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DIVISION**

**A DIGITALLY BASED PATTERN GENERATOR
FOR AN ELECTRON-BEAM WELDER**

L. G. Whitten, III

February 1981

**OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY**

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A DIGITALLY BASED PATTERN GENERATOR FOR AN ELECTRON-BEAM WELDER

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Y-12 Development Division

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fulfillment of the requirements for the
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ABSTRACT

A digitally based deflection generator for an electron-beam welder is presented. Up to seven patterns of any shape are stored in programmable read-only memory (PROM). The pattern resolution is 39% at frequencies from 10 Hz to 1 kHz and can be x-t, y-t, or x-y formed. Frequency and pattern selections may be chosen by the welder computer or manually selected on the front panel. The ability to repeatedly synchronize two waveforms of any shape and frequency enables an unlimited variety of welds.

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SUMMARY

Electron-beam welding (EBW) requires precise control of the beam with respect to the materials being joined. Control of the intensity, direction, and length-of-stay are primary requirements. Depending upon the material, penetration, coverage, and path required, the control of the beam can often be very complex. In the past, complex patterns have been created by the interaction of two signal generators. In an effort to adapt to a production environment, a more repeatable and accurate means of control (than is manual setting) of the test instruments was developed.

The heart of the system consists of seven pairs of low-cost programmable read-only memories (PROM) with each pair containing a different beam-deflection pattern. These seven patterns are multiplexed to one of their number, the selection being determined manually or by computer control (this auto/manual feature was incorporated into all phases of an electron-beam-welder-upgrading project). Additionally, the frequency at which the pattern is generated is selectable. Obtaining this frequency involves stepping through the PROM addresses at an appropriate rate.

Frequencies up to 1840 Hz (well above the response of the beam), selectable in 10-Hz increments, are obtained. A waveform resolution of 1 part in 256 is inherent in the design. Each pattern is appropriately attenuated before being inputted into programmable current supplies, which are capable of delivering 0 to ± 162.56 mA to the deflection coils that control the electron beam.

INTRODUCTION

An electron-beam welder's inherent properties of narrow fusion and heat-affected zones, high-metallurgical purity, and the variety of materials which can be mated¹ are most attractive to the nuclear industry because of the highly critical welds that are required. Previous welders have been manually controlled as are older joining technologies. Manual control consists of an operator's observation of the beam, the joining of the parts, and the adjustment of each with the appropriate control knob. This type of manipulation is adequate for less than critical work. Automatic control via computer is considered a must for the accurate repeatable welds needed in the production environment. A complete-upgrading endeavor of an electron-beam welder was undertaken at the Oak Ridge Y-12 Plant^(a) to develop the control needed for narrow deep-penetration welds. The 7.5-kW machine chosen for this project was to have computer or manual control of wire feeding, beam/seam tracking, accelerating voltage, beam current, focus current, filament current, chamber vacuum, and beam deflection. This report addresses the problems of beam deflection.

(a) Operated by the Union Carbide Corporation, Nuclear Division, for the Department of Energy.

DIGITAL GENERATOR FOR ELECTRON-BEAM WELDER

PRELIMINARY WORK

Circular deflection of the electron beam (EB) is usually employed to control heat distribution along a weld seam, to provide a stirring action to reduce porosity, to smooth out a weld, or to enable easier focusing at high-energy levels.² Materials that the EB welder is commonly used upon are listed in Table 1. Some commonly used patterns are shown in Figure 1. R. Mayer has reported research that has suggested the desirability of influencing the molten pool of metal generated during EB welding by previously untried patterns.³ In particular, it was found that the entire weld seam, upper bead, under bead, and internal seam region could be affected. The ability to control pipe cavities, to reduce liquid-metal drop-out, and to minimize spiking effects was shown. Although a detailed discussion of the metallurgical effects is beyond the scope of this report, it is the ability of the electron beam to travel quickly around and through a weld region that makes this possible.

Table 1
MATERIALS JOINED BY ELECTRON-BEAM WELDING

Steels to Magnesium Alloys
Aluminum Alloys to Copper and Copper Alloys
Rare and Precious Metals to Nickel
Refractory Metals to Rare and Precious Metals

Simple patterns have previously been created using interacting signal generators. This unrepeatable method gives varying results.

Y. Neuvo has reported on a digitally based sine-wave generator used in a very high frequency omnidirectional (VOR) system, which is a navigational aid for pilots. This system has only one possible pattern: that of a modified sine wave.⁴

A commercial device, specifically designed for electron-beam deflection, is available that produces circles of various shapes and frequencies.⁵ In developmental work, it is desirable to observe other effects upon a weld that is created with other patterns. While only one specific pattern was being considered, it was thought desirable to include the possibility for many patterns

without becoming unwieldy from a hardware standpoint. The number of patterns was set at seven. The patterns could be of any possible shape but had to be within 1% of the desired waveform.

Figure 1. COMMONLY USED DEFLECTION PATTERNS.

An electron-beam's speed-of-movement between two points is limited by the speed at which the magnetic field surrounding the beam may change. The welder chosen here has a measured response time of 1 kHz. For this reason, programmed speeds of $< 1 \text{ kHz}$ ($\pm 1\%$) are sufficient.

This report describes a digitally based pattern generator which controls electron-beam deflection in the electron-beam welder (Figure 2). The theory behind electron-beam deflection and the resultant approach taken to generate a desired deflection pattern is presented; and the system is described in detail including pattern generation, multiplexing, frequency generation, and timing considerations. Results are shown, and a discussion of those results and recommendations for future work are given in this report.

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Figure 2. ELECTRON-BEAM WELDER (7.5 kW).

THEORY

The electron-beam welder's most fundamental and critical assembly is the electron gun. This is a device which generates, accelerates, and slightly focuses a beam of electrons.⁵ Heating the filament of the gun (Figure 3) forces electrons to be emitted. A negative dc potential is impressed between the filament and a hollow anode, which is at ground potential. This potential difference results in an acceleration of the emitted electron through the anode. When applying the maximum possible voltage controlling acceleration (150 kV), the electrons approach a speed that is two-thirds of the speed of light.⁵ It is the impedance of

this high speed by the workpiece which generates heat around the impinging electrons. Since the electrons penetrate deeply into the material being joined, so does the heat.

Another gun element is the grid, which shapes and controls the intensity of the beam. Between the gun and the workpiece (also at ground potential) are two magnetic coils (Figure 4); one controls the focus of the beam, and the second controls deflection.

The location of the beam on the materials being mated is controlled by a magnetic field surrounding the electron beam. A magnetic field is capable of this control because of the very nature of electrons: their negative charge. The magnetic field either attracts or repels the electrons, depending upon the field's polarity. Deflection coils made of stator-wound high-linearity wire create the field whenever a current is passed through the coils (Figure 5). Any change in the current alters the magnetic field and, implicitly, the path of the beam traveling through the field.

There are four ways of supplying current to the deflection coils to obtain a desired two-dimensional pattern. One method, which is commonly used, is the manual setting of the potentiometers. This is unsatisfactory control of the beam. A second approach is an analog system, which generates one of many hard-wired patterns. Such a system is possible but would take many trials and errors to get a fix on the desired pattern.

The computer that controls functions of the welder such as beam intensity and acceleration voltage could deliver information to a digital-to-analog convertor (DAC). The DAC would, in turn, supply the desired current to the coils. Since the patterns are rarely

Figure 3. ELECTRON-BEAM FORMATION.

Figure 4. CROSS SECTION OF COLUMN AND WORK CHAMBER.

changed, this software scheme would be a waste of valuable computer time and programming effort.

The most flexible and promising method is a mixture of the above ideas. The ordinates and abscissas of a pattern are stored in PROMs which are programmed with a microprocessor (see **Appendix D**). To obtain different patterns, the method must multiplex several PROMs. Should a pattern be required other than those present, it is a simple matter of physically replacing any PROM (since they are contained in sockets). Varying the frequency of a pattern involves obtaining the contents of a PROM at an appropriate rate.

Figure 5. DEFLECTION COIL.

This digital hardware approach has been adopted and is presented here.

SYSTEM DESCRIPTION

A simplified block diagram of the digital pattern generator is shown in Figure 6. A more complete block diagram is shown in the **Complete System Layout** section which describes each of the blocks in detail.

The Auto/Manual switch selects one of those two parameter menus. For pattern generation, a programmable clock pulses a counter at the frequency chosen manually or by the computer. The counter is used as an address for the horizontal- and vertical-axis PROMs. The PROMs contain the magnitudes of the axis points.

To select the pattern that the computer or manual switches have chosen, all the PROMs are multiplexed. The appropriate data then goes to programmable current generators, which supply current to the electron-beam-welder deflection coils.

Current Supplies

Deflection coils of the electron-beam welder are capable of 200 mA in either the horizontal or vertical direction. Programmable current supplies able to deliver from 0 to ± 163.835 mA are commercially available and are shown in Figure 7.^(b) Current output of these supplies is formed in accordance with a 16-bit word coded in two's-complement form (see **Appendix A**). Rear port connections for the input data are indicated in Figure 8.

(b) Hewlett-Packard Co., Palo Alto, Calif.

Figure 6. SIMPLIFIED BLOCK DIAGRAM OF DEFLECTION SYSTEM.

Figure 7. HEWLETT-PACKARD DIGITAL CURRENT SOURCE.

