

*Conceptual Design of a Digital Control System
for Nuclear Criticality Experiments*

*Stephen Paul Rojas**



**Graduate Research Assistant at Los Alamos Group NIS-6.*

MASTER

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LIST OF ABBREVIATIONS

PLC: Programmable Logic Controller

SCRAM: quick decrease in system reactivity due to the engagement of mechanical motion devices

PROM: Programmable Read Only Memory

PID: Proportional Integral Derivative

TTL: Transistor Transistor Logic

ADC: Analog to Digital Converter

MCNP: Monte Carlo Neutron Photon Code

LACEF: Los Alamos Critical Experiments Facility

DOE: Department of Energy

NEMA: National Electrical Manufacturers Association

SHEBA: Solution High Energy Burst Assembly

RAP: Remote Autoranging Piccometer

SST: Stainless Steel

BCD: Binary Coded Decimal

CONCEPTUAL DESIGN OF A DIGITAL CONTROL SYSTEM FOR NUCLEAR CRITICALITY EXPERIMENTS

by

Stephen Paul Rojas

ABSTRACT

Nuclear criticality is a concern in many areas of nuclear engineering including waste management, nuclear weapons testing and design, basic nuclear research, and nuclear reactor design and analysis. As in many areas of science and engineering, experimental work conducted in this field has provided a wealth of data and insight essential to the formulation of theory and the advancement in knowledge of fissioning systems. In light of the many diverse applications of nuclear criticality, there is a continuing interest to learn and understand more about the fundamental physical processes through continued experimentation. This thesis addresses the problem of setting up and programming a microprocessor-based digital control system (PLC) for a proposed critical experiment using, among other devices, a stepper motor, a joystick control mechanism, and switches. This experiment represents a revised configuration to test cylindrical nuclear waste packages.

A Monte Carlo numerical study for the proposed critical assembly has been performed in order to illustrate how results from numerical calculations are used in the process of assembling the control system and to corroborate previous experimental data. This study involves modeling a solution system of uranyl nitrate in cylindrical geometry (two cylindrical "slab" tanks approximately 28 inches in diameter and 4 inches thick) with the Monte Carlo Neutron Photon code written at Los Alamos National Laboratory, New Mexico. The results of this study yielded the sensitivity effect of varying the distance between the tanks: information used as design criteria to size various control system components. In addition, the software necessary for experiment control was developed.

In summary, a control system utilizing some common devices necessary to perform a critical experiment (stepper motor, push-buttons, etc.) has been assembled. Control components were sized using the results of a probabilistic computer code (MCNP). Finally, a program was written that illustrates the coupling between the hardware and the devices being controlled in the new test fixture.

Chapter 1.

INTRODUCTION

1.1 Background

1.1.1 Nuclear Criticality

The term "criticality" generally refers to the study of fissioning systems that approach a state of equilibrium between the number of neutrons being produced and the number of neutrons "dying." Neutrons are produced by the process of nuclear fission. In a Los Alamos National Laboratory report [15], Hugh C. Paxton defines the fission process as:

The disintegration of a nucleus (usually, Th, U, Pu, or heavier) into two masses of similar order of magnitude, accompanied by a large release of energy and the emission of neutrons. Although some fissions take place spontaneously, neutron-induced fissions are of major interest in criticality safety....

Thus, the area of major interest in nuclear criticality is in the generation and death of neutrons. The same diffusion theory that has successfully been applied to heat transfer and fluid mechanics has also been successfully used to model the process of nuclear fission. In addition, as will be seen in chapter three of this document, probabilistic approaches have proven extremely useful in the design and analysis of fissioning systems.

1.1.2 Multiplication Factor

The multiplication factor is denoted with the symbol "k" and is defined as follows [9]:

$$k = \frac{\text{number of fissions in current generation}}{\text{number of fissions in preceding generation}}$$

So if the multiplication factor is less than one, then the system is called "subcritical" and the number of fissions occurring in the system is decreasing with time. On the other hand, if the multiplication factor is greater than one, then the system is said to be "supercritical" and the number of fissions increases with time. If the multiplication factor is equal to one, then the system is said to be exactly "critical" and the number of fissions occurring is constant with time. In a critical assembly, the ratio of the number of neutrons produced to the number of neutrons disappearing is commonly controlled by the use of "poison" control rods (material that absorbs neutrons). Typically there are two basic manners in which neutrons may vanish:

1. Absorption during a nuclear reaction
2. Leakage from the surface of the reactor

There are many methods used to model the fission process:

- diffusion theory (Fick's law; differential equations): a deterministic approach using finite differences
- Monte Carlo: a probabilistic approach using statistics
- transport theory (integral equations): a deterministic approach using discrete ordinates

The simplest, most fundamental approach and the approach used early on in nuclear system design is diffusion theory. However, the Monte Carlo method offers improved accuracy in modeling complex geometries and it has been the adapted method in the current study.

1.1.3 Fissile Material

A material is said to be fissile if it is capable of fission at low energy levels (i.e., slow neutrons with low kinetic energy). ^{235}U , which is abundant on the planet, is used to "breed" fissile plutonium by bombarding the ^{238}U with neutrons. Another

method used to create fissile material is the refinement process used to enrich the percentage of ^{235}U in naturally occurring uranium.

1.1.4 Prompt and Delayed Neutrons

More than 99 percent of the neutrons emitted in a fissioning system are emitted at the instant fission occurs; these neutrons are called "prompt." That fraction of a percent of neutrons that are emitted at a relatively long time after the initial fission event are called "delayed" neutrons. The average number of prompt and delayed neutrons released per fission event is given the symbol ν .

1.1.5 Cross Sections

A cross section is an experimentally determined parameter with units of cm^2 which indicates the probability of a certain event occurring. Different types of cross section data used in nuclear engineering include scatter cross sections, absorption cross sections, or fission cross sections. Cross sections take on the units of "barns" where $1 \text{ barn} = 1 \times 10^{-24} \text{ cm}^2$. In essence, the nuclear cross section is the "effective" cross section of the nucleus that a neutron sees when it is traveling near the nucleus. The total cross section is the combination of the fission cross section, absorption cross section, scatter cross section, etc., and is a measure of the probability that any type of interaction occurs when a beam of neutrons impinges on a target composed of many nuclei.

1.1.6 Moderators and Poisons

A moderator is a substance which tends to slow down ("thermalize") neutrons. Typical moderators include water and polyethylene. A poison is a substance which tends to absorb neutrons. Typical poisons include boron and cadmium. Poisons may be of the "burnable" type [14] which means their absorption cross section decreases as time progresses (thus increasing the reactivity of the system).

1.1.7 Over/Under Moderated Systems

A system is said to be "overmoderated" if the multiplication factor decreases (i.e., critical mass increases) with decreasing density (i.e., increase the amount of moderator). On the other hand, if as the density is decreased the multiplication factor increases (i.e., critical mass decreases), then the system is said to be "undermoderated." This information is typically illustrated in a plot of multiplication factor vs. density (or equivalently, a plot of critical mass vs. hydrogen to uranium ratio).

1.1.8 Prompt and Delayed Criticality

Delayed criticality is used to describe the state of a fissile material in which the multiplication factor is unity from the contribution of both delayed and prompt neutrons. Prompt criticality is a term used to describe the state of a fissile material in which the multiplication factor is unity solely from the contribution of prompt neutrons. Thus there is a "window" in between delayed criticality (the steady-state condition) and prompt criticality.¹ This window is given the symbol β and it follows that the fraction of fission neutrons that are prompt is $1-\beta$. This can be seen by considering that a k of unity is due to both prompt and delayed neutrons; therefore,

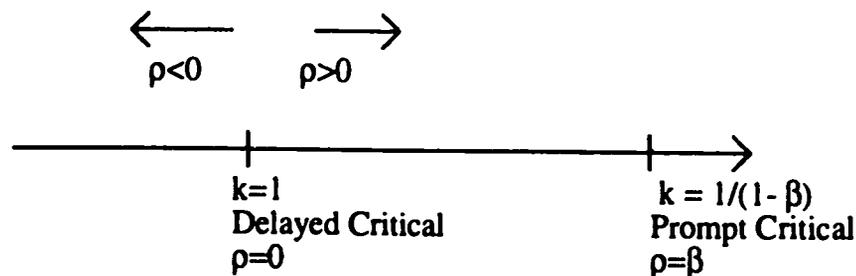


Figure 1-1 : Criticality Window

¹If not for this window, bombs would be rather easy to build while nuclear reactors would be more difficult; as it is, the reverse is true.

to get rid of the delayed neutrons, we subtract the reactivity amount β . One may question the validity of subtracting these two values since at first sight they appear to be different units; however, at closer inspection it is apparent that the units are identical since the reactivity β is simply the change in k which has been normalized in accordance with value of unity at delayed critical. Therefore, the multiplication factor considering only prompt neutrons is $(1-\beta)k$. When this value is unity, the system is said to be prompt critical since a multiplication factor of unity is reached with only prompt neutrons.

1.1.9 Reactivity

Reactivity is defined as the percentage the system is above delayed critical:

$$\rho = \frac{k - 1}{k}$$

Thus, negative reactivity indicates a system that is below delayed critical while positive reactivity indicates a system that is above delayed critical. Typically, the reactivity is expressed in "dollars" (or fractions of a dollar: "cents") by using the conversion factor: β reactivity = 1 dollar. The value β is the difference in reactivity between delayed criticality and prompt criticality. Thus, if a system is prompt critical, then $\rho = \beta$ (remember, if the system is delayed critical, then the multiplication factor is one, and the reactivity is zero). Typically, the term "adding reactivity" is used when the system is already at delayed critical (i.e., $k=1$, $\rho=0$).

1.1.10 Atom and Number Densities

Typically, number densities are used for Monte Carlo input files to define the material characteristics. The number and atom densities are defined as follows:

$$N = \frac{\rho N_A}{M} = \text{atom density} = \text{atoms} / \text{cm}^3$$

$$\text{number density} = (N)(1 \times 10^{-24} \text{ cm}^2 / \text{barn}) = \frac{\text{atoms}}{\text{barn} \cdot \text{cm}}$$

where:

N_A = Avogadro's Number

M = molecular weight

1.1.11 Scram System

A scram system refers to an electro-mechanical system which produces a prompt decrease in reactivity due to physical movement. For example, a scram for the uranyl nitrate experiment would consist of quickly moving the two fissile slab tanks apart from one another to quickly decrease the multiplication factor. Typically both automatic and manual scram systems are designed into critical experiment apparatus (the automatic mechanisms are coupled to particle detectors located around the experiment). In addition, for the experiment proposed in this study, an additional gravity assisted scram mechanism may be incorporated. Although this document focuses only on the primary manual scram mechanism (a hydraulic cylinder), it should be noted that two such redundant scram systems will also be incorporated: one automatic, and one gravity assisted.

1.1.12 Historical Perspective: LACEF

The urgency of World War II that spurred the Manhattan Project also demanded that a site be established at the Los Alamos National Laboratory which would serve as an area for experimental work as well as isolate the population from radiation in the event of a criticality accident [12]. The area chosen was in Los Alamos' Pajarito Canyon and came to be known as "Pajarito Site." Before 1947, critical experiments were performed at the site by hand. This changed when, in 1946, Louis Slotin was

killed as a result of a component of an assembly slipping into a more reactive position producing a superprompt-critical pulse of radiation. As a result, the site established much more exacting rules governing the operation of critical assemblies, one of which was the policy of performing most critical experiments remotely. Such experiments are now performed in what are called "kivas":² buildings housing critical experiments that are controlled from a remote location. The control system outlined in this document will serve as the main control system for the original "kiva" which is now referred to as KIVA I. Figure 1-2 displays a plan view of Pajarito Site. Today LACEF (Los Alamos Critical Experiments Facility) houses the most significant collection of critical assemblies in the western hemisphere. The assemblies that may be operated at LACEF can be divided into three categories:

- **Benchmark Assemblies** are configurations containing precisely known components that have interchangeable or adjustable fissile cores and reflectors.
- **Assembly Machines** are general purpose platforms into which fissile, moderating, reflecting, and control components may be loaded for short range studies of the neutronic properties of the materials. The assembly machine described in the following section falls into this category. It is worth noting that assembly machines do not actually contain fissile material; they only manipulate it.
- **Solution Assemblies** allow critical operations with fissile solutions. The experiment proposed in this study is a solution experiment mounted on an assembly machine.

²The Hopi Indian name for a round ceremonial chamber

1.2 Objectives

The main goal of this project is to create a numerical model of a fissioning system ("critical assembly") using a well-established computer code and then bring together a system for controlling the assembly based on the results of the numerical study. Although the numerical results will be specific to a certain critical experiment, the control system will be inherently general and may readily be used to control other experiments (specifically, an experiment involving a stepper motor and hydraulic system). In order to address the specific details that must be considered when sizing and selecting control components, a complete sizing analysis for the proposed system is given in chapter seven. An introduction to the proposed experiment follows.

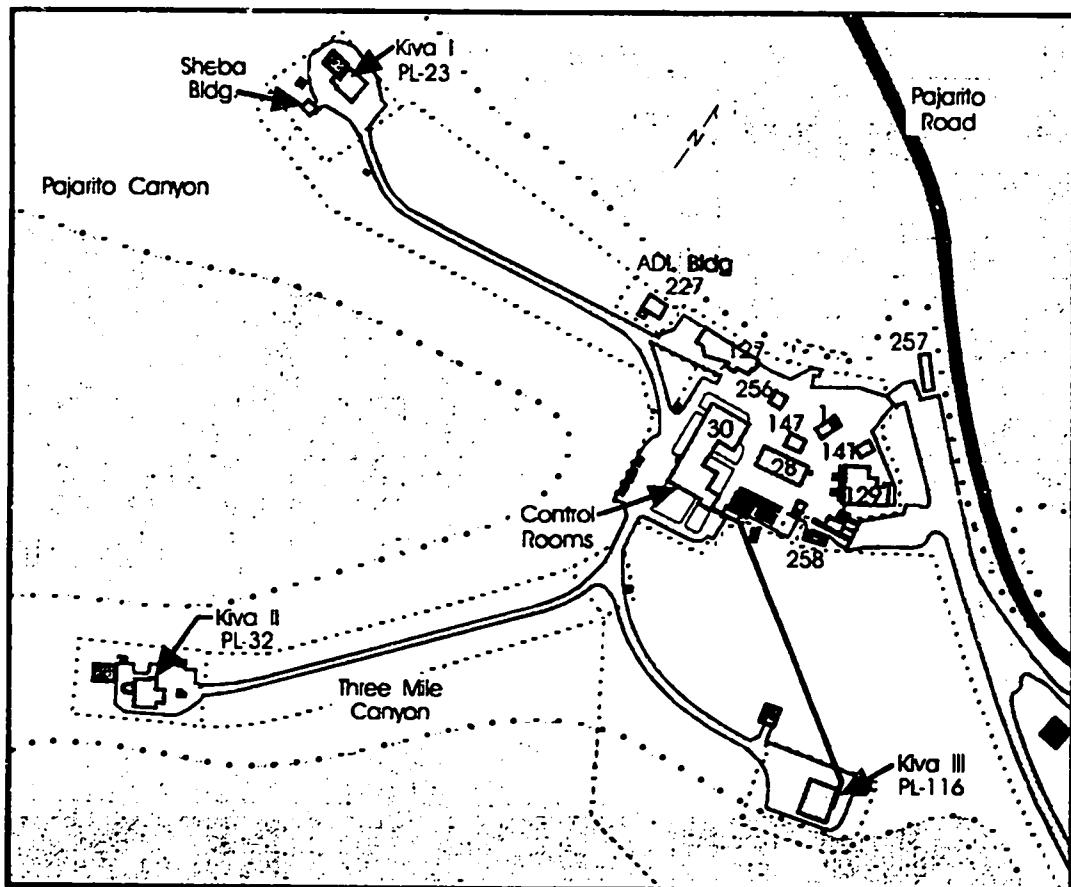


Figure 1-2 : Pajarito Site (TA-18)

1.2.1 Mechanical System

The system chosen for study is a uranyl nitrate solution system in cylindrical geometry. The experiment consists of two "slab" tanks filled with highly enriched uranyl nitrate, $\text{UO}_2(\text{NO}_3)_2$, that must be pushed together remotely. The general mechanical setup for achieving this is shown below [11]. Note that the detailed design of mechanical components (e.g., support brackets or translation tables) has been omitted in order to focus attention on the two systems of primary interest from a control system point of view: the stepper motor/lead screw combination and the hydraulic system.

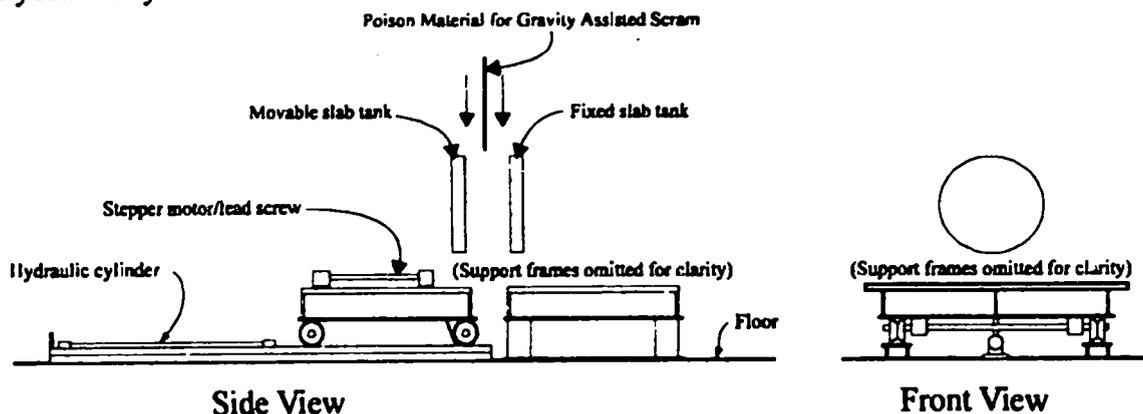


Figure 1-3 : Systems Overview

A hydraulic cylinder is used to push the movable cart toward the stationary tank. Once the air gap between the two tanks is decreased to a preset distance, the hydraulic cylinder is shut down and the final approach to critical is made with a stepper motor and lead screw that drive a linear translation table (upon which the moving tank sits). The stepper motor/lead screw combination is used in favor of the hydraulic system for final closure in order to increase resolution (as will become evident in the following chapters, such a system is extremely sensitive to small changes in the air gap). This document focuses only on the control of the stepper motor/lead screw and hydraulic systems. A complete specification of all the systems necessary to perform the

experiment would involve designing the framework for the secondary gravity assisted scram system (general concept illustrated in Figure 1-3) as well as all of the detail design for components such as mounting brackets or mechanical interfaces (e.g., the lead screw/translation table interface).

1.2.2 Hydraulic System

Figure 1-4 below shows the simplified hydraulic system circuit that is used to control the hydraulic cylinder portion of the assembly [10]. Basically, the pressure differential in the cylinder is controlled by running line pressure through a series of three normally open or normally closed control valves.³

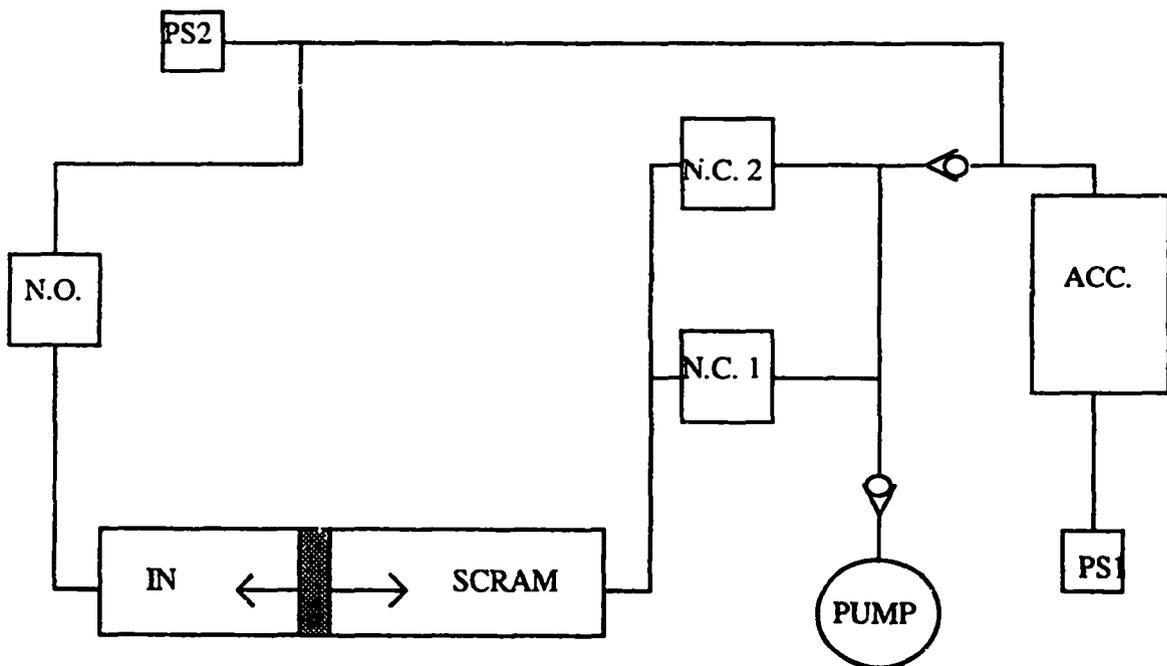


Figure 1-4 : Hydraulic System

³Normally open: when power is off, the valve is open
Normally closed: when power is off, the valve is closed

1.2.2.1 Valves

A total of three valves are used to regulate the pressure throughout the system. When N.O. is open and N.C. 1 and N.C. 2 are closed, the system is scrambled. When N.O. is closed, either N.C. 1 or N.C. 2 can be opened depending on the speed desired (speed is set by needle valves associated with N.C. 1 and N.C. 2). When all of the valves are off, the hydraulic cylinder is inactive.

1.2.2.2 Accumulator

The accumulator serves as a power source to the hydraulic cylinder in the case of power loss. If power is lost, the normally open valve connecting the accumulator to the scram line will open and N.C.1 and N.C.2 will close, causing the assembly to automatically scram.

1.2.2.3 Pressure Switches

Two pressure switches, identified by PS1 and PS2, are used to check the accumulator pressure range and the scram line pressure range. When a limit is reached, the switch is activated on.

1.2.2.4 Pump

The pump provides the pressure necessary to move the hydraulic cylinder and pressurize the accumulator. For the purposes of the control system that will be discussed in the following chapters, it is assumed that control of all hydraulic system components requires 10-60 volt DC power. Therefore, as will be made clear in the following chapters, the only type of control system output device needed is a DC output "module" to send the appropriate DC voltage to the desired valve or pump.

1.3 Scope of Study

This study completes the preliminary conceptual work necessary for conducting a critical experiment involving uranyl nitrate in cylindrical geometry using a horizontal split table and, in essence, proves that such an experiment is feasible by outlining the hardware and software necessary for conducting the experiment. The scope of this study includes the conceptual design of the main mechanical components as well as the system needed to control these components. Detailed design of mechanical components is outside the scope of this study and is taken as a "given."

1.4 Report Outline

This report begins with a numerical study of the physical system to be controlled. Next, the mechanical design requirements are outlined and the conceptual mechanical design that fulfills these requirements is illustrated and briefly discussed. The hardware needed to control this physical system is the next general topic addressed. In these chapters (chapters four, five, and six), the approach to control and the control system components are discussed and introduced. In chapter seven, the results of the numerical study are used to size hardware components for the experiment. In chapters eight and nine, the software used in conjunction with the control hardware is discussed. Finally, in chapter 10, a cost analysis for performing the experiment is presented and discussed.

Chapter 2.

