It is a simple matter to convert the diagram into solid state symbols as shown in Figure 2-13. As shown in this example, eight AC inputs and 4 AC outputs are needed. The rectangles

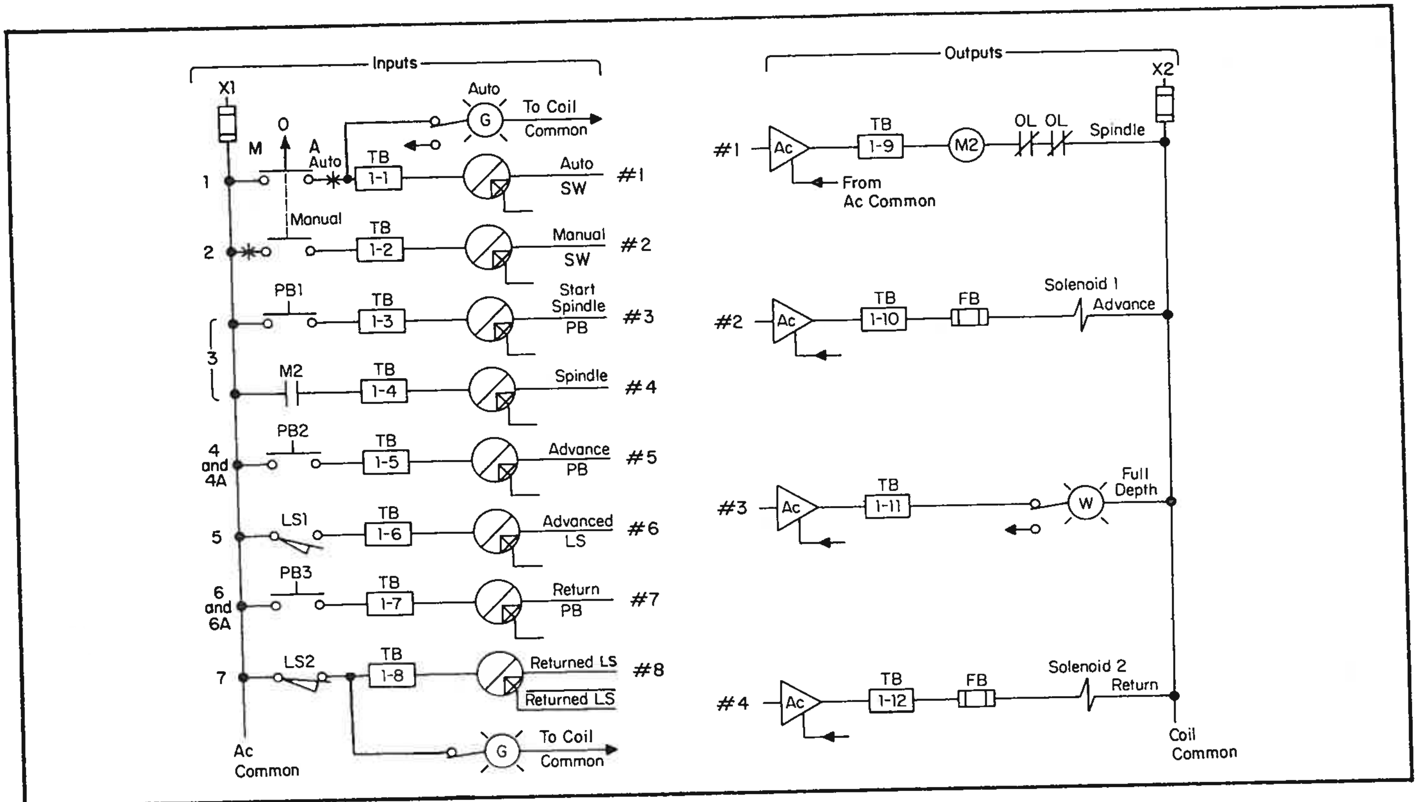

Figure 2-13: Solid state schematic of inputs and outputs.

numbered TB-1-1 through TB1-12 are terminal strips located on the module mounting rack.

Converting the logic portion of the circuit is almost as simple as the step just completed, but a few basic rules must be followed:

1. Start the conversion from output side of relay diagram (right vertical — X2) and work toward the input side (left vertical —X1). See Figure 2-14.

2. Convert each series of individual contacts to a logic AND as shown in Figure 2-15. Circle each contact first. Then count the number of contacts and draw the AND symbol with the appropriate number of inputs (2 or 4). If there are more than four contacts, then more than one AND symbol must be used. Unused inputs are connected to used inputs as shown. This is read: CR3 AND CR2 AND CR1 equals a logic AND.

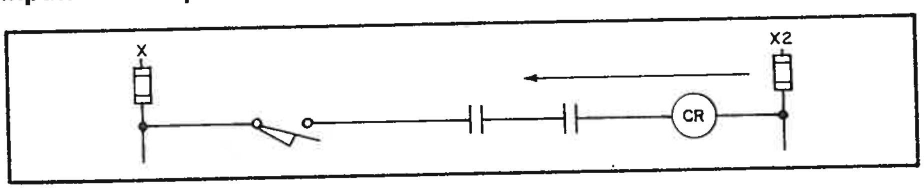

Figure 2-14: Rule 1.

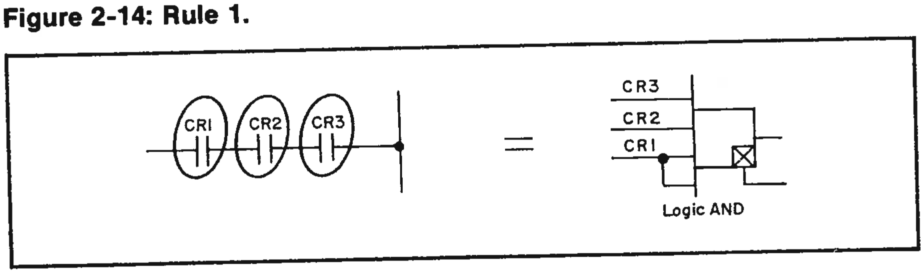

Figure 2-15: Rule 2.