Current-Supply Programming

For safety reasons (equipment), cable-interlock connections and voltage-limit information are required by the current supplies. The compliance voltage of the deflection coils determines the voltage limit by:

$$V = L \frac{di}{dt} + RI. \quad (1)$$

The inductance and the resistance of the coils were measured and found to be 43 mH and 90 Ω at 1 kHz. Measurements were taken at this frequency because it is the 3-dB attenuation point of the coils and the upper limit of the deflection generator. As a rule of

thumb, a square wave must have a rise time within 10% of the period. For a square wave at 1000 Hz, this is 100 μ s. The amount that the current may change in this time frame is from -162.56 mA to +162.56 mA, or 325.12 mA. Therefore:

$$\begin{aligned}
 V &= L \frac{di}{dt} + RI \\
 &= (43 \text{ mH}) \left(\frac{325.12 \text{ mA}}{100 \mu\text{s}} \right) \\
 &\quad + (90 \Omega) (325.12 \text{ mA}) \\
 &= 169.1 \text{ V.}
 \end{aligned} \tag{2}$$

Since the maximum voltage of the current supplies is 100 V, distortion of the square wave will occur as shown in Figure 9. The maximum frequency obtainable by a square wave without distortion is given by:

$$\begin{aligned}
 f &= \frac{0.1}{dt} \\
 &= \frac{(0.1) (V - RI)}{L di} \\
 &= \frac{(0.1) [100 \text{ V} - (90 \Omega) (325.12 \text{ mA})]}{(43 \text{ mH}) (325.12 \text{ mA})} \\
 &= 506 \text{ Hz.}
 \end{aligned} \tag{3}$$

Fortunately, the patterns being considered are closer to a sine wave, where the slew rate, di/dt , is better approximated:

$$\begin{aligned}
 \frac{di}{dt} &= A\omega \\
 &= (325.12 \text{ mA}) (2\pi) (1 \text{ kHz}) \\
 &= 628 \text{ mA/s,}
 \end{aligned} \tag{4}$$

and

Figure 8. INPUT/OUTPUT DATA CONNECTOR FOR CURRENT SOURCE.

$$V = L \frac{di}{dt} + RI \quad (5)$$

$$= (43 \text{ mH}) \frac{628 \text{ mA}}{\text{s}} + (90 \Omega) (325.12 \text{ mA})$$

$$= 29.3 \text{ V.}$$

The 100-V-limit condition was selected and hard-wired into the system in accordance with Table 2. When this limit is reached, a light-emitting diode (LED) on the supply faceplate is illuminated; and the computer is notified. At any time, the voltage limit may be set at its minimum level (2 V) by grounding the voltage-limit-override pin, Number 18. This would normally be done only in a panic situation.

Also hard-wired within the cable connectors are the cable continuity interlock and current range data. Pin 25 (cable continuity interlock) is tied to Pin 26 (input ground). In this manner, if the programming cable is removed, the LO output terminal is opened, thereby protecting the deflection coils.

The current range is increased by 10 by wiring Pin 20 to a HI level (Pin 26, ground for Hewlett-Packard Option 064 or left open for Hewlett-Packard Option 062).

The current range, voltage limit, and current magnitude are updated each time a gate is received from the computer at Pin 32. If the STORAGE DISABLE switch behind the supply's front panel is ON, the supplies track the input data. This was done in the subject design to obtain optimum frequency response.

Digitizing Effects

A key point in the design of the pattern generator is the quantity of points into which a waveform is to be digitized. The given of the problem is that only complete cycles of a waveform be programmed in a single PROM and that resolution error be less than 1% of the desired pattern.

First considered is the maximum magnitude programmed into the PROMs. The current sources to be programmed by the output of the PROMs have 1 sign bit and 15 magnitude bits. The accuracy of the current source is specified as $10 \mu\text{A} \pm 0.01\%$ of the programmed

Figure 9. SLEW-RATE DISTORTED AND NONDISTORTED SQUARE WAVE.

Table 2
VOLTAGE-LIMIT CODING

Voltage Limit (V)	Current-Source Pin Number		
	24	23	22
2	HI	HI	HI
5	HI	HI	LO
7	HI	LO	HI
10	HI	LO	LO
20	LO	HI	HI
50	LO	HI	LO
70	LO	LO	HI
100	LO	LO	LO

output. Table 3 presents the relative error as a function of the least significant bit (LSB) only. Current output of up to 1.275 mA are programmed with the LSB. From the table, it is apparent that programming only these eight bits can lead to significant error. To get below the 1% error required, the resolution must be 1.28 mA.

The maximum current available with the most significant 7 bits (LSB = 1.28 mA) is 162.56 mA, as compared to a possible 163.835 mA with the entire 15 bits. More than doubling the number of bits affords only a:

$$\frac{163.835}{162.56} = 1.008 \quad (6)$$

times increase in available current, but lowers the error by:

$$\frac{0.8}{0.005} = 160. \quad (7)$$

However, since 162.56 mA is essentially as close to 200 mA (limit of the deflection coils) as is 163.835 mA (81.3% versus 81.9%) and since 1% resolution is all that is required, magnitude programming of seven bits plus sign bits is the optimum choice.

Once the eight-bit arrangement of a word is decided upon, it is left to determine how many words a PROM needs to contain. Analyses were undertaken of the effects of digitizing one sine-wave cycle into 32, 64, 128, or 256 points. Tables 4, 5, 6, and 7 contain, respectively, the magnitude of the points programmed when using 256, 128, 64, and 32 words per cycle (only half of the programmed cycle is shown). These tables are based on a maximum magnitude of 127 ($2^7 - 1$).

In order for the analyses to be equivalent for the 4 digitized waveforms, a comparison was made to an accurate sine wave at 10° increments. Table 8 contains one half cycle of this comparison. $F(\phi)$ is defined as:

$$F(\phi) = 127 \sin(\phi). \quad (8)$$

Magnitudes of $f_1(\phi)$ (256 points), $f_2(\phi)$ (128 points), $f_3(\phi)$ (64 points), and $f_4(\phi)$ (32 points) at the 10° increments (as they are programmed based on Tables 4, 5, 6, and 7) are listed alongside $F(\phi)$. Table 8 contains the errors at the comparison points based on the formula:

Least Significant Bits (μA)	Resolution Error (%)	Least Significant Bits (μA)	Resolution Error (%)
0.005	200	1.28	0.79
0.01	100	2.56	0.40
0.02	50	5.12	0.21
0.04	25	10.24	0.11
0.08	12.5	20.48	0.06
0.16	6.25	40.96	0.03
0.32	3.14	81.92	0.02
0.64	1.57		

$$Z_n = \frac{[127 \sin(n\phi) - f_n(n\phi)]^2}{127 \sin(n\phi)} ; \text{ and} \quad (9)$$

Z_n is then utilized in two similar analyses designed to give a relative indication of error. The chi-square evaluation (X^2) is given by:

$$X^2 = \sum_{n=1}^{17} \frac{[F_i(10n) - f_i(10n)]^2}{F_i(10n)} \quad (10)$$

$$= \sum_{n=1}^{17} Z_i. \quad (11)$$

The integral-square evaluation (I) is given by:

$$I_i = \int_0^{180} \frac{[F_i(10t) - f_i(10t)]^2}{F_i(10t)} dt, \quad (12)$$

which is integrated using Simpson's rule:

$$I_i = \frac{h}{3} [Z_i(0) + 4Z_i(10) + 2Z_i(20) + \dots + 2Z_i(160) + 4Z_i(170) + Z_i(180)], \quad (13)$$

where:

$$h = \frac{180}{\text{points/waveform} - 1} \quad (14)$$

For Simpson's rule to be valid, the number of points must be odd. Point 18 ($\phi = 180$) is the start of the next half cycle and is ideally equal to zero [$127 \sin(180) = 0$]. In this case, it is impossible to calculate the error if $F(\phi) - f(\phi) \neq 0$ since it would be divided by $F(\phi) = 0$. Since it is known that a small error will be introduced, $Z(180)$ is set to zero in all four cases.

The four waveforms' chi-square and integral-square errors are listed in Table 9. It is seen that reducing the number of points per cycle from 256 to 128 increases the error 30 times (X^2) or 68 times (I). The smallest erasable PROM that is available is 256 words of eight bits per word. To decrease the points programmed per waveform to 128, one waveform is programmed in only one-half of the PROM, leaving the other 128 points zeroed. The programmable clock speed would be halved, and a seven-bit counter would be used instead of an eight-bit device. The hardware savings is minimal. Therefore, programming time must be balanced against desired resolution. The increase in resolution more than offsets the extra programming effort; in particular, programming is infrequent, but resolution is a continuous requirement.

Table 4
SINE APPROXIMATION — 256 POINTS

Point Number	F(ϕ)	f(ϕ)	ϕ	Point Number	F(ϕ)	f(ϕ)	ϕ
0	0	0	0	64	126.998	127	90.35
1	3.129	3	1.41	65	126.940	127	91.76
2	6.256	6	2.82	66	126.805	127	93.18
3	9.379	9	4.24	67	126.593	127	94.59
4	12.497	12	5.65	68	126.304	126	96.00
5	15.607	16	7.06	69	125.939	126	97.41
6	18.707	19	8.47	70	125.497	125	98.82
7	21.796	22	9.88	71	124.979	125	100.24
8	24.872	25	11.29	72	124.385	124	101.65
9	27.933	28	12.71	73	123.716	124	103.06
10	30.977	31	14.12	74	122.971	123	104.47
11	34.002	34	15.53	75	122.152	122	105.38
12	37.006	37	16.94	76	121.258	121	107.29
13	39.988	40	18.35	77	120.292	120	108.71
14	42.946	43	19.76	78	119.252	119	110.12
15	45.878	46	21.18	79	118.139	118	111.53
16	48.781	49	22.59	80	116.955	117	112.94
17	51.656	52	24.00	81	115.700	116	114.35
18	54.498	54	25.41	82	114.375	114	115.76
19	57.308	57	26.82	83	112.980	113	117.18
20	60.083	60	28.24	84	111.516	112	118.59
21	62.821	63	29.65	85	109.985	110	120.00
22	65.522	66	31.06	86	108.387	108	121.41
23	68.182	68	32.47	87	106.724	107	122.82
24	70.801	71	33.88	88	104.995	105	124.24
25	73.377	73	35.29	89	103.203	103	125.65
26	75.909	76	36.71	90	101.348	101	127.06
27	78.394	78	38.12	91	99.432	99	128.47
28	80.832	81	39.53	92	97.455	97	129.88
29	83.221	83	40.94	93	95.416	95	131.29
30	85.559	86	42.35	94	93.325	93	132.71
31	87.846	88	43.76	95	91.175	91	134.12
32	90.079	90	45.18	96	88.969	89	135.53
33	92.257	92	46.59	97	86.709	87	136.94
34	94.379	94	48.00	98	84.397	84	138.35
35	96.444	96	49.41	99	82.033	82	139.76
36	98.451	98	50.82	100	79.619	80	141.18
37	100.398	100	52.24	101	77.157	77	142.59
38	102.283	102	53.65	102	74.649	75	144.00
39	104.107	104	55.06	103	72.095	72	145.41
40	105.868	106	56.47	104	69.497	69	146.82
41	107.564	108	57.88	105	66.857	67	148.24
42	109.195	109	59.29	106	64.176	64	149.65
43	110.759	111	60.71	107	61.457	61	151.06
44	112.257	112	62.12	108	58.700	59	152.47
45	113.686	114	63.53	109	55.907	56	153.88
46	115.046	115	64.94	110	53.081	53	155.29
47	116.336	116	66.35	111	50.222	50	156.71
48	117.556	118	67.76	112	47.333	47	158.12
49	118.704	119	69.18	113	44.415	44	159.53
50	119.781	120	70.59	114	41.470	41	160.94
51	120.784	121	72.00	115	38.500	38	162.35
52	121.714	122	73.41	116	35.507	36	163.76
53	122.571	123	74.82	117	32.492	33	165.18
54	123.353	123	76.24	118	29.457	29	166.59
55	124.060	124	77.65	119	26.405	26	168.00
56	124.691	125	79.06	120	23.336	23	169.41
57	125.247	125	80.47	121	20.253	20	170.82
58	125.727	126	81.88	122	17.158	17	172.24
59	126.131	126	83.29	123	14.053	14	173.65
60	126.458	126	84.71	124	10.939	11	175.06
61	126.709	127	86.12	125	7.818	8	176.47
62	126.882	127	87.53	126	4.693	5	177.88
63	126.978	127	88.94	127	1.565	2	179.29