THE NUMERICAL STUDY

2.1 Introduction

Numerical studies (as well as any available experimental results) will give an idea of the characteristics of the physical system being controlled and yield such design information as: how fast the system can be moved together, what kind of torque is needed, and what kind of control system hardware is needed to satisfy all of the specifications. Used for this purpose, the Monte Carlo method (MCNP) is briefly discussed here and numerical results for the experiment introduced in chapter one are generated. The data generated here is used to size a stepper motor and the peripheral electrical devices needed for the uranyl nitrate experiment. An admittedly simple model of a uranyl nitrate solution system in cylindrical geometry has been created; however, at this level of design, it is sufficient to corroborate general trends in data from a previously conducted experiment involving uranyl nitrate and similar geometry. This numerical study is the first step in the following progression of events:

- MCNP studies to determine values needed for the sizing of basic control system components
- control system component sizing: stepper motor, stepper motor drive
- component installation
- programming and debugging

2.2 The Monte Carlo Method

The method of solving governing equations by statistical accumulation (playing a "game") is used in many areas of science and engineering including conductive and radiative heat transfer, turbulence, and most pertinent to this paper, neutron physics. The Monte Carlo method involves a physical process that inherently exhibits some

form of randomness. The terms "random walk" or "Markov chain" often arise in the discussion of such processes. Strictly defined, a Markov chain is a series of sequential events for which the probability of each succeeding event is uninfluenced by prior events [16]. From this definition arose the term "random walk": an expression describing the randomness with which a drunk man ambles down the street. This random walk phenomenon is present nearly everywhere in nature:

- the direction a bundle of photons is emitted during a radiative heat transfer process can be modeled as a random process
- the generation and death of vortices in turbulent fluid flow can be seen as a random process
- the life and death of a neutron during the fission process can be modeled as a random process

Thus, any seemingly random process can be modeled as long as one critical piece of experimental data is available: the frequency distribution of the event or events. For example, in a game of darts, the frequency of a dart hitting at some radial position on the dart board may be graphically displayed by plotting frequency (i.e., number of times the dart hits) vs. radial position on the dart board.

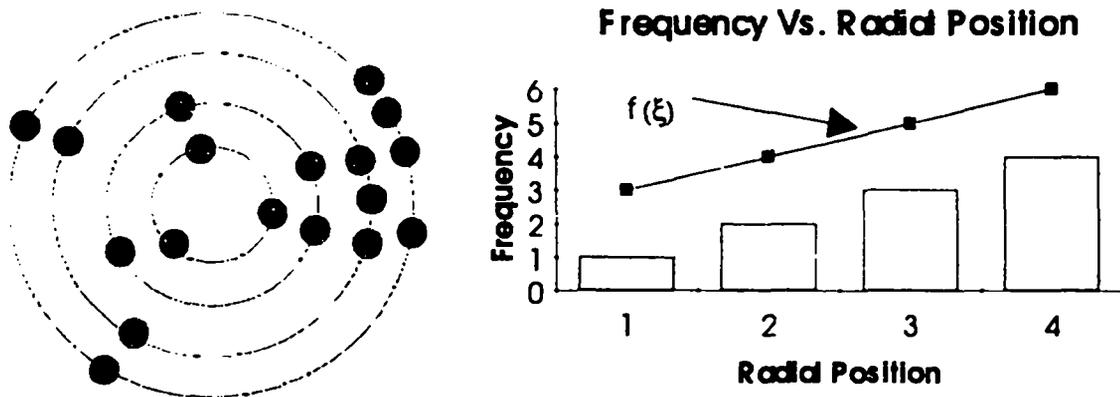


Figure 2-1: A Dart Game With a Hypothetical Frequency Distribution

Typically, the frequency distribution is mathematically manipulated in terms of more convenient functions such as the "probability density function" or the "cumulative distribution function." For instance, if the frequency distribution is denoted by $f(\xi)$ then the probability density function is found by normalizing the frequency distribution (i.e., dividing by the area under the $f(\xi)$ curve):

$$P(\xi) = \frac{f(\xi)}{\int_a^b f(\xi) d\xi}$$

So if random numbers are chosen for ξ , the resulting distribution must resemble that defined by the equation shown above. In other words, we may create a probabilistic model that repeatedly plays the same "game" utilizing random numbers and physics. However, those random numbers must agree with the probability density function that is observed in physical reality and defined by the general equation shown.

2.3 Los Alamos National Laboratory and Monte Carlo

The Monte Carlo method emerged from work done at Los Alamos National Laboratory during World War II and the invention of the method in general is attributed to Fermi, Von Neumann, and Ulam. This initial work on the Monte Carlo method eventually led to what is now known as MCNP: the Monte Carlo Neutron Photon computer code [6]. MCNP is a general purpose Monte Carlo code that can be used for neutron, photon, or coupled neutron/photon transport and is generally recognized as one of the best codes in its class since it incorporates state-of-the-art physics, data, and mathematical methods.

MCNP follows the entire life of many particles from life to death; the "game" (fission process) is started by a source of fixed strength specified by the user. When

run in neutron transport only mode, there are four possible events a neutron can see during its lifetime:

1. Neutron scatter
2. Fission
3. Neutron capture
4. Neutron leakage

MCNP simply follows the entire life of each particle by randomly selecting one of the possible events (and, if scatter is selected, a random direction) based on a set of rules (physics) and probabilities (transport data) governing the processes and materials involved. As the lifetime history of more and more neutrons is followed, the distribution of neutrons is better known. Typical fission cross section data for ^{235}U and other fissile materials is shown on the following page [15]. In addition to fission cross sections, other cross section data is used by MCNP including scatter, absorption, and capture data. As seen on the plot, ^{235}U has a much higher probability of fission occurring when the neutrons are in the "thermal" (i.e., ambient temperature) region rather than the "fast" (i.e., greater than ambient temperature) region. In between the thermal and fast regions, the probability for fission fluctuates greatly; because of this, nuclear systems are commonly referred to as being in one of two distinct states: "fast" or "thermal" (the system is forced to be thermal or fast by design).

2.4 Input File Overview

A typical MCNP input file is composed of four major sections; each section being composed of a number of input "cards" (horizontal rows of data). The four major sections are:

- Geometry specification cards
- Surface specification cards

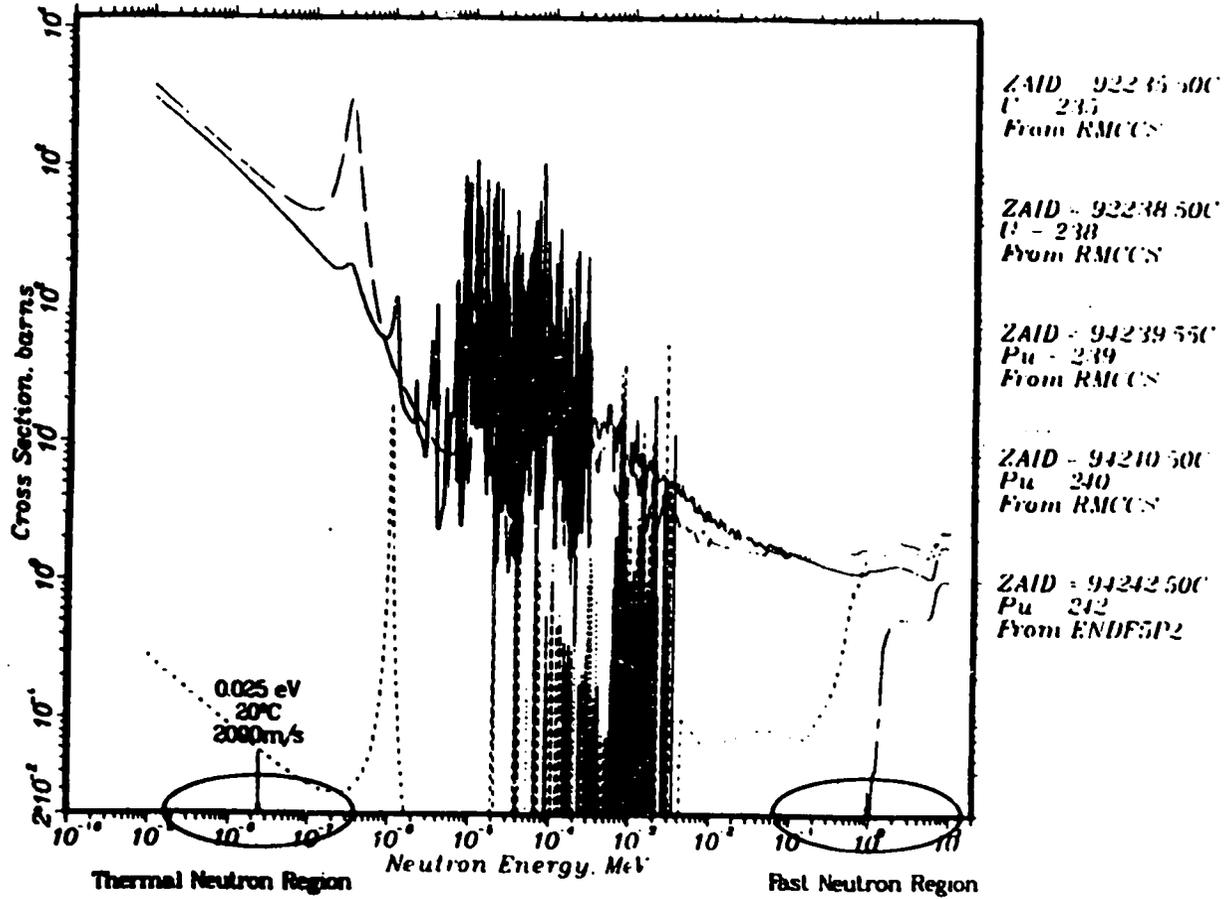


Figure 2-2 Fission cross sections for selected isotopes.

From: Schlessor, John A. et al. Los Alamos National Laboratory

- Importance cards
- Material specification cards
- MCNP "mode" cards
- Tally cards

Each of these sections is discussed in more detail in Appendix A.

2.5 Uranyl Nitrate Solution System

A simple model of a uranyl nitrate solution system in cylindrical geometry has been created. The geometry used in the study is shown in Figure 2-3 and the materials used in the model are defined in Table 2-2. This geometry was created by defining a total of 13 surfaces, nine of which were planes normal to the Y axis; three were cylinders centered on the Y axis, and two were spheres centered about the origin. The cells were created by defining the appropriate intersection and union of surface senses as explained in Appendix A. The two cylindrical slab tanks were surrounded by a spherical shell of six inch concrete; air was placed inside this sphere and around the tanks. The importance of the spherical region of interest was assigned a value of one while everything outside that region was assigned an importance of zero. The number densities used for the uranyl nitrate solution were calculated assuming the data shown in Table 2-1 (see Appendix B for the calculations) [4] while the number densities for the remaining materials were taken from published literature [17] (in reality, atom fractions were entered; but as explained in Appendix A, this is equivalent to number densities). While not to be used in practice, the concrete shell was used in order to crudely model any reflection effects from surrounding walls.

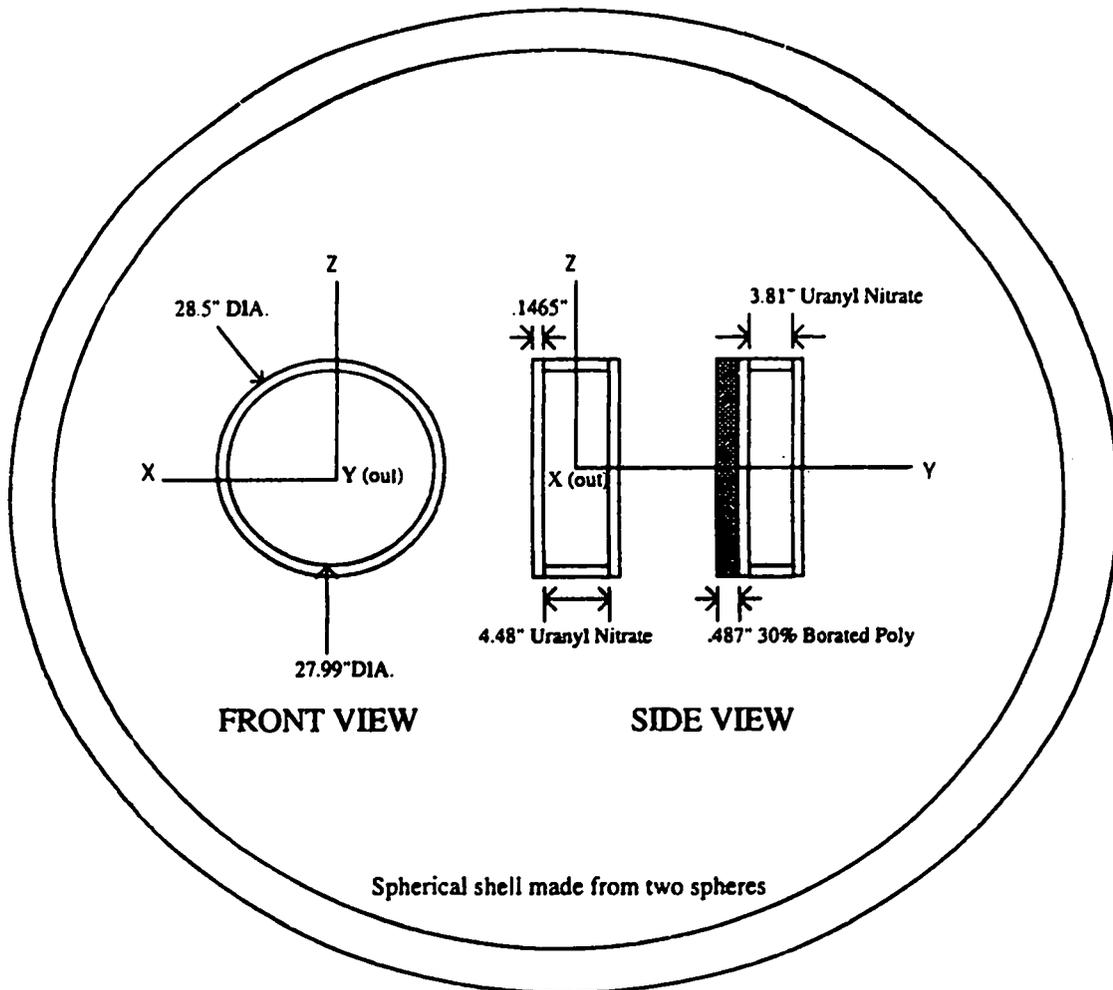


Figure 2-3 : Slab Geometry

Table 2-1 : Assumed Values for Number Density Calculations

| |
|---|
| Solution Concentration: 405.2 g/l |
| Nominal Overall Density of Uranyl Nitrate: 1.558 g/cc |
| Solution Acid Content: .32 Molar (HNO ₃) |
| Enrichment: 93.1 % ²³⁵ U |
| 5.9% ²³⁸ U |
| 1% ²³⁴ U |
| β for ²³⁵ U = .007 |

Fission products such as ^{236}U were not included in the model since the affect on the fission process has been assumed negligible. In addition, other extraneous elements that might be present in solution such as Fe, Na, or Al were not modeled. The general goal of this study was to determine the system sensitivity by varying the air gap between the two tanks, thereby revealing limitations and characteristics that must be considered when assembling the control system.

Table 2-2 : Model Materials

| Material | Composition | Number Density (atoms/barn-cm) |
|-------------------------|------------------|-----------------------------------|
| Uranyl Nitrate Solution | ^{234}U | 1.0433×10^{-5} |
| | ^{235}U | 9.6719×10^{-4} |
| | ^{238}U | 6.0521×10^{-5} |
| | H | .054439385 |
| | O | .03600846 |
| | N | .00226872 |
| Stainless Steel | C | .000317 |
| | Cr | .016471 |
| | Mn | .001732 |
| | Fe | .06036 |
| | Ni | .006483 |
| | Si | .001694 |
| Concrete | H | 1.4868×10^{-2} |
| | C | 3.814×10^{-3} |
| | O | 4.1519×10^{-2} |
| | Ca | 1.1588×10^{-2} |
| | Si | 6.037×10^{-3} |
| | Mg | 5.87×10^{-4} |
| | Fe | 1.968×10^{-4} |
| | Al | 7.35×10^{-4} |
| | Na | 3.04×10^{-4} |

(table continues)

| | | |
|---------------------|----|-----------|
| Air | Ni | .784 |
| | O | .211 |
| | Ar | .005 |
| 30 wt% Borated Poly | H | 5.19x10-2 |
| | C | 2.06x10-2 |
| | B | 3.54x10-2 |

2.6 Results

Figures 2-4 and 2-5 show the results of the air gap study. All values of k_{eff} shown are at the 68% confidence level. The k_{eff} values shown have been calculated by combining three separate estimation techniques that MCNP employs (collision, absorption, and track length estimates). The following general characteristics of the model are noteworthy when a comparison with experimental data is made:

- model does not include fission products or other elements such as iron, aluminum, or sodium that could be present in solution
- model geometry may differ slightly due ambiguities in some experimental dimensions

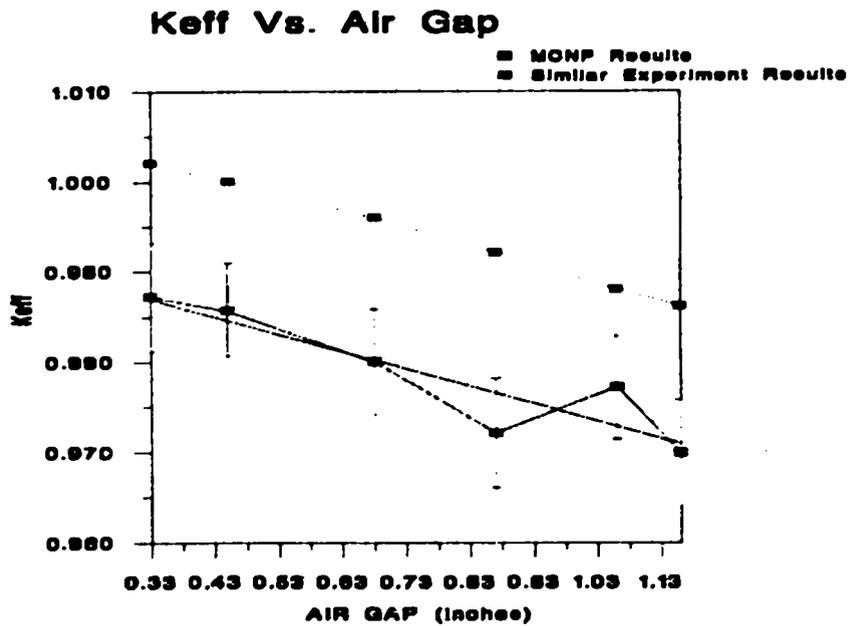


Figure 2-4 : K_{eff} Vs. Air Gap

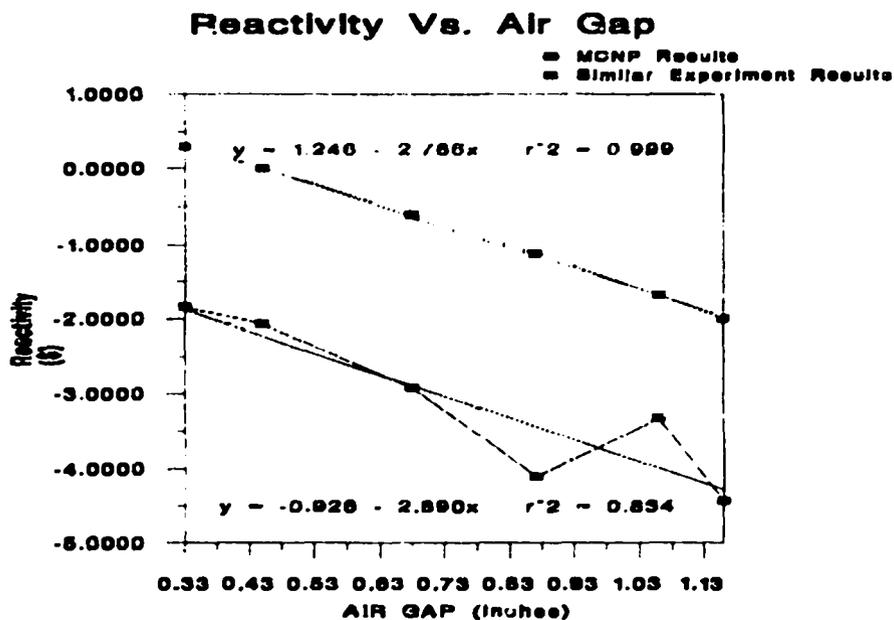


Figure 2-5 : Reactivity vs. Air Gap

The results shown are within two percent of similar experimental results for uranyl nitrate in slab geometry. Although this error might initially appear small, it is enormous in terms of criticality. For example, a 1.426 percent error in k_{eff} translates into approximately two dollars difference in reactivity: a difference between the system being well subcritical vs. the system being delayed critical; refer to air gap = .45" on Figures 2-4 and 2-5. While the experimental reactivity at this separation distance is zero, the reactivity from the MCNP study is calculated as:

$$\begin{aligned}
 \rho &= \left(\frac{k_{eff} - 1}{k_{eff}} \right) \times \left(\frac{1 \text{ dollar}}{\beta \text{ reactivity}} \right) \\
 &= \left(\frac{.98574 - 1}{.98574} \right) \times \left(\frac{1 \text{ dollar}}{.007 \text{ reactivity}} \right) \\
 &= -2.07 \text{ dollars}
 \end{aligned}$$

Due to the extreme effects of small changes in k_{eff} , any model that will be used to predict criticality must precisely account for the effect of each material in the general vicinity of the fissioning system. This was not the case for the experimental data referenced here; the model does not precisely account for all materials present in the actual experiment. So why model the system in the first place? Although the information shown in the two figures cannot (and absolutely should not) be used for criticality prediction, it *can* be used for sizing the control system. This is because, although the MCNP results are offset from the experimental results, the *slope* of the MCNP data is in approximate agreement with the experimental results. In fact, the Monte Carlo results yield a 4.5 % conservative estimate for the slope of the plot. This means that the maximum rate at which the assembly will be allowed to move (as defined by the conservative estimate) will be slower than the actual maximum speed allowable (as defined by the experimental results). In this case, we were lucky since there were experimental results with which to compare the numerical results. If an experiment were to be performed without such a luxury, we would need to painstakingly ensure that the model resembled the physical system as accurately as possible by modeling each material present in the experiment exactly (e.g.: exact dimensions, exact solution composition¹).

Nominally four to five million collisions were banked with approximately 140,000 neutrons generated per run. In assessing the results of these Monte Carlo calculations, a distinction is made between precision and accuracy. Precision is the uncertainty in the average value calculated by the program itself. Accuracy, on the other hand, is a measure of how close the calculated result is to truth. In other words, results may be precise and not very accurate, or conversely may be accurate and not very precise. In

¹Including the possible presence of unvented radiolytic gases

this case, since we know that the truthful value is approximately 10.89 cents/mm based on previous experiments with the uranyl nitrate packages, we may conclude that the model prediction of 11.38 cents/mm is very accurate (.49 cents/mm conservative) despite the lack of highly detailed modeling. The precision of the data shown is at the 68% confidence level; in other words, if 100 runs are performed, then 68 of the values (one standard deviation) will fall within the precision bars shown on the plot. While the data shown is not extremely precise, the number of cycles performed (50 cycles with a nominal 3000 neutrons generated per cycle) is considered large enough to result in adequate accuracy. Therefore, the numerical results shown here corroborate the slope measured from experiment and suggest a more conservative estimate for sizing the control components. This is the estimate that will be used in chapter eight.

2.7 Summary

The Monte Carlo studies performed indicate that approximately 11.38 cents of reactivity are added for each millimeter of closure between the tanks. This value conservatively corroborates the experimentally measured value of 10.89 cents per millimeter and, in general, provides an estimate for how much excess reactivity is present in the system (i.e., how sensitive the system is to small displacements). As will be shown in chapter seven, these values set the maximum allowable velocity, the stepper motor and drive type, the lead screw pitch, and the gear reduction ratio.

Chapter 3.

