dryer.

The equation for the proportional mode can be written as:

$$M = K \cdot E_n + C \quad (6.3)$$

where: M = output signal fed to a control device

K = a proportionality constant
(usually termed the "gain")

E_n = $PV - SP$ = error at time n

C = an output constant at $E=0$.
(termed the "manual reset")

Note that the proportional control mode leads to a steady state error whenever the load changes. The value of C must be reset to eliminate the offset.

The integral function acts as an automatic reset and is defined by the equation:

$$M = K_i * \int E \, dt \quad (6.4)$$

where: K_i = integral gain

dt = derivative of time, t .

The integral function can be combined with the proportional function to form a two-mode, PI control algorithm defined by:

$$M = K * E + K_i * \int E \, dt \quad (6.5)$$

The PI controller differs from a proportional-only controller in that the constant C in the proportional equation is replaced by the integral term.

The third term in a PID algorithm is derivative, or rate expressed as,

$$M = K_d \, dE/dt \quad (6.6)$$

where: K_d = rate constant.

The derivative term changes in accordance with the rate of change of the error signal. Combining the derivative mode with the PI algorithm forms the PID algorithm,

$$M = K*E_n + K_i * \int E \, dt + K_d \, dE/dt \quad (6.7)$$

The rate term affects the controller only during a change in the magnitude of the error. A steady state value of E is corrected only by the PI algorithm [Bibbero, 1977].

As mentioned previously, continuous flow grain dryers have considerable inherent deadtime following changes in inlet conditions. The derivative mode is ineffective for processes with large deadtimes [Smith, 1979] and thus only a PI algorithm could be used in this investigation.

Equation (6.5) presents the PI algorithm in continuous analog form. In order to implement the equation with a microcomputer, it must be transformed into its digital equivalent. The digital equivalent of the PI algorithm as presented by Bibbero [1977] is:

$$M = K*E_n + K_i * \sum_{j=0}^n (E_j * T_s) + M' \quad (6.8)$$

where: T_s = sampling period

M' = current controller output.

The integral gain K_i can be written in terms of the overall gain K as:

$$K_i = K/T_i \quad (6.9)$$

where: T_i = reset time.

When Equation (6.9) is substituted into Equation (6.8)

$$M = K*(E_n + 1/T_i * \sum_{j=0}^n (E_j * T_s)) + M' \quad (6.10)$$

which is the form of the equation used in this study.

6.2.1 System Analysis

The final step when implementing a control loop is the determination of the tuning parameters. Smith [1979] and Coon [1956] presented the Ziegler-Nichols open-loop[1] controller tuning method. The method utilizes a first-order approximation of the process. With the controller in manual mode the process is allowed to stabilize. Then a step change in the controller output (Δm) is made and the system response is recorded. From the response the reaction rate (R_r) and reaction lag (L_r) can be estimated (see Figure 6.5). The reaction rate (R_r)

[1] Open loop methods check the process with the controller in manual.

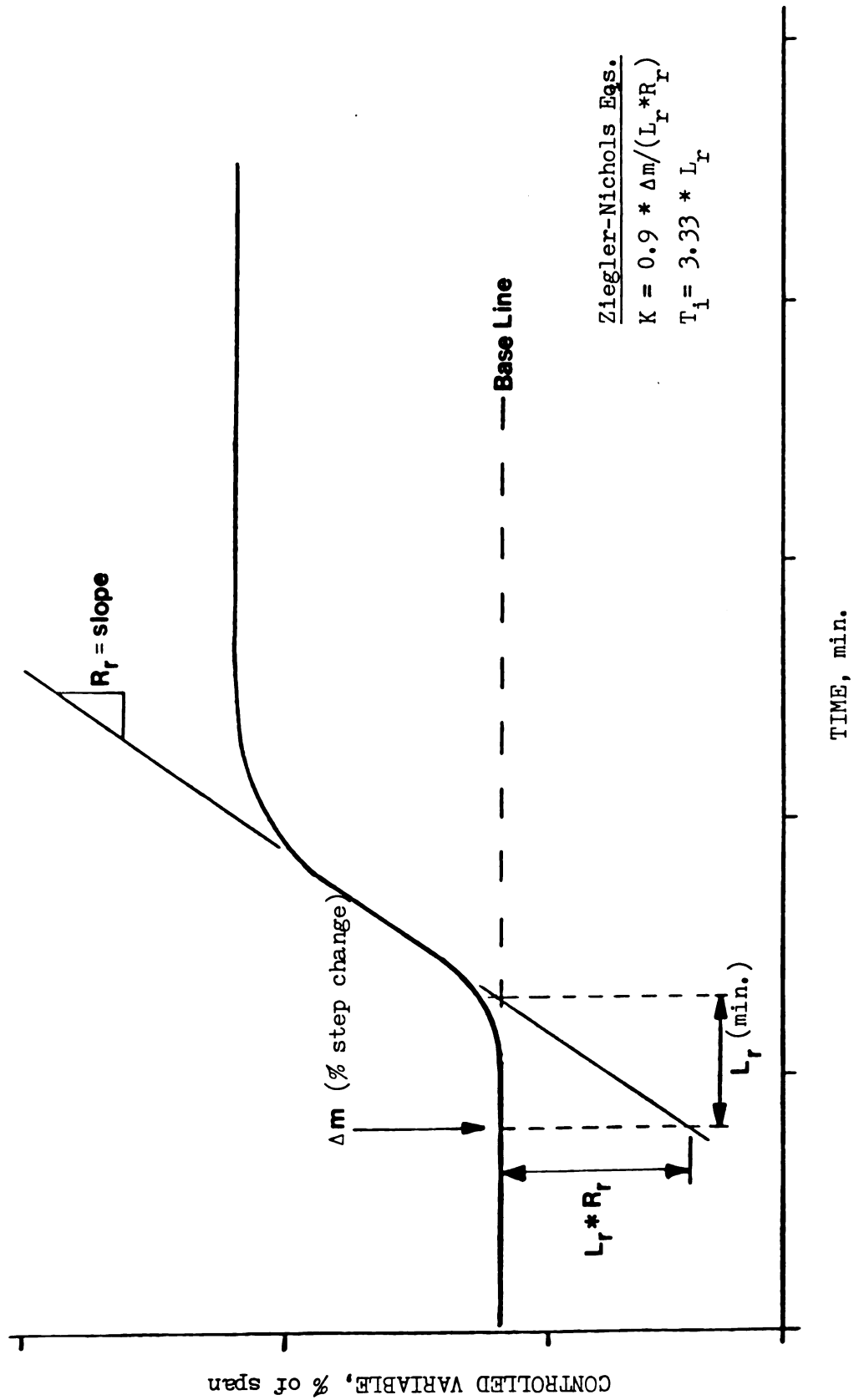


Figure 6.5 Determination of Ziegler-Nichols PI controller constants (Smith, 1979).

is the slope of a line drawn tangent to the response curve at its steepest point. These parameters are used in the equations:

$$K = 0.9 * \Delta m / (L_r * R_r) \quad (6.11)$$

$$T_i = 3.33 * L_r \quad (6.12)$$

to approximate the PI controller constants which will give a 1/4 - decay ratio response.

Using the Basic Controller, the Ziegler-Nichols open loop test was conducted on the pilot-scale dryer. The controller was programmed to allow manual setting of the discharge motor speed. After a steady-state outlet grain temperature was achieved the discharge motor speed was changed. The outlet grain temperature was measured every 15 seconds and recorded along with the time and motor speed on a cassette tape. Several tests were conducted to obtain a better representation of the response characteristics. The results of these trials are summarized in Figures 6.6 - 6.10. The input conditions, the response analysis parameters (Δm , R_r and L_r) and the corresponding Ziegler-Nichols PI controller constants for each test are given in Tables 6.1 - 6.4.

The step change of the controller output is specified as a percent of the operating speed range of the discharge motor (%RPM). The operating speed range of the

discharge motor was limited to 100-1300 RPM (0.5-6.1 tonne/hr/sq m). These limits were based on the required grainflow range as determined from the computer simulation results shown in Figures 5.2 and 5.3. The reaction rate (R_r) is given as a percent of the outlet grain temperature span per minute ($\%T_o/\text{min}$). The outlet temperature span was estimated to be 50 C based on the test data.

Figure 6.6 shows the outlet temperature response to a step change in grainflow rate of 4.0 to 2.4 tonne/hr/sq m (14.7 to 8.7 bu/hr/sq ft). Table 6.1 gives the input conditions for the test and the controller settings obtained using the Ziegler-Nichols method. Note that the response can be approximated by a first-order lag plus deadtime model.

Figure 6.7 shows the outlet temperature response to a step change in grainflow rate of 2.4 to 1.3 tonne/hr/sq m (8.7 to 4.9 bu/hr/sq ft). Table 6.2 gives the input conditions for the test and the Ziegler-Nichols controller constants obtained from the response curve. The shape of this curve is similar to the one in Figure 6.6. The fluctuations in the outlet temperature during the deadtime period appear to be due to variations in the inlet grain moisture content (estimated at ± 1.5 % wb).

Figure 6.8 shows the outlet temperature response to a step change in grainflow rate of 2.4 to 4.0 tonne/hr/sq m (8.7 to 14.7 bu/hr/sq ft). Table 6.3 gives the input