Table 5
SINE APPROXIMATION – 128 POINTS

Point Number	$F(\phi)$	$f(\phi)$	ϕ	Point Number	$F(\phi)$	$f(\phi)$	ϕ
0	0	0	0	32	126.99	127	90.71
1	6.28	6	2.84	33	126.76	127	93.54
2	12.55	13	5.67	34	126.21	126	96.38
3	18.78	19	8.50	35	125.36	125	99.21
4	24.96	25	11.34	36	124.20	124	102.05
5	31.10	31	14.17	37	122.74	123	104.88
6	37.15	37	17.01	38	120.98	121	107.72
7	43.11	43	19.84	39	118.92	119	110.55
8	48.96	49	22.68	40	116.57	117	113.39
9	54.70	55	25.51	41	113.93	114	116.22
10	60.30	60	28.35	42	111.02	111	119.06
11	65.75	66	31.18	43	107.83	108	121.89
12	71.05	71	34.02	44	104.38	104	124.72
13	76.16	76	36.85	45	100.68	101	127.56
14	81.10	81	39.69	46	96.72	97	130.39
15	85.83	86	42.52	47	95.54	96	133.23
16	90.36	90	45.35	48	88.12	88	136.06
17	94.66	95	48.19	49	83.49	83	138.90
18	98.73	99	51.02	50	78.66	79	141.73
19	102.56	103	53.86	51	73.63	74	144.57
20	106.14	106	56.69	52	68.42	68	147.40
21	109.46	109	59.53	53	63.05	63	150.24
22	112.51	113	62.36	54	57.52	58	153.07
23	115.28	115	65.20	55	51.85	52	155.91
24	117.78	118	68.03	56	46.05	46	158.74
25	119.98	120	70.87	57	40.14	40	161.57
26	121.90	122	73.70	58	34.13	34	164.41
27	123.51	124	76.54	59	28.04	28	167.24
28	124.82	125	79.37	60	21.88	22	170.08
29	125.83	126	82.20	61	15.67	16	172.91
30	126.52	127	85.04	62	9.42	9	175.75
31	126.91	127	87.87	63	3.14	3	178.58

Table 6
SINE APPROXIMATION – 64 POINTS

Point Number	ϕ	$F(\phi)$	$f(\phi)$	Point Number	ϕ	$F(\phi)$	$f(\phi)$
0	0	0	0	16	91.43	126.96	127
1	5.71	12.65	13	17	97.14	126.01	126
2	11.43	25.16	25	18	102.86	123.82	124
3	17.14	37.43	37	19	108.57	120.39	120
4	22.86	49.33	49	20	114.29	115.76	116
5	28.57	60.74	61	21	120.00	109.99	110
6	34.29	71.54	72	22	125.71	103.12	103
7	40.00	81.63	82	23	131.43	95.22	95
8	45.71	90.92	91	24	137.14	86.38	86
9	51.43	99.29	99	25	142.86	76.68	77
10	57.14	106.68	107	26	148.57	66.22	66
11	62.86	113.01	113	27	154.29	55.10	55
12	68.57	118.22	118	28	160.00	43.44	43
13	74.29	122.25	122	29	165.71	31.34	31
14	80.00	125.07	125	30	171.43	18.93	19
15	85.71	126.64	127	31	177.14	6.33	6

Programmable Read-Only Memories

The PROMs are devices that are capable of permanently storing digital information. Some PROMs are programmable only once, since this programming consists of physically destroying fusible links within the semiconductor device. The memory used in this application, an Intel 1702A,^(c) may be programmed any number of times by a commercial unit attached to a microcomputer. A 30-min exposure to ultraviolet light sets the memory contents to zero.

A total of 16,384 bits of information are possible in some PROMs. An orderly arrangement of these bits constitutes one or more words. The 2048-bit PROM chosen for this project (Figure 10) contains 256 8-bit words.

Table 7
SINE APPROXIMATION — 32 POINTS

Point Number	ϕ	$F(\phi)$	$f(\phi)$
0	0	0	0
1	11.61	25.56	26
2	23.23	50.08	50
3	34.84	72.55	73
4	46.45	92.05	92
5	58.06	107.78	108
6	69.68	119.09	119
7	81.29	125.54	126
8	92.90	126.84	127
9	104.52	122.95	123
10	116.13	114.02	114
11	127.74	100.43	100
12	139.35	82.72	83
13	150.97	61.63	62
14	162.58	38.02	38
15	174.19	12.85	13

To recover information from memory requires an addressing word. An address is a numerical value associated with some datum's relative location in memory. The 1702A is

Table 8
CONTINUOUS SINE WAVE VERSUS DIGITIZED SINE WAVE

ϕ	$F(\phi)$	$h = 1.41^\circ$	$h = 2.81^\circ$	$h = 5.63^\circ$	$h = 11.25^\circ$
		256 Points Per Cycle $f_1(\phi)$	128 Points Per Cycle $f_2(\phi)$	68 Points Per Cycle $f_3(\phi)$	32 Points Per Cycle $f_4(\phi)$
0	0	0	0	0	0
10	22.05	22	19	13	0
20	43.44	43	43	37	26
30	63.50	63	60	61	50
40	81.63	81	81	82	73
50	97.29	96	95	91	92
60	109.99	109	109	107	108
70	119.34	119	118	118	119
80	125.07	125	125	125	119
90	127.00	127	127	127	126
100	125.07	125	125	126	127
110	119.34	120	121	120	123
120	109.99	110	111	110	114
130	97.29	97	101	103	100
140	81.63	82	83	86	83
150	63.50	64	68	66	83
160	43.44	44	44	43	62
170	22.05	23	28	31	38
180	0	-2	-3		

(c) Intel Corporation, Santa Clara, Calif.

addressed through Pins 3, 2, 1, 21, 20, 19, 18, and 17; symbolized as A0 through A7, respectively. This eight-bit address allows access of memory locations 0 through 255. The contents of an addressed memory location is a binary number physically stored at that location. Because physical rather than electrical memory storage is used, power to the memory can be lost without losing the memory contents. A simplified example of a five-word-by-three-bit memory is shown (here, for instance, the content of Memory Location 4 is 110):

Address	Contents
5	010
4	110
3	000
2	010
1	110

Table 9
CHI-SQUARE AND INTEGRAL-SQUARE ERROR
OF DIGITIZED WAVEFORMS

ϕ	$h = \frac{360}{255}$ $Z_1(\phi)$	$h = \frac{360}{127}$ $Z_2(\phi)$	$h = \frac{360}{63}$ $Z_3(\phi)$	$h = \frac{360}{31}$ $Z_4(\phi)$
0	0	0	0	0
10	0.000113	0.422	3.71	22.1
20	0.00446	0.00446	0.955	0.7
30	0.00394	0.193	0.9840	2.87
40	0.00486	0.00486	0.00168	0.912
50	0.0171	0.0539	0.407	0.288
60	0.00891	0.00891	0.0813	0.036
70	0.000969	0.015	0.015	0.000969
80	0.0000392	0.0000392	0.0000392	36.8
90	0	0	0	0.00787
100	0.0000392	0.0000392	0.00692	0.0298
110	0.00365	0.0231	0.00365	0.112
120	0.0000009	0.00927	0.0000009	0.146
130	0.000864	0.141	0.335	0.0755
140	0.00168	0.023	0.234	0.023
150	0.00394	0.319	0.0984	6
160	0.00722	0.151	0.00445	7.93
170	0.0409	0.161	3.63	11.5
	$\chi^2 = 0.099$ $I = 0.160$	$\chi^2 = 2.98$ $I = 10.9$	$\chi^2 = 9.57$ $I = 68.1$	$\chi^2 = 95.8$ $I = 1070$

For the digital pattern generator, the PROMs contain 256 coordinates of a point in a two dimensional plane. Tables 10 and 11 are listings of the contents of two PROMs; with Table 10 containing the horizontal ordinates, and Table 11 the vertical. Figures 11 and 12 contain respective plots of contents versus memory locations for the horizontal and vertical