3. Convert each branch (parallel) circuit to a single relay contact as shown in Figure 2-16. Circle the complete circuit from where the current divides to where it rejoins. Label the equivalent contact as "Z" and modify the AND symbol as shown.

4. Convert legs of branch (parallel) circuits to OR circuits by first circling each leg of the circuit and treating it as one contact. In the example shown in Figure 2-17, the upper leg containing CR6 and CR5 is circled and treated as one contact "R". The lower leg containing CR8 and CR7 is circled and treated as contact "S". The two equivalent contacts are then drawn as inputs to a 2-input logic OR. This is read: R OR S equals a logic OR. If the example was a 3-input OR gate, the unused input would be left floating.

5. Convert series contacts within the legs of branch circuits to logic AND circuits. Circle each individual contact and then convert each series of contacts to a logic AND symbol. The output of each AND symbol connects to one input of the previously drawn OR symbol as shown in Figure 2-18.

Figure 2-19 combines all five rules. Note that when there are circles within circles, the outer circles are converted first. Contacts CR3, CR2 and CR1 are converted to three inputs of a 4-input AND. The total branch circuit is identified as the fourth input (Z) to the AND gate. The upper and lower legs of the branch circuit are converted to a 2-input OR gate, whose output is the fourth input to the AND gate. The series of individual contacts, CR6 and CR5, is converted to a 2-input AND; and CR8 and CR7 to another 2-input AND. The outputs of these two AND gates are connected to the inputs of the OR gate.

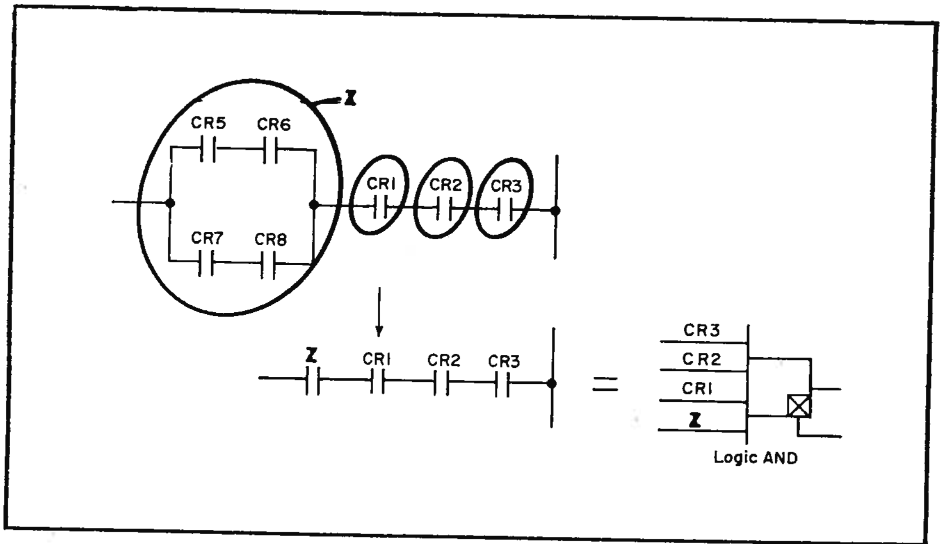

Figure 2-16: Rule 3.

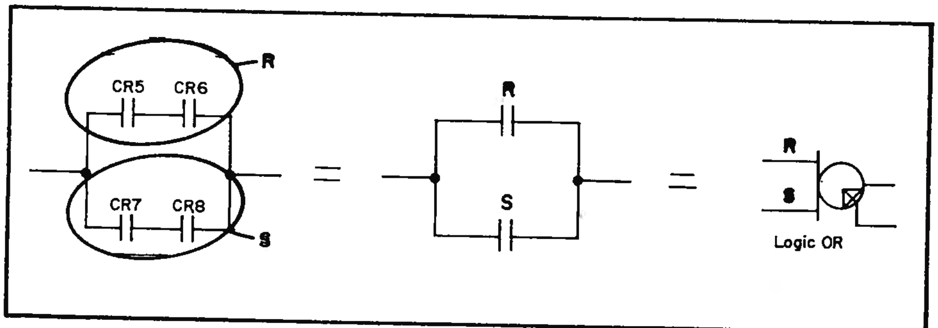

Figure 2-17: Rule 4.

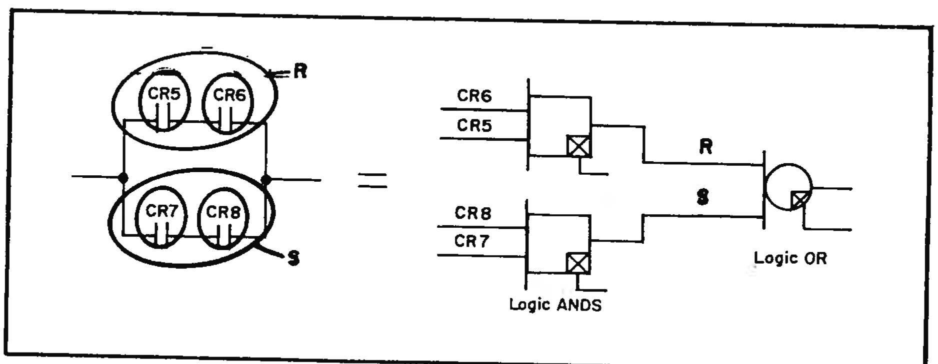

Figure 2-18: Rule 5.

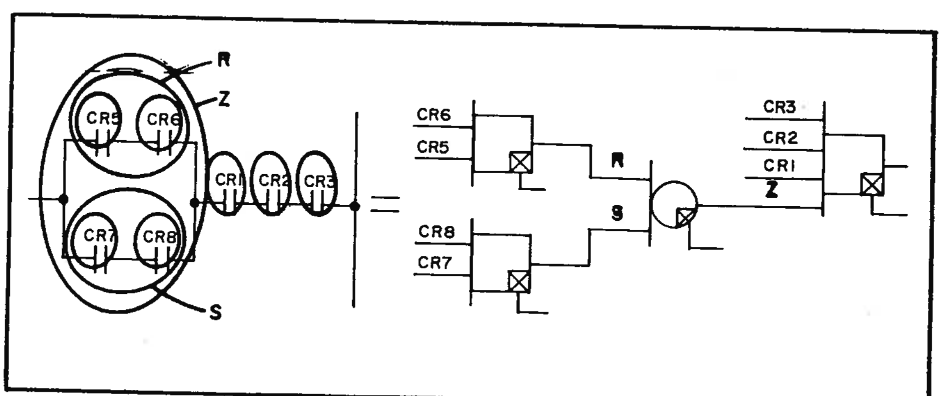

Figure 2-19: Five logic rules combined.