CONCEPTUAL MECHANICAL DESIGN

3.1 Basic Mechanical Requirements

While it is not the goal of this study to provide the detailed drawings for manufacturing experimental apparatus, the mechanical design aspect of the project must nevertheless be addressed on a conceptual level. The fundamental mechanical requirements for the experiment include the following:

- Two frames must be designed that will hold each of the two cylindrical tanks. Reflection from these frames must be held to a minimum; therefore, a minimum amount of material that still provides the greatest stability and reliability must be used. Since the mean free path of aluminum is relatively large, this material is somewhat transparent to neutrons and would serve well for the application.
- A translation device must be designed or purchased that will be driven by a stepper motor upon which the moving slab tank will rest.
- Adjustment devices must be designed or purchased in order to adjust the relative slab tank positions.

The main requirements can be summarized by the need to secure both slab tanks on each cart with the maximum adjustment capability (positional fine tuning) and the minimum neutron reflection. Since these goals are contradictory in nature, a number of design iterations will be necessary; a conceptual design to begin the process is offered in this chapter.

As seen in Figure 3-1 on the following page, the "honeycomb" structure is a lattice of extruded aluminum tubes that were placed together for a previous experiment on the horizontal split table referred to as "Honeycomb."

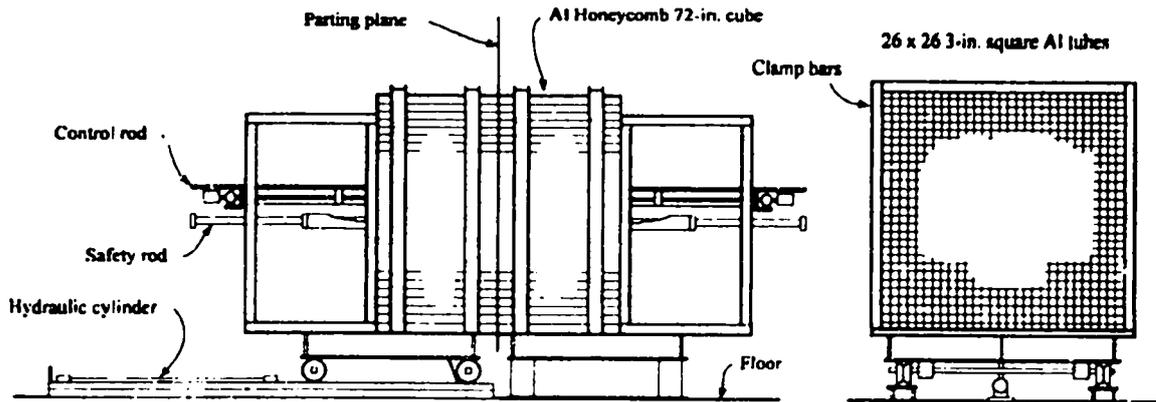


Figure 3-1 : Current Experimental Configuration ("Honeycomb")

This is the current configuration of the experimental assembly; as shown, the extruded aluminum tubes are held in place by four clamp bars. The next section discusses the options available in fitting this split table for the slab tanks experiment.

3.2 Options for Performing the Slab Tanks Experiment on Honeycomb

There are two options that may be considered when approaching the conceptual mechanical design. The first is to mount the tanks on the existing split table with the honeycomb structures in place. The second option (Figure 1-3) is to take the honeycomb structure off of both tables and design space frames for each tank from scratch (as opposed to retro-fitting a design to the existing honeycomb structure). The latter of these two options is preferable since positioning of the slab tanks may be accomplished in a much more precise manner using this approach. As the numerical study clearly indicated, the system is extremely sensitive to small changes in tank position; therefore, relatively small tolerances on the order of .001 inch must be imposed on the mechanical design. Although this avenue is more costly, it provides for greater experimental accuracy since positional adjustments may readily be designed into the structure from the outset. The advantage of removing the Honeycomb material is particularly evident when considering that locating any single point within the lattice is achieved at best with large uncertainties due to the structure's

construction and the original experimental intent: to mockup relatively large critical systems with inherently loose tolerances. As seen in Figure 3-2 below, the tank would ideally have adjustment capabilities in the X, Y, Z, THETA X, and THETA Z directions in order to ensure proper tank alignment and increase experimental flexibility. While this goal is ideal, cost and fabrication constraints practically limit the adjustment features to a minimum: the X and Y directions.

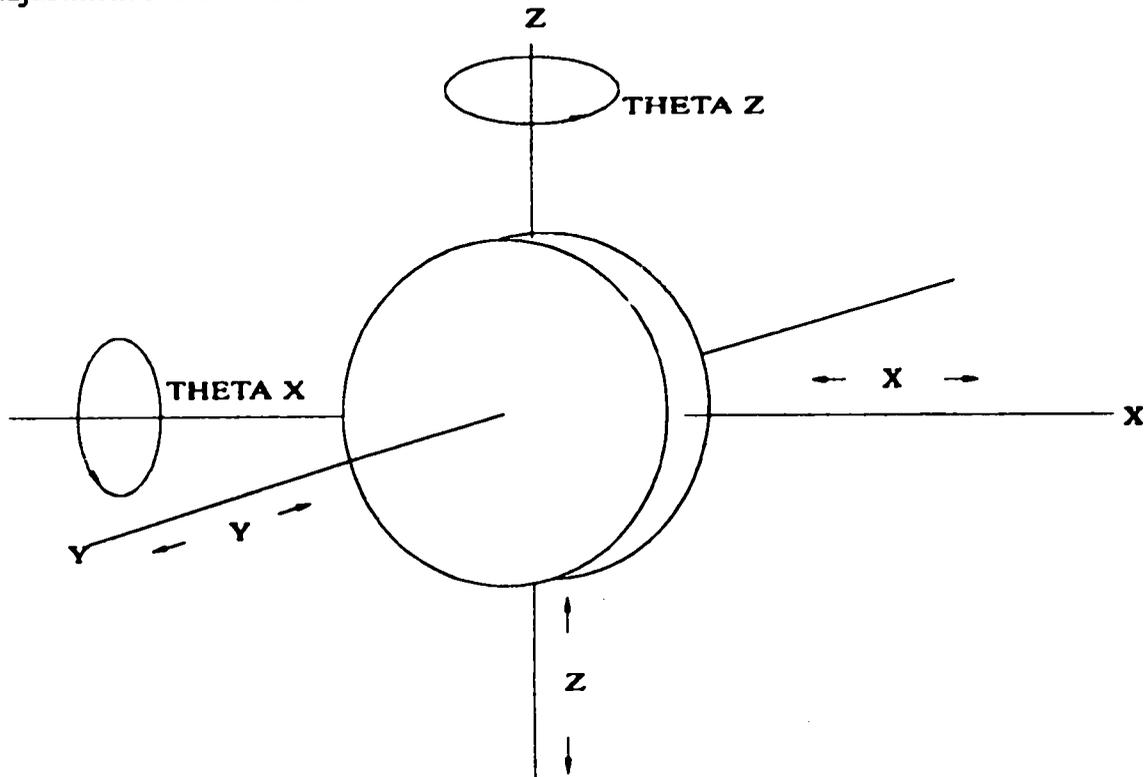


Figure 3-2 : Adjustments Ideally Available for Slab Tank Alignment (Slab Tank on Movable Cart)

Adjustment in the Y direction allows for final closure via a stepper motor/lead screw attached to a translation table while adjustment in the X direction offers fine adjustment to ensure the tanks are not offset with one another. The remaining adjustment axes shown must be fixed accurately by the mechanical design itself or adjusted with shims.

3.3 Mechanical Design Concepts

Table 3-1 displays the general design philosophy from the most essential, basic functions at the top, down to the less essential but no less desirable detailed functions at the bottom. Included in this table are likely hardware solutions to the desired functions.

Table 3-1 : Mechanical Function and Solution From Most to Least Essential

| FUNCTION | SOLUTION |
|---|---|
| Tank security and stability | Rigid aluminum space frame |
| Rough tank movement over a relatively long distance | Hydraulic cylinder |
| Fine tank movement over a relatively short distance | Stepper motor/lead screw |
| Tank alignment adjustment in the X direction | Micrometer head/lead screw device (figure 3-3) |
| Tank alignment adjustment in the Z direction | Micrometer head/lead screw device (figure 3-3) |
| Rotational adjustments | Rotational table/micrometer head device |

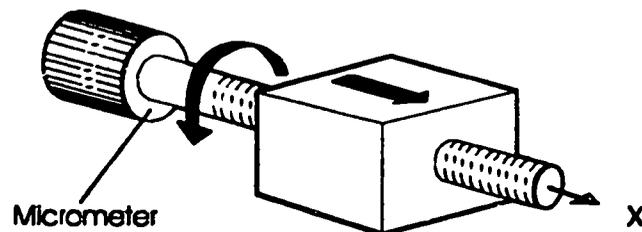


Figure 3-3 : Micrometer Adjustment with a Lead Screw Concept

Figure 3-4 below illustrates one possible mechanical configuration for achieving the minimum requirements. In this option, two translation tables are essentially stacked on top of one another in order to provide for the X and Y translation. A micrometer head is used as the means for adjustment in the X direction while a stepper motor is used to achieve final closure in the Y direction. Figure 3-4 presents one feasible option for the mechanical hardware configuration and is not intended to be exclusive of other configurations that may be equally viable such as different space frame designs or slab mounting methods. The following chapters discuss how such a system will be controlled remotely and assume a given mechanical configuration.

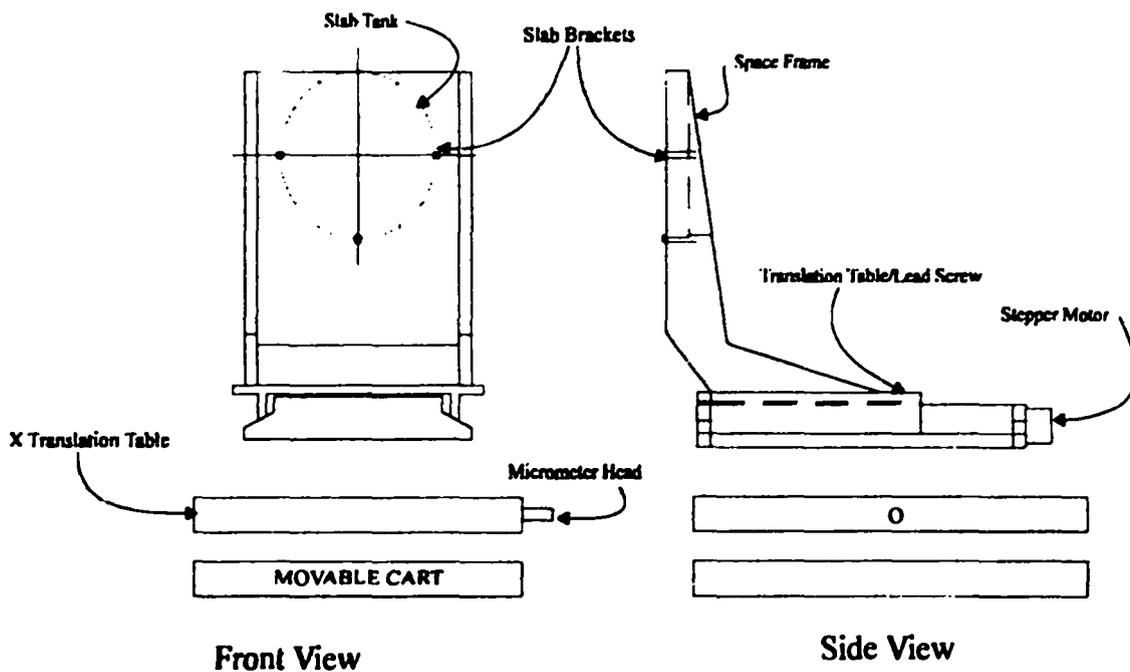


Figure 3-4 : An Option for the Mechanical Configuration

Chapter 4.

APPROACHES TO EXPERIMENT CONTROL

4.1 General Mode of Operation

After determining the basic system parameters (namely, the system's mechanical design and change in reactivity with linear position), we are in a position to consider the control system. Typically, the control system used for critical experiments will not operate using PID type automatic control and will not require the extremely fast response found in high performance servo-type control systems [8.19]. Instead, the system will incorporate simple feedback to verify the state and position of output devices; this is the simplest system that achieves consistent and reliable mechanical control. Although feedback is present in such systems (optical encoder, thermocouples, etc.), it will generally not be used for proportional type control of an experiment (as indicated by the dashed line in Figure 4-1 below). This restriction is dictated by current DOE enforced technical specifications.

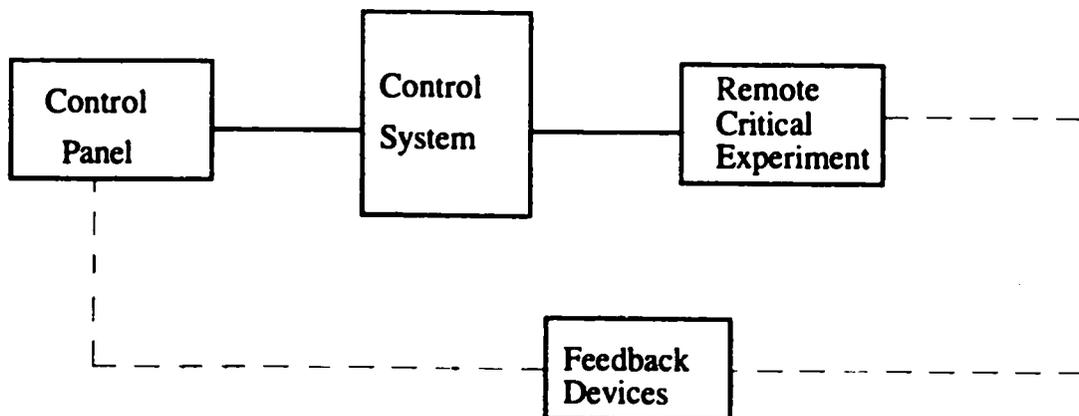


Figure 4-1 : Block Diagram of the General Control System

4.2 Digital Vs. Analog

In the past, control of critical experiment remote assembly machines has been achieved through the use of hard wired control systems. Although such systems have proven reliable, the advent of the powerful, dependable, low cost, microprocessor has made digital systems a very lucrative option. Unlike hardwired systems, a digital control system offers the flexibility of quickly and easily changing the controller characteristics by simply re-writing the control program. For example, if the estimate for the slope calculated in the previous chapter is later found to be too conservative, the closure velocity may be easily changed simply by re-writing a few lines of code. This flexibility, combined with increased power and reliability, has propelled the digital control system past its hardwired counterpart for critical experiment control applications. There are two avenues that might be pursued when controlling a system digitally: a custom designed system, or an off-the shelf purchased system.

4.3 Custom Digital Systems

The first option involves designing the entire control system around a single microcontroller chip. Typically, such chips contain on-board memory, timers, ports, and other support functions that would normally require separate IC chips.

Customized microcontroller-based systems offer the following advantages to the potential user:

- control of the system and software at the machine language level
- increased flexibility to meet exotic demands

On the other hand, customized systems involve the following drawbacks:

- the system is harder to maintain due to its increased complexity
- to construct such a system requires a PROM burner and other additional peripheral hardware investments

- debugging, maintenance and construction requires specialized knowledge and experience

Thus, for specialized applications demanding a large degree of flexibility in control, a customized system may be appropriate.

4.4 Purchased Systems

The other alternative is to purchase a pre-manufactured microprocessor based system, typically referred to as a Programmable Logic Controller (PLC) [13], from a vendor. This alternative is preferred in the nuclear criticality arena because in-depth documentation and verification of control system reliability is greatly simplified. Unlike most customized systems, pre-purchased digital systems offer relatively simple programming software and allow for more efficient and thorough maintenance. For these reasons, it was decided to purchase a PLC system from the Allen-Bradley corporation rather than creating a customized control system. This control system is introduced in the following chapter.

Chapter 5.

CURRENT CONTROL SYSTEM HARDWARE

5.1 Introduction

Currently, Control Room One at LACEF is fitted with a digital control system that was originally installed to control the SHEBA (Solution High Energy Burst Assembly) experiment (see Figure 1-2). Specifically, the system is manufactured by the Allen-Bradley corporation and incorporates convenient system modularity with a simple graphical programming language. An overview of the typical physical system to be controlled is seen below in Figure 5-1.

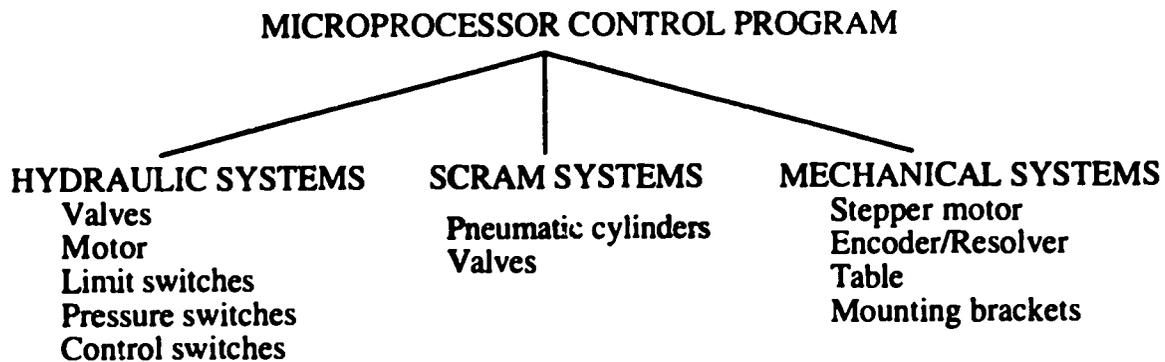


Figure 5-1 : Typical Critical Assembly Control Device Requirements

The main goal of this section of the study is to assemble a functional control system on a test bench that will allow for program development and hardware testing without intrusion on the current system in Control Room One at LACEF. With such a system, the following types of devices may be tested:

- DC stepper motors (with two different approaches to their control as discussed later)
- digitally controlled relay contact devices
- AC synchronous constant speed motors

The devices shown in Figure 5-1 are basic to controlling many types of critical assemblies. An assembly that requires rotational or translational motion will employ one or all of these devices in addition to the peripheral components that form the backbone of the control system; these peripheral components make up the test bench control system that is described in the following pages. In chapter seven, expansion of

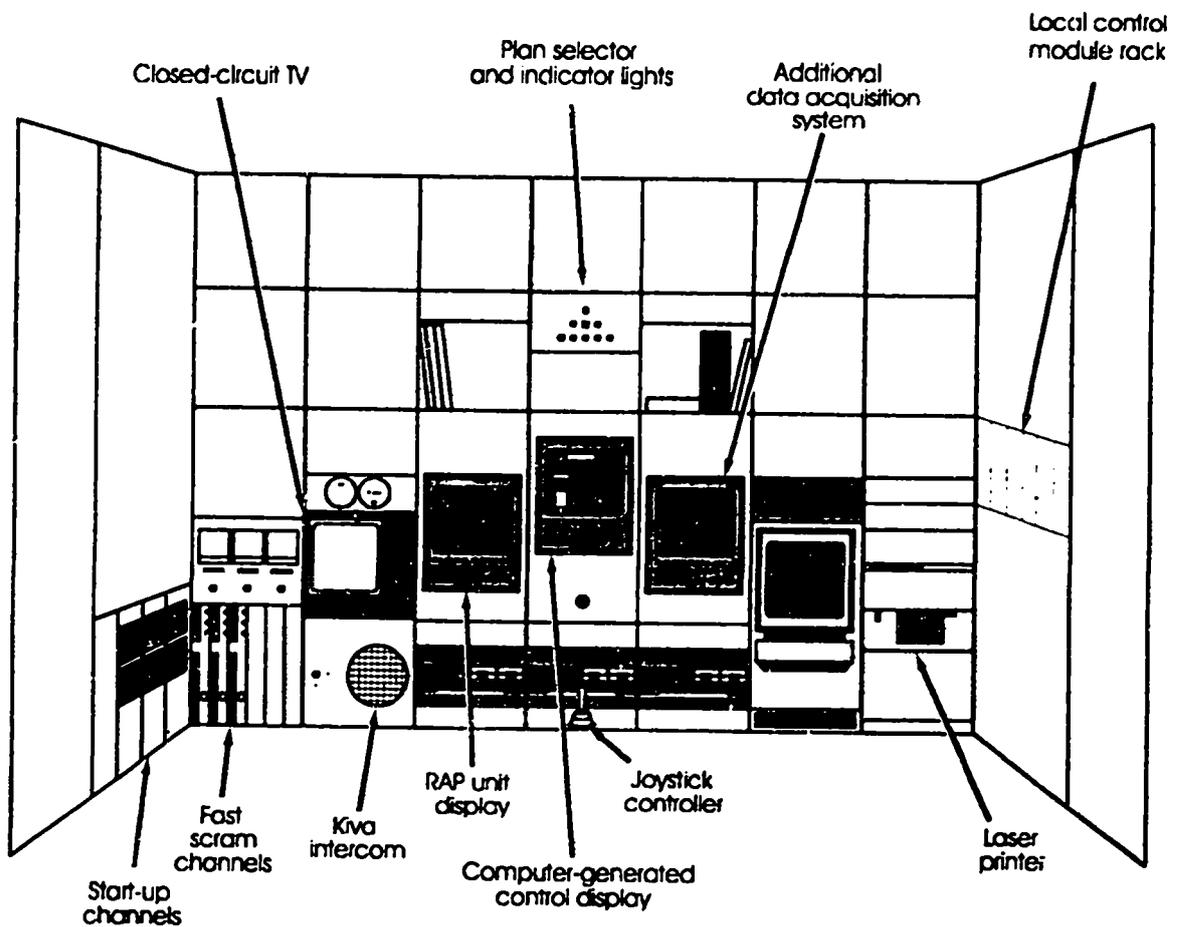


Figure 5-2: Current Control Room One Configuration

the control system that is already in use in Control Room One to include experiments in KIVA I is discussed. This chapter, as well as the next, form the groundwork for the eventual expansion into KIVA I (note in Figure 1-2 that the SHEBA building is

separate from KIVA I; the SHEBA building currently employs an Allen-Bradley system while KIVA I does not). Figure 5-2 on the previous page shows the current configuration of Control Room One.