Table 10
CONTENTS OF HORIZONTAL-AXIS PROGRAMMABLE READ-ONLY MEMORY FOR
RECTANGULAR DEFLECTION

ADD	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
000	00	02	04	06	08	0A	0C	0E	10	12	14	16	18	1A	1C	1E
010	20	22	24	26	28	2A	2C	2E	30	32	34	36	38	3A	3C	3E
020	40	42	44	46	48	4A	4C	4E	50	52	54	56	58	5A	5C	5E
030	60	62	64	65	67	69	6B	6D	6F	71	73	75	77	79	7B	7D
040	7F	7D	7B	79	77	75	73	71	6F	6D	6B	69	67	65	64	62
050	60	5E	5C	5A	58	56	54	52	50	4E	4C	4A	48	46	44	42
060	40	3E	3C	3A	38	36	34	32	30	2E	2C	2A	28	26	24	22
070	20	1E	1C	1A	18	16	14	12	10	0E	0C	0A	08	06	04	02
080	00	FE	FC	FA	F8	F6	F4	F2	F0	EE	EC	EA	E8	E6	E4	E2
090	E0	DE	DC	DA	D8	D6	D4	D2	D0	CE	CC	CA	C8	C6	C4	C2
0A0	C0	BE	BC	BA	B8	B6	B4	B2	B0	AE	AC	AA	A8	A7	A5	A3
0B0	A1	9F	9D	9B	99	97	95	93	91	8F	8D	8B	89	87	85	83
0C0	81	83	85	87	89	8B	8D	8F	91	93	95	97	99	9B	9D	9F
0D0	A1	A3	A5	A7	A8	AA	AC	AE	B0	B2	B4	B6	B8	BA	BC	BE
0E0	C0	C2	C4	C6	C8	CA	CC	CE	D0	D2	D4	D6	D8	DA	DC	DE
0F0	E0	E2	E4	E6	E8	EA	EC	EE	F0	F2	F4	F6	F8	FA	FC	FE

Figure 10. PROGRAMMABLE READ-ONLY MEMORY (1702A).

Figure 11. HORIZONTAL-AXIS PROGRAMMABLE-READ-ONLY-MEMORY CONTENTS VERSUS ADDRESS FOR RECTANGULAR DEFLECTION.

Figure 12. VERTICAL-AXIS PROGRAMMABLE-READ-ONLY-MEMORY CONTENTS VERSUS ADDRESS FOR RECTANGULAR DEFLECTION.

Table 11
CONTENTS OF VERTICAL-AXIS PROGRAMMABLE READ-ONLY MEMORY FOR
RECTANGULAR DEFLECTION

ADD	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
000	7F	7D	7B	79	77	75	73	71	6F	6D	6B	69	67	65	64	62
010	60	5E	5C	5A	58	56	54	52	50	4E	4C	4A	48	46	44	42
020	40	3E	3C	3A	38	36	34	32	30	2E	2C	2A	28	26	24	22
030	20	1E	1C	1A	18	16	14	12	10	0E	0C	0A	08	06	04	02
040	00	FE	FC	FA	F8	F6	F4	F2	F0	EE	EC	EA	E8	E6	E4	E2
050	E0	DE	DC	DA	D8	D6	D4	D2	D0	CE	CC	CA	C8	C6	C4	C2
060	C0	BE	BC	BA	B8	B6	B4	B2	B0	AE	AC	AA	A8	A7	A5	A3
070	A1	9F	9D	9B	99	97	95	93	91	8F	8D	8B	89	87	85	83
080	81	83	85	87	89	8B	8D	8F	91	93	95	97	99	9B	9D	9F
090	A1	A3	A5	A7	A8	AA	AC	AE	B0	B2	B4	B6	B8	BA	BC	BE
0A0	C0	C2	C4	C6	C8	CA	CC	CE	D0	D2	D4	D6	D8	DA	DC	DE
0B0	E0	E2	E4	E6	E8	EA	EC	EE	F0	F2	F4	F6	F8	FA	FC	FE
0C0	00	02	04	06	08	0A	0C	0E	10	12	14	16	18	1A	1C	1E
0D0	20	22	24	26	28	2A	2C	2E	30	32	34	36	38	3A	3C	3E
0E0	40	42	44	46	48	4A	4C	4E	50	52	54	56	58	5A	5C	5E
0F0	60	62	64	65	67	69	68	6D	6F	71	73	75	77	79	7B	7D

components. The pair of PROMs are addressed and their contents processed, simultaneously. This creates a synchronous change of the magnetic field produced by the deflection coils of the electron-beam welder. The interaction of the PROM contents of Figures 11 and 12 is shown in Figure 13.

Auto/Manual Selection

A main requirement of the welder-upgrade program is the availability of switching between computer and manual modes. The two selections are multiplexed with integrated chip devices. A 2-input 1-output chip is used for the deflection generator (Figure 14). When the selection line is high, manually generated parameters are switched through; when low, the computer parameters are chosen. Three multiplexers for the three bits of the pattern number are used; eight are required for the frequency selection word.

Figure 13. HORIZONTAL PROGRAMMABLE-READ-ONLY-MEMORY CONTENTS VERSUS VERTICAL PROGRAMMABLE-READ-ONLY-MEMORY CONTENTS WITH RESPECT TO ADDRESS.

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Eight-To-One Multiplexer Function Table				
Inputs			Outputs	
Select			Strobe S	Y
C	B	A		
X	X	X	H	L
L	L	L	L	D0
L	L	H	L	D1
L	H	L	L	D2
L	H	H	L	D3
H	L	L	L	D4
H	L	H	L	D6
H	H	L	L	D6
H	H	H	L	D7

Figure 14. TYPICAL DATA MULTIPLEXER.

The frequency chosen at the multiplexers is allowed to change at any time during a weld. The pattern may change only at the end of a cycle, which is also when the most significant bit of the PROM address word changes from "1" to "0." This negative-going pulse triggers a one-shot monostable multivibrator which trips a D-type flip-flop used as a latch (Figure 15). New data is then transferred from input to output for 0.1 μ s, after which time the flip-flop holds the output constant—regardless of the input.

Figure 15. LATCHING CIRCUIT FOR PATTERN-SELECTION WORD.

Manual Selection Generation -

Thumbwheel Switches - Four binary-coded-decimal (BCD) thumbwheel switches (Figure 16) make up the front-panel representation of the manually selected frequency (an explanation of BCD coding is given in **Appendix A**). The least significant digit of the switches is locked into the "0" position, as only 10-Hz resolution (1% of 1000 Hz) is required. The most significant bit (MSB) is limited to "0" or "1" since 1000 Hz is the maximum frequency of which the deflection coils of the welder are capable. The two middle digits are allowed the entire "0" to "9" range, giving possible selections of from "0000" to "1990."

Because of physical limitations of the welder console, the deflection circuits are in a rack which houses other equipment. Since the switches are physically distant from the logic boards, the ground references are different. Unequal ground levels can create a phenomenon known as a ground loop; whereby noise and oscillations are impressed upon a signal. Presently, optical isolation offers the greatest noise-free transfer of signals available. A miniature LED and a photodiode are used in the devices, as illustrated in Figure 17. The LED is powered by the supply from which the switches contact ground. The photodiode is powered by the supply powering the distant logic boards. The transistor-transistor logic (TTL) level pulse to the LED creates a light-level change which is perceived by the photodiode. The photodiode, in turn, transfers this light-level change into an electrical one. With a capability of 3000 V dc isolation in the HP 4160(b) chip, ground-level differences are minimized.

Binary-Coded-Decimal to Binary Conversion - The manual frequency selection was not compatible with the computer selection at the auto/manual stage and beyond because it is in the BCD format. This necessitates conversion of the selection to a binary representation. Since 1 of the 4 frequency switches is locked onto "0" only three digits are converted. Table 12 lists some frequency selections along with their equivalent binary and decimal codings.

The commercial converter that is used must be signaled as to when to accept new data and when to convert that data. Consequently, the binary output is not valid at certain times between conversion pulses. Obtaining the correct data requires a latch. This latch is enabled for 0.1 ms after a conversion-complete pulse is delivered by the BCD to binary circuit. While enabled, new data from the converter is allowed to transfer to the output of the latch and on to the next stage. At all other times, the output of the latch is locked onto known good data. The system is shown in Figure 18.

When the maximum input of 4095 is applied to the converter, 0.82 ms is required to complete the conversion. A clock with a 1.6-ms period was fabricated to initiate conversion at an essentially constant rate. Other methods were contemplated that would provide a better indication of the frequency desired (such as triggering conversion only when the selection switches were changed) but rejected as unnecessary, as frequencies were rarely changed.

Computer Selection Generation - A minicomputer programmed by members of the upgrading project generates an 11-bit binary-coded word (**Appendix A**) indicating pattern

Figure 16. MANUAL PARAMETER-SELECTION SWITCH.

Figure 17. OPTICAL ISOLATOR.

Table 12
FREQUENCY REPRESENTATION

Frequency Desired (Hz)	Binary Coded Decimal Representation	Binary Representation	Decimal Representation
10	0 0000 0001	00000001	1
20	0 0000 0010	00000010	2
40	0 0000 0100	00000100	4
80	0 0000 1000	00001000	8
160	0 0001 0110	00010000	16
320	0 0011 0010	00100000	32
640	0 0110 0100	01000000	64
1000	1 0000 0000	01100100	100

Figure 18. BINARY-CODED-DECIMAL-TO-BINARY CONVERSION CIRCUIT.

number and frequency. The bit pattern is arranged as in Figure 19 and is derived from either disk or keyboard. The minicomputer is shown in Figure 20.^(d) Figure 21 is a conversation between computer and operator for setting control parameters. The entered frequency is divided by 10 and rounded upward. This is because of the 10-Hz resolution requirement, which allows the least significant bit to be dropped, as it was in the manual switch. The pattern-deflection code and frequency are converted to binary and loaded into an output register (Figure 22). The selection of this register or the manual switches is made with the AUTO/MANUAL switch.

Y-80-507

Pattern Number	Frequency Word
<u>010</u>	<u>01100011</u>

Figure 19. COMPUTER PARAMETER-SELECTION FORMAT.