Returning to the machine tool example, line 3 is converted in Figure 2-20. The M2 coil and overload relays were previously converted to outputs and thus, are ignored in this step. Following Rule 1, proceed from right to left. Following Rule 2, circle the two branch circuits, labeling them A and B. These, then, are converted to a 2-input AND having inputs A and B.

Using Rule 4, circle each leg of the branch circuits and convert them to OR gates. There are two legs in each branch circuit resulting in two 2-input OR gates, whose outputs are connected to the inputs of the AND gate.

In converting line 4 (Figure 2-21), all five rules are used. Starting at the right (Rule 1), bypass CR1 coil because it has no function in the solid state circuit. Following Rules 2 and 3, C AND D AND E become three inputs to a 4-input AND gate. Using Rule 4, F OR G become inputs to a 2-input OR gate. Following Rule 5, TD2 AND CR50 AND CRA, become three inputs to a 4-input AND, and PB2 AND CRM become the inputs to a 2-input AND. Note: CR50 is a logic level signal from the machine's master control calling for the drilling unit to cycle.

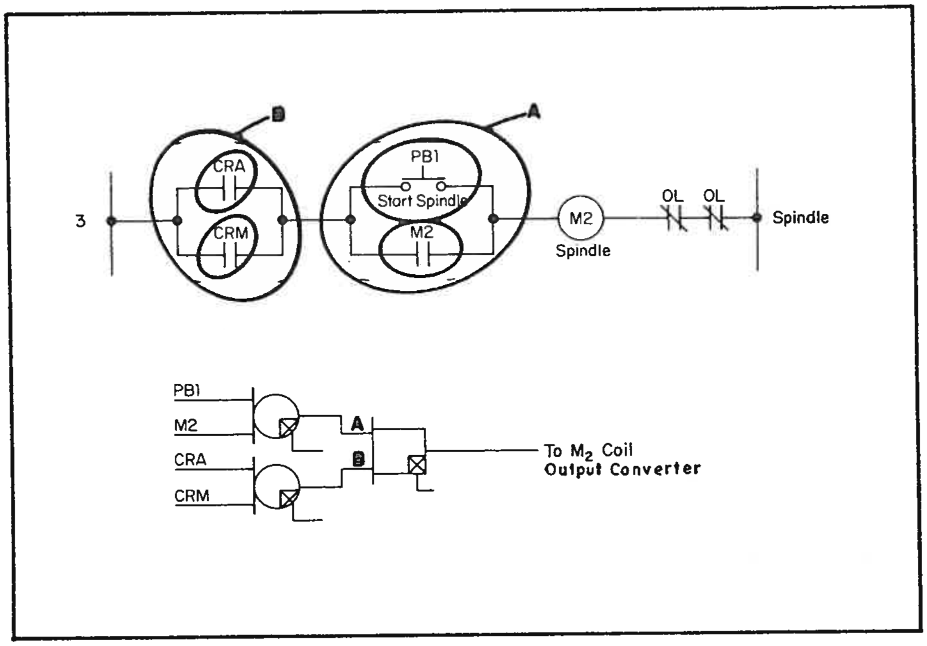

Figure 2-20: Conversion for line 3.

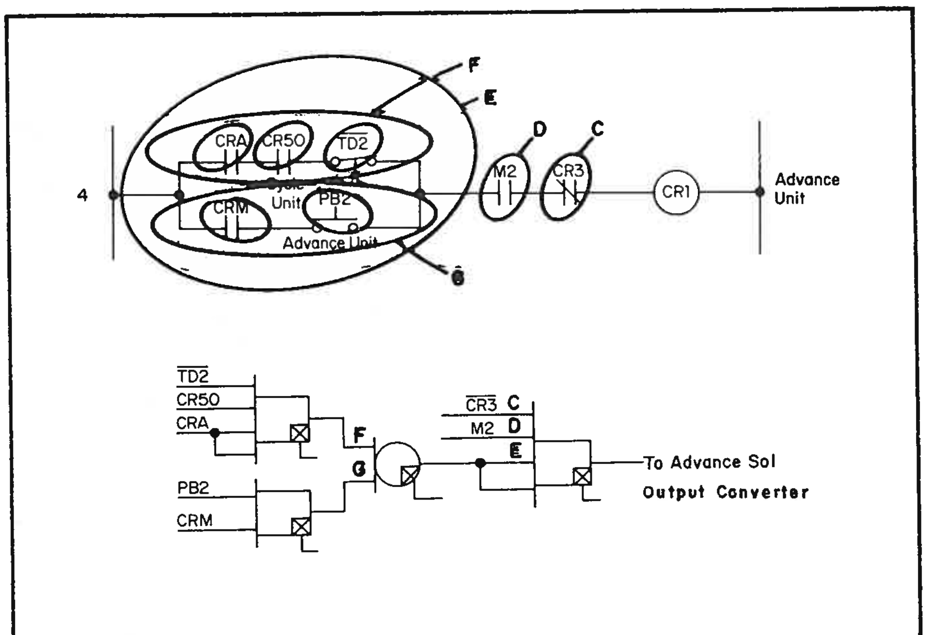

Figure 2-21: Conversion for line 4.

In line 5 (Figure 2-22), the indicating light is bypassed because it was already converted to an output. Next, note the time delay coil TD2, indicating the need for a solid state On-Delay Timer. Going left to the branch circuit, using Rule 3, treat circle H as one contact. Rule 2 converts series contacts H and I into a 2-input AND. By Rule 4, circle H equals TD2 or LS1. Note that the TD2 contact is obtained by feeding back the TD2 output of the On-Delay Timer.