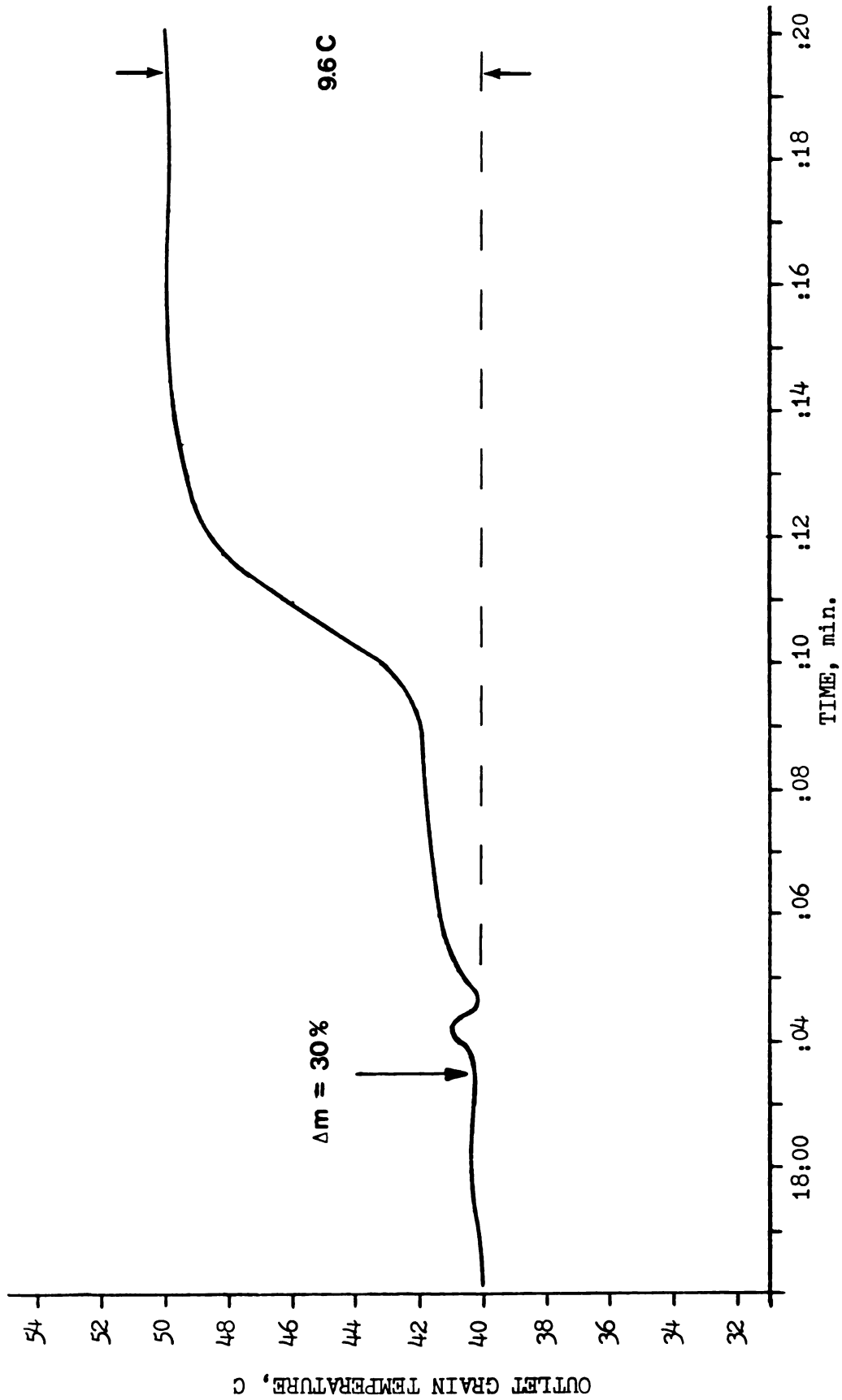


Figure 6.6 Outlet grain temperature response to a step change in grainflow rate from 4.0 to 2.4 (tonne/hr-sq m.) for a single-stage concurrent flow corn dryer.

Table 6.1: Input conditions and calculated controller settings for grainflow step change test from 4.0 to 2.4 (tonne/hr/sq m).

Grainflow Rate, tonne/hr/sq m	4.0 to 2.4
Inlet Air Temp., C	230
Inlet Airflow Rate, cu m/min-sq m @ Tamb	45
Ambient Temp., C	28.0
Inlet Grain Temp., C	10.0
Inlet Grain Moisture, %wb	18.5
Outlet Grain Moisture, % wb	16.0

Step Change (Δm), %RPM	30
Reaction Lag (Lr), min	11.5
Reaction Rate (Rr), %To/min	3.2
Transportation Time (t), min	19.5

<u>Ziegler Nichols Constants</u>	
Gain (K), %/%	0.72
Reset Time (Ti) min	38.3

conditions for the test and the corresponding controller settings.

Note that the shape of the curve in Figure 6.8 is much different from the corresponding negative step change of Figure 6.6. The initial increase in outlet temperature can be attributed to the temperature distribution within the concurrent flow drying stage (see Figure 3.2). When the grain flow rate is increased, the outlet temperature probe senses the passing of the warmer (and wetter) grain

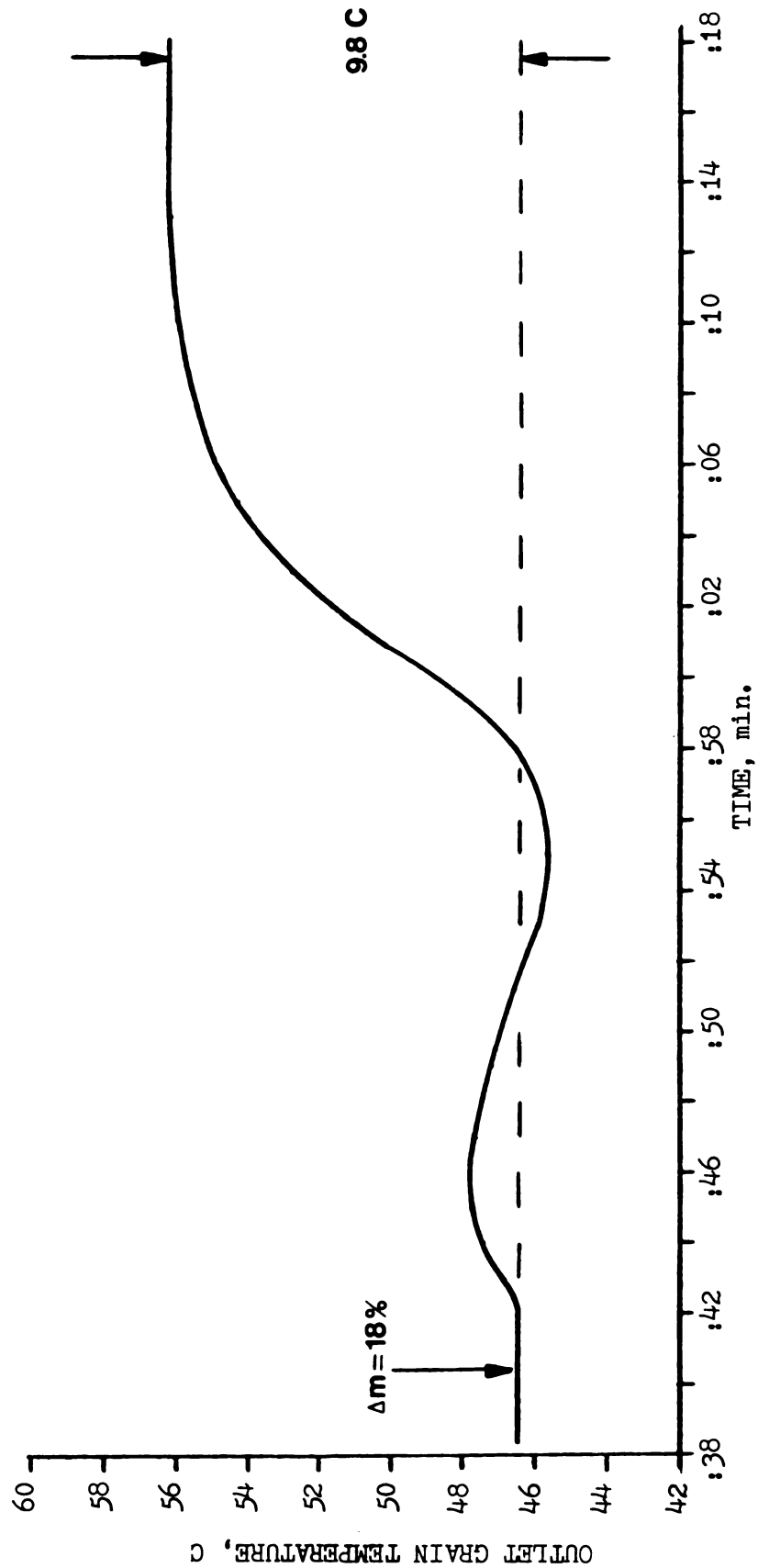


Figure 6.7 Outlet grain temperature response to a step change in grainflow rate from 2.4 to 1.3 (tonne/hr-sq m.) for a single-stage concurrent flow corn dryer.

Table 6.2: Input conditions and calculated controller settings for grainflow step change test from 2.4 to 1.3 (tonne/hr/sq m).

Grainflow Rate tonne/hr/sq m	2.4 to 1.3
Inlet Air Temp., C	23.0
Inlet Airflow Rate, cu m/min-sq m @ Tamb	45
Ambient Temp., C	28
Inlet Grain Temp, C	8
Outlet Grain Moisture, %wb	14.5

Step Change (Δm), %RPM	18
Reaction Lag (L_r), min	17.7
Reaction Rate (R_r), %To/min	2.6
Transportation Time (t), min	29.2

<u>Ziegler Nichols Constants</u>	
Gain (K), %/%	0.35
Reset Time (T_i), min	58.9

which has been accelerated through the drying process.

Figure 6.9 shows the outlet temperature response to a grainflow rate step change of 1.4 to 2.4 tonne/hr/sq m (5.3 to 8.7 bu/hr/sq ft). The shape of the curve is similar to that of Figure 6.8. Once again an increase of the outlet temperature occurs before the desired decrease is realized. Table 6.4 summarizes the test and the controller constants.