Frequency Generation

Each PROM contains one cycle of a waveform digitized into 256 points. Therefore a PROM's contents must be sequentially accessed at 256 times the actual frequency desired.

Figure 20. THE PDP 11/40 MINICOMPUTER.

(d) Digital Equipment Corp., Maynard, Mass.

WHICH OPTION? (1-27)
11

CONVERT DATA?
Y

INPUT THE FOLLOWING PARAMETERS.
THE CONVERTED VALUES WILL BE ECHOED.
BEAM SLOPE?
120

378
FOCUS SLOPE? BEAM CURRENT?
60
2

9
164
FOCUS CURRENT? X PTRN DEFL CODE?
1
3

4
3
PTRN FREQ? WIRE SLOPE?
1000
20

100
20
WIRE INDEX? WIRE FEED RATE?
2
2

1
2
SET # (NO DEC POINT)? SET CHANGE ANGLE?
11
360

17

13824

RPM?
10

1575
PARAMETERS LOADED.

Figure 21. PARAMETER SELECTION.

Figure 22. COMPUTER OUTPUT REGISTER.

For example, a pattern running at 10 Hz requires a 2.56-kHz clock; while the maximum pattern frequency of 1 kHz needs a 256-kHz clock. Thus, if

$$C = \frac{256F}{N}, \quad (15)$$

where:

C is the required clock rate,

F is the desired frequency, and

N is the number of cycles per PROM,

it is seen that two cycles per PROM require a clock 128 times the desired frequency (four per PROM need only 64 times, and so on). A discussion of the error involved according to the number of cycles per PROM is found in **Digitizing Effects**.

The 8 binary bits of the frequency selection form the most significant part of the 12-bit input into a DAC, as indicated in Figure 23. The four remaining bits are set to zero. It is possible to use 8 bits (maximum number = 256) instead of 10 (maximum number = 1024) as a result of coding the frequency at one-tenth of the frequency desired. Table 13 lists the frequencies for the computer program selection.

The output of the DAC is set such that a selection of 10 Hz produces 0.0391 volts. When 1 kHz is requested, the converter delivers 9.963 V. The DAC output goes to a voltage-to-frequency converter (V/F) whose full-scale output is reduced to 256 kHz for an input of 9.963 V and whose offset is adjusted such that 0.0391 V produces 2.56 kHz (Figure 24). The block diagram of the system is shown in Figure 25.

Pattern Generation

The programmable-clock output is given to the first of two four-bit binary counters (Figure 26) daisy-chained to produce an eight-bit count output. Each time a pulse is received from the clock, the count is incremented by one up to a maximum of 255;

Figure 23. DIGITAL-TO-ANALOG CONVERTER.

whereupon, it automatically recycles to zero (this produces the "1" to "0" transition of the MSB needed for determination of the end of a cycle—see **Auto/Manual** section). The eight address lines of the PROMs are paralleled from the counter outputs so that each clock pulse indirectly increments the memory address of all PROMs simultaneously. The rate at which the clock pulses the counters, F , determines the rate at which a waveform is generated, which is:

$$F = \frac{\text{clock rate}}{\text{number of PROM locations}} \quad (16)$$

$$= \frac{\text{clock rate}}{256}$$

Table 13
FREQUENCY CODING

Frequency Desired	Binary Number Coding	Equivalent Decimal Representation	Frequency Desired	Binary Number Coding	Equivalent Decimal Representation
0	00000000	0	510	00110011	51
10	00000001	1	520	00110100	52
20	00000010	2	530	00110101	53
30	00000011	3	540	00110110	54
40	00000100	4	550	00110111	55
50	00000101	5	560	00111000	56
60	00000110	6	570	00111001	57
70	00000111	7	580	00111010	58
80	00001000	8	590	00111011	59
90	00001001	9	600	00111100	60
100	00001010	10	610	00111101	61
110	00001011	11	620	00111110	62
120	00001100	12	630	00111111	63
130	00001101	13	640	01000000	64
140	00001110	14	650	01000001	65
150	00001111	15	660	01000010	66
160	00010000	16	670	01000011	67
170	00010001	17	680	01000100	68
180	00010010	18	690	01000101	69
190	00010011	19	700	01000110	70
200	00010100	20	710	01000111	71
210	00010101	21	720	01001000	72
220	00010110	22	730	01001001	73
230	00010111	23	740	01001010	74
240	00011000	24	750	01001011	75
250	00011001	25	760	01001100	76
260	00011010	26	770	01001101	77
270	00011011	27	780	01001110	78
280	00011100	28	790	01001111	79
290	00011101	29	800	01010000	80
300	00011110	30	810	01010001	81
310	00011111	31	820	01010010	82
320	00100000	32	830	01010011	83
330	00100001	33	840	01010100	84
340	00100010	34	850	01010101	85
350	00100011	35	860	01010110	86
360	00100100	36	870	01010111	87
370	00100101	37	880	01011000	88
380	00100110	38	890	01011001	89
390	00100111	39	900	01011010	90
400	00101000	40	910	01011011	91
410	00101001	41	920	01011100	92
420	00101010	42	930	01011101	93
430	00101011	43	940	01011110	94
440	00101100	44	950	01011111	95
450	00101101	45	960	01100000	96
460	00101110	46	970	01100001	97
470	00101111	47	980	01100010	98
480	00110000	48	990	01100011	99
490	00110001	49	1000	01100100	100
500	00110010	50

Figure 24. BLOCK DIAGRAM OF PROGRAMMABLE CLOCK.

Figure 25. VOLTAGE-TO-FREQUENCY CONVERTER.

Pattern Multiplexing

All PROMs are accessed simultaneously and, therefore, generate their programmed patterns concurrently. The selection of one of the seven patterns available requires multiplexing (the same method used to select manual or computer control).

Figure 26. DETERMINATION OF PROGRAMMABLE-READ-ONLY-MEMORY ACCESS RATE.

Since a multiplexer chooses only a single bit and not an entire pattern, each of the eight bits of a pattern must be multiplexed. The first multiplexer input is bit 1 of all the PROMs; the second chip receives bit 2; and so on. The correct bit pattern is chosen with an appropriate three-bit address which comes from either the front-panel switches or the computer, depending on the mode of control at the time. Paralleling the address bits from the eight-bit counter to each multiplexer allows simultaneous access of all eight bits from any one PROM. A simplified example of two patterns with two bits is shown in Figure 27. As can be seen from this example, the number of path crossovers required for seven patterns of eight bits each becomes very unwieldy on the printed-circuit-board layout.

As each PROM contains the coordinates for only one of the two axes required, two identical boards are constructed. Each board contains seven PROMs and eight multiplexers. When selecting the PROM pattern from one board, the corresponding PROM pattern of the second board is also chosen. The patterns travel separate but parallel paths until combined at the deflection coils. Their interaction produces the required two-dimensional waveform.

Attenuation

Since any chosen pattern is programmed to provide a full-scale output of ± 162.56 mA, attenuation of the signal is sometimes needed for narrower welds. Coming from the PROMs,

Figure 27. MULTIPLEXING TWO PATTERNS OF TWO-BIT WORDS.

the x- and y-coordinates (X and Y) are scaled through a digital multiplier (Figure 28).^(e) An 8-bit X 8-bit parallel multiplier, which produces a 16-bit output, is used. The output consists of two parts; each having seven bits plus one sign bit. Only the most significant eight bits (including sign) are read, which effectively reduces the product by $2^7 = 128$ (the number is shifted right seven places). Therefore the output is:

$$\frac{X \text{ (or Y)} \times X \text{ (multiplication factor)}}{128} \quad (17)$$

The multiplication factor is derived from switches located inside the welder console. Since the multiplication factor can never exceed 127 (the MSB is a sign bit), the full-scale output will never go above ± 162.56 mA (limited to $127/128 \times 162.56 = 161.29$ mA).

A detrimental result of any attenuation is the accompanying decrease in resolution. The LSB of 1.28 mA represents more and more of a waveform as attenuation increases. For example, full-scale output is +162.56. The LSB, 1.28 mA, is $1.28/162.56 = 0.79\%$ of this. With a 50% attenuation (multiplication factor = 64), full-scale output is +81.28 (closest programmable current = +80.64), but the minimum controllable current is still 1.28 mA, which is $1.28/80.64 = 1.59\%$ of the whole. See Figure 29 for a graphical example.

Timing

As with most digital function circuits, there are times when the data presented by certain devices is not valid. The PROMs' contents are unusable $1\mu\text{s}$ after they are called for (when a new address word is input). The digital multiplier whose multiplicand is the PROMs' output is used as a bad-data filter. Since the multiplier requires a pulse to instruct it as to when to accept new data, it is only natural to synchronize this pulse with the clock incrementing the PROM's addresses. The address clock is delayed $1.4\mu\text{s}$ and then relayed to the load-input-register clock of the multiplier. By the time this delayed signal is received, the data from the PROMs has settled to a usable state.

Unfortunately, the multiplier also has a period of uncertainty. For approximately 45 ns after the device is instructed to multiply, the output data is invalid. The multiplier data is given to a latch which lets new data through $1.4\mu\text{s}$ after the multiplying signal is received. The multiply pulse comes at the same instance as the load-input-register pulse.

The timing diagrams for the BCD/binary converter and pattern generator, both at 10 Hz and 1000 Hz are illustrated in Figures 30, 31, and 32, respectively.

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Y-80-515

Logical Block

Figure 28. DIGITAL MULTIPLIER.

Output Drivers

From the multipliers, the selected pattern coordinates go to appropriate drivers. Capability to travel the known cable distances to the current supplies is possible with minimum noise as a result of the current sourcing ability of the drivers. One driver for the horizontal information and one for the vertical is provided as shown in Figure 33. The horizontal driver uses positive logic, while the vertical driver uses negative. This is because the programmable current supplies (that the drivers feed) use different logic inputs. One unit has a binary interface for totem-pole outputs; the other has an interface for open-collector outputs. Essentially, an open-collector output produces an inverted signal, while a totem-pole output does not. The open-collector arrangement is generally used where greater current-carrying capabilities are needed, such as driving more than 10 TTL loads.