Converting line 6 (Figure 2-23) is straightforward. CR3 is not needed because it performs no function in the solid state circuit. According to Rule 4, J OR K become the two inputs to a 2-input OR. Following Rule 5, CR1 AND CRA AND $\overline{\text{CR4}}$ require one 4-input AND, and PB3 AND CRM require one 2-input AND.

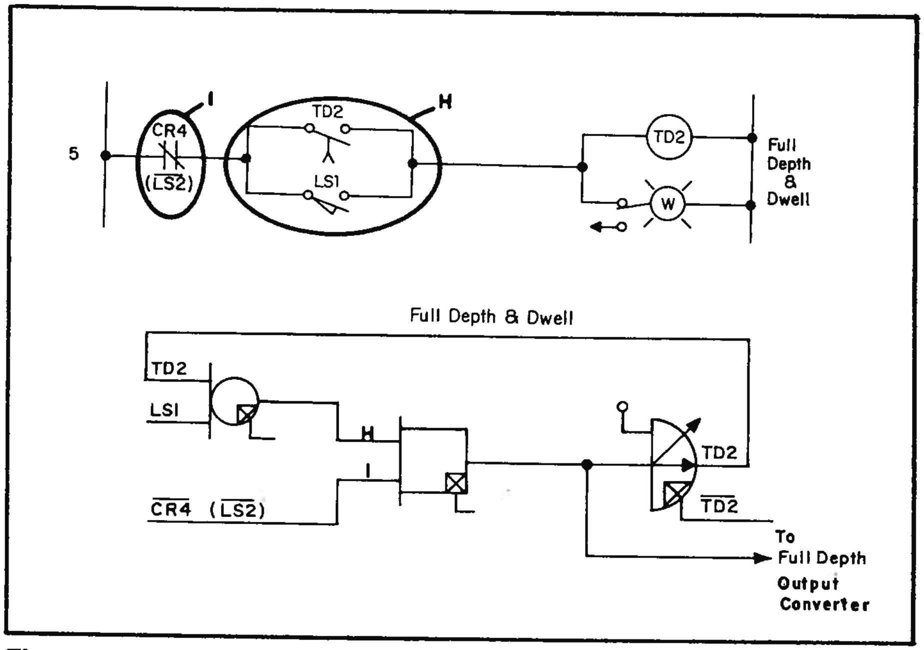

Figure 2-22: Conversion of line 5.

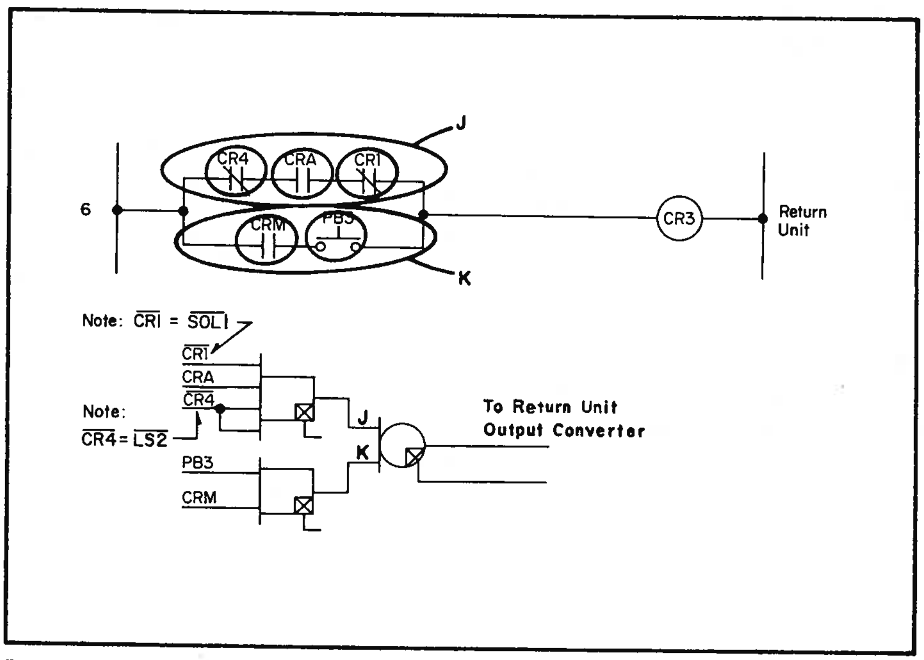

Figure 2-23: Conversion of line 6.

Figure 2-24 illustrates the composite solid state diagram. The logic input designations have been changed to correspond to the correct functional input title. Please note that the INPUTS are not connected to the LOGIC components, since the primary concern is to determine which solid state components are required. The interconnection of the complete diagram will be covered in Section 3 under "Preparing the Drawing Set".