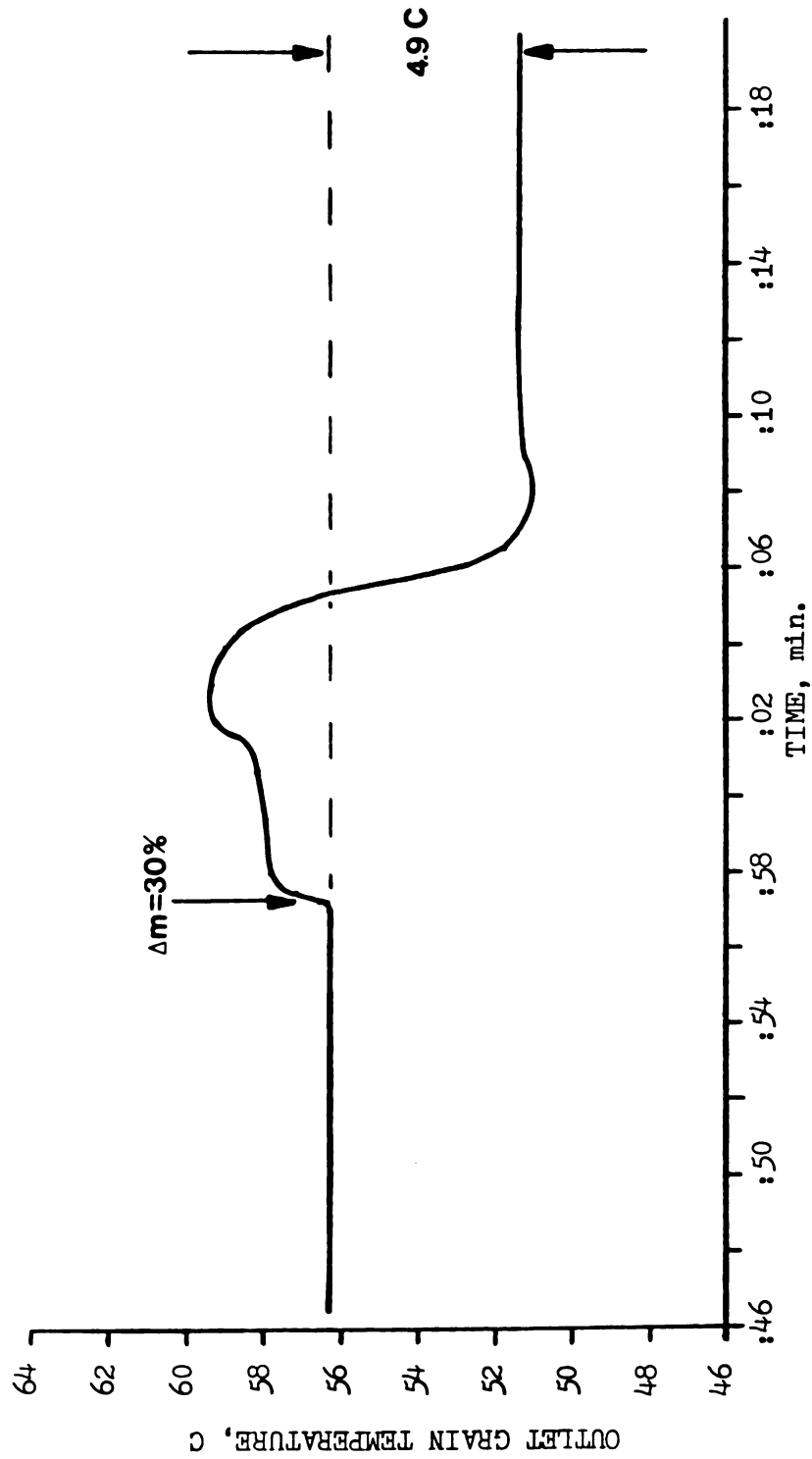


Figure 6.8 Outlet grain temperature response to a step change in grainflow rate from 2.4 to 4.0 (tonne/hr-sq m.) for a single-stage concurrent flow corn dryer.

Table 6.3: Input conditions and calculated controller settings for grainflow step change test from 2.4 to 4.0 (tonne/hr/sq m).

Grainflow Rate, tonne/hr/sq m	2.4 to 4.0
Inlet Air Temp., C	260
Inlet Airflow Rate, cu m/min-sq m @ Tamb	45
Ambient Temp., C	30.0
Inlet Grain Temp., C	30.0
Inlet Grain Moisture, % wb	17.0
Outlet Grain Moisture, % wb	15.4

Step Change (Δm), %RPM	30
Reaction Lag (L_r), min	7.8
Reaction Rate (R_r), %To/min	9.6
Transportation Time (t), min	9.8

Ziegler Nichols Constants

Gain (K), %/%	0.39
Reset Time (T_i), min	26.0

6.2.2 Controller Implementation and Testing

Because of its inherent inflexibility a traditional analog PI controller has difficulty controlling the process represented in Figures 6.6 - 6.9 [Bibbero, 1977]. Perhaps the most powerful feature of using a high-level language programmable microcomputer controller is that it allows the operator to easily experiment with variations of the

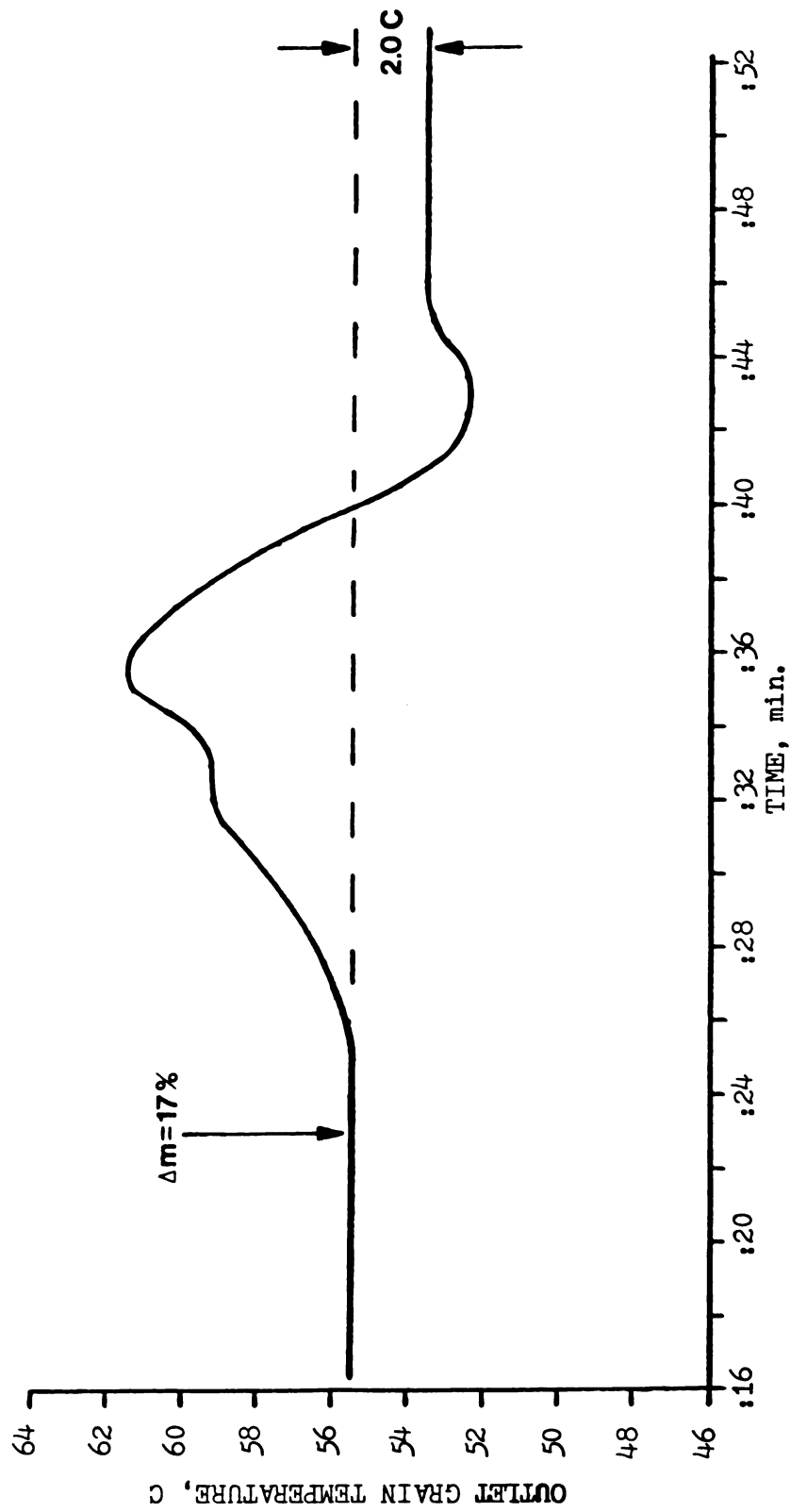


Figure 6.9 Outlet grain temperature response to a step change in grainflow rate from 1.4 to 2.4 (tonne/hr-sq m.) for a single-stage concurrent flow corn dryer.

Table 6.4: Input conditions and calculated controller
 settings for grainflow step change test from
 1.4 to 2.4 (tonne/hr/sq m).

Grainflow Rate, tonne/hr/sq m	1.4 to 2.4
Inlet Air Temp., C	26.0
Inlet Airflow Rate, cu m/min-sq m @ Tamb	45
Ambient Temp., C	34
Inlet Grain Temp., C	7.0
Inlet Grain Moisture, % wb	20.3
Outlet Grain Moisture, % wb	16.0

88

Step Change (Δm), %RPM	17
Reaction Lag (Lr), min	15.0
Reaction Rate (Rr), %To/min	6.0
Transportation Time (t), min	16.5

Ziegler Nichols Constants

Gain (K), %/%	0.19
Reset Time (Ti), min	50.0

control algorithm. Utilizing the computer's decision making capabilities, an operator can tailor a general purpose control algorithm to better suit a particular control system.

Several modifications to the standard PI algorithm were incorporated to effect better control of the concurrent flow dryer. These modifications were based on the following observations made during analysis of the system response:

1. The reaction lag or deadtime (L_r) was found to be approximately 60% of the transportation time (t) for the negative step changes and 90% of t for the positive step changes. Thus, the deadtime can be estimated from a knowledge of the direction and the final value of the grainflow rate step change, as calculated by the proportional response;
2. The reaction rates (R_r) for the positive step changes in grainflow rate are approximately 2.7 times faster than the reaction rates for the corresponding negative step changes;
3. Bibbero [1977] recommended setting the sampling period equal to the process deadtime, if possible.

In light of the unpredictable outlet temperature fluctuations observed during the transient period following a negative step change of grainflow rate and the initial rise in outlet temperature observed following a positive step change, setting the sampling period(T_s) equal to the deadtime (L_r) is a desirable modification for the control algorithm. In effect, this modification incorporates a zero-order hold, error sensing mode into the control algorithm [Zachariah and Isaacs, 1966].

The Ziegler-Nichols Equations (6.11 and 6.12) are based on a first order model assuming that the process to be controlled has a constant reaction lag and reaction rate. Because of the variable deadtime and reaction rate of the control system in this investigation, the results of these equations cannot be implemented directly. However, knowing the direction of the step change needed to correct an outlet temperature error, the microcomputer can calculate a set of PI controller constants for a particular grainflow rate. The reaction lag can be estimated by utilizing the approximations presented previously:

$$L_r = 0.6 * t \quad (\text{min}) \quad (6.13)$$

for negative changes of grainflow rate, and

$$L_r = 0.9 * t \quad (\text{min}) \quad (6.14)$$

for positive changes of grainflow rate, where t is defined by Equation (6.2). The reaction rate and step change needed to calculate the gain (K) (Equation (6.11)) are set equal to the average value for the respective step change direction as determined from Figures 6.6 - 6.10, i.e.:

$$R_r = 2.9 \quad (\%T_o/\text{min}) \quad (6.15)$$

for a negative change in grainflow rate, and

$$R_r = 7.8 \quad (\%T_o/\text{min}) \quad (6.16)$$

for a positive change in grainflow rate, and

$$\Delta m = 23.8 \quad (\%RPM) \quad (6.17)$$

for changes in both directions.

Setting the sampling rate equal to the deadtime and utilizing Equation (6.12) to calculate the reset time (T_i), in effect sets the integral term of Equation (6.10) equal to :

$$\sum_{j=0}^n (E_j * T_s) = \sum_{j=0}^n E_j / 3.33$$

which is independent of the calculated deadtime. Therefore, the reset time of Equation (6.12) is replaced by the constant:

$$T_i' = 3.33 \text{ (min)} \quad (6.18)$$

in the dryer control algorithm. Utilizing Equations (6.10 - 6.18) the microcomputer can continually adjust the PI algorithm constants to maintain a desirable controller response over the entire range of grainflow rates. Also, due to the normal fluctuations of outlet grain temperature found even during steady-state periods, a +1.5 C proportional band can be assumed to be acceptable about the outlet temperature setpoint. Thus, the average outlet temperature error over a one minute interval must be greater than 1.5 C before a proportional correction of the grainflow rate is initiated.