5.2 Test Bench Control System

Shown in Figure 5-3 is a schematic of the control system test station that has been setup at Pajarito site. This system has been created from spare parts available from the SHEBA system; when it is required to expand the current Control Room One system, parts from this system may be used. The purpose of the setup that currently exists is to provide a platform for on-line programming and testing that can be used to write and debug "ladder logic" programs which will eventually be uploaded to the processor

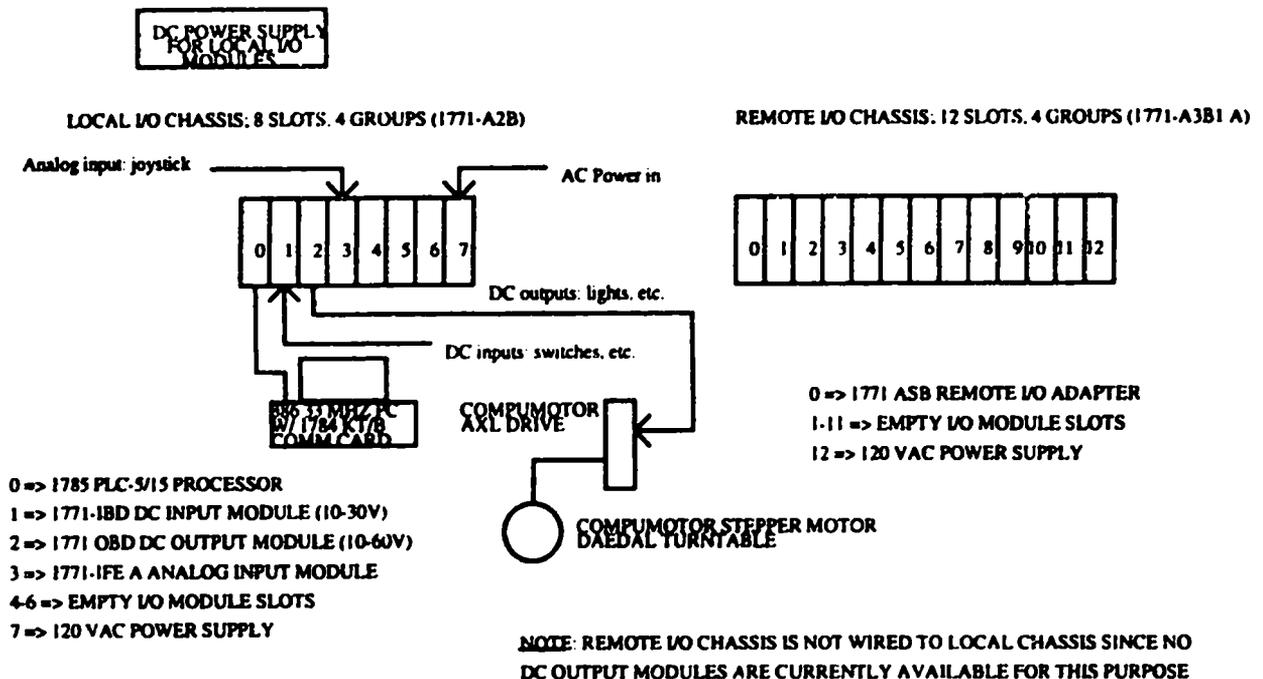


Figure 5-3 : Program and Hardware Test Station

currently used in Control Room One. In addition, such a test platform serves as a center for the test and evaluation of hardware that might eventually be used for the KIVA I system. This separate system allows for on-line programming and hardware

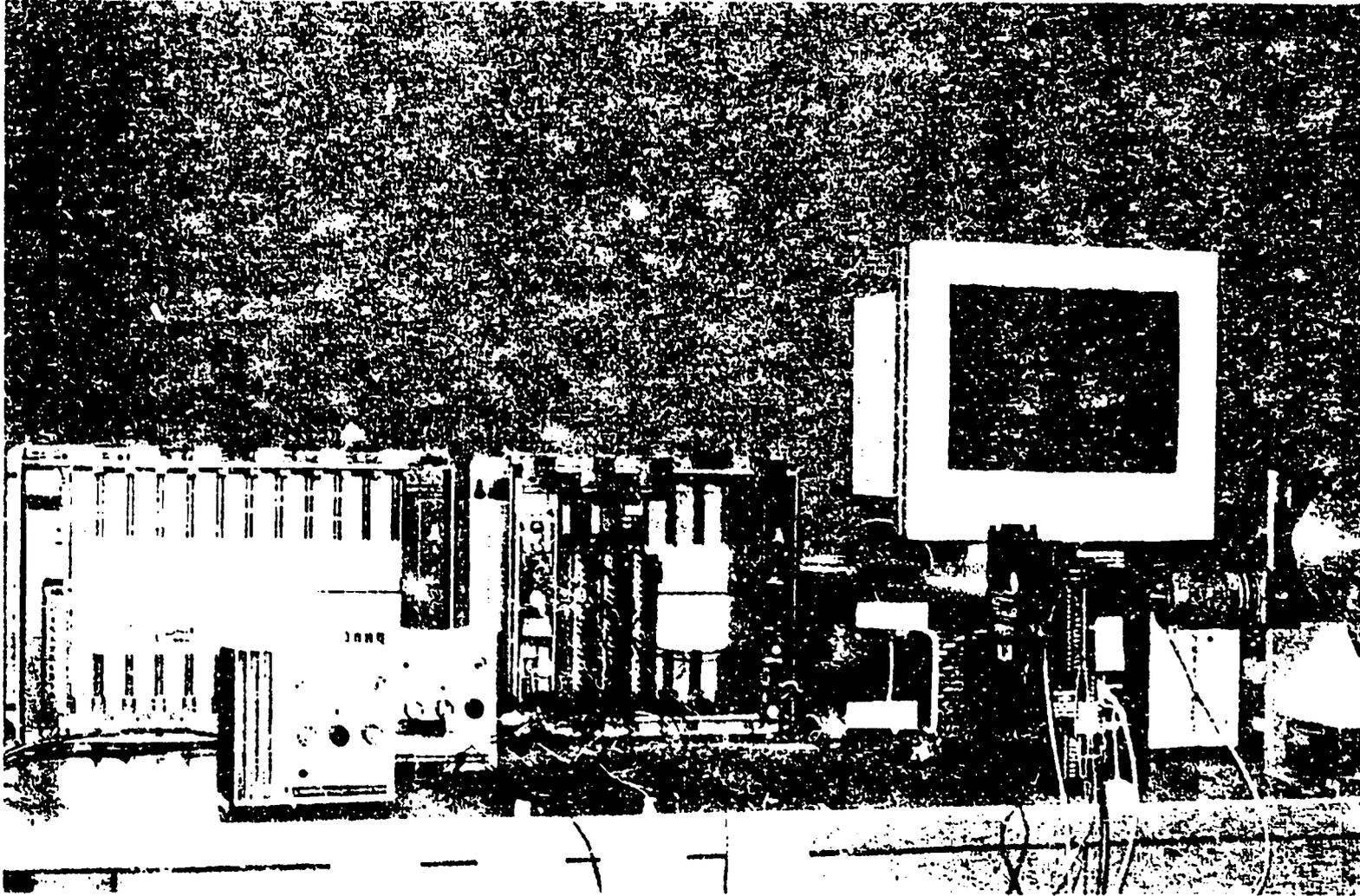


Figure 5-4 : Control Hardware at Pajarito

familiarization without intruding on the system currently in operation in Control Room One. As seen in Figure 5-3, the assembly uses a driver which controls a stepper motor attached to a turntable; this is one of two options for driving a stepper motor.

5.3 Configuring the System

System configuration involved setting dip switches on the top and bottom of the PLC-5/15 processor module and the I/O chassis backplane [1,2,3]. These switch settings defined parameters like the rack number, the I/O group (used when programming the PLC system), the transmission rate, and the power supplies present. The Compumotor AX drive was configured by setting a single dip switch assembly near the bottom of the case [7]. This switch assembly defined what kind of motor (i.e., current requirement) was to be driven and the address of the AX drive (to be used when writing a program to be stored in the drive).

5.4 Component Summary

5.4.1 1785 PLC-5/15 Processor

This is the heart of the control system. The control program (written in "ladder logic" using the PLC software) is uploaded to the PLC-5 PROM from the personal computer via the 1784 KT/B communication board. A short test program utilizing two switches and LED indicators available on the DC output module was written to validate that each component seen in Figure 5-3 is operable [1]. The PLC-5 module serves as the main control module; the sole purpose of the PC is as a programming terminal and data monitor station (using ControlView software). The PC does not directly control anything.

5.4.2 1771 IBD DC Input Module

The DC input module accepts input from common DC devices such as switches or push buttons and communicates with the processor via the "backplane" (printed circuit board) located on rear the I/O chassis. DC input and output modules require a separate DC power source as seen in Figures 5-3 and 5-4. For the KIVA I expansion discussed in chapter six, a DC input module has been placed in the remote I/O rack in order to provide for the option of a scram mechanism located inside the KIVA itself.

5.4.3 1771 OBD DC Output Module

The DC output module is the logical counterpart to the DC input module and, like all other modules in the chassis, communicates with the processor via the backplane. The output module is wired to devices requiring 10-60 V DC power such as lights, seven-segment displays, horns, or valves.

5.4.4 1771 IFE A Analog Input Module

As its name implies, the analog module accepts analog signals from real world devices. For control of a critical assembly, this module will accept analog signals from the potentiometers that makeup the joystick control device (a typical joystick is made using one or more potentiometers). The ladder logic program will dictate the details of the interface between the joystick and the output device. This module is simply an analog to digital converter.

5.4.5 120 VAC Power Supply

This provides power (converting voltage from AC to DC) via the backplane to the modules located in the rack. A power supply of this type is required for each I/O chassis.

5.4.6 Compumotor AXL Drive

The compumotor AXL drive combines two functions in one package. First, it acts as a pulse source. This is basically a source of square pulse waves that is used to tell the stepper motor how far and fast it should rotate. The second function of the Compumotor package is as a drive or "translator." A translator takes the pulse train generated by the programming commands and translates it into the voltage necessary for energizing the motor windings. The motor drive may be programmed via an RS-232 port from a regular PC. The program is written in a simple language developed by compumotor and is stored in the AXL's resident PROM (up to seven such programs may be stored). A stored program may be executed via the RS-232 connection, or, it may be executed via the PLC control system. To run the program via the PLC system, one sends a pseudo BCD number (3 bits instead of four) to the SEQ1, SEQ2, and SEQ3 lines of the AXL drive. Depending on the combination of the three sequences, one of the seven programs will be run. Although this method of stepper motor control offers a great deal of power and flexibility, there is another option to stepper control that is preferred. This option (a separate pulse source) is discussed in the next section. The programming that accompanies the integrated drive is discussed in chapter eight as well. In the future, detailed developments include adding following components to the system:

- encoder feedback module
- power contact relay module
- stepper positioning modules, translator, and new stepper motor

5.5 Control of DC Stepper Motors

Often, an experimental application requires small, precise changes in motion; this is typically achieved with a DC stepping motor. A DC motor uses direct current power

in order to induce a current on the rotor of the motor that causes the output shaft to rotate [5]. This is accomplished by the use of a commutator and brush. The commutator is a cylindrical object upon which the brushes ride to change the direction of current in the windings in order to keep the rotor rotating. A "brush" is a piece of conductive material riding on the commutator which conducts current from the power supply to the rotor windings (stator). A "permanent magnet" DC motor uses a permanent magnet as the stator instead of windings; windings are used for the rotor.

There are two main options available for the control of a standard permanent magnet hybrid stepper motor. The first option involves purchasing an integrated unit from a manufacturer (like the Compumotor AXL drive discussed in the previous chapter). The second option involves purchasing a standalone pulse source from the

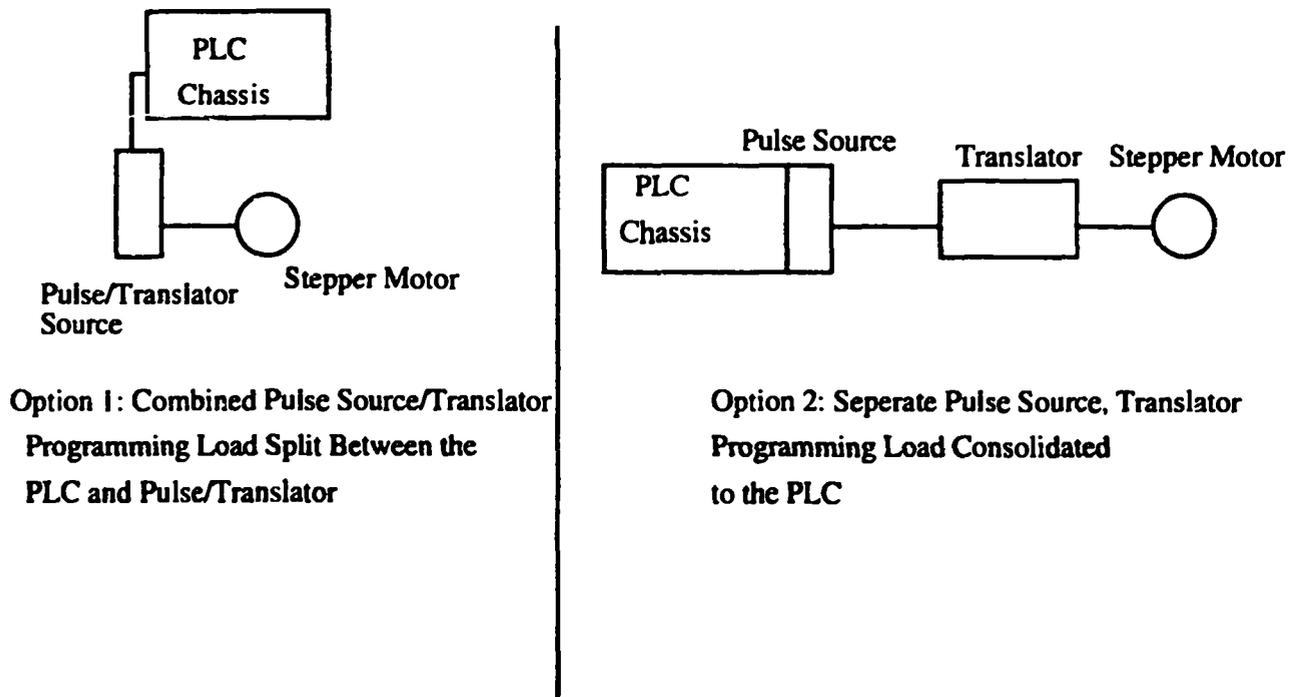


Figure 5-5 : DC Stepper Control Options

PLC vendor and sending that pulse train through a separate translator (i.e., split up the translation and pulse generation functions). DC stepper motors are controlled by varying the pulse rate sent to the motor translator (or "drive"). The translator and motor are sized according to the specific task and the pulse rate is controlled through software. As described before, a translator basically takes the pulse rate (generated externally this time) and "translates" the pulse rate into the appropriate voltage necessary to move the motor. The first of these two options was realized on the test bench; however, it is preferable to consolidate all of the programming and control to only the remote PLC chassis (instead of programming both an integrated drive and the PLC system). For this reason, a stepper positioning assembly that splits translation and pulse generation functions has been used in the Control Room One expansion layout discussed in chapter six.

5.6 The Stepper Motor Drive: Characteristics and Selection

The stepper motor translator contains the logic necessary to "translate" the pulses generated by stepper motor control assembly (indexer) into the correct voltage needed by the stepper motor for shaft rotation. The stepper motor will rotate one step for each pulse received from the controller and its performance is very closely coupled to the translator's performance. If a low performance translator is used in conjunction with a high performance stepper motor, the overall performance is defined by the lowest performing device and a costly mismatch exists. Translators may be purchased to operate in a number of different modes; typically, full, half, or micro-stepping mode. In the full step mode, the translator will step the motor one full step for each pulse received while in the half step mode the motor will be stepped one-half of its full step (0.9 degrees if the motor used has 1.8 degrees/step). Microstepping refers to a

feature found on more expensive translator devices which are capable of stepping the motor by as little as 1/125 of the full step per pulse received. The translator also contains the circuitry necessary to optically isolate the higher voltage area from the control system.

Chapter 6.

CONTROL SYSTEM EXPANSION

6.1 PLC System Expansion Into KIVA I

Figure 6-1 shows a control system design that may be used for the current PLC control system expansion into KIVA 1. In particular, the configuration shown may be used to control up to three stepper motors and would be ideal for a variety of experimental setups including the uranyl nitrate experiment on the horizontal split table "honeycomb."

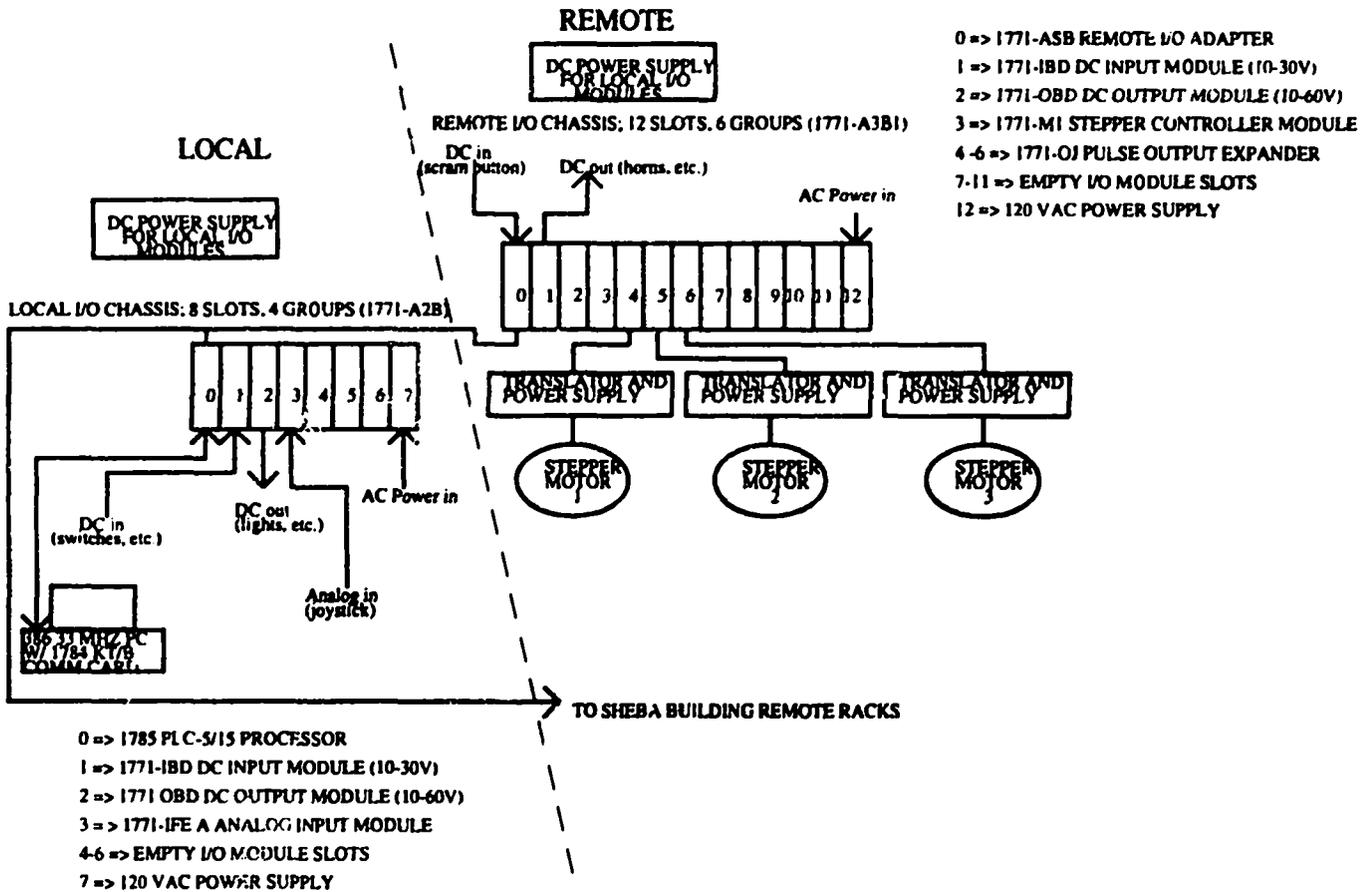


Figure 6-1 : Anticipated KIVA I Control System

This layout contains the following additional modules that have not been used in the test bench setup shown in chapter five.

6.1.1 1771-ASB Remote I/O Adapter

The remote I/O adapter serves as a communication link with the local PLC-5 processor and communicates with all of the other modules in its rack via the backplane.

6.1.2 1771-M1 Stepper Control Module

This module controls the pulse output that is sent out to the stepper motor.

6.1.3 1771-OJ Pulse Output Expander

One pulse output expander is required for each stepper motor to be controlled. One stepper control module may accommodate a maximum of three such modules and therefore three stepper motors. The pulse output expander is responsible for communicating the pulse information from the control module to the stepper motor itself. In order to fabricate the system shown in Figure 7-1, the following parts must be used from the test station that is currently setup in building 30:

Table 6-1: Control Components for KIVA I on Hand

| ITEM | FUNCTION |
|-------------------------------|---------------------------------------|
| 1771-IBD DC input module | provide for local DC input |
| 1771-OBDC DC output module | provide for local DC output |
| 1771-A3B1 12 slot I/O chassis | house remote I/O modules |
| 1771-ASB remote I/O adapter | provide communication for remote rack |
| 1771-A2B 8 slot I/O chassis | house local I/O modules |

In addition, the following components which are not in stock are needed:

Table 6-2 : Necessary Control System Components for KIVA I

| ITEM | FUNCTION |
|--|--|
| 1771-OBDC DC output module | Provide for remote DC output |
| PLC-5/15 to 1771 ASB twinaxial cable (either 1770-CD or custom made) | Enable connection between local and remote rack (maximum distance is 10,000 feet) |

(table continues)

| | |
|---|--|
| 1 1771-QA stepper positioning assembly | Generate pulse source for stepper motor control |
| Slo-Syn stepper motor | Convert electrical energy into useful mechanical energy |
| Slo-Syn translator/power supply (stepper motor drive) | Translate digital information from pulse source to motor shaft rotation; provide power and isolation |

The remaining items necessary to realize the system shown in Figure 6-1 are in stock on site (i.e., PC, power supplies, and connectors).

6.2 Control of AC Synchronous Constant Speed Motors

When an application requires less demanding precision in small movements, an AC constant speed motor is often used as an on/off device to fulfill the requirements. For example, while a stepper motor might be used to precisely push two tanks together through a lead screw in one experiment, an AC constant speed motor might be used to rotate safety drums (containing poison) in and out by 180° in another experiment. An AC motor is differentiated from a DC motor by the fact that, for AC motors, rotor currents are not induced by a commutator and brushes. Instead, current is induced in the rotor conductors by the stator's changing magnetic field (sometimes referred to as "induction action"); thus, this type of motor operates by setting up a rotating magnetic field on a rotor. Typically, the rotor is of the "squirrel cage" type and the rotating magnetic field is setup by sending single phases of multiphase AC power into specific "pole windings" (wound up conductive wire). When each phase of the polyphase AC power is correctly directed to its pole winding, a magnetic field is setup which tends to rotate the squirrel cage. By continually keeping a rotating magnetic field applied in this way, the cage (rotor) is kept continually rotating. Typically, one, two, or three phase AC power is used to rotate the cage. The difference between the speed of the rotating magnetic field and the cage itself is termed the "slip." When the design of the

motor allows the cage to "lock" into the speed of the rotating magnetic field, the "slip" is zero and the motor is said to be operating at "synchronous speed." When this mode of operation is reached, the motor operates at a constant speed that is directly proportional to the frequency of the power supply.

AC synchronous constant speed motors, specifically Slo-Syn SS series motors, may be controlled with a PLC system by utilizing the RC circuit shown in Figure 6-2 [18].

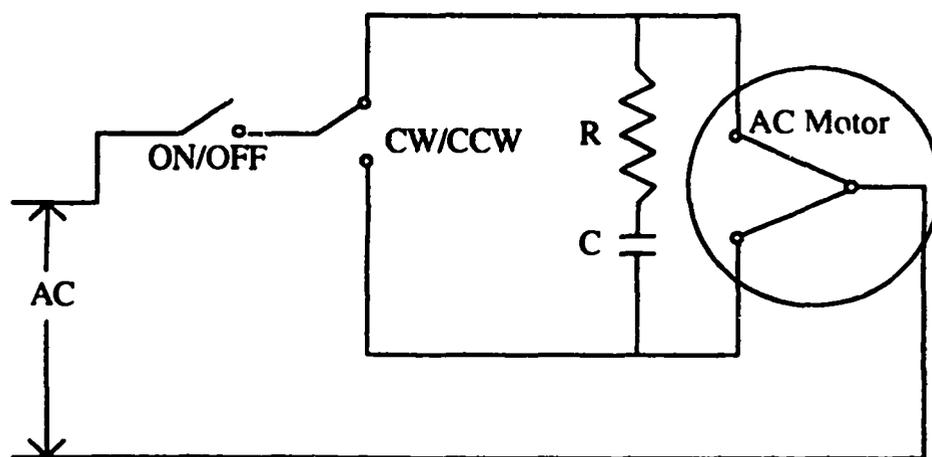


Figure 6-2 : AC Motor Control Circuit

The constant speed motor is turned on and off and changes direction by selecting the appropriate switch shown in Figure 6-2. The purpose of the resistor and capacitor is to change the single phase line voltage into the two phase voltage that is appropriate for energizing the motor coils. Although an actual three way switch could be used to control the motor status, critical experiments must be operated remotely; therefore, a power contact output module that can open and close relays may be used to select from among the three switch positions. Basically, this type of module allows remote relays to be turned on and off via the control program stored in the microprocessor

memory (located in a local I/O chassis). Once the motor has reached its final position, a limit switch can be used to turn the motor to its off position. In this way, use of optical encoder feedback is eliminated without losing final positional information.