Figure 29. ATTENUATION RESOLUTION.

Beam Positioning

To obtain precision welds, the welder control system must have prior knowledge of the beam's position. The beam is moved to a known beginning by bringing the deflection system to rest. A voltage may be applied to the analog programming-input port of the

Figure 30. BINARY-CODED-DECIMAL/BINARY CONVERSION TIMING.

Figure 31. TIMING, 10 Hz.

Figure 32. TIMING, 1 Hz.

Figure 33. OUTPUT DRIVERS.

programmable current supplies. This voltage is derived from either front-panel potentiometers in the manual mode or a DAC in the computer mode.

The deflection system never actually halts. Rather, its output is set to zero. Output drivers for the system are logical AND (for the X supply) and NAND (for the Y supply) gates, which are equivalent to the equation $X = AB$. Either A or B may be "1" or "0." X will be "1" only if A and B are both equal to "1." In a driver configuration, A is hardwired to a +5-volt power supply (logical "1"). To make use of the drivers as pull-down circuits, the permanently high side is disconnected and tied to a switch on the front panel (Figure 34).

This switch has four positions:

1 = OFF

2 = POSITION

3 = PATTERN

4 = PATTERN + POSITION

Figure 34. BEAM POSITION/PATTERN SWITCH.

In the first two positions, the AND gates are pulled low; thereby pulling the output low. The third and fourth positions sets A to "1" which allows the output to track Input B. The last position also adds a dc offset to the pattern. The offset is determined by the front panel potentiometers which control position.

Deflection Generator Reset

The current supply's outputs must be brought to zero in two cases. Case 1 occurs whenever the input registers of the deflection generator are set to zero. Because the latch holds the pattern number until the end of a cycle, the end of a cycle does not occur if the pattern frequency is set to zero; and the latch is not allowed to pass pattern number zero. This rules out the possibility of disabling the current output based upon a pattern selection of zero. Instead, the frequency word is checked for all zeroes; and, if so, the output drivers are set to zero.

Case 2 takes place when the beam POSITION/PATTERN switch is in the OFF or POSITION setting. The output of these switch positions are ANDed with the output of the zero-frequency detector. If either of the inputs are zero, then the input to one side of the NAND (y axis) or the AND (x-axis) output driver becomes zero, as does the output of the driver. The logic design of Figure 35 accomplishes this.

Figure 35. ZERO-FREQUENCY DETECTOR/PULL-DOWN CIRCUIT LOGIC.

If the pattern number is set to zero but the frequency is not (as would happen if the manual-switch frequency was zero, since the BCD/binary converter cannot convert zero), the outputs are brought to zero by having a programmed input of zero. This is done by hard-wiring Input 1 to ground. Since there are only seven patterns and eight multiplexer bits, this is easily done.

Control Panel Layout

The previous welder console that controls beam deflection is shown in Figure 36. Except for the potentiometers (X and Y), the former controls have been abandoned. The updated control panel is shown in Figure 37. Thumbwheel switches give a digital readout of frequency and pattern number when in the manual mode. Control potentiometers with digital indication are provided for manual positioning of the beam. A switch chooses manual positioning of the beam, deflection generator location of the beam, or both. If predetermined left, right, top, or bottom limits are exceeded, LEDs positioned in a symbolic coordinate system are illuminated. The controls have no function when in the automatic mode.

Complete System Layout

The building blocks of the pattern generator are interconnected as depicted in Figure 38. The schematics and a wiring list may be found in Reference 6.

Figure 36. PREVIOUS CONTROL PANEL.

Figure 37. PRESENT CONTROL PANEL.

Figure 38. COMPLETE SYSTEM LAYOUT.

RESULTS

Frequency Linearity

Table 14 shows the frequency selected versus the frequency generated by the voltage-to-frequency converter. The points are fitted to a linear equation of the form $y = ax + b$ by a technique of linear regression using the method of least squares. (A straight line is fitted through the given points such that the sum of the squares of the vertical distances of those points from the straight line is a minimum. The curve-fitting program comes from the *HP-25 Applications Programs* book.⁷⁾ This gives $Y = 1.01x - 1.12$ and a correlation coefficient of 0.99985. The correlation coefficient is a numerical indication of the degree of correlation between two sets of data. Perfect correlation has a coefficient of 1. The closer the coefficient is to 1, the better the fit of the points is to a linear equation.

Even with the seemingly excellent linearity, notice that points alternate in being either higher or lower than the chosen frequency. For example, choosing 400 Hz indicates 102.4 kHz is to be generated (see **Frequency Generation**). In actuality, 103.905 kHz results. This is a

$$\frac{103.905 - 102.400}{102.400} = 1.47\% \text{ relative error.} \quad (18)$$

Notice that 450 Hz calls for 115.2 kHz, rather than the low 114.111 kHz generated. The previous point was high by 1505 Hz too, while this last point is low by 1089 Hz.

Pattern Resolution

In addition to inaccuracies introduced by digitally programming an analog waveform, there are errors caused by response-time limitations of the integrated circuits. The current supplies were replaced with digital-to-analog converters to produce oscilloscope traces of square, triangular, sine, cosine, and hysteresis waveforms, as shown in Figure 39. The sine and cosine outputs were compared to each other as a rough measure to see if the 90° phase shift was accurate. No further shift was detected. The rise and fall times of the square wave was measured, along with the fall time of the ramp function. The triangular shape was examined to determine that the rise and fall times were identical. Results show an acceptable resolution based on typical rise and fall times.

Waveform	Rise Time	Fall Time
1 kHz square wave	3.75 μ s	2.5 μ s
1 kHz hysteresis	-	4 μ s
1 kHz triangle	52 ms	48 ms
1 kHz triangle	0.52 ms	0.48 ms

Table 14
FREQUENCY ERROR

Frequency Desired	Required Clock Frequency (kHz)	Actual Clock Frequency (kHz)
50	12.8	12.760
100	25.6	27.925
150	38.4	38.127
200	51.2	53.343
250	64.0	63.427
300	76.8	78.709
350	89.6	88.703
400	102.4	103.907
450	115.2	114.111
500	128.0	129.286
550	140.8	139.490
600	153.6	154.692
650	166.4	164.722
700	179.2	180.006
750	192.0	190.090
800	204.8	205.299
850	217.6	215.502
900	230.4	230.670
950	243.2	240.874
1000	256.0	255.983

(a) Circle.

(b) Circle Components.

(c) Hysteresis.

(d) Hysteresis Components.

(e) Square.

(f) Square Components.

(g) Star.

(h) Star Components.

Figure 39. PROGRAMMABLE-READ-ONLY-MEMORY PATTERNS.

CONCLUSIONS AND RECOMMENDATIONS

Although other work has been done on the electron-beam deflection,⁸⁻¹³ it is believed that this design is unique. The digitally based pattern generator has been shown to work within the specifications and versatility desired. Ultimately, the usefulness of the device is limited only by the imagination of those who will determine and program the deflection patterns to be used. If the unit is used only for standard deflection patterns (such as sine, circle, or square) the development effort may have been ill spent. It is the responsibility of those that utilize the pattern generator and those familiar with the metallurgical effects involved to derive patterns of suitable use for the weld quality desired.

In terms of future work, there are several areas that could be optimized and/or improved. Chief among these is the attenuation scheme. Presently, the amount of attenuation desired is derived from a DIP switch inconveniently located behind the welder-console front panel. It would be much more flexible if the full-scale current desired was programmed into the computer (or switches on the front panel). The output of the PROMs would be sent to the computer, modified as required, and returned to the current supply drivers. This approach is currently under investigation.

For smaller space requirements, the PROM patterns could be consolidated into 1 PROM rather than 7. This would significantly involve more gating and logic, but the end result would be a smaller unit. Unfortunately, the flexibility of physically placing a single pattern would be lost. In addition, the welder setup is so large that only a minute space savings would be possible. This approach would only be useful if a final set of patterns was ever agreed upon, which seems doubtful at the present time.

Presently, if a waveform to be programmed is not defined by a some equation, digitizing the waveform by hand becomes a very tedious process. There are digitizing graphics tables available which electronically digitize a hand-drawn waveform by using a light pen. Interfacing this to a microcomputer and a PROM programmer would be immensely helpful in terms of the time saved.

A convenience feature would be a display of the computer values of the pattern number and frequency on the front panel when in the AUTO mode of operation. This would be easily accomplished, and space is available on the front panel.

It is interesting to note that design time would have been shortened if the computer had complete control of the pattern-generation process, since switching of parameters and conversion of the frequency word would have been eliminated.

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APPENDIX A

CODING

The three coding schemes used in the pattern generator were:

1. Binary
2. Two's-complement
3. Binary Coded Decimal (BCD)

Binary is the most straightforward coding, but does not strictly allow for negative numbers. In this method, each bit represents a power of two:

2 ⁷	2 ⁶	2 ⁵	2 ⁴	2 ³	2 ²	2 ¹	2 ⁰
128	64	32	16	8	4	2	1

Two's-complement is a means of coding that does away with a symbolic negative zero, as occurs with one's-complement. It always consists of 1 sign bit, and here, 7 magnitude bits. For positive numbers, the sign bit is "0"; for negative numbers, "1." When positive, the seven magnitude bits form a binary-coded number, as above. To obtain a negative number, the corresponding positive number is complemented and one is added to the least significant bit. For example; decimal 13 in binary form is 01101, where the most significant bit, "0", represents a positive number. To obtain -13, +13 is complemented:

1's-complement: 10010

One is then added to the least significant bit:

2's-complement: 10010

$$\begin{array}{r} 10010 \\ + \quad 1 \\ \hline 10011 \end{array}$$

Therefore, -13 is coded as 10011.

Binary coded decimal is a stand-alone binary coding of four bits representing each individual digit of a decimal number. For example, 13 is coded by representing the 1 by 0001, and the 3 by 0011, to give 0001 0011.