The flowchart for the program DRYERPI, which executes the dryer control algorithm, is presented in Figure 6.10. The ZIBL code which implements the flowchart can be found in Appendix B. Note that the proportional correction is executed in the main program while the integral correction is implemented in program RPMSET (see Figure 6.3) which runs continuously during the sample

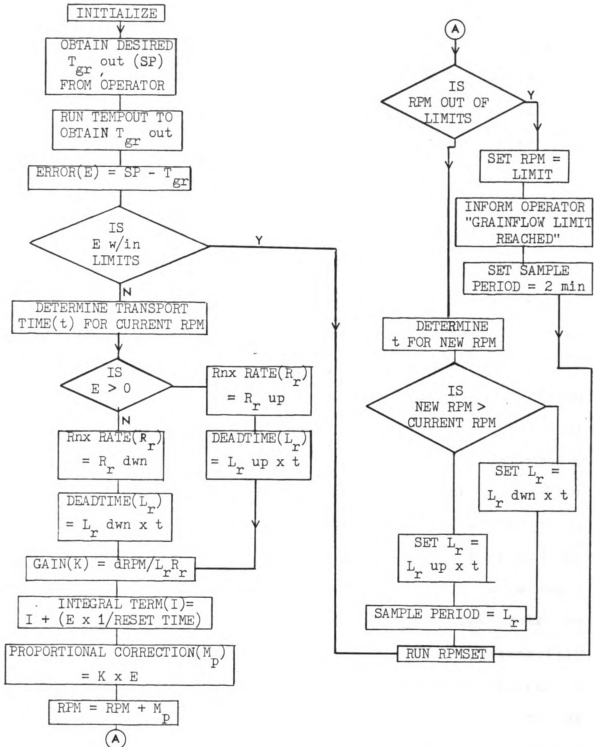


Figure 6.10 Flowchart DRYERPI - Program which controls the outlet grain temperature.

period. Note that the grainflow rate is controlled between high and a low limit. Should one of the limits be reached, the operator is informed (an alarm could be set off if desired) to allow corrective action to be taken if necessary.

Note also that the temperature error is calculated during every iteration of the RPMSET program. Should the outlet temperature come within 0.5 C of the set-point value, the sample period is interrupted and program DRYERPI is executed. This prevents the controller from continuing a grainflow correction which is in the wrong direction.

Figure 6.11 shows a representative time-frame from the experimental run designed to test the performance of the outlet grain temperature controller. Table 6.5 summarizes the dryer input conditions and the controller settings for the test run. The top portion of Figure 6.11 depicts the outlet grain temperature during the test. The bottom portion of Figure 6.11 is the actual discharge auger motor speed and the corresponding grainflow rate as controlled by the microcomputer. Note that approximately one minute after the outlet grain temperature moves out of the 1.5 C temperature error band (due to a change in the inlet grain characteristics) the controller initiates a proportional correction of the grainflow rate. The controller then calculates the sample period based on the corrected speed of the discharge motor. The integral

Table 6.5: Input conditions and controller constants for testing of the outlet grain temperature control system.

Grainflow Rate, tonne/hr/sq m	Computer Controlled
Inlet Air Temp., C	245
Inlet Airflow Rate, cu m/min-sq m @ Tamb	45
Ambient Temp., C	26
Inlet Grain Temp., C	10.0 to 40.0
Inlet Grain Moisture, % wb	10.0 to 30.0
Est. Amb. RH, %	50

Control Algorithm Constants

Reaction Rate, neg. corrections (Rr dwn), %To/min	2.9
Reaction Rate, pos. corrections (Rr up), %To/min	7.8
Reset Time Constant (Ti'), min	3.33

response is executed during the sample period by program RPMSET (see Figure 6.3). If the outlet grain temperature comes within 0.5 C of the set-point value or the sample period expires, program DRYERPI recalculates the PI algorithm constants based on the current grainflow rate.

The performance of the controller was generally satisfactory. However, the input of very wet grain (30% wb) followed by relatively dry grain (16% wb) caused an unstable controller response (the control algorithm was not able to handle the large error). Smith [1979] noted that the Ziegler-Nichols tuning technique gives only a starting point from which the desired system response

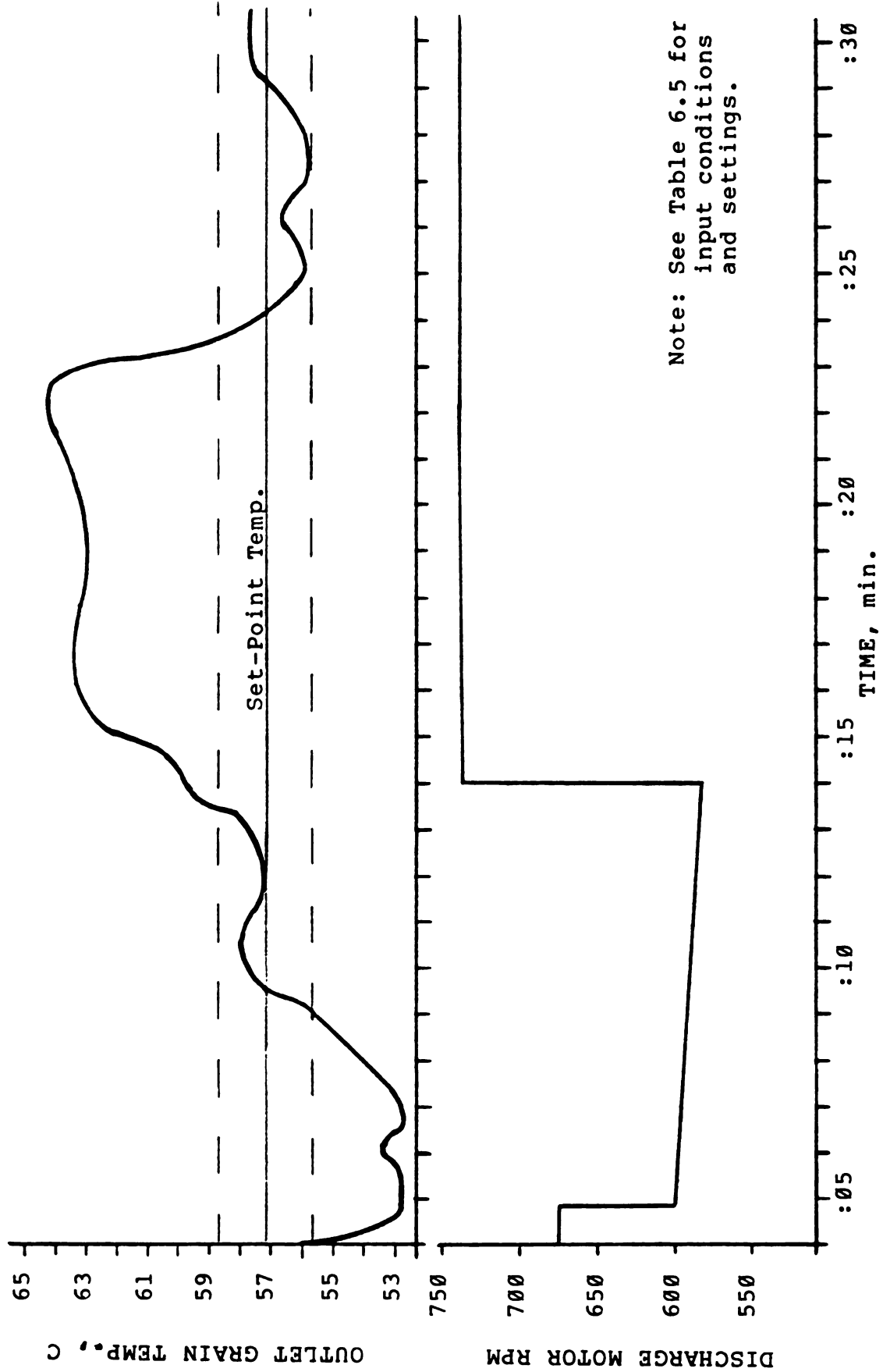


Figure 6.11 Experimental test results for the outlet grain temperature controller.

characteristics can be obtained after some final adjustments to the tuning parameters. It was determined from the initial testing period that the gain (K) as calculated by the Basic Controller was too large, especially for positive corrections of the grain flow rate. Also, the integral response was slower than desired. After a period of fine-tuning the controller constants (known as "knob-twiddling") the following controller parameters were obtained:

$$R_r = 2.9 \quad (\%T_o/\text{min}) \quad (6.19)$$

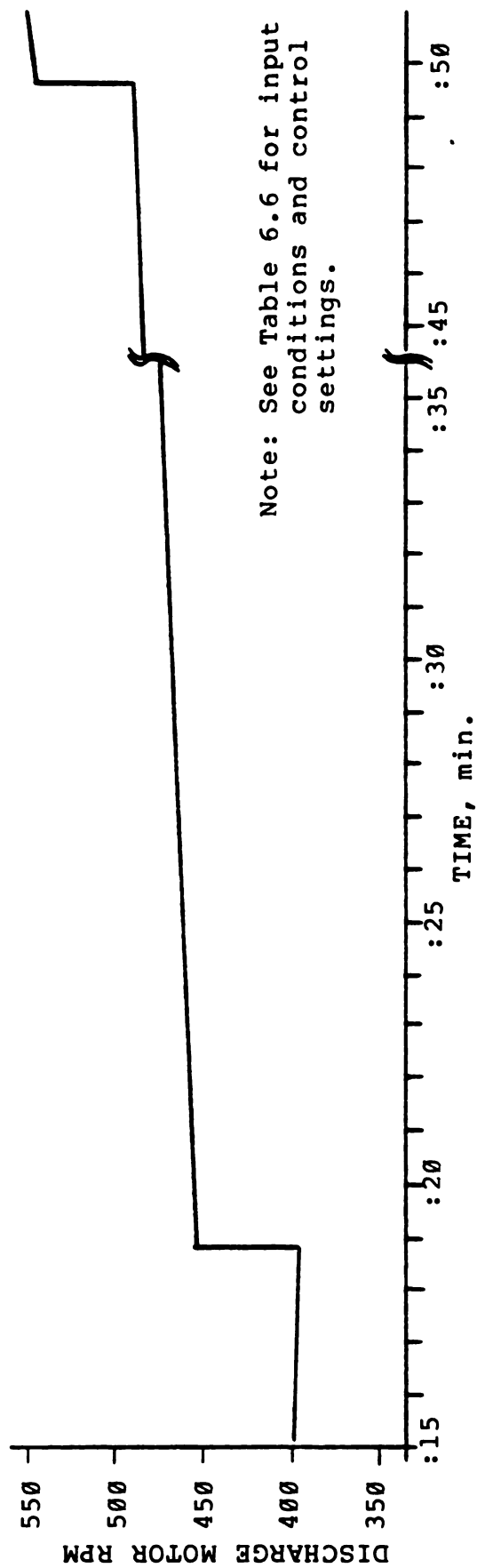
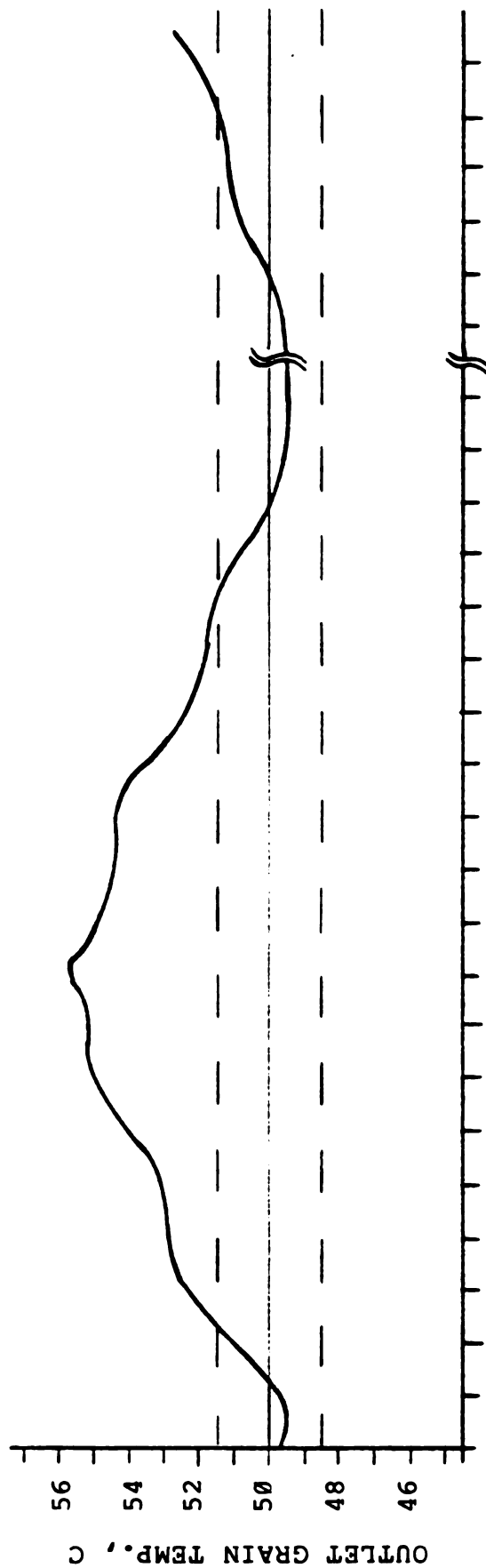
for negative changes of grainflow rate, and

$$R_r = 10.0 \quad (\%T_o/\text{min}) \quad (6.21)$$

for changes in both directions. The reset time constant was decreased to:

$$T_i' = 1.66 \quad (\text{min}) \quad (6.22)$$

The use of Equations (6.19-6.22) in the control software gave stable system performance during the test period. Figure 6.12 presents the outlet grain temperature and the corresponding discharge motor speed (grainflow rate), as calculated by the microcomputer, from a representative portion of the final controller test period.



Note: See Table 6.6 for input conditions and control settings.

Figure 6.12 Experimental test results for the final outlet grain temperature controller.

The dryer input conditions and controller settings for the test are summarized in Table 6.6. Note that the magnitude of the controller's proportional response to errors in the outlet grain temperature are less than those of Figure 6.11. During the final test period the controller maintained the average outlet grain temperature within 0.5 C of the set-point value with a standard deviation of ± 2.4 C (this corresponds to a simulated average outlet corn moisture content within 0.2 % wb of a set-point value with a standard deviation of ± 0.7 % wb).

Table 6.6: Input conditions and controller constants for testing of the final outlet grain temperature control system.

Grainflow Rate, tonne/hr/sq m	Computer Controlled
Inlet Air Temp., C	245
Inlet Airflow Rate, cu m/min-sq m @ Tamb	45
Ambient Temp., C	26
Inlet Grain Temp., C	10.0 to 40.0
Inlet Grain Moisture, % wb	20.0 to 30.0
Est. Amb. RH, %	50

Control Algorithm Constants

Reaction Rate, neg. corrections (Rr dwn), %To/min	2.9
Reaction Rate, pos. corrections (Rr up), %To/min	10.0
Reset Time Constant (Ti'), min	1.66

The final test period was limited to approximately two hours due to a shortage of corn needed to conduct the tests. Because of the limited test period, conclusive evidence of the control algorithm's ability to satisfactorily control grainflow rate under all circumstances was not obtained. However, the author feels that with the following modifications, based on the tests conducted, the control algorithm can be successfully implemented to control the outlet grain temperature/moisture content of a single-stage concurrent flow grain dryer:

1. The deadtime should be shortened to improve the time response characteristics of the control algorithm. This could be accomplished by moving the temperature sensor nearer to the dryer inlet or perhaps utilizing the average of a series of temperature sensors placed along the length of the drying stage. Investigations would be needed to determine whether temperatures other than those at the dryer outlet can be used as indicators of outlet grain moisture content.
2. A temperature sensor to detect changes in the inlet grain temperature should be used as a feed

forward control signal to reduce the effect of variable inlet temperature on the grain temperature(s) being used as the controlled process variable.

3. The controller constants presented in this study are for the particular dryer and grain utilized. In the absence of a computer simulation to predict the transient response characteristics of other dryers and grain types, a system analysis, similar to the one presented in this study, is needed to obtain the controller constants for each dryer/grain combination.

6.3 Airflow Rate

In order to gain some insight into the transient response characteristics following a change of the airflow rate, two experimental tests were conducted using the MSU pilot scale dryer. These tests were conducted to aid in development of future concurrent flow dryer control algorithms. The outlet grain temperature response to step changes of airflow rate are presented in Figures 6.13 and 6.14. The step changes were of equal magnitude but in opposite directions. Equal grainflow rates and inlet air

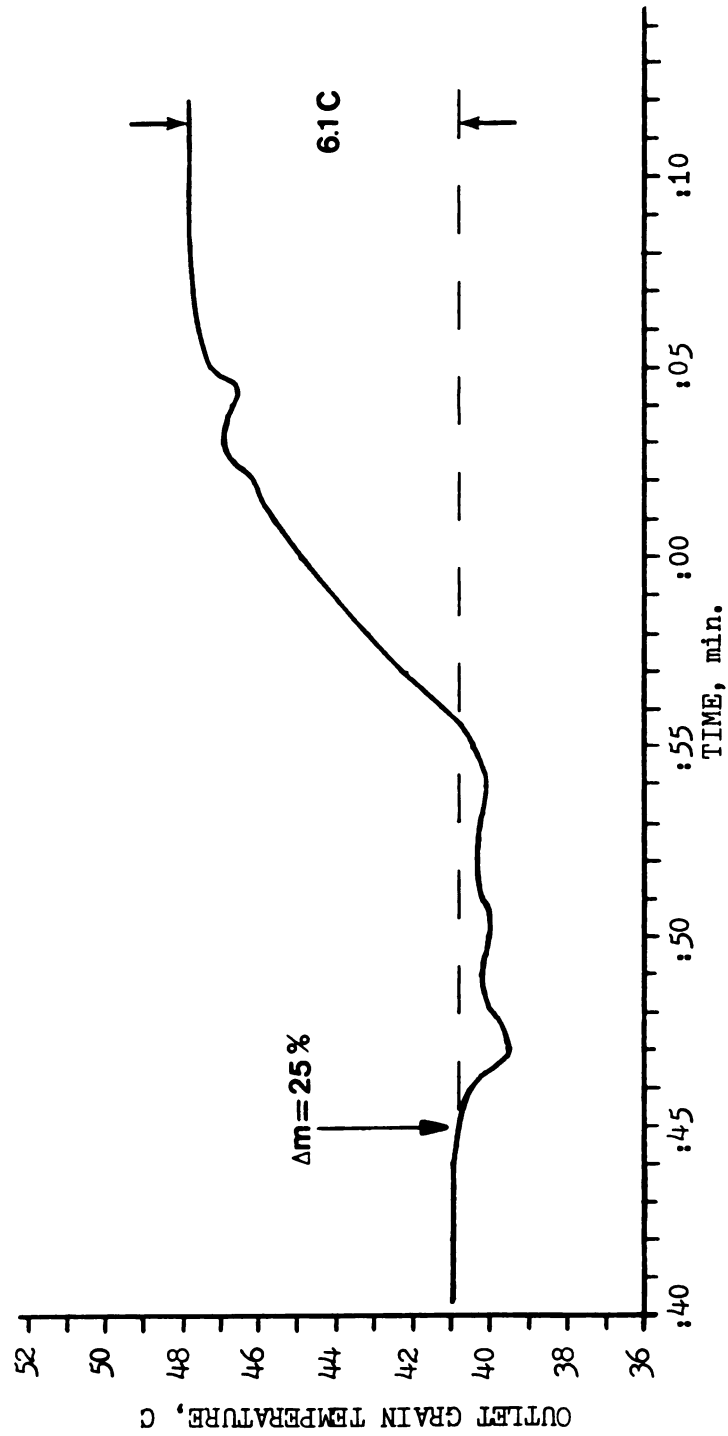


Figure 6.13 Outlet grain temperature response to a positive step change in airflow rate from 34 to 45 (cu m/min-sq m.) for a single-stage concurrent flow corn dryer.