Chapter 7.

USING THE NUMERICAL RESULTS TO SIZE HARDWARE

7.1 Introduction

Now that the general control system components have been established, the next step is to size a motor and translator drive to the specific job of running the uranyl nitrate experiment. Typically, this involves performing the following tasks:

- determine what type of motion is desired: typically either linear or rotational
- approximate the maximum and minimum allowable velocities based on criticality calculations or measurements
- determine what type of translator will be used
- determine the motor torque required

This general process has been performed for the uranyl nitrate slab tank experiment.

The general approach is to define all of the requirements based on the system information and then match the manufactured hardware to those specifications.

7.2 Horizontal Solution Assembly: the Slab Tanks

Recall the geometry and physical setup discussed in the previous chapters. The mechanical goal is to push two cylindrical tanks together without adding more than five cents of reactivity per second. This will be achieved, in part, through the use of a stepper motor and lead screw that will push the table supporting one of the tanks toward the other stationary tank.

7.2.1 Requirements

In order to precisely choose the correct stepper motor, it is first necessary to decide what general performance characteristics must be satisfied. The blocks of information on the following page serve as a data summary area for a stepper motor that will be driving a 61 kg mass through a lead screw. Note that certain characteristics are listed

as "to be calculated." These values will be determined later. Figure 7-1 shows a graphical representation of the desired velocity profile.

Table 7-1 : Mechanical Requirements

| MECHANICAL REQUIREMENTS | VALUE |
|---|---|
| Application | Translational Table |
| Weight | Weight = 61 kg |
| Mounting | NEMA type flange |
| Resolution | 200 steps per revolution (1.8°/step) |
| Accuracy | .054°/step (3% of resolution) |
| Environmental | Because of low power operation, there are no special environmental considerations |
| Damper (to reduce settling time for each step) | None |
| Leads or Terminals | 8 leads |
| Gearing/Lead Screws | Thompson lead screw |

Table 7-2 : Load Requirements

| LOAD REQUIREMENTS | VALUE |
|------------------------------------|--|
| Torque at speed | to be calculated |
| Inertia | to be calculated |
| Maximum Speed | to be calculated (see figure 1) |
| Acceleration/Deceleration Required | .5 sec to max velocity .5 sec to standstill |
| Single step time response desired | 2.5 ms |

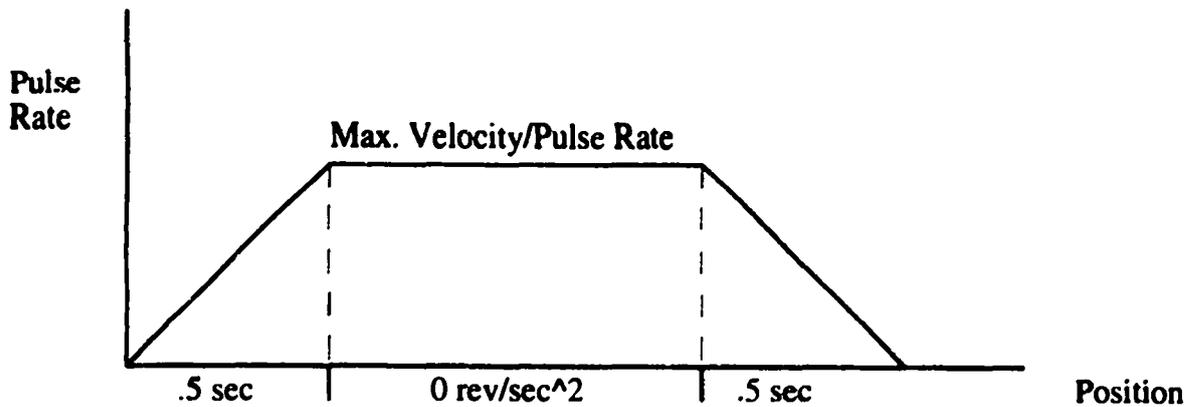


Figure 7-1 : Stepper Motor Velocity Profile

7.2.2 Maximum Speed Allowable

In chapter three, the absolute value of the slope of the reactivity vs. air gap plot was found to be approximately 11.38 cents/mm, which equals 2.89 \$/inch. The maximum reactivity insertion rate for a Class II reactor (reactor that goes delayed critical) as specified by the technical specification is five cents/sec. With this information, we may calculate the maximum permissible linear speed of the system as follows. This value will be used when writing the control program in chapter eight.

$$\begin{aligned}
 \text{max linear speed} &= \frac{(\text{max allowable reactivity})(\text{constant})}{\text{slope}} \\
 &= \frac{\left(5 \frac{\text{cents}}{\text{sec}}\right) \left(\frac{1\$}{100 \text{ cents}}\right)}{2.89 \frac{\$}{\text{inch}}} \\
 &= 1.038 \frac{\text{inches}}{\text{sec}}
 \end{aligned}$$

Due to this extremely slow speed, a gear head reduction will be needed in order to increase the nominal operating speed of the motor and avoid low power resonance effects.

7.2.3 Basic Formulas

There are three basic formulas that are often used in choosing control system components for a translational type system using a lead screw. In the case presented here, equation (1) may be used to solve for the gear head output speed, equation (2) yields the motor shaft speed, and equation (3) may be used to calculate the pulse rate.

$$GH = (P)(Linear\ Speed)[=] rpm \quad (1)$$

where:

GH = gear head output shaft speed in rpm

P = lead screw pitch in threads/inch

Linear Speed = speed in inches/minute

Next, the speed at which the motor is rotating is found with:

$$MS = (x)(GH)[=] rpm \quad (2)$$

where:

MS = motor shaft speed in rpm

x = the planetary gear ratio x:1

Finally, the maximum pulse rate allowable can be found using the equation:

$$PSEC = \frac{MS}{(SP)(DS)} [=] \frac{Pulses}{Second} \quad (3)$$

where:

PSEC = pulses/sec output by the stepper positioning assembly

SP = steps/pulse

DS = degrees/step

7.2.4 Maximum Pulse Rate

Using the value determined for the maximum speed allowable, the maximum pulse rate of the stepper control assembly may be calculated. Using equation (1), the maximum gear head output shaft speed is found to be:

$$\text{GH} = 10 \text{ rpm}$$

Using equation (2), the maximum motor speed is found to be:

$$\text{MS} = 520 \text{ rpm}$$

Finally, using equation (3), the maximum pulse rate that the stepper positioning assembly may send out without exceeding the reactivity insertion limit is:

$$\text{PSEC} = 3460 \text{ pulses/sec}$$

7.2.5 Minimum Speed Possible

The absolute minimum speed at which the unit can be run can be determined by considering the smallest pulse rate the control device is capable of generating. Assuming the minimum is 1 pulse/sec, use of equations (1) through (3) yield a minimum speed of .0025 in/min. Since this pulse rate is extremely low and might result in motor vibrations, a minimum pulse rate of 500 pulses/sec is assumed. With this value, the minimum linear speed is found to be .15 in/min.

7.2.6 Resolution

The resolution may be calculated by considering the minimum number of single pulses the stepper assembly can send out in a one second period. Thus the resolution is just the minimum velocity (in/sec) multiplied by the total time to generate the finite

number of pulses. For a minimum pulse rate of 1 pulse/sec, the resolution is .00004 in.

For a minimum pulse rate of 500 pulses/sec, the resolution is .0025 in.

7.2.7 Required Operating Torque

The last step is to calculate the amount of torque required to move the 61 kg mass at the desired velocity by applying the basic equation:

$$\sum Moments = I\alpha \quad (4)$$

where:

I = total system mass moment of inertia

α = angular acceleration

The total system mass moment of inertia is found by adding each separate inertia component:

$$I_{total} = I_{eq} + I_{screw} + I_{rotor} \quad (5)$$

Where I_{eq} is the equivalent inertia of the mass being moved. The rotor inertia is found from manufacture's published literature for a selected stepper motor to be 2.5 lb-in² while the screw and equivalent inertias are found with the following equations [18]:

$$I_{eq}(lb - in^2) = \frac{weight \times .025}{screw\ pitch} \quad (6)$$

where:

weight is in pounds

screw pitch is in threads per inch

$$I_{screw}(lb - in^2) = diameter^4 \times length \times .028 \quad (7)$$

where:

screw diameter and length are both in inches

.028 is the nominal density of steel lb/in³

Next, the total torque required is found using the following equation:

$$\begin{aligned} T_{total}(oz - in) &= T_{acc.sys.} + T_{friction} \\ &= I_{total} \times \frac{velocity}{time} \times conversion\ factor + \frac{force}{screw\ pitch \times \eta \times conversion\ factors} \end{aligned} \tag{8}$$

where:

velocity [=] rad/sec

time [=] sec

force [=] in/lb

η = screw efficiency

Note the velocity used here is the velocity in rad/sec of the gearhead output shaft. An additional 10 oz-in of torque has been added to account for miscellaneous torques from gearhead inertia or offset loads. Assuming the constants shown in Table 7-3, equations (4) through (8) yield a required torque of 8.05 in-lb.

7.2.8 Gearhead Reduction

The final step is to choose the translator-motor-gearhead combination that will satisfy all of the requirements summarized above. The total torque required to accelerate the load without a gearhead attached was calculated as 8.05 in-lb. When the gearhead is added, it will have the effect of multiplying the nominal motor torque to increase the output torque:

$$\text{Output Torque} = \text{Motor Torque} \times \text{Efficiency} \times \text{Ratio} \tag{9}$$

So for a motor with a rated torque of 1.87 in-lb at 750 rpm, the actual output torque due to the gearhead is approximately 79.475 in-lb (assuming a gearhead efficiency of .85); this obviously exceeds the required amount and would suffice for accelerating the load to the maximum velocity in .5 seconds. "Pull-in" torque is the maximum torque that can accelerate a load without losing synchronism with the pulse rate. The motor chosen must have a pull-in torque that is greater than the calculated value of 38.97 oz-in. In addition to providing a torque multiplication, the gearhead reduction was used in order to reduce the speed of the stepper motor and avoid possible vibration problems that may be present at the low or high end of the torque vs. speed (steps/sec) curve. The translator chosen for this application is the Slo-Syn 430-PT packaged translator drive. This drive operates in half step mode (0.9 deg/step) and utilizes a bipolar chopper, 2 phase stepper motor drive.

7.3 Summary

All of the calculations discussed have been placed in a spreadsheet to expedite the process of parametric variation. The results are shown in Table 7-3 on the following page. The calculations performed in this section have defined the basic velocity profile and motor torque to be used for the stepper motor in the uranyl nitrate solution experiment. In .5 seconds, the 17.85 in/lb (minimum) stepper motor will accelerate the mass to a maximum velocity of 1.038 in/min. This corresponds to an acceleration of 17.3 rev/sec^2 to a pulse rate of 3461 pulses/sec. With knowledge of the numbers summarized in Table 7-3, along with the general profile shown in Figure 7-1, we are now in the position to program a system utilizing either an integrated drive or a separate pulse source.

Table 7-3 : Sizing Calculations Summary

| INPUT PARAMETERS | | |
|-------------------|--|----------|
| 1 | Slope of reactivity plot (\$/in) | 2.89 |
| 2 | Max. Insertion Rate (cents/sec) | 5 |
| 3 | Lead Screw Pitch (th/in) | 10 |
| 4 | Max. Pulse Rate (pulses/sec) | 20000 |
| 5 | Planetary Gear Reduction Ratio | 50 |
| 6 | Translator Stepping Mode (steps/pulse) | 0.5 |
| 7 | Stepping Motor Resolution (deg/step) | 1.8 |
| 8 | Desired Resolution (in) | 0.0001 |
| 9 | Total Weight (lb) | 4347 |
| 10 | Time to reach velocity (sec) | 0.5 |
| 11 | Screw diameter (in) | 1.5 |
| 12 | Screw length (in) | 48 |
| 13 | Screw pitch (th/in) | 5 |
| 14 | Screw efficiency | 0.9 |
| 15 | Motor rotor Inertia (lb-in ²) | 2.5 |
| 16 | Friction force to slide weight (oz) | 6 |
| 17 | Minimum Pulse Rate (pulses/sec) | 500 |
| 18 | Misc. Torque (oz-in) | 5 |
| OUTPUT PARAMETERS | | |
| 1 | Max. Linear Speed Allowed (in/min) | 1.038062 |
| 2 | Max. Gear Head Output Shaft Speed (rpm) | 10.38062 |
| 3 | Max. Motor Speed (rpm) | 519.0311 |
| 4 | Max. Motor Speed (deg./sec) | 3114.187 |
| 5 | Max. Pulse Rate (pulses/sec) | 3460.208 |
| 6 | Min. Motor Speed (rpm) | 75 |
| 7 | Min. Motor Speed (deg/s) | 450 |
| 8 | Min. Gear Head Output Shaft Speed (rpm) | 1.5 |
| 9 | Min. Linear Speed (in/min) | 0.15 |
| 10 | Min. Linear Speed (in/sec) | 0.0025 |
| 11 | Equivalent Mass Inertia (lb-in ²) | 4.347 |
| 12 | Screw Inertia (lb-in ²) | 6.804 |
| 13 | Acceleration/Deceleration (rev./sec ²) | 17.30104 |
| 14 | Total Inertia (lb-in ²) | 30.95204 |
| 15 | Torque to overcome friction (oz-in) | 0.212044 |
| 16 | Torque to accelerate system (oz-in) | 280.3891 |
| 17 | Total torque required (oz-in) | 285.6011 |
| 18 | Total torque required (in-lb) | 17.85007 |

Chapter 8.

CONTROL SYSTEM PROGRAMMING

8.1 Introduction

In this chapter, the information generated in the previous sections will be used to write a control program for the two main systems: the hydraulic circuit and the stepper motor package. The numerical results and sizing calculations of chapters two and seven will be used to set the motor speed in the program and the control system hardware outlined in the other chapters will be "wired with software." This is the main advantage of a digital control system: the system characteristics may be quickly modified without a great deal of hardware or effort invested; if the calculations prove to be overly conservative, the speed of closure may be changed simply by re-writing a few lines of code.

Programming of the PLC control system is achieved through the use of what is known as "ladder logic" programming [2]. The term "ladder" refers to the ladder like structure of this graphic programming language (see program listing in Appendix C). The programming is done on an IBM compatible computer, can be saved to the hard drive, and then uploaded to the programmable logic controller located in the local I/O chassis; or, the programming can be done "on-line" while connected directly to the processor. The basic signal flow through the system is shown on the following page in Figure 8-1 [1].

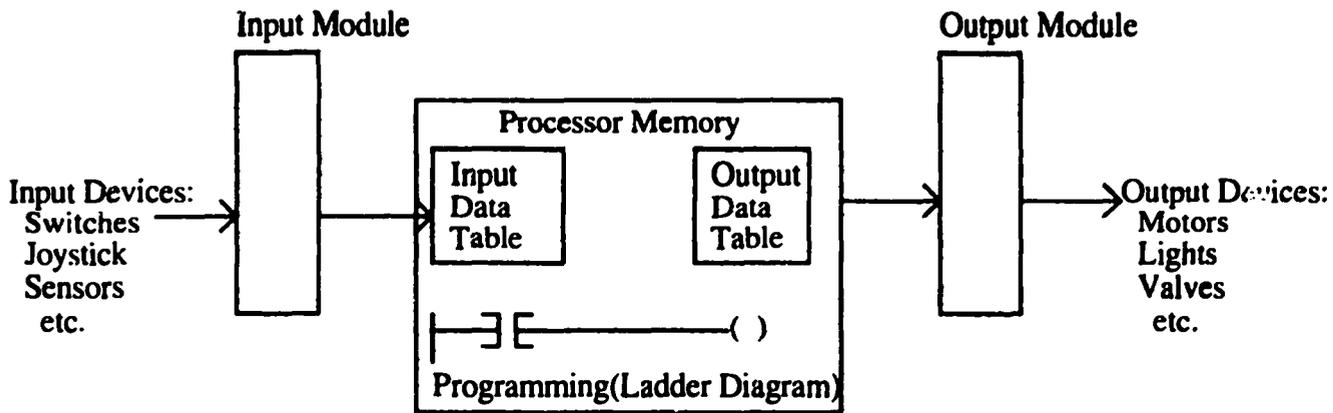


Figure 8-1: Signal Flow Through the System

Some of the more basic ladder logic instructions include:

- "Examine-on": if the examined bit is "1" the instruction is true
- "Examine-off": if the examined bit is "0" the instruction is true
- "Block transfer read/write": transfer blocks of data to or from an intelligent module
- "Timer on (TON)/Timer off (TOF)": time events
- "File/Arithmetic/Logical (FAL)": convert, manipulate, and move data

Each of these instructions has associated with it a mnemonic and a graphical symbol that is displayed on the screen when used and will be discussed in this chapter.

The concept of a examining and manipulating bits is essential to understanding how a PLC is programmed. The fact that inputs and outputs can have only a value of "on" or "off" can greatly simplify the often daunting task of programming a seemingly complex system. The "on" (or "high") setting is defined by a pre-determined voltage. If the voltage on the line is greater than that pre-defined value, then the line is said to be "high"; likewise, if the voltage on the line is less than the pre-determined value, the status of the line is said to be "low" (or zero or "off"). With such simple binary logic in place, one may then apply Boolean algebra to the status of different lines by utilizing simple integrated circuit chips such as "nand" gates, "nor" gates, or "exclusive or"

gates (TTL logic). Basically, the microprocessor based control system operates by assigning a label to each bit that is used within the microprocessor. In this way, the status of each bit may be examined, managed, and manipulated as desired through the use of a program.

8.2 Basic Programming Concepts

Figure 8-2 shows the fundamental idea behind programming a PLC. Basically, the entire program consists of a number of "rungs" inside "steps." The steps define the overall program flow while the rungs define the details of the program (i.e., the logic dictating what will be turned off and on for example). The rung shown in Figure 8-2

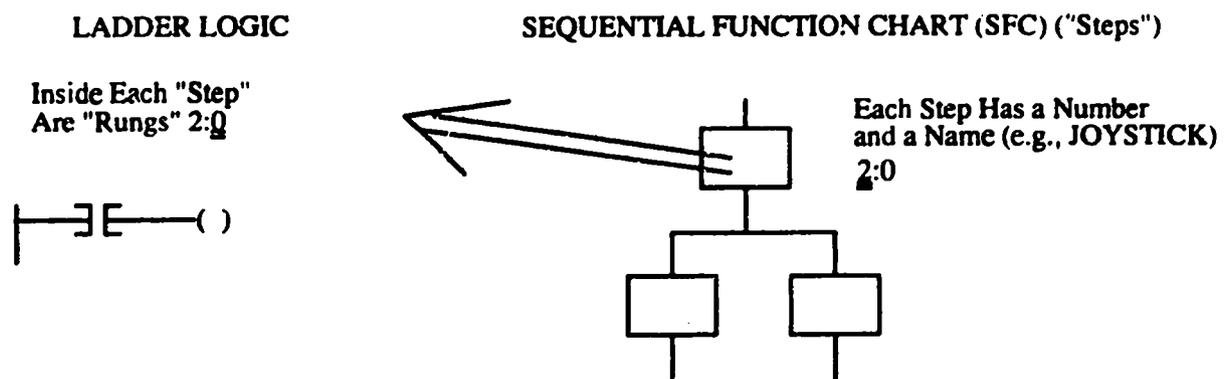


Figure 8-2: Basic PLC Programming Concepts

will examine the state of a bit (either "1" or "0") and then set an output bit to "1" if the examined bit was found to be "1" (i.e., a true path results in an energized output). This is the "examine on" instruction.

8.3 Programming the Analog Input Module

Programming the analog input module consists of initializing the module with a "block transfer write" (usually pre-conditioned with a switch). Next, a "block transfer read" must be done in order to continually read the input from the module (i.e., the value of the analog signal coming in as well as other status bits). Once the value of the

analog signal coming in is known and scaled by the user as desired, the programmer may manipulate, display, or store the data in any way needed. For example, input from a potentiometer hooked into a constant voltage DC source could be read into the input module, read by the PLC, and then displayed in a seven segment display.

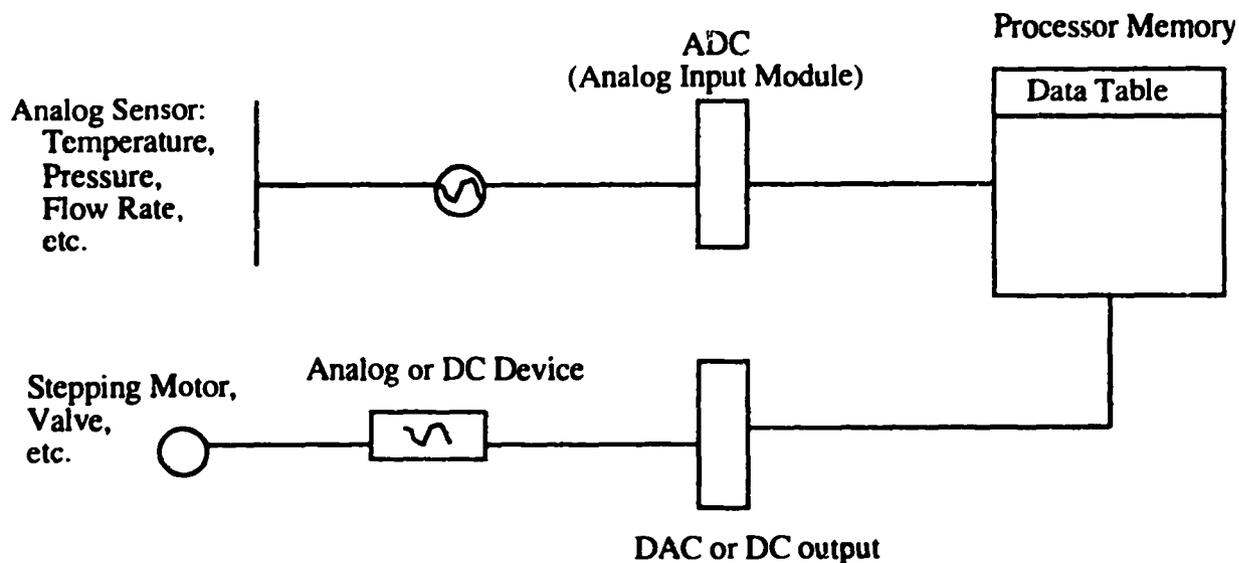


Figure 8-3 : Analog Input Programming

8.4 Programming the Stepper Motor Modules

Programming the stepper motor assembly involves initializing the assembly with a block transfer read and write, and then programming the desired motion using the ladder logic language. The number and rate of pulses sent by the stepper motor assembly determines the rate at which the motor turns. Pulses are output to the motor through the use of "moves" in the ladder logic programming language. Although this module was not used in the program written, it is planned to use this (as well as an optical encoder module) in the future.

8.5 Programming an Integrated Drive

As discussed in chapter six, the other alternative to stepper motor control is an integrated drive unit. Typically with such a unit, programming is achieved via an RS-

232 interface as described in chapter five. Shown below is the program that was written and stored in the memory of the compumotor AXL drive. This program was then executed from the ladder logic program stored in the processor module memory .

LD3 MN A17.3 V5 D2500 G

where:

LD3: disables the limit switches

MN: sets the mode to "normal" (i.e., can set distance, acceleration, and velocity)

A17.3: sets the acceleration to 17.3 rev/sec²

V5: sets the velocity to 5 rps (max: 8.65 rps as calculated earlier)

D2500: sets the distance to 2500 steps

G: executes the move

This programming language is completely separate from that of the PLC. As mentioned before, this is one incentive for using a stepper positioning assembly rather than an integrated drive: centralized programming reduces documentation and complexity.