APPENDIX B

BOARD PIN-OUTS

Board 3A3: Optical Isolators Input

B1	Frequency Selection Word 3	
	Pattern Selection Bits	
C1	1	
D2	2	
E2	3	

Board 3B3: Optical Isolators Output

V2	Frequency Selection Word 3	
	Pattern Selection Bits	
V1	1	
U2	2	
U1	3	

Board 5A3: Optical Isolators Input

	Multiplicand Bits	
B1	1	
C1	2	
D2	3	
E2	4	
F2	5	
H2	6	
J2	7	
K2	Sign	
	Manual Frequency Selection	
	Word	Bit
L2	1	1
M2	1	2
N2	1	3
P2	1	4
R2	2	1
S2	2	2
U2	2	3
V2	2	4

Board 5B3: Optical Isolators Output

Manual Frequency Selection		
	Word	Bit
P2	1	1
P1	1	2
N2	1	3
M2	1	4
L2	2	1
K2	2	2
J2	2	3
H2	2	4

Multiplicand Bits	
V2	1
V1	2
U2	3
U1	4
S2	5
S1	6
R2	7
R1	Sign

Board A1: AUTO/MANUAL Frequency Selection

+5 V	
A1	
A2	
L2	

Ground	
B1	
K1	
T1	
C2	
K2	
M2	

AUTO Selection Bits	
U2	1
R2	2
E2	3
J2	4
S1	5
N1	6
F1	7
C1	8

Board A1: (continued)

MANUAL Selection Bits

T2 1
P2 2
D2 3
H2 4
R1 5
M1 6
H1 7
D1 8

Final Selection Bits

S2 1
N2 2
V1 3
F2 4
P1 5
L1 6
J1 7
E1 8

AUTO/MANUAL Selector

U1
V2

Board B1: Output Drivers

X-Axis Inputs

H2 1
J1 2
E2 3
F1 4
D1 5
C1 6
A1 7
L1 Sign

X-Axis Outputs

J2 1
K1 2
F2 3
H1 4
E1 5
D2 6
B1 7
M1 Sign

Board B1: (continued)

Y-Axis Inputs

K2	1
N1	2
M2	3
R1	4
P2	5
V1	6
S2	7
U2	Sign

Y-Axis Outputs

L2	1
P1	2
N2	3
S1	4
R2	5
U1	6
T2	7
V2	Sign

B1	Pull-Down
----	-----------

Board A2: Pattern Multipliers

A1	AUTO/MANUAL Pattern Selector
----	------------------------------

AUTO Bits

B1	1
D1	2
F1	3

MANUAL Bits

C1	1
E1	2
H1	3

Final Pattern Bits

D2	1
E2	2
F2	3

Y-Pattern Input

N2	1
P2	2
R2	3
S2	4
T2	5
U2	6
V2	7
M2	Sign

Board B2:

Pattern Multipliers

Multiplicand	
B1	1
C1	2
D1	3
E1	4
F1	5
H1	6
J11	7
A1	Sign
X Product Bits	
N1	1
M1	2
L1	3
K1	4
S1	5
U1	6
V1	7
P1	Sign
X Pattern Inputs	
E2	1
M2	2
L2	3
K2	4
J2	5
H2	6
F2	7
D2	Sign
R1	Clock Input
T2	Reset Output
U2	Counter Pulse Input

Board A3:

Programmable Clock

Grounds	
B2	
D2	
E2	
H2	
S1	-15 V
U1	+15 V
N1	Clock Output

Board A3: (continued)

Programming Input Bits	
V2	1
U2	2
T2	3
S2	4
M2	5
L2	6
K2	7
J2	8

Board A5: X Pattern Generation

Pattern Output Bits	
V2	1
U2	2
T2	3
S2	4
R2	5
P2	6
N2	7
M2	Sign
D1	-9 V

Board B5: X Pattern Generation

Pattern Selection Bits	
D2	1
E2	2
F2	3
U1	Reset Out
H2	Reset Input
J2	Clock Input

Board A6: Y Pattern Generation

Pattern Output Bits	
V2	1
U2	2
T2	3
S2	4
R2	5
P2	6
N2	7
M2	Sign
D1	-9 V

Board B6: Y Pattern Generation

 Pattern Selection Bits

D2 1

E2 2

F2 3

H2 Reset Input

U1 Reset Output

J2 Clock Input

Board A7: BCD/Binary Converter

 Grounds

D1

E1

F1

H1

J1

K1

L1

M1

N1

P1

R1

S1

 +5 V

U1

V1

T2

 Binary Outputs

D2 1

E2 2

F2 3

H2 4

J2 5

K2 6

L2 7

M2 8

 A1 Load/Convert Pulse Input

Board B7: BCD/Binary Converter

BCD Input (Switches)		
	Word	Bit
D1	1	1
E1	1	2
F1	1	3
H1	1	4
J1	2	1
K1	2	2
L1	2	3
M1	2	4
N1	3	

T2	Conversion Complete Pulse Output	
----	----------------------------------	--

Board A8: X Multiplier Latch

Inputs	
D1	1
E1	2
F1	3
H1	4
J1	5
K1	6
L1	7
M1	Sign

Outputs	
D2	1
E2	2
F2	3
H2	4
J2	5
K2	6
L2	7
M2	Sign

B1	Ground
----	--------

Board B8: Y Multiplier Latch

Inputs	
D1	1
E1	2
F1	3
H1	4
J1	5
K1	6
L1	7
M1	Sign

Board B8: (continued)

 Outputs

D2 1

E2 2

F2 3

H2 4

J2 5

K2 6

L2 7

M2 Sign

B1 Ground

Board A9: BCD/Binary Converter Latch

 Inputs

D1 1

E1 2

F1 3

H1 4

J1 5

K1 6

L1 7

M1 8

B1 Ground

 Outputs

D2 1

E2 2

F2 3

H2 4

J2 5

K2 6

L2 7

M2 8

Board A13: Manual Switch Inverter

 Frequency-Selection Input

Word Bit

A1 1 1

C1 1 2

D1 1 3

F1 1 4

E2 2 1

J1 2 2

H2 2 3

L1 2 4

K2 3

Board A13: (continued)

 Pattern-Selection Bits Input

N1	1
M2	2
R1	3

 Frequency Selection Output

	Word	Bit
--	------	-----

B1	1	1
D2	1	2
E1	1	3
H1	1	4
F2	2	1
K1	2	2
J2	2	3
M1	2	4
L2	3	

 Pattern-Selection Bits Output

P1	1
N2	2
S1	3

APPENDIX C

PROGRAMMABLE-READ-ONLY MEMORY PROGRAMS

Tables C-1 through C-9 show the PROM programs.

Table C-1
SINE WAVE PROGRAM

ADD	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
000	00	03	06	09	0C	10	13	16	19	1C	1F	22	25	28	2B	2E
010	31	33	36	39	3C	3F	41	44	47	49	4C	4E	51	53	55	58
020	5A	5C	5E	60	62	64	66	68	6A	6B	6D	6F	70	71	73	74
030	75	76	78	79	7A	7A	7B	7C	7D	7D	7E	7E	7E	7F	7F	7F
040	7F	7F	7F	7F	7E	7E	7E	7D	7D	7C	7B	7A	7A	79	78	76
050	75	74	73	71	70	6F	6D	6B	6A	68	66	64	62	60	5E	5C
060	5A	58	55	53	51	4E	4C	49	47	44	41	3F	3C	39	36	33
070	31	2E	2B	28	25	22	1F	1C	19	16	13	10	0C	09	06	03
080	00	FD	FA	F7	F4	F0	ED	EA	E7	E4	E1	DE	DB	D8	D2	CF
090	CD	CA	C7	C4	C1	BF	BC	B9	B7	B4	B2	AF	AD	AB	A8	A6
0A0	A4	A2	A0	9E	9C	9A	98	96	95	93	91	90	8F	8D	8C	8B
0B0	8A	88	87	86	86	85	84	83	83	82	82	82	81	81	81	81
0C0	81	81	81	82	82	82	83	83	84	85	86	86	87	88	8A	8B
0D0	8C	8D	8F	90	91	93	95	96	98	9A	9C	9E	A0	A2	A4	A6
0E0	A8	AB	AD	AF	B2	B4	B7	B9	BC	BF	C1	C4	C7	CA	CD	CF
0F0	D2	D5	D8	DB	DE	E1	E4	E7	EA	ED	F0	F4	F7	FA	FD	FF

Table C-2
COSINE WAVE PROGRAM

ADD	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
000	7F	7F	7F	7F	7E	7E	7E	7D	7D	7C	7B	7A	7A	79	78	76
010	75	74	73	71	70	6F	6D	6B	6A	68	66	64	62	60	5E	5C
020	5A	58	55	53	51	4E	4C	49	47	44	41	3F	3C	39	36	33
030	31	2E	2B	28	25	22	1F	1C	19	16	13	10	0C	09	06	03
040	00	FD	FA	F7	F4	F0	ED	EA	E7	E4	E1	DE	DB	D8	D2	CF
050	CD	CA	C7	C4	C1	BF	BC	B9	B7	B4	B2	AF	AD	AB	A8	A6
060	A4	A2	A0	9E	9C	9A	98	96	95	93	91	90	8F	8D	8C	8B
070	8A	88	87	86	86	85	84	83	83	82	82	82	81	81	81	81
080	81	81	81	82	82	82	83	83	84	85	86	86	87	88	8A	8B
090	8C	8D	8F	90	91	93	95	96	98	9A	9C	9E	A0	A2	A4	A6
0A0	A8	AB	AD	AF	B2	B4	B7	B9	BC	BF	C1	C4	C7	CA	CD	CF
0B0	D2	D5	D8	DB	DE	E1	E4	E7	EA	ED	F0	F4	F7	FA	FD	FF
0C0	00	03	06	09	0C	10	13	16	19	1C	1F	22	25	28	2B	2E
0D0	31	33	36	39	3C	3F	41	44	47	49	4C	4E	51	53	55	58
0E0	5A	5C	5E	60	62	64	66	68	6A	6B	6D	6F	70	71	73	74
0F0	75	76	78	79	7A	7A	7B	7C	7D	7D	7E	7E	7E	7F	7F	7F