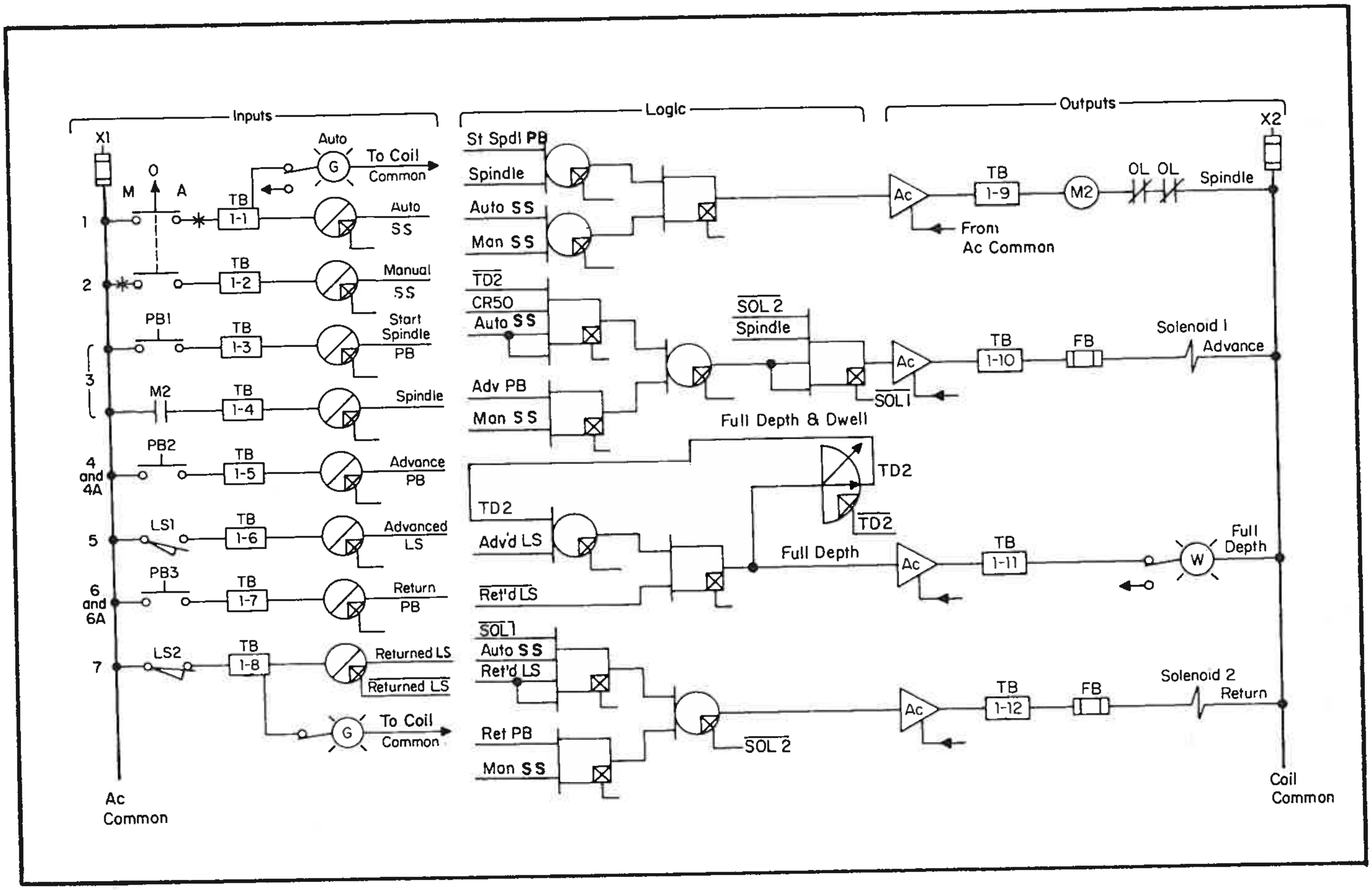

Figure 2-24: Composite solid state diagram.

Converting word descriptions to solid state diagrams

Word descriptions usually are the starting point for making any control diagram, whether it be conventional relay ladder or solid state. Therefore, it often is desirable to convert directly from the word description to a solid state schematic, thereby eliminating the effort required to develop a relay ladder diagram first. To examine this direct approach, the same machine tool example covered in relay to solid state conversion (starting on Page 8) of this section will be used.

The first step is to detail the input and output devices that are required. These are determined as functions of:

- the required machine motions (outputs)
- the required machine sensing devices (inputs)
- the operator controls (inputs)

These functions already may have been determined by the time the word descriptions have been prepared, but examining them in detail allows a better understanding of the problem.

Referring to Figure 2-8, the drilling slide unit requires AC outputs for the following functions:

1. Start spindle motor.
2. Energize advance solenoid to operate hydraulic cylinder, advancing the slide.
3. Turn on indicating light at operator's station, indicating the drill is at full depth.
4. Energize return solenoid to operate hydraulic cylinder, returning the slide.

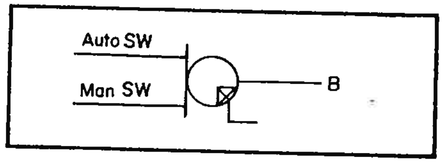

Figure 2-25: Solid state circuit for "manual OR automatic" operation.

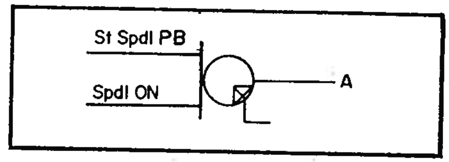

Figure 2-26: Solid state circuit for "start spindle pushbutton OR spindle on (M2 interlock)."

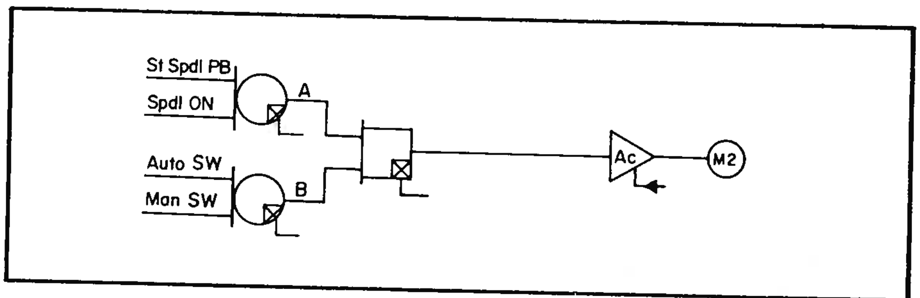

Figure 2-27: Combining the two OR circuits with an AND circuit.

The drilling unit also senses the slide position through the following AC inputs:

1. Advanced limit switch.
2. Returned limit switch.

The remaining AC inputs are operator controls consisting of:

1. Selecting manual or automatic operation by a manual-off-automatic selector switch.
2. Starting the spindle motor by a start spindle pushbutton.
3. Manually advancing or returning the slide unit by pressing either an advance pushbutton or a return pushbutton.

With this background, the logic circuits can be drawn directly from word descriptions which describe the combinations of inputs required to produce each desired output.

Start spindle motor
Word description: "Spindle motor will run when:

1. M-O-A selector switch is at either manual OR automatic.

   AND

2. Start spindle pushbutton OR spindle starter holding interlock (M2) is made."

The first expression has two parts separated by an OR, indicating the need for a 2-input OR solid state device as shown in Figure 2-25.

The second expression also has two parts separated by an OR, requiring another 2-input OR (Figure 2-26).

The AND between the two expressions dictates that both conditions must be met. Therefore, the two OR circuits must feed a 2-input AND device as shown in Figure 2-27.