8.6 Stepper Control Via an Integrated Drive

A program has been written that sets the framework for control of the slab tanks experiment through ladder logic code. The two main systems controlled by the program are the hydraulic and stepper motor systems (refer to Figures 1-3 and 1-4). An integrated compumotor AXL drive was used to drive the stepper motor while lights on the 10-60V DC output panel were used to symbolize the on/off action of hydraulic components. By no means is the program shown complete. Writing and putting together the control system for the entire experiment would involve additional hardware components, lines of code, and systems (e.g., automatic and secondary scram systems). The program discussed in this section is intended to provide a clear

example of the programming process and methods and serves as the first version of the software that will eventually control the slab tanks experiment.

A listing of the Allen-Bradley program is shown in Appendix C and the following section gives a rung by rung interpretation of this program. The program is divided into files. Typically, the file may be a ladder logic file or a sequential function chart file. A sequential function chart is the "overall" picture of the program and contains steps, shown as rectangles on the listing. Within each step is a ladder logic program. This is directly analogous to the concept of modular programming in FORTRAN with subroutines. The flow within the SFC is controlled by "transition" ladder logic files which dictate whether or not continuity will be granted so that the particular step may be run. Transitions operate like on/off valves regulating which ladder logic programs will be scanned by the processor. These concepts are clarified greatly by walking through each section of the program shown in Appendix C (the next section).

As programmed, the basic operation of the critical assembly is as follows (refer to the SFC in Appendix C). After the initialization and clear steps are automatically completed, the user has two modes to select from via toggle switches: either run or test. In run mode, the user is forced to first close the air gap with the hydraulic cylinder. Once closure via the cylinder has reached a pre-defined limit, the user may then close the air gap via the stepper motor. Throughout the approach to critical, the user has the option of scrambling the machine using the scram button. Once the minimum possible air gap is reached, both the hydraulic cylinder and the stepper motor are de-activated (to prevent a runaway chain reaction, an automatic scram system is usually built into the system as well). In test mode, the stepper motor and hydraulic ram are both de-energized in order to provide for testing of the valves. The valves may be forced on and off by forcing bits on or off from the control program.

8.7 Sequential Function Chart: File 001

The actual sequential function chart (SFC) is shown in Appendix C and it is illustrated for clarity in Figure 8-4. A total of 12 files were created (Table 8-1).

Table 8-1 : Slab Tank Program Files

| File Number | Name | Function |
|-------------|-----------|---|
| 001 | MAIN | Sequential function chart file |
| 002 | JOYSTICK | Control the DC outputs via switches and the potentiometer. This is fundamentally the same as a joystick control device. |
| 003 | INIT_DONE | Control the transition from file 004 (INIT) to file 006 (CLEAR) |
| 004 | INIT | Initialize hardware |
| 006 | CLEAR | Ensure that all outputs are off before continuing |
| 007 | RUN | Select the run branch to run the machine |
| 008 | TESTS | Select the test branch to test the machine |
| 009 | DONE | Control the transition from testing or running to the finish |
| 10 | CONTROLS | Control the stepper motor and hydraulic system |
| 11 | MAINTAIN | Test the hydraulic valves with the motor and pump off |
| 12 | NOPS | Empty transition |

Files 5, 13, and 14 shown on the program listing remained empty and were never used.

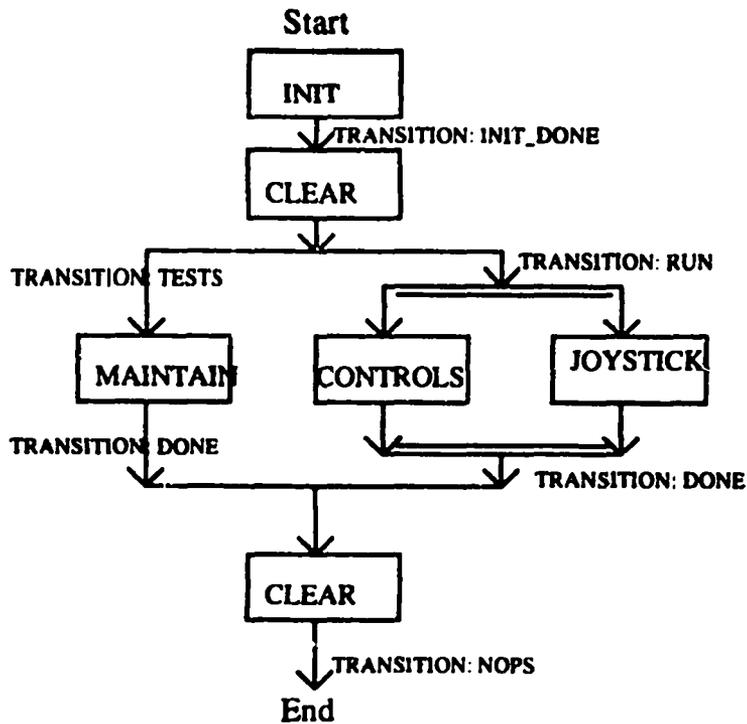


Figure 8-4 : General Features of the SFC

Program flow for the sequential function chart is from top to bottom. When two files ("steps") are placed in parallel like files 002 and 10 (CONTROLS AND JOYSTICK), they are scanned (i.e., run) simultaneously by the processor. When a transition like INIT_DONE (file 003) goes true, it allows the processor to drop down and branch to either of two option modes: run or test. When the run mode is selected, JOYSTICK (002) and CONTROLS(10) are both simultaneously scanned by the processor allowing the user to operate the assembly for an experiment. When the test mode is selected, the assembly is deactivated to allow for testing of the hydraulic valves. Once either test or run has been completed and the machine is scrambled, the processor runs through the CLEAR step that ensures the assembly is off and then returns program control to file INIT at the top of the sequential function chart.

8.8 Ladder Logic: Files 002-12

A rung is specified by the file that it is in, and the rung number. So, for example, in Appendix C at the beginning of the ladder listing, "Rung 2:0" indicates that within file 002 (denoted by the "2"), this is the first rung (denoted by "0"). When the path on a rung is true, it proceeds to the instruction furthest right and executes it. The instructions found on the right are referred to as output instructions and are used to turn on motors, lights, or any other device that must be controlled. The processor scans the rungs from left to right and top to bottom.

8.8.1 Rung 2:0

This is the first rung in file 2 "JOYSTICK." The first two instructions on this rung examine two different bits for their status. If the bits are found to be "0" in the data table, then the path is true; otherwise, if both bits are "1," then the path is false (this is the "examine off" instruction discussed earlier). The bits examined are "enable" bits that tell the program whether or not the analog input module can be read. When the path is true, the "BTR" (Block Transfer Read) instruction is executed. This instruction reads the power status of the analog input module.

8.8.2 Rung 2:1

This rung basically says: "if the BTW (Block Transfer Write) is not already done, then do it" by examining the BTW done bit. When the BTW write instruction is executed, it writes a configuration file to the analog input module. This configuration file determines things like what kind of analog input will be used, how the analog input will be scaled, or whether the input will be digitally filtered.

8.8.3 Rung 2:2

This rung checks the analog input value from the variable voltage source and sets bits located in a binary data table depending on the value. A literal interpretation of

this rung is as follows: if the joystick value is greater than 5000 *and* less than 9619 *and* if the stepper motor is off *and* if switch 1 is on *and* if push button 1 is pushed, then set the "pump" bit to 1. This bit is examined in the CONTROLS step to determine whether the pump should be energized or not.

8.8.4 Rung 2:3

This is the same logic used in rung 2:2 with the exception that the "stepmotor" bit is being set instead of the "pump" bit. This bit is examined in the CONTROLS step to determine whether the stepper motor should be energized.

8.8.5 Rung 3:0

This is the transition file INIT_DONE used to verify that proper initialization has occurred in the INIT step. The transition becomes true once the INIT_DONE bit is set true in the initialization routine.

8.8.6 Rungs 4:0

This is the initialization step, the first block executed by the processor. Typically, a number of I/O devices require some form of initialization before being used. Although no such devices were used as part of this example, this step was included since such blocks are so common when writing a lengthy control program. The external lights located on the DC output module were reserved to represent initialization outputs. When switch one is turned on, rung 4:0 starts a ten second timer. When the timer reaches one, two, three, and four seconds respectively, lights 10, 11, 12, and 13 are "latched" on. A latch command retentively sets the output state high; that is, when power is lost, the output will remain in a high state.

8.8.7 Rung 4:1

This rung turns off ("unlatches") lights 10-13 if switch 1 is turned off. An "unlatch" command retentively sets the output device's status to "0."

8.8.8 Rung 4:2

This rung checks the value of the timer. When the value reaches 5 seconds, lights 10-13 are turned off.

8.8.9 Rung 4:3

This rung turns all of the initialization lights back on when the timer reaches 6 seconds.

8.8.10 Rungs 4:4 - 4:8

Rung 4:4 performs an FAL instruction ("File Arithmetic/Logical") when the timer value reaches 7 seconds. The FAL instruction allows the user to send any word (16 bits) to an output location. In this example, a random 16 bit sequence is sent to the DC output module to flash the lights in a random sequence to further simulate initializing a module. This instruction may be used to arithmetically manipulate, convert, move, and perform Boolean logic to individual bits or coded numerical data. Rungs 4:5-4:8 utilize the FAL instruction in a similar manner to flash and blank the initialization lights.

8.8.11 Rungs 4:9 -4:10

This rung resets timers that are used in the CONTROLS step and latches the INIT_DONE bit in order to record in the data table that initialization has been completed.

8.8.12 Rung 6:0

This rung ensures that the PUMP and STEPMOTOR bits in the data table are unlatched and also unlatches the INIT_DONE bit in case the user goes through the SFC more than once.

8.8.13 Rung 7:0

If the run selection switch is on *and* if the test selection switch is off, then this transition rung becomes true and run mode has been selected.

8.8.14 Rung 8:0

If the test selection switch is on *and* if the run selection switch is off, then this transition rung becomes true and test mode has been selected.

8.8.15 Rung 9:0

If the pump *and* stepper *and* N.O. valve *and* N.C.1 valve *and* N.C.2 valve are off *and* if the scram button is on, then this transition is true, and control is returned to file 004 (INIT).

8.8.16 Rung 10:0

If the pump bit is true, then start a 5 second retentive timer, energize the pump, and open the N.C.1 valve. Along with rung 10:1, this pressurizes the cylinder and begins moving the tanks together via the hydraulic ram. The retentive timer retains the accumulated time the pump has been run (even though the rung may go false) as a means of determining when the pump should be abandoned in favor of the increased resolution offered by the stepper motor.

8.8.17 Rung 10:1

If PB2 is off, *and* if the scram latch bit is off *and* if the run selection switch is on, then energize the N.O. valve (thus closing it and preventing a scram) and de-energize the N.C. 2 valve (thus selecting the closure speed set by the N.C. 1 valve).

8.8.18 Rung 10:2

If the stepper motor is on, then start a ten second retentive timer and energize the stepper motor for operation. The timer is used in conjunction with limit switches to determine when all closure should be terminated. Knowing the linear velocity of the table (calculated in chapter eight as 1.03 in/min) and given the maximum distance the tank may be moved via the stepper, then the maximum amount of time the stepper may be operated is known and may be set in the timer. This information may be used as a

redundancy to the limit switches which physically sense when a certain position has been reached. The same idea applies to the hydraulic timer mentioned earlier.

8.8.19 Rung 10:3

If the pump timer is done (i.e., five seconds have been reached) *or* if the limit switch for the hydraulic ram has been activated, then turn off the pump, unlatch the pump bit, and close the N.C. 1 valve (thus halting movement of the slab tank via the hydraulic ram).

8.8.20 Rung 10:4

If the stepper timer is done (i.e., ten seconds has been reached) *or* if the stepper limit switch has been activated, then unlatch the stepper motor bit and turn off the stepper motor (thus halting all movement via both the hydraulic ram and the stepper motor).

8.8.21 Rung 10:5

If the scram button is pressed, then open the N.O. valve, close the N.C. 1 and N.C. 2 valves, latch the scram latch bit, and turn off the stepper motor. This pressurizes the cylinder causing it to quickly move the tanks apart and ensuring no closure via the stepper motor.

8.8.22 Rung 11:0

If the test selection switch is on, then turn off the pump and stepper motor. This is the maintenance mode that allows for testing of the valves without the pump or stepper motor on.

8.8.23 Rung 11:1

This rung is exactly the same as rung 10:5 interpreted above with the exception that it is placed in the MAINTAIN step.

8.9 Summary

This program was written with the major goal of illustrating the basics of programming a typical PLC. The analog input simulates a joystick and the DC I/O are used to control valves, motors, or any other device requiring 10-60V DC voltage. When writing the program to control any system using this type of PLC, the commands and structures shown will be used repeatedly; therefore, the program discussed is a representative sample of much larger, but no more conceptually difficult, control program. The program shown in Appendix C is version one of the uranyl nitrate slab tank experiment control program.

Chapter 9.

USER INTERFACE SOFTWARE

9.1 Overview

Once the microprocessor control program has been written and debugged and the hardware established, the user interface must be defined and created. Ideally, the user would interface with a graphical representation of the physical system being controlled as well as a control panel consisting of switches, buttons, a joystick, and any other similar input devices that might be necessary. As in the selection of the control system hardware, there are two options that may be pursued when considering how the user will interact with the control system. If the custom approach is being followed, one must write the interface software "from scratch" using programming languages such as C or BASIC. On the other hand, if a system has been purchased, a software package is typically available to augment the hardware and serve as a link between the user, the control program, and the actual hardware. In the case of the system that was purchased and outlined in the previous chapters, a software package called ControlView was available.

9.2 General Features

ControlView offers a wide variety of capabilities that involve a relatively small amount of labor. The software allows the user to "tag" memory locations in the PLC and display the values on the screen in a graphical or numerical manner; it "talks" to the PLC via the 1784 KT/B communications card shown in Figure 5-3. Once the memory locations of interest have been tagged, a database of the current values is created and continually updated as the software scans the processor for the values located in each of the tagged memory positions. After this database is created, the user may proceed to the graphics editor; here, a graphical representation of the

physical process being controlled may be created. The user may display the numerical value of tagged memory, draw geometric shapes, and even animate or fill such shapes at a rate proportional to a value in memory. For example, if the position of the hydraulic ram is fed back as an analog value via an optical encoder, then a rectangular figure can be drawn on the interface screen that will fill with a color proportional to the position of the ram. When the ram is at its "out" position, the rectangle will be empty of color; when the ram is at its full "in" position, the rectangle will be completely filled with the color chosen. Such an interface was created for the uranyl nitrate experiment and is discussed in the following section. In addition to such features, the software provides other capabilities such as event detection, alarming, mathematical manipulation of data, menu creation, and security administration.

9.3 Uranyl Nitrate Experiment Interface

An interface for the program and hardware developed for the uranyl nitrate experiment was created using the ControlView software. Basically, Figures 1-3 and 1-4 were taken, reproduced into one display using the graphics editor available, and then linked to memory locations defined in the ladder program listed in Appendix C. The stepper motor and hydraulic ram are drawn as rectangles of different sizes that fill green when fully extended. The normally open and normally closed valves as well as the pump in the program are shown as red when closed (or off) and green when open (or on). The switches and push buttons controlling these actions are wired as shown in Figure 5-3 and placed inside a small aluminum box serving as the control panel. These switches are displayed on the control screen as rectangular buttons that turn green when on and red when off. When the hydraulic ram is actuated, the entire cart is animated and moves forward towards the fixed slab tank while the rectangle representing the ram is filled green. Once the maximum displacement via the ram is

realized, it is deactivated and the stepper motor is selected. When the stepper motor is activated, the rectangle representing the stepper motor begins to fill with green and the movable slab tank continues its approach toward the fixed tank. When the system is scrambled, the cart is returned to its original position and the air gap between the tanks is increased to its maximum value. Figure 9-2 on the following page shows a screen shot of the interface that was created.

The creation of the user interface completes the programming example that was begun in the previous chapter. It is worth noting that the interface is just that: an interface. Although it reads values from the PLC, it in no way controls the physical system. The only software capable of energizing output bits is the ladder logic program discussed in the previous chapter. Again, although the interface, ladder program, and hardware that have been discussed do not fully satisfy each and every requirement necessary for performing the uranyl nitrate experiment, their development as outlined here lays the preliminary groundwork that is crucial to creating the much larger, but no more conceptually difficult final system.

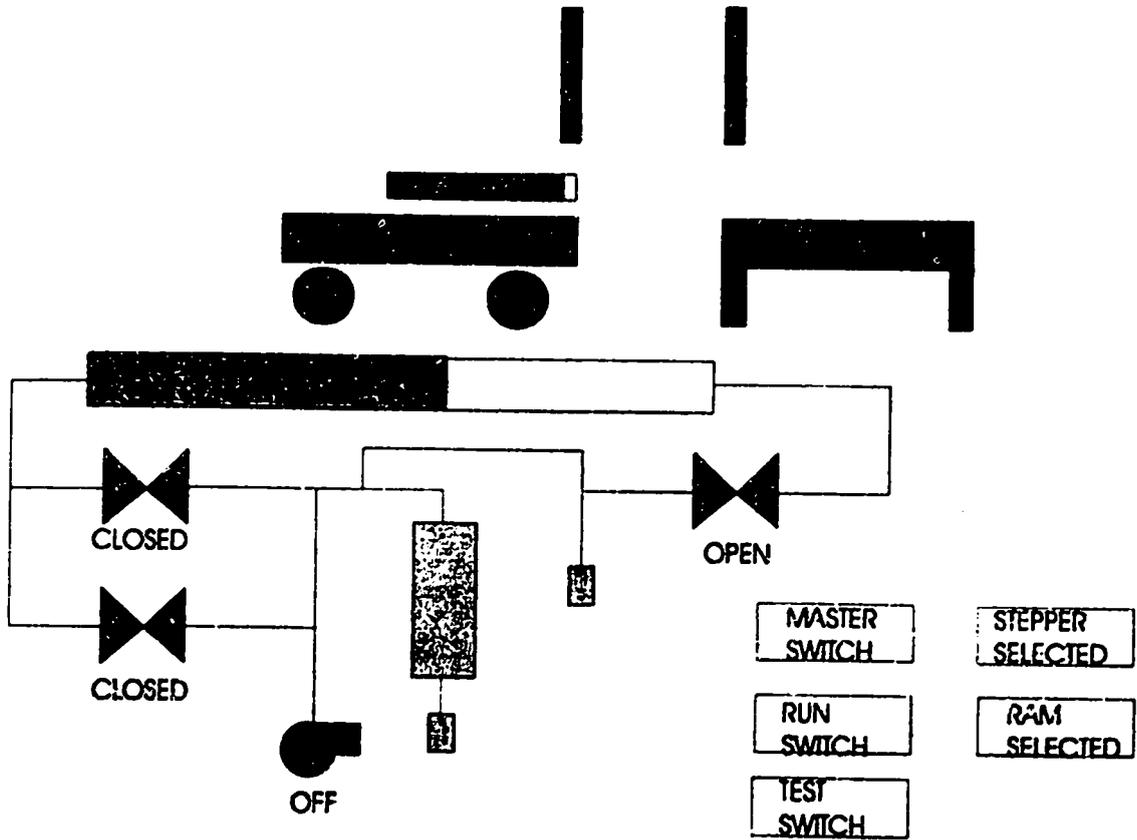


Figure 9-1 : Screen Shot of Computer Generated Interface

Chapter 10.

COST ESTIMATE

10.1 Labor Costs

It is estimated that two full-time engineers will be needed in order to implement the experiment outlined in this document. One engineer will be responsible for implementation of the control system and hardware manufacturing while the other engineer will be responsible for the nuclear engineering concerns; it is assumed that both will work on experiment documentation. Assuming approximately three months of work time, the engineering cost is calculated as:

$$(50 \text{ \$/hr}) \times (8 \text{ hr/day}) \times (90 \text{ days}) \times (2) = \$72,000 \quad (10)$$

It is anticipated that two technicians (one mechanical, one electrical) will be needed to complete the experiment. In addition, one draftsman will be needed. The mechanical technician will be responsible for fabricating parts in the shop while the electrical technician will be responsible for wiring the control system; the draftsman will be responsible for documenting electrical and mechanical construction. Assuming three months of work, technician cost is calculated as:

$$(30 \text{ \$/hr}) \times (8 \text{ hr/day}) \times (90 \text{ days}) \times (3) = \$64,800 \quad (11)$$

10.2 Material Costs

The hardware needed for the experiment may be broken up into two areas: the mechanical hardware and the control system hardware.

10.2.1 Mechanical Hardware

The mechanical hardware costs are estimated with the assumption that hardware will be manufactured and designed "in house." Table 10-1 summarizes the general anticipated hardware costs.

Table 10-1 : Approximate Hardware Costs

| ITEM | APPROXIMATE COST |
|---|-------------------------|
| Material for two translation stages (SST) | \$100 |
| Micrometer head | \$100 |
| Stepper Motor | \$120 |
| Aluminum Material | \$100 |
| Miscellaneous hardware (fasteners, welding materials, etc.) | \$100 |
| APPROXIMATE TOTAL HARDWARE COST | \$520 |

10.2.2 Control System Hardware

Table 10-2 : Approximate Control Hardware Costs

| ITEM | APPROXIMATE COST |
|--|-------------------------|
| 2 DC Output Modules | \$600 |
| Electrical Cabling | \$100 |
| Stepper Positioning Modules | \$2,080 |
| Translator | \$800 |
| APPROXIMATE TOTAL CONTROL HARDWARE COST | \$3,580 |

10.3 Cost Summary

Summing together the labor and material costs and adding 10% for unforeseen contingencies, the total estimated cost for the experiment is shown below in Table 10-3.

Table 10-3 : Total Estimated Cost

| ITEM | VALUE |
|-----------------------------|------------------|
| Materials | \$4,100 |
| Labor | \$136,800 |
| TOTAL DIRECT COST | \$140,900 |
| 10% Contingencies | \$14,090 |
| TOTAL ESTIMATED COST | \$154,990 |

Chapter 11.

CONCLUSIONS

This thesis has addressed the problem of setting up and programming a microprocessor based digital control system (PLC) for controlling a critical experiment involving highly enriched uranyl nitrate in cylindrical geometry. As a result of this study, we may draw the following conclusions:

- An Allen-Bradley microprocessor-based digital control system is the ideal choice for critical experiment control because of its flexibility, relative simplicity, and proven track record. Implementing this type of control system for critical experiment control is highly desirable since it provides a common platform from which to control a variety of critical experiments. This is generally not the case for systems customized to specific experiments since the result is a patchwork of different control systems, each with its own unique approach to control. An Allen-Bradley PLC unifies the approach to control while maintaining the flexibility to perform many different experiments.
- The mechanical design requirements for performing a critical experiment with cylindrical geometry on a horizontal table are achievable. These requirements include the design of space frames to hold the slab tanks, as well as a translation table for positioning the movable tank. In addition, there are distinct safety advantages in performing such an experiment horizontally rather than vertically including the possibility of a gravity assisted scram mechanism and elimination of the worst case scenario in which one tank drops vertically onto the other.
- A probabilistic computer code such as MCNP may be used for sensitivity studies to provide a rough estimate of system sensitivity; however, due to the statistical nature of such a code, it is not ideally suited to sensitivity studies requiring a high

degree of accuracy. We may conclude that the cylindrical uranyl nitrate system discussed is very sensitive to changes in the air gap: approximately 9 cents/mm to 14 cents/mm.

- The resolution required for the uranyl nitrate experiment is achievable using a stepper motor, lead screw, and gearhead reduction for fine adjustment.

In general, this study has proven that a PLC system manufactured by the Allen-Bradley corporation offers the flexibility needed to perform not only the uranyl nitrate experiment, but a wide variety of critical experiments involving fissile material. A unified approach to critical experiment control has been presented that, when implemented, will greatly enhance the capability of the Los Alamos Critical Experiments Facility to safely and expeditiously gather valuable criticality data via a common control system.