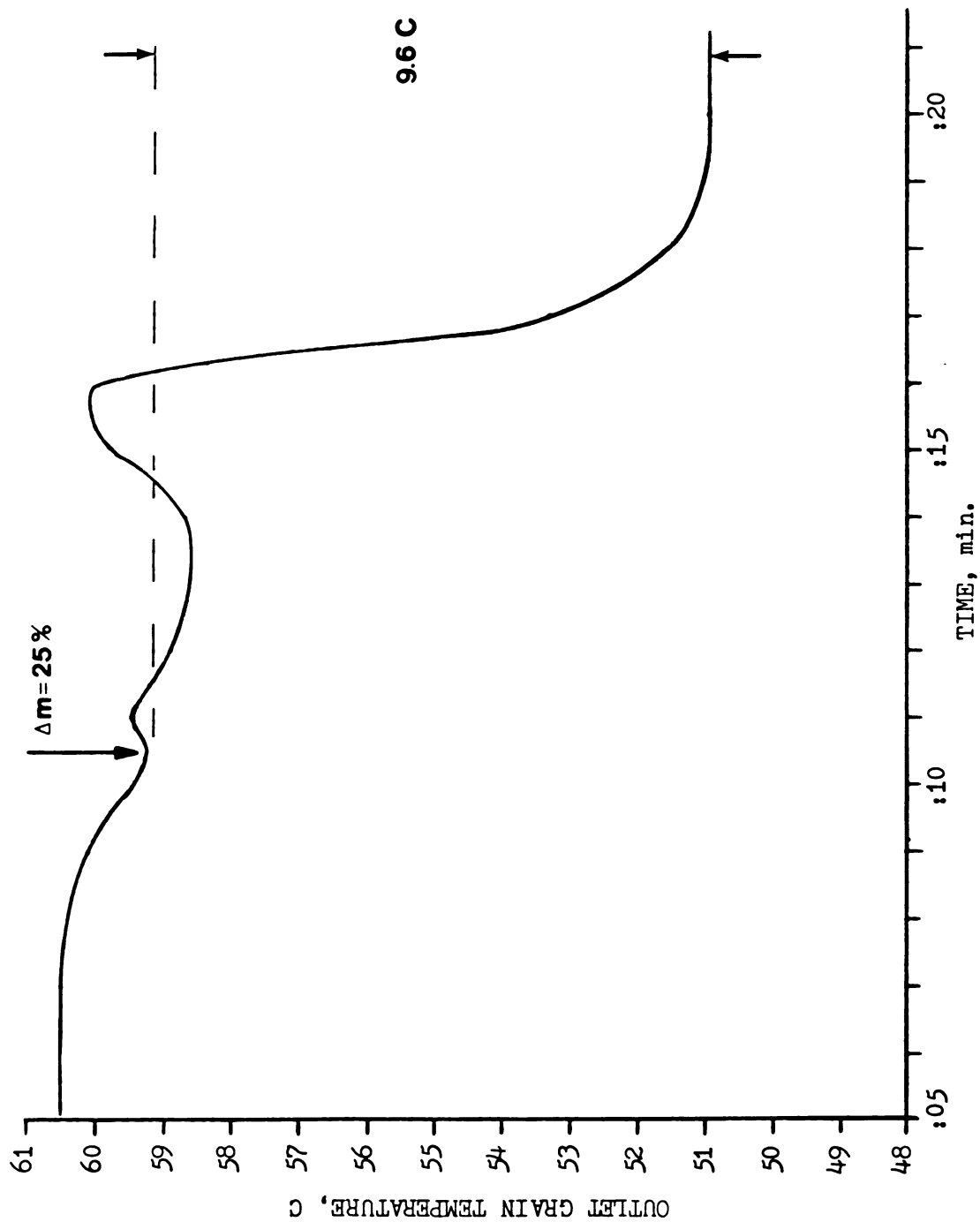


Figure 6.14 Outlet grain temperature response to a negative step change in airflow rate from 45 to 34 (cu m/min-sq m.) for a single-stage concurrent flow corn dryer.

temperatures were used during both tests. Table 6.7 summarizes the dryer input conditions for both airflow tests.

As noted previously, using airflow rate as a controlled variable introduces a variable deadtime element into the control system [Shinskey, 1978]. However, note that the deadtime is approximately the same following the airflow rate step change in both tests. Also, noting that the grainflow rate is the same for both tests, one can assume that the deadtime of the outlet grain temperature response following a change in airflow rate, is more a function of the grainflow rate than the airflow rate for a concurrent flow dryer. It is important to consider this point when controlling both airflow rate and grainflow rate in a multi-stage dryer as proposed in Section 5.6.

Table 6.7: Input conditions for airflow step change tests.

Grainflow Rate, tonne/hr/sq m			2.4
Inlet Air Temp., C			230
Inlet Airflow Rate, cu m/min-sq m	Test 1	34 to 45	
	Test 2	45 to 34	
Ambient Temp., C			33.0
Inlet Grain Temp., C			6.0
Inlet Grain Moisture, % wb			20.5
Outlet Grain Moisture, % wb	Test 1	17.0	
	Test 2	18.0	
Est. Amb. RH, %			75

CHAPTER 7

C O N C L U S I O N S

1. Automated control of continuous flow commercial grain dryers is needed. A microcomputer control system has the potential to maintain dryer parameters close to optimum values and to free the dryer operator for other duties.
2. Time, temperature and airflow rate are the three primary variables that determine the moisture content of grain discharged from a continuous flow dryer or drying stage. Each of these primary variables can be controlled utilizing a microcomputer controller.
3. Direct on-line measurement of grain moisture content which is both relatively inexpensive and

sufficiently accurate for control purposes, is not (yet) possible with commercially available instrumentation.

4. The moisture content of grain discharged from a concurrent flow dryer can be satisfactorily regulated by controlling the outlet grain temperature. A microprocessor-based controller was used to maintain the average outlet grain temperature of a pilot-scale concurrent flow corn dryer within 0.5 C of a pre-selected set-point value with a standard deviation of +2.4 C (corresponding to a simulated average outlet grain moisture content within 0.2 % wb of a set point value with a standard deviation of +0.7 % wb).

CHAPTER 8

SUGGESTIONS FOR FUTURE STUDY

1. The computer simulation used in the control parameter analysis of this study predicts steady-state responses to change in dryer input conditions. Development of computer simulation which can predict transient (real-time) responses to changes in dryer input conditions would greatly facilitate improved control algorithm development.
2. Controller response can be greatly improved by shortening the process deadtime. Investigations should be conducted to determine if temperatures other than those at the dryer outlet (perhaps nearer the dryer inlet or the average of a series of sensors) can be used as indicators of outlet grain moisture content.
3. The experimental investigation of this study was

conducted under laboratory conditions. A thorough investigation into the commercial grain dryer environment (temperature, electrical noise, etc.) and how it effects the microcomputer control electronics should be conducted.

4. As the capacity of microcomputer systems increases it may become possible to utilize grain dryer simulation, similar to those utilized in this study, for on-line control purposes. Adapting a simulation model for a particular grain dryer may make this possible in the near future.

APPENDICES

APPENDIX A

Circuit Diagrams and Specifications for Equipment Used in the Experimental Investigation

MODEL BC2 BASIC CONTROLLER**• SPECIFICATIONS •**

MICROPROCESSOR	Zilog Z80-CPU, operating at 2.5MHz (crystal-controlled)
MEMORY	RAM: 16K bytes (dynamic) EPROM: Sockets for 4K bytes (two TMS2716 type) with on-board automatic EPROM programmer. RAM and EPROM are externally expandable in any combination up to 48K bytes total (exclusive of ZIBL in ROM).
LANGUAGE	Z80 Industrial BASIC Language (ZIBL) in 8K bytes of ROM. Fully memory-mapped variable and I/O structure with 24-bit integer arithmetic capability. 90 statements, commands, mathematical functions and operators.
INTERRUPTS	6 user-available vectored hardware interrupts activated by negative-going LS-TTL level input signal. LS-TTL level interrupt acknowledge output signal.
REAL-TIME CLOCK	24 hour format with 1 second resolution (HHMMSS display), software accessible. Requires 1PPS LS-TTL level interrupt input signal, 16 mS nominal width (normally provided by BCX-01-001 and BCX-01-200 Power Supplies). Timekeeping accuracy dependent on input signal accuracy and stability.
KEYBOARD PORT	8-bit parallel LS-TTL level input port, accepts positive-logic ASCII code. Selectable positive or negative-going LS-TTL level Data Strobe input (strap option). MS bit-line is used to select BC2 "Auto-start" feature.
VIDEO PORT	RS-170 composite video output signal, 75 Ohm impedance. Memory-mapped video format of 16 lines by 64 characters per line. 64 ASCII character display on a 7 X 9 dot-matrix. Underline cursor with X-Y cursor control. Additional "Supervisory" line continually displays current time and number of remaining free memory bytes.
SERIAL PORTS	2 separate RS-232C serial I/O ports with software-selectable baud rates from 110 to 9600 (independently adjustable). CTS and RTS handshake signals; 5 to 8 bit word-length (software-selectable). Strap option on serial channel 2 for 20 mA TTY current-loop operation.
PARALLEL PORT	OUT: 8-bit parallel output port, Schottky TTL levels. 400 nS negative-going LS-TTL level Output Strobe signal. IN: 8-bit parallel input port, LS-TTL levels. LS-TTL level Input Strobe and Port Busy output signal.

CASSETTE PORT	300 baud "BYTE" standard audio cassette interface for storage/retrieval of programs and/or data on cassette tape. On-board relay for automatic start/stop cassette recorder motor operation under software control.
SENSE INPUTS	32 general-purpose LS-TTL level inputs with on-board 2K Ohm pull-up resistors for contact-closure sensing. Externally expandable to 64 total SENSE inputs.
FLAG OUTPUTS	32 general-purpose LS-TTL level outputs. Externally expandable to 64 total FLAG outputs.
RELAY OUTPUTS	8 on-board electromechanical relays. Externally expandable to 64 total RELAY outputs. 4 SPDT power type; contacts rated 5 Amps @ 25 VDC, 3 Amps @ 115 VAC, 2 Amps @ 220 VAC (non-inductive loads). 4 SPST dry-reed type; contacts rated 10 VA (200 VDC maximum or 0.75 Amp maximum, non-inductive loads).
LITE OUTPUTS	8 LS-TTL level outputs, each driving an on-board LED lamp (may be removed to access LS-TTL outputs for off-board use). Externally expandable to 64 total LITE outputs.
LITEPORT	8-bit parallel LS-TTL level output port driving LED lamps for display of a binary data byte (lamps may be removed to access LS-TTL outputs for off-board use).
ANALOG INTERFACE	Optional BCX-30-001 Analog Interface Module (AIM) provides A/D and D/A conversion capability via interface with Analog Devices RT1-1220-12 Data Acquisition Board and RT1-1221-10 Analog Output Board. A/D conversion: 16 channels, 12-bit resolution D/A conversion: 4 channels, 10-bit resolution One AIM supports two Analog Devices boards in any combination. Up to 6 Modules may be paralleled to implement a simultaneous total of 64 A/D and 32 D/A channels.
POWER & SIGNAL REQUIREMENTS	Maximum current-drain. Operating voltage tolerance: +/-5% +5 VDC @ 3.20 Amps +27 VDC @ 0.05 Amps -5 VDC @ 0.10 " +12 VDC @ 0.32 " 1PPS signal, LS-TTL level (16 mS width) -12 VDC @ 0.10 "
PHYSICAL CHARACTERISTICS	Maximum dimensions and weight. Height dimensions increase by 0.13 inches when protective plexi-glass cover is added. PC board only With Mounting Plate Length: 14.75 inches 15.25 inches Width: 12.50 " 14.25 " Height: 0.75 " 1.40 " Weight: 2.00 pounds 4.50 pounds Operating temperature range: 0 to +55 degrees Celsius Storage temperature range: -55 to +95 degrees Celsius

DYNABYTE

115 INDEPENDENCE DRIVE, MENLO PARK, CA. 94025 (415) 329-2021

SPECIFICATIONS (typical @ +25°C, $V_S = \pm 15V$ unless otherwise noted)