To complete this circuit, the input interfaces must be added as shown in Figure 2-28. Note that starter interlock contact M2 operates on 120 VAC and therefore requires its own AC input.

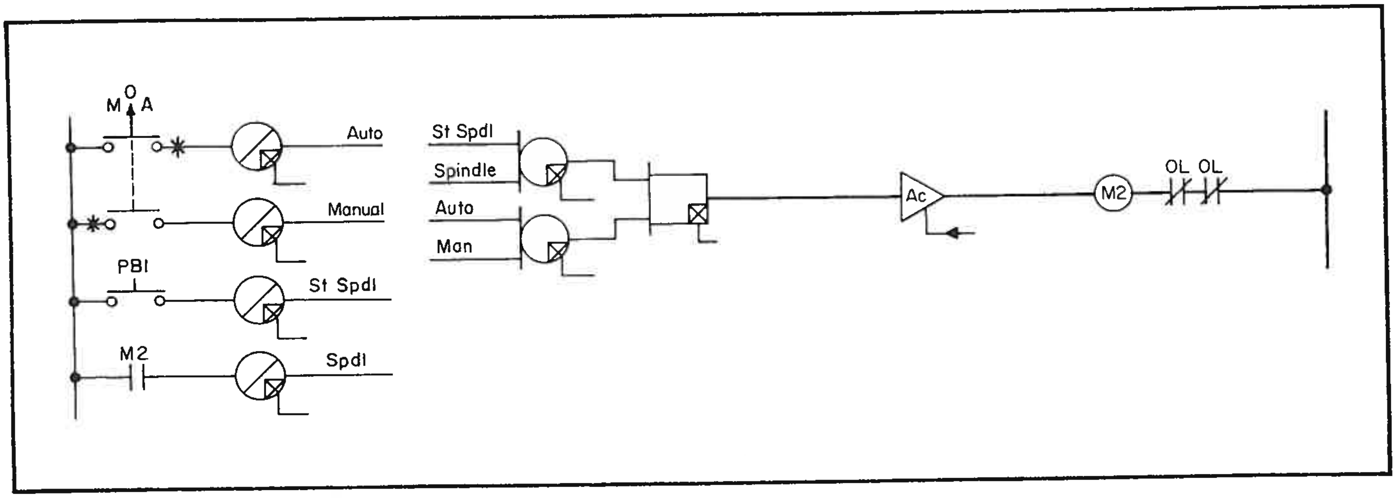

Figure 2-28: Input interfaces added.

Energize advance solenoid

Word description: "Advance solenoid will be energized automatically when:

1. M-O-A selector switch is set at 'Auto'

   AND
2. Cycle unit is on (this is a logic level signal from the machine's master control calling for the drilling unit to cycle)

   AND
3. Drill has NOT completed full depth and dwell

   AND
4. Spindle motor is on (M2).

   AND
5. Return solenoid is NOT energized."

To operate automatically, the description calls for five requirements to be met simultaneously, necessitating a 5-input AND device. To make a 5-input AND circuit, use a 2-input and a 4-input AND. The first four requirements supply the inputs to the 4-input AND. Then, the output from the 4-input AND is used as one of the inputs to the 2-input AND along with the fifth requirement.

See Figure 2-29.

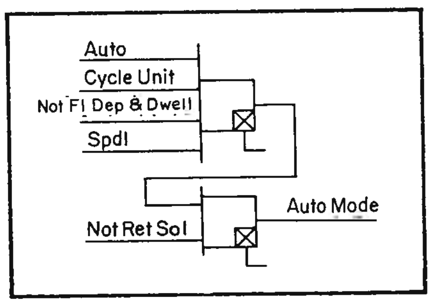

Figure 2-29: 5-input AND created with a 4-input AND and a 2-input AND.

Word description:

"Advance solenoid will be energized manually when:

1. M-O-A selector switch is set at 'manual'

   AND
2. Advance pushbutton is depressed

   AND
3. Spindle motor is on (M2)

   AND
4. Return solenoid is NOT energized."

To operate manually, the description calls for four AND requirements which, of course, can be handled by a 4-input AND as shown in Figure 2-30.

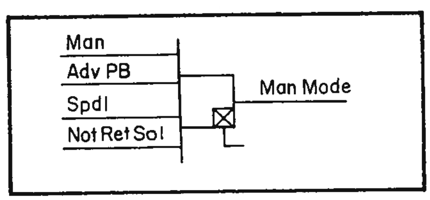

Figure 2-30: Manual mode inputs feed a 4-input AND.

Assembling the pieces, Figure 2-31 shows the complete schematic for controlling the energize advance solenoid function.

Figure 2-31 is only one of many solutions to the control logic for the advance solenoid.

In translating these statements, the first three conditions result in three inputs to a 4-input AND. The third input is the output of a 2-input OR to provide for the automatic OR manual mode.

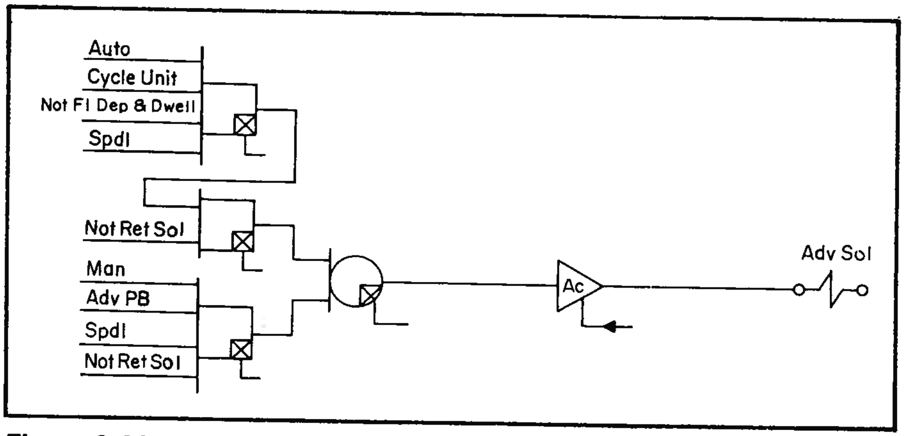

Figure 2-31: First possible schematic for controlling the "energize advance solenoid" function.