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Appendix A
MCNP Card Summary

Surface Cards

The surface cards define generic surfaces such as cylinders, spheres, planes, or ellipsoids. Surface cards are referenced by a surface card number. For example, in order to define an infinite cylinder along the y axis, one would enter the following line in the input file:

1 cy 36.195

This card says "surface 1 is defined by an infinite cylinder along the y axis with a radius of 36.195 cm." Similar surface card mnemonics may be used to define spheres, infinite planes, and other standard geometrical shapes whose equations are well defined by analytic geometry.

Cell Cards

The geometry of the system is specified by applying Boolean operators to the surface cards. For example, surface card 1 may specify a cylinder (infinite in length) along the Y axis and surface cards 2 and 3 may specify two infinite planes perpendicular to that cylinder (planes 1 and 2). In order to define a system consisting of a cylinder with finite ends (referred to as a "cell"), one may insert the following geometry card in the input file:

1 10 -7.9 2 -3 -1

This card says "cell 1 is defined by everything to the positive sense (to the right) of surface 2 *intersected* with everything to the negative sense (to the left) of surface 3 *intersected* with everything to the negative sense (inside) surface 1" (italic numbers). The numbers that aren't in italic type represent the material type (10, in reference to material card 10) and the material density (7.9) in grams/cc.

Variance Reduction: Importance Cards

Importance cards are the most common form of variance reduction available to the MCNP user. With this card, the "importance" of each cell may be assigned a value of one (important) or zero (not important). If a cell is assigned an importance of zero, particles entering that cell will not be followed or banked as part of the "game." Cells that are "voids" (contain no material) and that are predicted to have little or no influence on the system under study are typically assigned an importance of zero in order to reduce computer time.

Material Cards

Material specification cards do just what their name implies: tell the computer what kind of material the cell is composed of. This information is typically transmitted in the form of number densities (atoms/barn-cm) and cross section table references. Material specification cards fix the relative proportion of each element or nuclide within each cell and dictate which cross section tables will be used (the probability portion of the "game" being played). MCNP really cares only about the relative proportion of each element or nuclide within the material; therefore, either number densities or atom fractions can be entered in the material card since atom fractions are found simply by multiplying the number densities by a constant. Also as a result of this, the number densities of a certain material can be summed and the resulting value may be entered as the density on the cell card. This is indicated by entering the value without a negative sign preceding it (see input files, Appendix D).

Mode and Tally Cards

Lastly, MCNP mode and tally cards are used to determine the operation mode of MCNP and the data that is to be tabulated as the simulation is being run. When doing criticality calculations, the "kcode" card is always used. This card allows for the definition of the position, and size of neutron sources that are present as well as a few other parameters related to program execution. The tally cards determine what data will be generated by the program. Options (among many others) include neutron flux, current, and fluence. For this study, the main parameter of interest was k_{eff} : a parameter that is automatically calculated for the user when doing kcode calculations.

Computer Characteristics

A total of six input files were created. These files were accessed by MCNP version 3A on a Sun Sparc 10 workstation with 32 megabytes of memory and a 40 MHZ clock speed. The operating system used was Solaris 1.0.1.

Appendix B

Number Density Calculations

Assumptions

The following data is assumed for purposes of the uranyl nitrate model created.

405.2 g/l uranyl nitrate solution

U-235 93.1%

U-238 5.9%

U-234 1%

Nominal Overall Density of Uranyl Nitrate: 1.558 g/cc

Solution Acid Content: .32 Molar HNO₃

For the solution

In general, the number density for each uranium isotope in the solution may be found by considering the density, molecular weight, and percent enrichment as shown below.

$$\begin{aligned} [\text{component}] &= \frac{\frac{g}{cc}}{\frac{g}{mol}} \times \frac{\text{particles}}{mol} \times \frac{cm^2}{barn} \\ &= \frac{mol}{cc} \times \frac{\text{particles}}{mol} \times \frac{cm^2}{barn} \\ &= \frac{\text{particles}}{barn-cm} \end{aligned}$$

Applying this to each of the three uranium isotopes assumed present yields the following number densities:

$$[U - 235] = (.931) \times \left(\frac{.4052}{234.9} \right) \times (6.023 \times 10^{23}) \times (1 \times 10^{-24})$$

$$= 9.6712476 \times 10^{-4}$$

$$[U - 238] = (.059) \times \left(\frac{.4052}{237.9} \right) \times (6.023 \times 10^{23}) \times (1 \times 10^{-24})$$

$$= 6.05206822 \times 10^{-5}$$

$$[U - 234] = (.01) \times \left(\frac{.4052}{237.9} \right) \times (6.023 \times 10^{23}) \times (1 \times 10^{-24})$$

$$= 1.04331637 \times 10^{-5}$$

The molecular weight of the uranyl nitrate solution $UO_2(NO_3)_2$ is found to be:

$$\text{Mol. Wt. } UO_2(NO_3)_2 = 235 + 2(16) + 2(14 + 48)$$

$$= 391 \text{ g/mol}$$

Then, for 405.2 g/l of uranyl nitrate, the density of $O_2(NO_3)_2$ is found by multiplying the percent $O_2(NO_3)_2$ in solution by the total volume of solution:

$$O_2(NO_3)_2 = \left(\frac{391 - 235}{235} \right) \times (405.2)$$

$$= 268.98 \frac{\text{g}}{\text{l}} \text{ of } O_2(NO_3)_2$$

Where the molecular weight of $O_2(NO_3)_2$ is $391 - 235 = 156 \text{ g/mol}$

So using the formula introduced on page one for the number density of one component, the number density of the $O_2(NO_3)_2$ is found to be:

$$\left(\frac{.26898}{391 - 235} \right) \times (6.023 \times 10^{23}) \times (1 \times 10^{-24}) = 1.03841798 \times 10^{-3} \frac{\text{atoms}}{\text{barn-cm}}$$

From this, the oxygen and nitrogen content in the $O_2(NO_3)_2$ is found to be:

$$\text{Oxygen content is } (2 + 6) \times (1.038 \times 10^{-3}) = 8.307 \times 10^{-3}$$

$$\text{Nitrogen content is } (2) \times (1.038 \times 10^{-3}) = .002076$$

The molarity of the solution was assumed to be .32. This means that there is .32 mol HNO₃ per liter of solution. Therefore, the density of HNO₃ is found to be:

$$\begin{aligned} (\text{molecular weight of HNO}_3) \times (\text{molarity}) &= (1 + 14 + 48) \times (.32) \\ &= 20.16 \text{ g/l HNO}_3 \end{aligned}$$

Therefore, the number density of HNO₃ is:

$$\begin{aligned} [\text{HNO}_3] &= \left(\frac{.02016}{63} \right) \times (6.023 \times 10^{23}) \times (1 \times 10^{-24}) \\ &= .00019272 \end{aligned}$$

The contributions of hydrogen, nitrogen, and oxygen to this number may be found by multiplying by the number of atoms in the molecule:

$$\text{Hydrogen} = (1) \times (.00019272) = .00019272$$

$$\text{Nitrogen} = (1) \times (.00019272) = .00019272$$

$$\text{Oxygen} = (3) \times (.00019272) = .00057816$$

The remainder of the solution is H₂O so the density of the water in solution is found to be:

$$\begin{aligned} \text{H}_2\text{O} &= (\text{g/cc total solution}) - (\text{g/cc uranium}) - (\text{g/cc O}_2(\text{NO}_3)_2) - (\text{g/cc HNO}_3) \\ &= 1.558 - .4052 - .26898 - .02016 \\ &= .86366 \text{ g/cc H}_2\text{O} \end{aligned}$$

The number densities for the hydrogen and oxygen from this are found to be:

$$\begin{aligned} \text{Oxygen} &= \left(\frac{.86366}{18} \right) \times (6.023 \times 10^{23}) \times (1 \times 10^{-24}) \\ &= .0288966 \\ \text{Hydrogen} &= (.0288966) \times (2) \\ &= .057793248 \end{aligned}$$

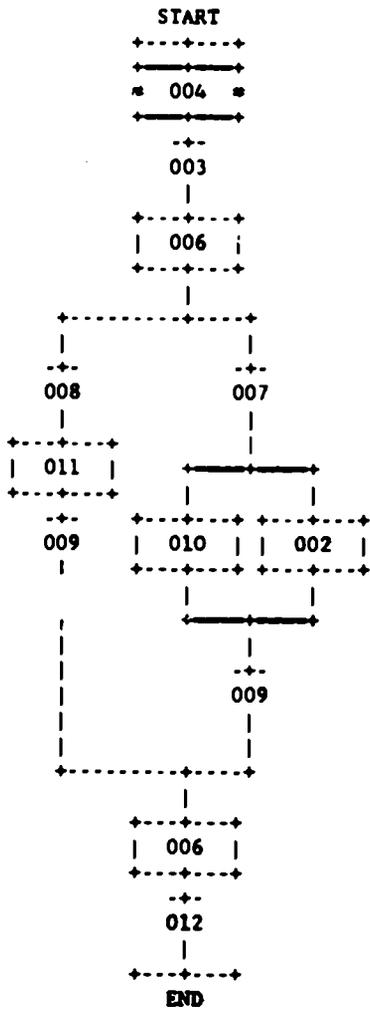
Finally, the total nitrogen, oxygen, and hydrogen number densities may be found by summing the contributions of each component:

$$\begin{aligned} \text{total nitrogen} = [\text{N}] &= \text{O}_2(\text{NO}_3)_2 \text{ nitrogen} + \text{HNO}_3 \text{ nitrogen} \\ &= .002076 + .00019272 \\ &= .00226872 \end{aligned}$$

$$\begin{aligned} \text{total oxygen} = [\text{O}] &= \text{H}_2\text{O oxygen} + \text{HNO}_3 \text{ oxygen} + \text{O}_2(\text{NO}_3)_2 \text{ oxygen} \\ &= .0288966 + .00057816 + 8.307 \times 10^{-3} \\ &= .03778176 \end{aligned}$$

$$\begin{aligned} \text{total hydrogen} = [\text{H}] &= \text{H}_2\text{O hydrogen} + \text{HNO}_3 \text{ hydrogen} \\ &= .0577932 + .00019272 \\ &= .057985968 \end{aligned}$$

Appendix C
Control Program Listing



+ PROGRAM DIRECTORY FOR PROCESSOR: SAMPLE [ONLINE]+

| File | Name | Type | Size(words) |
|------|-----------|----------------|-------------|
| 0 | | system | 65 |
| 1 | MAIN | function chart | 63 |
| 2 | JOYSTICK | ladder | 42 |
| 3 | INIT_DONE | ladder | 3 |
| 4 | INIT | ladder | 122 |
| 5 | TRANS2 | ladder | 17 |
| 6 | CLEAR | ladder | 10 |
| 7 | RUN | ladder | 7 |
| 8 | TESTS | ladder | 7 |
| 9 | DONE | ladder | 8 |
| 10 | CONTROLS | ladder | 63 |
| 11 | MAINTAIN | ladder | 23 |
| 12 | NOPS | ladder | 1 |
| 13 | empty1 | ladder | 1 |
| 14 | empty2 | ladder | 1 |

NORMAL OPERATING MODE

Sym Table Report

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Address 83/96

| Address | Symbol | Comment |
|----------|------------|---|
| B3/96 | INIT_DONE | |
| B3/112 | PUMP | |
| B3/113 | STEPMOTOR | |
| B3/114 | SCRM_LATCH | SCRAM LATCH BIT |
| B3:0 | | |
| B3:1 | | |
| B3:2 | | |
| B3:3 | | |
| B3:4 | | |
| B3:6 | | |
| I:000/00 | SW1 | MASTER SWITCH |
| I:000/01 | PB1 | |
| I:000/02 | SW2 | TEST SELECTION SWITCH |
| I:000/03 | SW3 | RUN SELECTION SWITCH |
| I:000/04 | PB2 | SCRAM BUTTON |
| I:000/05 | SW5 | HYDRAULIC LIMIT SWITCH |
| I:000/06 | SW6 | STEPPER LIMIT SWITCH |
| N10:0 | | FORCE READ OF ADC |
| N10:0/15 | | |
| N10:5 | | ENABLE ADC |
| N10:5/13 | | |
| N10:5/15 | | |
| ? 0 | | |
| N11:4 | | CHECK FOR JOYSTICK SELECTION OF PUMP OR STEPPER |
| N11:5 | | |
| O:000 | | |
| O:000/00 | LITE1 | PUMP |
| O:000/01 | LITE2 | STEPPER |
| O:000/02 | LITE3 | N.O. VALVE |
| O:000/03 | LITE4 | N.C.1 VALVE |
| O:000/04 | LITES | N.C.2 VALVE |
| O:000/10 | | |
| O:000/11 | | |
| O:000/12 | | |
| O:000/13 | | |
| R6:0 | | |
| R6:1 | | |
| R6:2 | | |
| R6:3 | | |
| R6:4 | | |
| R6:6 | | |
| T4:0 | | |
| T4:0.ACC | | INIT. TIMER |
| T4:0.DN | | |
| T4:1 | | |
| T4:1.DN | | PUMP TIMER |
| T4:2 | | |
| T4:2.DN | | STEPPER TIMER |

STEPMOTOR
< B3
<---()---+
< 113

Rung 2:4

|
+-----[END OF FILE]-----+
|

Rung 4:0
 | MASTER
 | SWITCH

SW1
 I:000
] [00

+TON-----+

+TIMER ON DELAY + (EN)+

| | |
|-----------|-----------|
| Timer | T4:0 |
| Time base | 1.0+ (DN) |
| Preset | 10 |
| Accum | 0 |

INIT.
 TIMER

+EQU-----+ 0:000

↔↔EQUAL ↔↔ (L) ↔↔

| | |
|-------------------|----|
| Source A T4:0.ACC | 10 |
| | 0 |
| Source B | 1 |
| | |

INIT.
 TIMER

+EQU-----+ 0:000

↔↔EQUAL ↔↔ (L) ↔↔

| | |
|-------------------|----|
| Source A T4:0.ACC | 11 |
| | 0 |
| Source B | 2 |
| | |

INIT.
 TIMER

+EQU-----+ 0:000

↔↔EQUAL ↔↔ (L) ↔↔

| | |
|-------------------|----|
| Source A T4:0.ACC | 12 |
| | 0 |
| Source B | 3 |
| | |

INIT.
 TIMER

+EQU-----+ 0:000

↔↔EQUAL ↔↔ (L) ↔↔

| | |
|-------------------|----|
| Source A T4:0.ACC | 13 |
| | 0 |
| Source B | 4 |
| | |

Rung 4:4

| | | |
|-------------------|--|------------------------------|
| INIT. TIMER | | |
| +EQU-----+ | | +FAL-----+ |
| +EQUAL-----+ | | +FILE ARITH/LOGICAL+- (EN)-+ |
| Source A T4:0.ACC | | Control R6:0 |
| 0 | | Length 1+- (DN) |
| Source B 7 | | Position 0 |
| | | Mode ALL+- (ER) |
| +-----+ | | Dest 0:000 |
| | | -256 |
| | | Expression |
| | | B3:0 |
| | | +-----+ |

Rung 4:5

| | | |
|-------------------|--|------------------------------|
| INIT. TIMER | | |
| +EQU-----+ | | +FAL-----+ |
| +EQUAL-----+ | | +FILE ARITH/LOGICAL+- (EN)-+ |
| Source A T4:0.ACC | | Control R6:1 |
| 0 | | Length 1+- (DN) |
| Source B 8 | | Position 0 |
| | | Mode ALL+- (ER) |
| +-----+ | | Dest 0:000 |
| | | -256 |
| | | Expression |
| | | B3:1 |
| | | +-----+ |

Rung 4:6

| | | |
|------------------|--|------------------------------|
| MASTER SWITCH | | |
| SW1 | | |
| I:000 | | |
| +-----+ | | +FAL-----+ |
| / | | +FILE ARITH/LOGICAL+- (EN)-+ |
| 00 | | Control R6:2 |
| +-----+ | | Length 1+- (DN) |
| | | Position 0 |
| | | Mode ALL+- (ER) |
| | | Dest 0:000 |
| | | -256 |
| | | Expression |
| | | B3:2 |
| | | +-----+ |

NORMAL OPERATING MODE
Program Listing Report

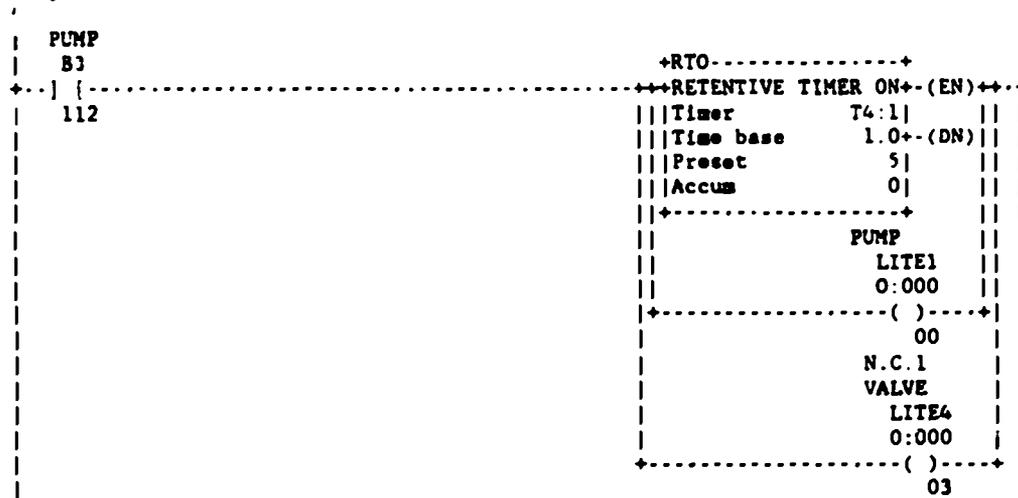
PLC-5/15 Addr 0

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Rung 8:0

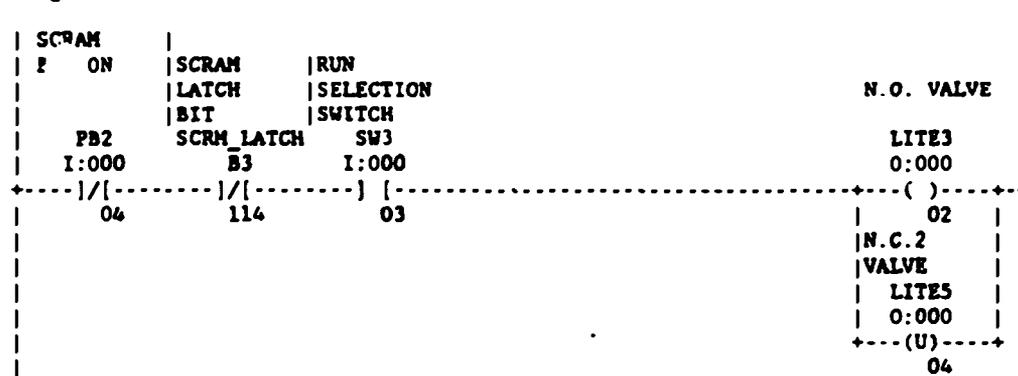
```
Rung 8:0
| TEST                               SCRAM |
| SELECTION                          LATCH |
| SWITCH                              BIT  |
|   SW2                              SCRM_LATCH |
|   I:000                             B3   |
+---|/|------(U)-----+
|   02                               114  |
Rung 8:1
| TEST | RUN | SCRAM |
| SELECTION | SELECTION | LATCH |
| SWITCH | SWITCH | BIT |
|   SW2 | SW3 | SCRM_LATCH |
|   I:000 | I:000 | B3 |
+---| (-) |/| (-) |/| (-) |-----[EOT]---+
|   02 | 03 | 114 |
Rung 8:2
|
+-----[END OF FILE]-----+
|
```

```
Rung 9:0
|
|                                     | SCRAM
|                                     | BUTTON
|                                     |
| PUMP      | STEPPER      | N.O. VALVE | N.C. 1   | N.C. 2   |
| LITE1     | LITE2     | LITE3     | LITE4     | LITE5     | PB2
| 0:000     | 0:000     | 0:000     | 0:000     | 0:000     | I:000
|-----|/|-----|/|-----|/|-----|/|-----|/|-----| [EOT]
| 00       | 01       | 02       | 03       | 04       | 04
Rung 9:1
|-----[END OF FILE]-----|
```

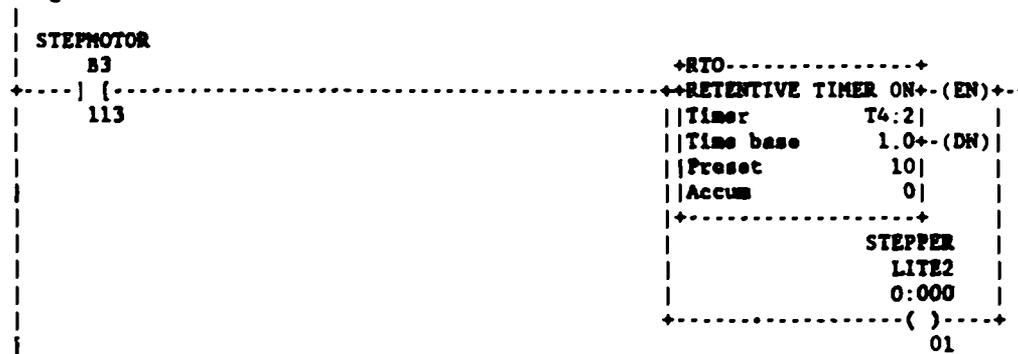
Rung 10:0



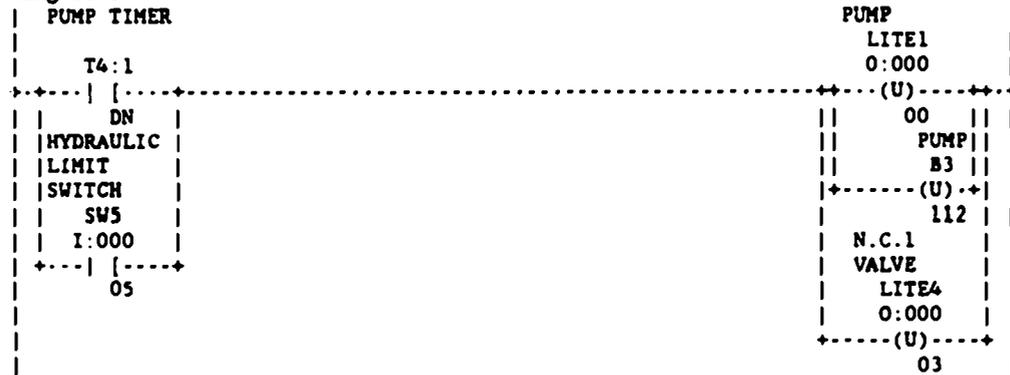
Rung 10:1



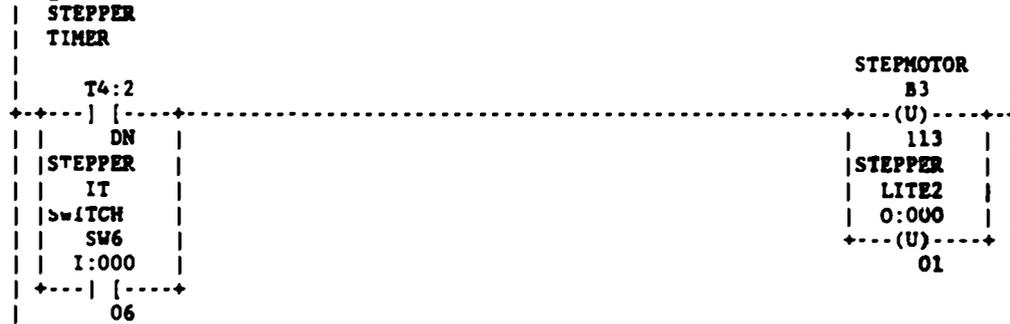
Rung 10:2



Rung 10:3



Rung 10:4



Rung 10:5

SCRAM
BUTTON

PB2
I:000

{
04

N.O. VALVE

LITE3
O:000

(U)