Table C-3
X-AXIS STAR PROGRAM

ADD	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
000	00	FE	FC	FA	F6	F4	F2	F0	EC	EA	E8	E6	E2	E0	DE	DC
010	D8	D6	D4	D2	CE	CC	CA	C8	C4	C2	C0	BE	BA	B8	B6	B4
020	B0	AE	AC	AA	A6	A4	A2	A0	9C	9A	98	96	92	90	8E	8C
030	88	86	84	82	84	86	88	8A	8E	90	92	94	98	9A	9C	9E
040	A2	A4	A6	A8	AC	AE	B0	B2	B6	B8	BA	BC	C0	C2	C4	C6
050	CA	CC	CE	D0	CE	CC	CA	C8	C4	C2	C0	BE	BA	B8	B6	B4
060	B6	B8	BA	BC	C0	C2	C4	C6	CA	CC	CE	D0	D4	D6	D8	DA
070	DE	E0	E2	E4	E8	EA	EC	F0	F2	F4	F6	F8	FC	FE	00	00
080	02	06	08	0A	0C	10	12	14	16	1A	1C	1E	20	24	26	28
090	2A	2E	30	32	34	38	3A	3C	3E	42	44	46	48	4C	4C	4A
0A0	48	44	42	40	3E	3A	38	36	34	30	30	32	34	38	3A	3C
0B0	3E	42	44	46	48	4A	4C	4E	50	52	56	58	5A	5C	60	62
0C0	64	66	6A	6C	6E	70	74	76	78	7A	7E	7E	7C	7A	76	74
0D0	72	70	6C	6A	68	66	62	60	5E	5C	58	56	54	52	4E	4C
0E0	4A	48	44	42	40	3E	3A	38	36	34	30	2E	2C	2A	26	24
0F0	22	20	1E	1C	1A	18	16	12	10	0E	0C	08	06	04	02	00

Table C-4
Y-AXIS STAR PROGRAM

ADD	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
000	7F	79	72	6C	5F	58	52	4B	3E	38	31	2B	24	24	24	24
010	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
020	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
030	24	24	24	24	22	20	1F	1E	1B	1A	18	16	13	12	11	0F
040	0C	0B	09	08	05	03	02	01	FE	FC	FB	F9	F6	F5	F3	F2
050	EF	EE	EC	EB	E0	DA	D3	CD	C0	BA	B3	AD	A0	9A	93	8D
060	8C	8E	8F	91	94	95	97	98	9B	9D	9E	A0	A3	A4	A6	A7
070	AA	AC	AD	AF	B2	B3	B5	B6	B8	B9	BB	BC	BE	C1	C2	C4
080	C2	BF	BE	BC	BB	B8	B6	B5	B3	B0	AF	AD	AC	A9	A7	A6
090	A4	A1	A0	9E	9D	9A	98	97	95	92	91	8F	8E	8B	8D	93
0A0	9A	A6	AD	B3	BA	C6	CD	D3	DA	E6	EB	EC	EE	F1	F2	F3
0B0	F5	F8	F9	FB	FC	FE	FF	01	02	03	06	08	09	0B	0E	0F
0C0	11	12	15	16	18	19	1C	1E	1F	20	23	24	24	24	24	24
0D0	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
0E0	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
0F0	24	24	24	24	2B	31	38	45	4B	52	58	65	6C	72	79	7F

Table C-5
TRIANGULAR WAVE PROGRAM

ADD	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
000	00	02	04	06	08	0A	0C	0E	10	12	14	16	18	1A	1C	1E
010	20	22	24	26	28	2A	2C	2E	30	32	34	36	38	3A	3C	3E
020	40	42	44	46	48	4A	4C	4E	50	52	54	56	58	5A	5C	5E
030	60	62	64	65	67	69	6B	6D	6F	71	73	75	77	79	7B	7D
040	7F	7D	7B	79	77	75	73	71	6F	6D	6B	69	67	65	64	62
050	60	5E	5C	5A	58	56	54	52	50	4E	4C	4A	48	46	44	42
060	40	3E	3C	3A	38	36	34	32	30	2E	2C	2A	28	26	24	22
070	10	1E	1C	1A	18	16	14	12	10	0E	0C	0A	08	06	04	02
080	00	FE	FC	FA	F8	F6	F4	F2	F0	EE	EC	EA	E8	E6	E4	E2
090	E0	DE	DC	DA	D8	D6	D4	D2	D0	CE	CC	CA	C8	C6	C4	C2
0A0	C0	BE	BC	BA	B8	B6	B4	B2	B0	AE	AC	AA	A8	A7	A5	A3
0B0	A1	9F	9D	9B	99	97	95	93	91	8F	8D	8B	89	87	85	83
0C0	81	83	85	87	89	8B	8D	8F	91	93	95	97	99	9B	9D	9F
0D0	A1	A3	A5	A7	A8	AA	AC	AE	B0	B2	B4	B6	B8	BA	BC	BE
0E0	C0	C2	C4	C6	C8	CA	CC	CE	D0	D2	D4	D6	D8	DA	DC	DE
0F0	E0	E2	E4	E6	E8	EA	EC	EE	F0	F2	F4	F6	F8	FA	FC	FE

Table C-6
NINETY-DEGREE TRIANGULAR WAVE PROGRAM

ADD	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
000	7F	7D	7B	79	77	75	73	71	6F	6D	6B	69	67	65	64	62
010	60	5E	5C	5A	58	56	54	52	50	4E	4C	4A	48	46	44	42
020	40	3E	3C	3A	38	36	34	32	30	2E	2C	2A	28	26	24	22
030	20	1E	1C	1A	18	16	14	12	10	0E	0C	0A	08	06	04	02
040	00	FE	FC	FA	F8	F6	F4	F2	F0	EE	EC	EA	E8	E6	E4	E2
050	E0	DE	DC	DA	D8	D6	D4	D2	D0	CE	CC	CA	C8	C6	C4	C2
060	C0	BE	BC	BA	B8	B6	B4	B2	B0	AE	AC	AA	A8	A7	A5	A3
070	A1	9F	9D	9B	99	97	95	93	91	8F	8D	8B	89	87	85	83
080	81	83	85	87	89	8B	8D	8F	91	93	95	97	99	9B	9D	9F
090	A1	A3	A5	A7	A8	AA	AC	AE	B0	B2	B4	B6	B8	BA	BC	BE
0A0	C0	C2	C4	C6	C8	CA	CC	CE	D0	D2	D4	D6	D8	DA	DC	DE
0B0	E0	E2	E4	E6	E8	EA	EC	EE	F0	F2	F4	F6	F8	FA	FC	FE
0C0	00	02	04	06	08	0A	0C	0E	10	12	14	16	18	1A	1C	1E
0D0	20	22	24	26	28	2A	2C	2E	30	32	34	36	38	3A	3C	3E
0E0	40	42	44	46	48	4A	4C	4E	50	52	54	56	58	5A	5C	5E
0F0	60	62	64	65	67	69	6B	6D	6F	71	73	75	77	79	7B	7D

Table C-7
SQUARE WAVE PROGRAM

[illegible]

Table C-8
NINETY-DEGREE SQUARE WAVE PROGRAM

[illegible]

Table C-9

SAWTOOTH WAVE PROGRAM

ADD	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
000	81	82	83	84	85	86	87	88	89	8A	8B	8C	8D	8E	8F	90
010	91	92	93	94	95	96	97	98	99	9A	9B	9C	9D	9E	9F	A0
020	A1	A2	A3	A4	A5	A6	A7	A8	A9	AA	AB	AC	AD	AE	AF	B0
030	B1	B2	B3	B4	B5	B6	B7	B8	B9	BA	BB	BC	BD	BE	BF	C0
040	C1	C2	C3	C4	C5	C6	C7	C8	C9	CA	CB	CC	CD	CE	CF	D0
050	D1	D2	D3	D4	D5	D6	D7	D8	D9	DA	DB	DC	DD	DE	DF	E0
060	E1	E2	E3	E4	E5	E6	E7	E8	E9	EA	EB	EC	ED	EE	EF	F0
070	F1	F2	F3	F4	F5	F6	F7	F8	F9	FA	FB	FC	FD	FE	FF	00
080	01	02	03	04	05	06	07	08	09	0A	0B	0C	0D	0E	0F	10
090	11	12	13	14	15	16	17	18	19	1A	1B	1C	1D	1E	1F	20
0A0	21	22	23	24	25	26	27	28	29	2A	2B	2C	2D	2E	2F	30
0B0	31	32	33	34	35	36	37	38	39	3A	3B	3C	3D	3E	3F	40
0C0	41	42	43	44	45	46	47	48	49	4A	4B	4C	4D	4E	4F	50
0D0	51	52	53	54	55	56	57	58	59	5A	5B	5C	5D	5E	5F	60
0E0	61	62	63	64	65	66	67	68	69	6A	6B	6C	6D	6E	6F	70
0F0	71	72	73	74	75	76	77	78	79	7A	7B	7C	7D	7E	7F	81

APPENDIX D

PROGRAMMING A PROGRAMMABLE-READ-ONLY MEMORY

This description applies only to the Intel MDS and UPP (Universal PROM Programmer) systems.

1. Power up MDS, VT50, UPP
2. On MDS: push BOOT on
push RESET
3. Depress space bar on VT50
4. System responds with "MDS MONITOR, V1.1"
5. Push BOOT off
6. System responds with "."
Load data into memory:
7. Type "S1000" and space
8. System responds with content of location 1000
9. Enter first two digit hexadecimal coded point
10. Type space to continue, return to end
11. Repeat steps 8-10 for each data point, hitting return after last point
12. Insert PROM into socket Y
13. Type "PTY1000,1OFF,0"
14. When system completes programming PROM, it will respond with "."
15. Repeat steps 7-14 for each PROM
16. To transfer contents of PROM to memory, type "TTY1000,1OFF"
17. To display contents of memory, type "D1000,1OFF"
18. To compare PROM contents against memory contents, type "CTY1000,1OFF"

Notice that 1000 and 1OFF are arbitrary memory locations and can be any other numbers.

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