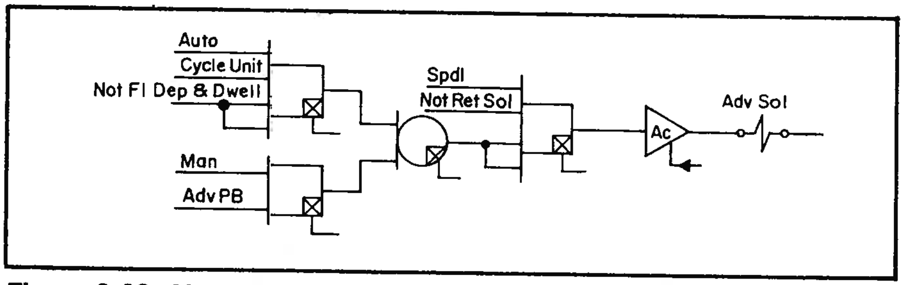

Figure 2-32: Alternate schematic for controlling the "energize advance solenoid" function.

One alternate approach to controlling this same function is depicted in Figure 2-32.

In examining the word description, note the statements "the spindle motor is on" AND "the return solenoid is NOT energized" are common to both the automatic and manual modes. Therefore, the description can be restated: "Advance solenoid will be energized when the spindle motor is on AND the return solenoid is NOT energized AND the other conditions for automatic or manual mode are met."

The two inputs to the OR gate are thus expanded to accommodate the "other conditions for automatic or manual mode."

Full depth and dwell

Word description: "When the unit reaches the advanced limit switch, it shall turn on a dwell timer, stopping the unit from advancing after a short time delay. Further, the full depth indicating light shall remain on and the unit shall be prevented from advancing again until the unit has returned to home position." (In general practice, returned and advanced limit switches are interlocked, as in this example.)

Taking the last statement first, the conditions required for full depth and dwell timer output are:

1. Not returned limit switch

   AND

2. Advanced limit switch or seal-in.

This results in the circuit shown in Figure 2-33.

Energize return solenoid

Word description: "The return solenoid will be energized automatically when:

1. M-O-A selector switch is set at 'Auto'
   AND
2. Advance solenoid is NOT energized
   AND
3. Returned limit switch is NOT energized."

"The return solenoid will be energized manually when:

1. M-O-A selector switch is set at 'Manual'.
   AND
2. Return pushbutton is depressed."

As described, the return solenoid can be operated automatically OR manually, calling for a 2-input OR. See Figure 2-34.

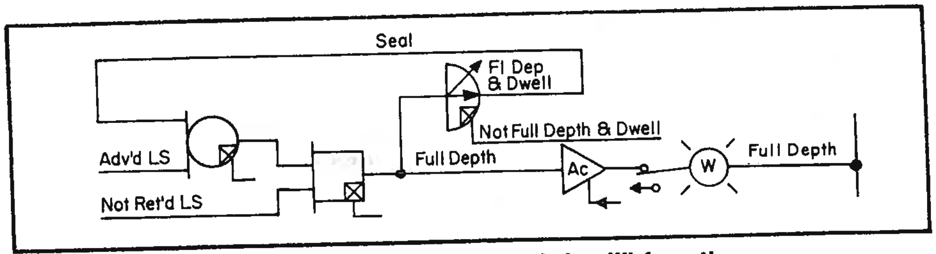

Figure 2-33: Schematic for "full depth and dwell" function.

The automatic operation calls for three AND conditions, indicating three inputs to a 4-input AND. The manual operation indicates a 2-input AND. The complete circuit is shown in Figure 2-35.

Now that all the logic circuits and their associated outputs have been developed, it is a simple matter to organize them on one drawing as shown in Figure 2-36. The input interfaces are added in the same manner described for Figure 2-28.

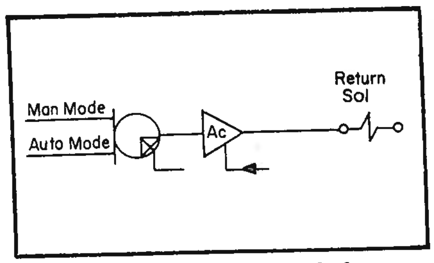

Figure 2-34: Basic circuit for automatic or manual operation.

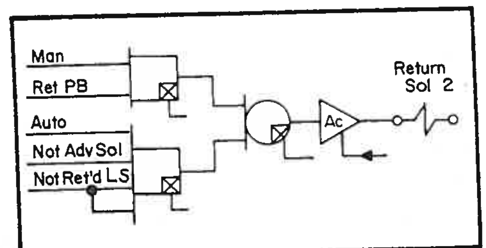

Figure 2-35: Schematic for "energize return solenoid" function.