02

N.C.1
VALVE

LITE4
O:000

(U)

03

N.C.2
VALVE

LITE5
O:000

(U)

04

SCRAM
LATCH

BIT

SCRM_LATCH

B3

(L)

114

STEPPER

LITE2

O:000

(U)

01

Rung 10:6

[END OF FILE]

Appendix D

Input Files

INPUT FILE CCR1 AIR GAP = .33"

1 10 -7.900 -2 3 -1 \$ cell 1: first slab cover tank 1
2 10 -7.900 4 -5 -1 \$ cell 2: second slab cover tank 1
3 10 -7.900 6 -1 -3 5 \$ cell 3: steel annulus tank 1
4 11 -1.558 -6 -3 5 \$ cell 4: uranyl nitrate solution tank 1
5 14 5.068e-5 -1 -11 2 \$ cell 5: air in between tanks
6 10 -7.900 7 -8 -1 \$ cell 6: first slab cover tank 2
7 10 -7.900 9 -10 -1 \$ cell 7: second slab cover tank 2
8 10 -7.900 6 -1 8 -9 \$ cell 8: steel annulus tank 2
9 11 -1.558 -6 8 -9 \$ cell 9: uranyl nitrate solution tank 2
10 12 -1.140 11 -7 -1 \$ cell 10: 30 wt% borated poly for tank 2
11 0 13 \$ cell 11: outer void
12 14 5.068e-5 (-4:1:10) -12 \$ cell 12: surrounding sphere of air
13 13 -2.37 12 -13 \$ 5 inch concrete spherical shell

i cy 36.195 \$ outer cylinder specification
2 py 6.1121 \$ first plane specification tank 1 (base) ***
3 py 5.7400 \$ second plane specification tank 1
4 py -6.0161 \$ third plane specification tank 1
5 py -5.644 \$ fourth plane specification tank 1
6 cy 35.550 \$ inner cylinder specification
7 py 8.18728 \$ first plane specification tank 2 + 1.23698
8 py 8.55938 \$ second plane specification tank 2 + .3721
9 py 18.23108 \$ third plane specification tank 2 + 9.0424
10 py 18.60318 \$ fourth plane specification tank 2 + .3721
11 py 6.9503 \$ 30 wt% 1.23698 cm borated poly plane for tank 2 ***
12 so 500 \$ inner sphere
13 so 512.7 \$ outer sphere

imp:n 1 1 1 1 1 1 1 1 1 0 1 1 \$ importance of cells 1 through 11 respectively
m10 6000.50c .00364 24000.50c .189197 25055.50c .019896
26000.55c .693336 28000.50c .074473 14000.50c .019458 \$ steel tanks
m11 92234.50c 1.0433e-5 92235.50c 9.6719e-4 92238.50c 6.052e-5
1001.50c .057986 8016.50c .037782 7014.50c .00226872 \$Ur. Ni. sol
m12 1001.50c .480991 6000.50c .191264 5010.50c .327745 \$ 30 wt% bp
m13 1001.50c 1.4868e-2 6000.50c 3.814e-3 8016.50c 4.1519e-2
20000.50c 1.1588e-2 14000.50c 6.037e-3 12000.50c 5.87e-4
26000.55c 1.968e-4 13027.50c 7.35e-4 11023.50c 3.04e-4 \$ concrete
m14 7014.50c 0.784 8016.50c 0.211 18000.35c 0.005 \$ air
mt11 lwtr.01t \$ thermal neutron cross sections for water in uranyl nitrate
mt12 poly.01t \$ thermal neutron cross sections for poly
kcode 3000 1. 5 50 \$ 3000 source size, ig = 1, skip 5, do 50 cycles
ksrc 0. 0. 0. 0. 10.9093 0. \$ init source points are at 0,0,0 and 0,10.9093,0

INPUT FILE CCR2 AIR GAP = .45"

1 10 -7.900 -2 3 -1 \$ cell 1: first slab cover tank 1
2 10 -7.900 4 -5 -1 \$ cell 2: second slab cover tank 1
3 10 -7.900 6 -1 -3 5 \$ cell 3: steel annulus tank 1
4 11 -1.558 -6 -3 5 \$ cell 4: uranyl nitrate solution tank 1
5 14 5.068e-5 -1 -11 2 \$ cell 5: air in between tanks
6 10 -7.900 7 -8 -1 \$ cell 6: first slab cover tank 2
7 10 -7.900 9 -10 -1 \$ cell 7: second slab cover tank 2
8 10 -7.900 6 -1 8 -9 \$ cell 8: steel annulus tank 2
9 11 -1.558 -6 8 -9 \$ cell 9: uranyl nitrate solution tank 2
10 12 -1.140 11 -7 -1 \$ cell 10: 30 wt% borated poly for tank 2
11 0 13 \$ cell 11: outer void
12 14 5.068e-5 (-4:1:10) -12 \$ cell 12: surrounding sphere of air
13 13 -2.37 12 -13 \$ 5 inch concrete spherical shell

1 cy 36.195 \$ outer cylinder specification
2 py 6.1121 \$ first plane specification tank 1 (base) ***
3 py 5.7400 \$ second plane specification tank 1
4 py -6.0161 \$ third plane specification tank 1
5 py -5.644 \$ fourth plane specification tank 1
6 cy 35.550 \$ inner cylinder specification
7 py 8.49208 \$ first plane specification tank 2 + 1.23698
8 py 8.86418 \$ second plane specification tank 2 + .3721
9 py 18.53588 \$ third plane specification tank 2 + 9.6717
10 py 18.90798 \$ fourth plane specification tank 2 + .3721
11 py 7.2551 \$ 30 wt% 1.23698 cm borated poly plane for tank 2 ***
12 so 500 \$ inner sphere
13 so 512.7 \$ outer sphere

imp:n 1 1 1 1 1 1 1 1 1 0 1 1 \$ importance of cells 1 through 13 respectively
m10 6000.50c .00364 24000.50c .189197 25055.50c .019896
26000.55c .693336 28000.50c .074473 14000.50c .019458 \$ steel tanks
m11 92234.50c 1.0433e-5 92235.50c 9.6719e-4 92238.50c 6.052e-5
1001.50c .057986 8016.50c .037782 7014.50c .00226872 \$Ur. Ni. sol
m12 1001.50c .480991 6000.50c .191264 5010.50c .327745 \$ 30 wt% bp
m13 1001.50c 1.4868e-2 6000.50c 3.814e-3 8016.50c 4.1519e-2
20000.50c 1.1588e-2 14000.50c 6.037e-3 12000.50c 5.87e-4
26000.55c 1.968e-4 13027.50c 7.35e-4 11023.50c 3.04e-4 \$ concrete
m14 7014.50c 0.784 8016.50c 0.211 18000.35c 0.005 \$ air
mt11 lwtr.01t \$ thermal neutron cross sections for water in uranyl nitrate
mt12 poly.01t \$ thermal neutron cross sections for poly
kcode 3000 1. 5 50 \$ 3000 source size, ig = 1, skip 5, do 50 cycles
ksrc 0. 0. 0. 0. 10.9093 0. \$ init source points are at 0,0,0 and 0,10.9093,0

INPUT FILE CCR3 AIR GAP = .68"

1 10 -7.900 -2 3 -1 \$ cell 1: first slab cover tank 1
2 10 -7.900 4 -5 -1 \$ cell 2: second slab cover tank 1
3 10 -7.900 6 -1 -3 5 \$ cell 3: steel annulus tank 1
4 11 -1.558 -6 -3 5 \$ cell 4: uranyl nitrate solution tank 1
5 14 5.068e-5 -1 -11 2 \$ cell 5: air in. between tanks
6 10 -7.900 7 -8 -1 \$ cell 6: first slab cover tank 2
7 10 -7.900 9 -10 -1 \$ cell 7: second slab cover tank 2
8 10 -7.900 6 -1 8 -9 \$ cell 8: steel annulus tank 2
9 11 -1.558 -6 8 -9 \$ cell 9: uranyl nitrate solution tank 2
10 12 -1.140 11 -7 -1 \$ cell 10: 30 wt% borated poly for tank 2
11 0 13 \$ cell 11: outer void
12 14 5.068e-5 (-4:1:10) -12 \$ cell 12: surrounding sphere of air
13 13 -2.37 12 -13 \$ 5 inch concrete spherical shell

1 cy 36.195 \$ outer cylinder specification
2 py 6.1121 \$ first plane specification tank 1 (base) ***
3 py 5.7400 \$ second plane specification tank 1
4 py -6.0161 \$ third plane specification tank 1
5 py -5.644 \$ fourth plane specification tank 1
6 cy 35.550 \$ inner cylinder specification
7 py 9.07628 \$ first plane specification tank 2 + 1.23698
8 py 9.44838 \$ second plane specification tank 2 + .3721
9 py 19.12008 \$ third plane specification tank 2 + 9.6717
10 py 19.49218 \$ fourth plane specification tank 2 + .3721
11 py 7.8393 \$ 30 wt% 1.23698 cm borated poly plane for tank 2 ***
12 so 500 \$ inner sphere
13 so 512.7 \$ outer sphere

imp:n 1 1 1 1 1 1 1 1 1 0 1 1 \$ importance of cells 1 through 13 respectively
m10 6000.50c .00364 24000.50c .189197 25055.50c .019896
26000.55c .693336 28000.50c .074473 14000.50c .019458 \$ steel tanks
m11 92234.50c 1.0433e-5 92235.50c 9.6719e-4 92238.50c 6.052e-5
1001.50c .057986 8016.50c .037782 7014.50c .00226872 \$Ur. Ni. sol
m12 1001.50c .480991 6000.50c .191264 5010.50c .327745 \$ 30 wt% bp
m13 1001.50c 1.4868e-2 6000.50c 3.814e-3 8016.50c 4.1519e-2
20000.50c 1.1588e-2 14000.50c 6.037e-3 12000.50c 5.87e-4
26000.55c 1.968e-4 13027.50c 7.35e-4 11023.50c 3.04e-4 \$ concrete
m14 7014.50c 0.784 8016.50c 0.211 18000.35c 0.005 \$ air
mt11 lwtr.01t \$ thermal neutron cross sections for water in uranyl nitrate
mt12 poly.01t \$ thermal neutron cross sections for poly
kcode 3000 1. 5 50 \$ 3000 source size, ig = 1, skip 5, do 50 cycles
ksrc 0. 0. 0. 0. 10.9093 0. \$ init source points are at 0,0,0 and 0,10.9093,0

INPUT FILE CCR4 AIR GAP = .87"

1 10 -7.900 -2 3 -1 \$ cell 1: first slab cover tank 1
 2 10 -7.900 4 -5 -1 \$ cell 2: second slab cover tank 1
 3 10 -7.900 6 -1 -3 5 \$ cell 3: steel annulus tank 1
 4 11 -1.558 -6 -3 5 \$ cell 4: uranyl nitrate solution tank 1
 5 14 5.068e-5 -1 -11 2 \$ cell 5: air in between tanks
 6 10 -7.900 7 -8 -1 \$ cell 6: first slab cover tank 2
 7 10 -7.900 9 -10 -1 \$ cell 7: second slab cover tank 2
 8 10 -7.900 6 -1 8 -9 \$ cell 8: steel annulus tank 2
 9 11 -1.558 -6 8 -9 \$ cell 9: uranyl nitrate solution tank 2
 10 12 -1.140 11 -7 -1 \$ cell 10: 30 wt% borated poly for tank 2
 11 0 13 \$ cell 11: outer void
 12 14 5.068e-5 (-4:1:10) -12 \$ cell 12: surrounding sphere of air
 13 13 -2.37 12 -13 \$ 5 inch concrete spherical shell

1 cy 36.195 \$ outer cylinder specification
 2 py 6.1121 \$ first plane specification tank 1 (base) ***
 3 py 5.7400 \$ second plane specification tank 1
 4 py -6.0161 \$ third plane specification tank 1
 5 py -5.644 \$ fourth plane specification tank 1
 6 cy 35.550 \$ inner cylinder specification
 7 py 9.55888 \$ first plane specification tank 2 + 1.23698
 8 py 9.93098 \$ second plane specification tank 2 + .3721
 9 py 19.60268 \$ third plane specification tank 2 + 9.6717
 10 py 19.97478 \$ fourth plane specification tank 2 + .3721
 11 py 8.3219 \$ 30 wt% 1.23698 cm borated poly plane for tank 2 ***
 12 so 500 \$ inner sphere
 13 so 512.7 \$ outer sphere

imp:n 1 1 1 1 1 1 1 1 1 1 0 1 1 \$ importance of cells 1 through 13 respectively
 m10 6000.50c .00364 24000.50c .189197 25055.50c .019896
 26000.55c .693336 28000.50c .074473 14000.50c .019458 \$ steel tanks
 m11 92234.50c 1.0433e-5 92235.50c 9.6719e-4 92238.50c 6.052e-5
 1001.50c .057986 8016.50c .037782 7014.50c .00226872 \$Ur. Ni. sol
 m12 1001.50c .480991 6000.50c .191264 5010.50c .327745 \$ 30 wt% bp
 m13 1001.50c 1.4868e-2 6000.50c 3.814e-3 8016.50c 4.1519e-2
 20000.50c 1.1588e-2 14000.50c 6.037e-3 12000.50c 5.87e-4
 26000.55c 1.968e-4 13027.50c 7.35e-4 11023.50c 3.04e-4 \$ concrete
 m14 7014.50c 0.784 8016.50c 0.211 18000.35c 0.005 \$ air
 mt11 lwtr.01t \$ thermal neutron cross sections for water in uranyl nitrate
 mt12 poly.01t \$ thermal neutron cross sections for poly
 kcode 3000 1. 5 50 \$ 3000 source size, ig = 1, skip 5, do 50 cycles
 ksrc 0. 0. 0. 0. 10.9093 0. \$ init source points are at 0,0,0 and 0,10.9093,0

INPUT FILE CCR5 AIR GAP = 1.06"

1 10 -7.900 -2 3 -1 \$ cell 1: first slab cover tank 1
 2 10 -7.900 4 -5 -1 \$ cell 2: second slab cover tank 1
 3 10 -7.900 6 -1 -3 5 \$ cell 3: steel annulus tank 1
 4 11 -1.558 -6 -3 5 \$ cell 4: uranyl nitrate solution tank 1
 5 14 5.068e-5 -1 -11 2 \$ cell 5: air in between tanks
 6 10 -7.900 7 -8 -1 \$ cell 6: first slab cover tank 2
 7 10 -7.900 9 -10 -1 \$ cell 7: second slab cover tank 2
 8 10 -7.900 6 -1 8 -9 \$ cell 8: steel annulus tank 2
 9 11 -1.558 -6 8 -9 \$ cell 9: uranyl nitrate solution tank 2
 10 12 -1.140 11 -7 -1 \$ cell 10: 30 wt% borated poly for tank 2
 11 0 13 \$ cell 11: outer void
 12 14 5.068e-5 (-4:1:10) -12 \$ cell 12: surrounding sphere of air
 13 13 -2.37 12 -13 \$ 5 inch concrete spherical shell

1 cy 36.195 \$ outer cylinder specification
 2 py 6.1121 \$ first plane specification tank 1 (base) ***
 3 py 5.7400 \$ second plane specification tank 1
 4 py -6.0161 \$ third plane specification tank 1
 5 py -5.644 \$ fourth plane specification tank 1
 6 cy 35.550 \$ inner cylinder specification
 7 py 10.04148 \$ first plane specification tank 2 + 1.23698
 8 py 10.41358 \$ second plane specification tank 2 + .3721
 9 py 20.08528 \$ third plane specification tank 2 + 9.6717
 10 py 20.45738 \$ fourth plane specification tank 2 + .3721
 !1 py 8.8045 \$ 30 wt% 1.23698 cm borated poly plane for tank 2 ***
 12 so 500 \$ inner sphere
 13 so 512.7 \$ outer sphere

imp:n 1 1 1 1 1 1 1 1 1 0 1 1 \$ importance of cells 1 through 13 respectively
 m10 6000.50c .00364 24000.50c .189197 25055.50c .019896
 26000.55c .693336 28000.50c .074473 14000.50c .019458 \$ steel tanks
 m11 92234.50c 1.0433e-5 92235.50c 9.6719e-4 92238.50c 6.052e-5
 1001.50c .057986 8016.50c .037782 7014.50c .00226872 \$Ur. Ni. sol
 m12 1001.50c .480991 6000.50c .191264 5010.50c .327745 \$ 30 wt% bp
 m13 1001.50c 1.4868e-2 6000.50c 3.814e-3 8016.50c 4.1519e-2
 20000.50c 1.1588e-2 14000.50c 6.037e-3 12000.50c 5.87e-4
 26000.55c 1.968e-4 13027.50c 7.35e-4 11023.50c 3.04e-4 \$ concrete
 m14 7014.50c 0.784 8016.50c 0.211 18000.35c 0.005 \$ air
 mt11 lwtr.01t \$ thermal neutron cross sections for water in uranyl nitrate
 mt12 poly.01t \$ thermal neutron cross sections for poly
 kcode 3000 1. 5 50 \$ 3000 source size, ig = 1, skip 5, do 50 cycles
 ksrc 0. 0. 0. 0. 10.9093 0. \$ init source points are at 0,0,0 and 0,10.9093,0

INPUT FILE CCR6 AIR GAP = 1.16"

1 10 -7.900 -2 3 -1 \$ cell 1: first slab cover tank 1
 2 10 -7.900 4 -5 -1 \$ cell 2: second slab cover tank 1
 3 10 -7.900 6 -1 -3 5 \$ cell 3: steel annulus tank 1
 4 11 -1.558 -6 -3 5 \$ cell 4: uranyl nitrate solution tank 1
 5 14 5.068e-5 -1 -11 2 \$ cell 5: air in between tanks
 6 10 -7.900 7 -8 -1 \$ cell 6: first slab cover tank 2
 7 10 -7.900 9 -10 -1 \$ cell 7: second slab cover tank 2
 8 10 -7.900 6 -1 8 -9 \$ cell 8: steel annulus tank 2
 9 11 -1.558 -6 8 -9 \$ cell 9: uranyl nitrate solution tank 2
 10 12 -1.140 11 -7 -1 \$ cell 10: 30 wt% borated poly for tank 2
 11 0 13 \$ cell 11: outer void
 12 14 5.068e-5 (-4:1:10) -12 \$ cell 12: surrounding sphere of air
 13 13 -2.37 12 -13 \$ 5 inch concrete spherical shell

1 cy 36.195 \$ outer cylinder specification
 2 py 6.1121 \$ first plane specification tank 1 (base) ***
 3 py 5.7400 \$ second plane specification tank 1
 4 py -6.0161 \$ third plane specification tank 1
 5 py -5.644 \$ fourth plane specification tank 1
 6 cy 35.550 \$ inner cylinder specification
 7 py 10.29548 \$ first plane specification tank 2 + 1.23698
 8 py 10.66758 \$ second plane specification tank 2 + .3721
 9 py 20.33928 \$ third plane specification tank 2 + 9.6717
 10 py 20.71138 \$ fourth plane specification tank 2 + .3721
 11 py 9.0585 \$ 30 wt% 1.23698 cm borated poly plane for tank 2 ***
 12 so 500 \$ inner sphere
 13 so 512.7 \$ outer sphere

imp:n 1 1 1 i 1 1 1 1 1 0 1 1 \$ importance of cells 1 through 13 respectively
 m10 6000.50c .00364 24000.50c .189197 25055.50c .019896
 26000.55c .693336 28000.50c .074473 14000.50c .019458 \$ steel tanks
 m11 92234.50c 1.0433e-5 92235.50c 9.6719e-4 92238.50c 6.052e-5
 1001.50c .057986 8016.50c .037782 7014.50c .00226872 \$Ur. Ni. sol
 m12 1001.50c .480991 6000.50c .191264 5010.50c .327745 \$ 30 wt% bp
 m13 1001.50c 1.4868e-2 6000.50c 3.814e-3 8016.50c 4.1519e-2
 20000.50c 1.1588e-2 14000.50c 6.037e-3 12000.50c 5.87e-4
 26000.55c 1.968e-4 13027.50c 7.35e-4 11023.50c 3.04e-4 \$ concrete
 m14 7014.50c 0.784 8016.50c 0.211 18000.35c 0.00f \$ air
 mt11 lwtr.01t \$ thermal neutron cross sections for water in uranyl nitrate
 mt12 poly.01t \$ thermal neutron cross sections for poly
 kcode 3000 1. 5 50 \$ 3000 source size, ig = 1, skip 5, do 5, times
 ksrc 0. 0. 0. 0. 10.9093 0. \$ init source points are at 0,0,0 and 0,10.9093,0

Appendix E
Number Density Tables

Table E-1 : Number Densities

| Mixture | Nominal Density (g/cc) | Number Density (atoms/barn-cm) |
|--------------------------|------------------------|---|
| Stainless Steel 304l | 7.9 | C=3.1691-4, Cr=1.6471-2, Mn=1.7321-3, Fe=6.036-2, Ni=6.4834-3, Si=1.694-3 |
| Ordinary Concrete | 2.37 | H=1.4868-2, C=3.814-3, O=4.1519-2, Ca=1.1588-2, Si=6.037-3, Mg=5.87-4, Fe=1.968-4, Al=7.35-4, Na=3.04-4 |
| 30% Borated Polyethylene | 1.14 | H=5.1898-2, C=2.0637-2, B=3.5363-2 |

Table E-2 : Atom Fractions

| Element/Nuclide | N (atoms/cm ³) | V (cm ³) | # Atoms | Atom Fraction |
|-----------------------------|----------------------------|----------------------|----------|---------------|
| steel tanks | | | | |
| C | 0.000317 | 84.62294 | 2.68E+22 | 0.003641 |
| Cr | 0.016471 | | 1.39E+24 | 0.189198 |
| Mn | 0.001732 | | 1.47E+23 | 0.019895 |
| Fe | 0.06036 | | 5.11E+24 | 0.693339 |
| Ni | 0.006483 | | 5.49E+23 | 0.074458 |
| Si | 0.001694 | | 1.43E+23 | 0.019459 |
| Sum AD= | 8.71E+22 | | Sum = | 1 |
| AD (atoms/cm ³) | 8.71E+22 | Tot. Atom | 7.37E+24 | |
| uranyl nitrate | | | | |
| U234 | 8.70E-06 | 2395.59 | 2.08E+22 | 3.34E-06 |
| U235 | 0.000955 | | 2.29E+24 | 0.000367 |
| U236 | 2.80E-06 | | 6.71E+21 | 1.08E-06 |
| U238 | 5.80E-05 | | 1.39E+23 | 2.23E-05 |
| Ex. H+ | 0.000194 | | 4.65E+23 | N/A |
| Ni & Ur O | 0.00891 | | 2.13E+25 | N/A |
| H2O | 0.864 | | 2.07E+27 | N/A |
| Na | 7.70E-06 | | 1.84E+22 | 2.96E-06 |
| Fe | 1.30E-06 | | 3.11E+21 | 5E-07 |
| Al | 1.20E-05 | | 2.87E+22 | 4.61E-06 |
| O from H2O | | | 2.07E+27 | N/A |
| H from H2O | | | 4.14E+27 | N/A |
| Total H | | | 4.14E+27 | 0.66414 |
| Total O | | | 2.09E+27 | 0.335457 |
| Sum AD= | 8.74E+23 | | Sum = | 1 |
| AD (atoms/cm ³) | 2.6E+24 | Tot. Atom | 6.23E+27 | |
| 30% Borefed Poly | | | | |
| H | 5.19E-02 | 281.314 | 1.46E+25 | 0.480991 |
| C | 2.06E-02 | | 5.81E+24 | 0.191264 |
| B | 3.54E-02 | | 9.95E+24 | 0.327745 |
| Sum AD= | 1.08E+23 | | Sum = | 1 |
| AD (atoms/cm ³) | 1.08E+23 | Tot. Atom | 3.04E+25 | |