MODEL	2B56A
COLD JUNCTION COMPENSATION	
Thermocouple Types	J, K, T
Internally Compensated	B, E, R, S, None
Externally Programmable	0°C
Reference Temperature	
Compensation Accuracy	
Total Output Error @ +25°C ¹	±0.2°C
vs. Ambient Temperature (+5°C to +45°C) ¹	±0.8°C max
Compensation Error	
vs. Sensor Temperature (+5°C to +45°C) ²	±0.4°C max (±0.15°C typ)
vs. Compensator Module Temperature (0 to +70°C) ³	±0.02°C/°C max (0.01°C/°C typ)
Cold Junction Temperature Sensing Element	AD590 or 2N2222
INPUT SPECIFICATIONS	
Voltage Signal Range	±10V
Input Impedance	100kΩ
Signal Gain ⁴	+1V/V
vs. Temperature	±10ppm/°C
Input Offset Voltage	±1mV max
vs. Temperature	±15μV/°C max
OUTPUT SPECIFICATIONS⁵	
Output Voltage	±10V @ ±5mA
Output Impedance	0.1Ω
DYNAMIC RESPONSE	
Selection Settling Time	0.5ms
Signal Settling Time, to ±0.01%	50μs
DIGITAL INPUTS	
Select Inputs A & B	TTL, CMOS Compatible
POWER SUPPLY	
Analog, Rated Performance	±15V dc ±10% @ ±5mA
Operating	(±12V to ±18V dc)
Digital, V_{DD}	+5V to +15V dc @ 2mA max
TEMPERATURE RANGE	
Rated Performance	0 to +70°C
Operating	-25°C to +85°C
Storage	-55°C to +125°C
CASE SIZE	
	1.5" X 2" X 0.4"
PRICE	
(1 - 9)	\$75
(10 - 24)	\$67
(100's)	\$49

¹ Total compensation error composed of errors of temperature sensor and module at the same ambient temperature.

² Compensation error contributed by ambient temperature changes at temperature sensor.

³ Compensation error contributed by ambient temperature changes at the module.

⁴ Signal gain of 2 is also available by jumper selection.

⁵ Protected for shorts to ground or either supply voltage.

Specifications subject to change without notice.

SPECIFICATIONS

(typical @ +25°C, $V_S = \pm 15V$ and $V_{OSC} = +15V$, unless otherwise noted)

Model	2B54A	2B54B	2B55A
ANALOG INPUTS			
Number of Channels	4	•	•
Input Span Range	$\pm 5mV$ to $\pm 100mV$	•	$\pm 50mV$ to $\pm 5V$
Gain Equation	$G = 1 + 10k\Omega/R_G$	•	•
Gain Error	$\pm 0.2\%$ max ($G = 50$ to 300) $\pm 1\%$ max ($G = 1000$)	•	$\pm 0.2\%$ max ($G = 1$ to 100) NA
Gain Temperature Coefficient	$\pm 35ppm/^{\circ}C$ max	$\pm 25ppm/^{\circ}C$ max	$\pm 25ppm/^{\circ}C$ max
Gain Nonlinearity ¹	$\pm 0.03\%$ max ($G = 50$ to 300) $\pm 0.03\%$ ($G = 1000$)	$\pm 0.02\%$ max ($\pm 0.012\%$ typ)	$\pm 0.02\%$ max ($G = 1$ to 100) NA
Offset Voltage			
Input Offset, Initial (Adj. to Zero)	$\pm 20\mu V$ max	•	$\pm 50\mu V$ max
vs. Temperature	$\pm 2.5\mu V/^{\circ}C$ max	$\pm 1\mu V/^{\circ}C$ max ($\pm 0.5\mu V/^{\circ}C$ typ)	$\pm 5\mu V/^{\circ}C$ max
vs. Time	$\pm 1.5\mu V$ /month	•	•
Output Offset (Adjustable to Zero)	$\pm 12mV$ max	•	•
vs. Temperature	$\pm 50\mu V/^{\circ}C$ max	•	•
Total Offset Drift (RTI), max	$\pm (2.5 + \frac{50}{G})\mu V/^{\circ}C$	$\pm (1 + \frac{50}{G})\mu V/^{\circ}C$	$\pm (5\mu V + \frac{50}{G})\mu V/^{\circ}C$
Input Noise Voltage			
0.01Hz - 100Hz, $R_S = 1k\Omega$	$1\mu V$ p-p	•	•
CMV, Channel-to-Channel or Channel-to-Ground			
Continuous, ac, 60Hz	750V rms	•	•
Continuous, ac or dc	$\pm 1000V$ pk max	•	•
Common Mode Rejection			
$R_S \leq 100\Omega$, $f \geq 50Hz$	156dB min ($G = 1000$)	•	145dB min ($G = 100$)
$R_S \leq 100\Omega$, $f \geq 50Hz$	128dB min ($G = 50$)	•	110dB min ($G = 1$)
Normal Mode Input, Without Damage	130V rms, 60Hz	•	•
Normal Mode Rejection, @ 60Hz	55dB min ($G = 1000$)	•	55dB min ($G = 100$)
Input Resistance, Power On	100M Ω	•	•
Power Off	35k Ω min	•	74k Ω min
Input Bias Current	+8nA max	•	•
Open Input Detection Time ²	6 sec ($G = 1000$) 120 sec ($G = 50$)	•	NA NA
Open Input Response	Negative Overscale	•	NA
ANALOG OUTPUT			
Output Voltage Swing ³	$\pm 5V$ @ $\pm 5mA$	•	•
Output Noise, dc - 100kHz	0.8mV p-p	•	•
Output Resistance			
Direct Output	0.1 Ω	•	•
Switched Output	35 Ω	•	•
CHANNEL SELECTION			
Channel Selection Time to $\pm 0.01\%$ FS	2.5ms max	•	•
Channel Scanning Speed	400 chan/sec min	•	•
Channel Select Input Reverse Voltage			
Rating	3V max	•	•
POWER SUPPLY			
Voltage			
Output $\pm V_S$ (Rated Performance)	$\pm 15V$ dc $\pm 10\%$	•	•
(Operating)	$\pm 12V$ to $\pm 18V$ dc max	•	•
Oscillator + V_{OSC}			
(Rated Performance)	+13.5V to +24V	•	•
Absolute max + V_{OSC}	+26V	•	•
Current			
Output $\pm V_S = \pm 15V$	$\pm 4mA$ max	•	•
Oscillator + $V_{OSC} = +15V$	40mA max	•	•
Supply Effect on Offset			
Output $\pm V_S$	100 $\mu V/V$ RTO	•	•
Oscillator + V_{OSC}	1 $\mu V/V$ RTI	•	•
ENVIRONMENTAL			
Temperature			
Rated Performance	0 to +70°C	•	•
Operating	-25°C to +85°C	•	•
Storage	-55°C to +85°C	•	•
Relative Humidity			
Non-Condensing to +40°C	0 to 85%	•	•
CASE SIZE	2" X 4" X 0.4"	•	•
PRICES			
1-9	\$225	\$275	\$220
10-24	\$205	\$256	\$200
100's	\$144	\$180	\$140

*Specifications same as 2B54A.

¹ Gain nonlinearity is specified as a percentage of output signal span representing peak deviation from the best straight line, e.g. nonlinearity at an output span of 10V pk-pk ($\pm 5V$) is $\pm 0.02\%$ or $\pm 2mV$.

² Response time can be reduced by addition of external resistors. More than one open input may cause output to saturate on all channels. To prevent this, use external resistors for a positive overscale response (Figure 8).

³ Protected for shorts to ground and/or either supply voltage.

Specifications subject to change without notice.

APPENDIX B

ZIBL Code Implementing The Dryer
Control Algorithm

ZIBL SUMMARY CHART

ZIBL - STATEMENTS

FOR **NEXT**
DO **UNTIL**
IF **(THEN)**
GOTO
GOSUB **RETURN**
REM
(LET)VAR=exp
LINK exp
DTOA exp,exp
TURNON LITE, RELAY or FLAG exp
TURNOFF LITE, RELAY or FLAG exp
READ DATA RESTORE
DELAY exp
PRINT PRINT%exp
PR PR%exp
LIST LIST%exp
NEW
CLEAR
CLEAR GLOBALS
RUN
RUN NAME
NAME NAME
RENAME NAME

INPUT LOAD
END
END NAME
DIR
STAT=exp
TRACE ON
TRACE OFF
TIME=exp
IN%exp
OUT%exp

ZIBL - OPERATORS

+, -, *, /, =, >, <, NOT
>., <., <>, AND, OR, XOR

ZIBL - FUNCTIONS

MOD(exp,exp)
RND(exp,exp)
ATOD(exp)
SENSE(exp)
TOP
STAT
FREE(o)

ZIBL - CONSTANTS

**HEX**
 DECIMAL
"...." **STRINGS**

ZIBL - VARIABLES

A% TO Z% **GLOBAL ARITH**
A\$ TO Z\$ **GLOBAL 32 CHARACTER STRINGS**
A TO Z **LOCAL ARITH**

ZIBL - STRINGS

= CHARACTER MASK IN STRING COMPARISONS
& = REMAINDER OF STRING MASK IN
 STRING COMPARISONS

ZIBL - SPECIAL ADDRESSES

VIDEO SCREEN	FA00 TO FDFF
SENSE 0 TO 63	FE00 TO FE3F
ATOD 0 TO 63	FE40 TO FE7F
FLAG 0 TO 63	FE80 TO FEBF
LITE 0 TO 63	FEC0 TO FEFF
RELAY 0 TO 63	FF00 TO FF3F
DTOA 0 TO 63	FF40 TO FF7F
PORTS	FF80 TO FFBF

USER DEFINED	FFC0 TO FFFF
PARALLEL PORT	FFB1
LITE PORT	FFB2
TAPE PORT	FFB3
KEYBOARD PORT	FFB4

SYSTEM INPUT PORT AT FF80H BITS:

BIT0	RXD0	SERIAL RECEIVE CHANNEL 0
BIT1	CTS0	CLEAR TO SEND, CHANNEL 0
BIT2	RXD1	SERIAL RECEIVE CHANNEL 1
BIT3	CTS1	CLEAR TO SEND, CHANNEL 1
BIT4	UNUSED	
BIT5	PIPST	PARALLEL INPUT PORT STATUS
BIT6	RTC	REAL TIME CLOCK AS INPUT
BIT7	QRXD	CASSETTE RECEIVE CHANNEL

SYSTEM OUTPUT PORT AT FF80 BITS:

BIT0	TXD0	SERIAL SEND CHANNEL 0
BIT1	RTS0	READY TO SEND CHANNEL 0
BIT2	TXD1	SERIAL SEND CHANNEL 1
BIT3	RTS1	READY TO SEND CHANNEL 1
BIT4	FLAG0	INTERNAL CONTROL
BIT5	FLAG1	INTERNAL CONTROL
BIT6	FLAG2	INTERNAL CONTROL
BIT7	RTCLR	REALTIME CLK CLEAR

```

DRYERPI
50   GOSUB 3000
70   Q%=0 : I% = 0: O=0
100  RUN TEMPOUT
300  U5=166
500  Q5=Q5+1
600  E%=P%-T%
620  E=E%/10
625  PR:PR "ERROR= ",E," [DEG. C*10]"
650  IF E%>=150 GOTO 750
660  IF E%>-150 GOTO 2400
670  F=29 : GOTO 800
750  F=100
800  GOSUB 4000
900  K%=-150000/(L%*F)
950  I%=I%+(E%*100/U%)
1100 M=K5*E%/1000
1300 R5=R5+M
1350 IF R5<=100 OR >=1200 GOTO 2000
1400 PR:PR "NEW SPEED= ",R%
1500 GOSUB 4000
1600 B%=((4*L%)+5/10
1700 GOTO 2500
2000 B%=8
2005 IF R%<=1000 R5=100 :IF R%>=1200 R%>=1200
2010 PR:PR "GRAIN FLOW LIMIT REACHED"
2020 PR:PR "CHECK INLET AIR TEMP."
2030 GOTO 2500
2400 B%=4
2410 PR:PR "NO SPEED CHANGE"
2500 RUN RPMSET
2600 GOTO 500
3000 PUT 12:PR
3010 PR "ENTER DESIRED OUTLET GRAIN TEMP., C
3030 PR : INPUT P%:P%=P%*10:RETURN
4000 Y=(1718*R%+12024)/100
4100 y=144000/y
4200 IF P%>T% GOTO 4500
4400 L%=(60*Y)/100
4500 RETURN
5000 END

```

RPMSET

```

10  OUT%127:LINK #F003:OUT%0
20  B=0 : T=0
21  REM -- R=RESET RATE x 100000
20  REM -- R=RESET RATE x 100000
25  R=50
26  M%=I%*K%/1000
27  H-R%*100
30  IF Q%<=1 N%=0
31  DO : A%=0 : X=0
35  IF B%<>4 GOSUB 2000
37  W=W+M%
39  R%=(H+W)/100
40  DO
45  A%=0:X%=0
50  REM -- PI CONTROL LOOP FOR MOTOR SPEED
100 DO
110 GOSUB 500
120 E-R%-A
122 IF E> 50 GOTO 132
124 IF E<-50 GOTO 132
126 K=48
128 GOTO 135
132 K=20
135 A%=A%+A
140 E=E*10
150 N%=N%+(E*R/100000)
160 M=K*(E+N%)/10000
170 S%=S%-M
180 IF S%<=35 S%=35:IF S%>=240 S%=240
190 @#FF81=S%:@#FF82=S%
200 X=X+1
210 REM -- C% IS USED FOR TIMING OF THE LOOP
230 GOTO 575
500 C=0:S=0
510 DO:A=ATOD(3)
520 A=((A*1000)/4095)*25)/10
530 S-S+A:C=C+1
540 UNTIL C=10
550 A=S/C
560 RETURN
575 A%=A%/C%
600 PUT 12
610 RUN TEMPOUT
620 PR:PR "COMPUTED SPEED= ",R%,"[RPM]"
630 PR "SPEED= ",A%,"[RPM]"
640 PR:PR PR "SETPOINT TEMP= ",S$,"[DEG. C]"
650 PR:PR "OUTLET GRAIN TEMP= ",O$,"[DEG. C]"
660 PR "INLET AIR TEMP= ",X%,"[DEG. C]"
700 RUN TAPEOUT
800 GOTO 45

```

```
1000 END
2000 Y=P%-T%
2010 IF Y>=50 GOTO 2050
2020 IF Y>-50 GOTO 2040
2030 GOTO 2050
2040 B=B%-1
2050 RETURN
```

LIST OF REFERENCES

LIST OF REFERENCES

- Aguilar, C. S. and Boyce, D. S. 1966. Temperature ratios for measuring efficiency and for the control of driers. Jour. of Agr. Eng. Res. 11(1):19-23.
- Bailey, S. J. 1980. Moisture sensors 1980: On-line roles increase. Control Engineering 27(9):112-117.
- Bakker-Arkema, F. W. 1981. Personal communication. Professor, Dept. of Agr. Eng., Michigan State University: East Lansing, MI.
- Bakker-Arkema, F. W., Brooker, D. B. and Hall, C. W. 1972. Comparative evaluation of crossflow and concurrent flow grain dryers. ASAE Paper No. 72-849. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Bakker-Arkema, F. W., DeBoer, S. F., Lerew, L. E. and Roth, M. G. 1973. Energy conservation in grain dryers: I. Performance evaluation. ASAE Paper No. 73-327. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Bakker-Arkema, F. W., Rodriguez, J. C., Brook, R. C. and Hall, G. E. 1981. Grain quality and energy efficiency of commercial grain dryers. ASAE Paper No. 81-3019. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Beveridge, G. S. G. and Schecter, R. S. 1970. Optimization: Theory and Practice. McGraw-Hill: New York, NY.
- Bibbero, R. J. 1977. Microprocessors in Instruments and Control. John Wiley and Sons, Inc.: New York, NY.
- Blount Agribusiness. 1981. Commercial brochure. Montgomery, AL.
- Brook, R. C. 1977. Design of multistage grain dryers. Unpublished Ph.D. dissertation, Michigan State University: East Lansing, MI.

- Brook, R. C. and Bakker-Arkema, F. W. 1980. Design of multistage corn dryers using computer optimization. Transactions of the ASAE 23(1):200-203.
- Burton, D. P. and Dexter, A. L. 1977. Microprocessor Systems Handbook. Analog Devices, Inc.: Norwood, MA.
- Cloud, H. A. 1957. Accuracy and limitations of automatic controls for crop drying. Presented at the 1957 winter meeting of ASAE.
- Colliver, D. G., Peart, R. M., Brook, R. C. and Barret, J. R., Jr. 1979. Comparison of minimal energy usage management procedures for low temperature grain drying. ASAE Paper No. 79-3027. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Coon, G. A. 1956. How to find controller settings from process characteristics. Control Engineering 3(5):66-76.
- Dalpasquale, V. A. 1981. Drying of soybeans in continuous-flow dryers and fixed-bed systems. Unpublished Ph.D. dissertation, Michigan State University: East Lansing, MI.
- DICKEY-john Corporation. 1980. CFMM-A Continuous flow moisture monitor, installation and operating manual. Dickey-john Corporation: Auburn, IL.
- Fadum, O. and Shinskey, F. G. 1980. Saving energy through better control of continuous and batch dryers. Control Engineering 27(3):69-72.
- Franklin, G. F. and Powell, D. J. 1980. Digital Control of Dynamic Systems. Addison-Wesley Publ. Co. Inc.: Reading, MA.
- Harrell, R. C., Allison, J. M. and McLendon, B. D. 1979. Microprocessor-based control system for solar assisted grain drying. ASAE Paper No. 79-5524. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Henry, Z. A., ed. 1975. Instrumentation and measurement for environmental sciences. ASAE Special Publication SP-0375. Am. Soc. Agr. Eng. St. Joseph, MI.

- Hinkle, C. N. 1980. 8-Bits for a grain dryer. ASAE Paper No. 80-5021. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Holtman, J. B. and Zachariah, G. L. 1969a. Computer controls for grain driers. Transactions of the ASAE 12(4):433-437.
- Holtman, J. B. and Zachariah, G. L. 1969b. Continuous crossflow modeling for optimal control. Transactions of the ASAE 12(4)430-432.
- Hukill, W. V. 1954. Storage of Cereal Grain and their Products. Am. Assoc. of Cereal Chemists: St. Paul, MN.
- Kalchik, S. J. 1977. Drying of soybeans in a pilot scale concurrent flow dryer. Unpublished M.S. thesis Michigan State University: East Lansing, MI.
- Jakeway, J. J. 1981. Personal communication. M.S. candidate, Michigan State University: East Lansing, MI.
- Manufacturing Engineering. 1980. A different type of control - industrial control microcomputers. Manufacturing Engineering 84(5):54-55.
- Matthews, J. 1963a. Automatic moisture content control for grain dryers. Jour. of Agr. Eng. Res. 8(3):207-220.
- Matthews, J. 1963b. The design of an electrical capacitance-type moisture meter for agricultural use. Jour. of Agr. Eng. Res. 8(1):17-30.
- Matthews, J. 1964. Performance of an automatic moisture control unit. Jour. of Agr. Eng. Res. 9:180-187.
- Melsa, J. L. and Schultz, D. G. 1969. Linear Control Systems. McGraw Hill: New York, NY.
- Morrison, R. 1977. Grounding and Shielding Techniques in Instrumentation. Second edition. John Wiley and Sons, Inc.: New York, NY.
- Muhlbauer, W. and Isaacs, G. W. 1975. Warmeruckgewinnung bei Kornerfruchttrocknungsanlagen. Landtechnik 24:161-164.

- Omega Engineering, Inc. 1981. Temperature Measurement Handbook. Omega Engineering, Inc.: Stamford, Conn.
- Ott, H. W. 1976. Noise Reduction Techniques in Electronic Systems. John Wiley and Sons, Inc.: New York, NY.
- Sabbah, M. A., Keener, H. M. and Meyer, G. C. 1977. Simulation of solar grain drying using the logarithmic model. ASAE Paper No. 77-3012. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Sen, R. K. 1981. Personal communication. President, Diversified Engineering, Inc.: Richmond, VA.
- Sen, R. K. 1980. Personal communication. President, Diversified Engineering, Inc.: Richmond, VA.
- Sheingold, D. H., ed. 1981. Transducer Interfacing Handbook. Analog Devices, Inc.: Norwood, MA.
- Shinskey, F. G. 1978. Energy Conservation through Control. Academic Press, New York, NY.
- Short, K. L. 1981. Microprocessors and Programmed Logic. Prentice-Hall, Inc.: Englewood Cliffs, NJ.
- Smith, C. L. 1979. Fundamentals of control theory. Chemical Engineering 86(22):11-39.
- U. S. Dept. of Energy. 1979. Computer technology: Its potential for industrial energy conservation. Technology Applications Manual DOE/CS/2123-T2: Technical Information Center, U. S. Dept. of Energy: Washington, D. C.
- Westelaken, C. M. 1981. Personal communication. Blount Inc.: Montgomery, AL.
- Wise, K. D., Chen, K. and Yokely, R. E. 1980. Microcomputers: A Technology Forecast and Assessment to the Year 2000. John Wiley and Sons: New York, NY.
- Yang, L. C. 1981. Developments in moisture sensors. M & C Measurements and Control 15(1):98-108.
- Zachariah, G. L. and Isaacs, G. W. 1966. Simulating a moisture-control system for a continuous-flow drier. Transactions of the ASAE 9:297-302.

Zagorzycki, P. E. 1979. Automatic control of conveyor
dryers. Chemical Engineering Progress,
19(82):50-56.