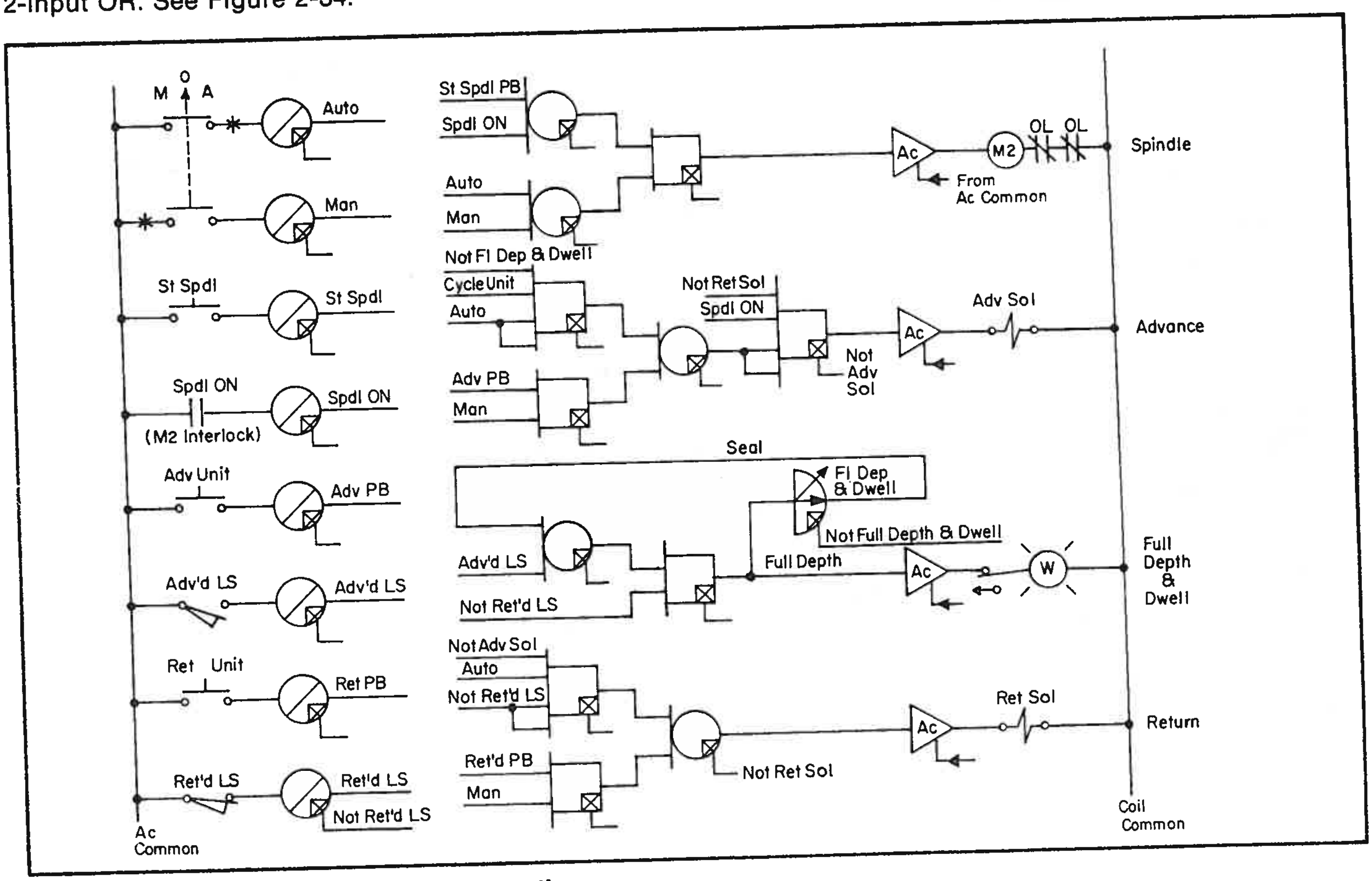

Figure 2-36: Complete solid state schematic.

Converting Boolean equations to solid state diagrams

Another method of designing a control system is by using Boolean algebra. In addition to being a shorthand method that saves considerable time, Boolean algebra has the unique characteristic of permitting algebraic manipulations that result in circuit simplification, thereby reducing the control hardware required.

The subject of Boolean algebra and its companion circuit simplification is covered in numerous textbooks. The purpose of this discussion is to explain the method of converting to a solid state diagram, once the Boolean design has been completed. Again, the machine tool example covered on the preceding pages will be used.

Written in Boolean equations, the control circuit shown in Figure 2-10 would be:

Line 1. AUTO =
AUTO SW • $\overline{\text{MAN SW}}$

Line 2. MAN =
$\overline{\text{AUTO SW}}$ • MAN SW

Line 3. SPDL=
(CRM + CRA) • (PB1 + M2)

Lines 4 & 4A. SOL1 = CR1 =
$\overline{\text{SOL2}}$•M2•[($\overline{\text{TD2}}$•CR50•CRA)+(PB2•CRM)]

Line 5. FL DEP & DWELL =
$\overline{\text{LS2}}$•(TD2+LS1)

Lines 6 & 6A. SOL2 = CR3 =
($\overline{\text{LS2}}$•CRA•$\overline{\text{SOL1}}$)+(CRM•PB3)

Line 7. RET'D=CR4=LS2

The conversion to a solid state diagram is quite easy, requiring only simple examination. Remember that the symbols • equals AND, + equals OR, and $\overline{\quad\quad}$ equals NOT. The letter and number combinations, of course, are the same abbreviations as used in standard relay circuitry.

The first Boolean equation is read: automatic operation equals automatic switch on AND manual switch NOT on. The second equation is read: manual operation equals automatic switch NOT on AND manual switch on. These two equations, of course, establish the need for a two-position selector switch which provides circuit inputs AUTO and MAN.

In examining the third equation:
SPDL=(CRM+CRA) • (PB1+M2)
note the two parenthetical expressions are separated by an AND, indicating a 2-input AND gate. Each parenthetical expression has two units separated by an OR, indicating that the two logic inputs to the 2-input AND are two 2-input OR gates. The abbreviation SPDL is the output to the spindle motor. The equivalent solid state circuit is shown in Figure 2-20.

The fourth equation is written as follows:
SOL1=CR3=$\overline{\text{SOL2}}$ • M2 • [($\overline{\text{TD2}}$ •CR50•CRA) + (PB2•CRM)]
Note: CR50 is a logic signal from the master control.

This equation is a little more complicated in that it has two minor expressions within a major expression. This is no problem as long as primary elements are converted first, then secondary elements, then tertiary elements etc. There are three primary elements($\overline{\text{SOL2}}$, M2 and the major expression) connected by AND's, indicating three inputs to a 4-input AND. There are two minor expressions connected by an OR, indicating a 2-input OR (whose output is one of the inputs to the 4-input AND). The first minor expression has three elements connected by AND's, indicating three inputs to another 4-input AND (whose output is an input to the 2-input OR). The second minor expression, of course, indicates a 2-input AND (whose output is the other input to the 2-input OR). The equivalent solid state circuit is shown in Figure 2-21.

In the fifth equation:
FL DEP & DWELL = $\overline{\text{LS2}}$ • (TD2 + LS1) the delay timer is converted. The parenthetical expression calls for a 2-input OR with one of the inputs being TD2 – a time delay. It follows that this input must be supplied by a delay timer, which is located last in the string of logic units. The equivalent solid state circuit is shown in Figure 2-22.

The last two equations follow the same procedure. The equivalent solid state circuit for Figure 2-23, equation 7 states CR4 equals LS2.