Antenna Options: A Yagi Case Study
Part 1—Design Options

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Introduction

"This antenna is the best thing since sliced bread." Such is too often the claim made for antennas by individual builders and commercial makers alike. I'll bet those who make this and similar claims have not stopped to consider that for many meals, sliced bread is exactly the wrong bread to serve. I know a nice little restaurant that serves excellent soups in freshly baked bread bowls. I would not eat there if they tried to serve the soup in sliced bread.

So it is, too, with antennas. For any general application, we have options. Only when we evaluate those options against our specific requirements and our situational limitations can we decide on the best antenna for the circumstances. Notice that the result is not simply "the best antenna." It is the best antenna for the given job and the conditions under which it will have to do that job.

Since I cannot know every circumstance in which amateurs set up antennas, I cannot say what the best antenna is for any amateur activity. I can, however, use the space that *QEX* has allotted to me to discuss some options and alternatives for specific tasks. In small spaces, I cannot cover every possible option and certainly not all of the details that attach to each option. However, I can (hope to) begin a thinking process that may ultimately let you make the best final decisions for yourself. The options that I have in mind are not brand A vs brand B commercial offerings. I do not have the appropriately rated test range for this kind of discussion. Instead, I shall look at options among antenna types, antenna construction, matching systems and so forth that one might face in deciding what to build.

In virtually all areas of antennas, there are facets of design and performance that we easily overlook, and many of them have an important place in our decision-making processes. To make the process even more concrete, let's look at the myriad of options that attach to a seemingly simple case study that I call *A Tale of Three Yagis*.

Yagi arrays require the antenna-builder to make three major decisions on the way from idea to reality:

1. What design is best?
2. What material is best for the elements?
3. What assembly method is best?

These three questions ultimately rest on another: What are the uses, purposes, or goals for the antenna? How all of these questions interrelate is part of the motivation for this set of notes.

To keep our work confined within a space that we can control, I shall examine only 2 m Yagis. Within that space, I shall further assume that the user will take the antenna into the field for one or more of a variety of portable operations. To make matters even simpler, I shall restrict the discussion to 3-element Yagis with 30-inch boom lengths or less.

Even with these restrictions, we still have design choices. We may select a narrow-band, high-gain design to maximize potential for point-to-point com-

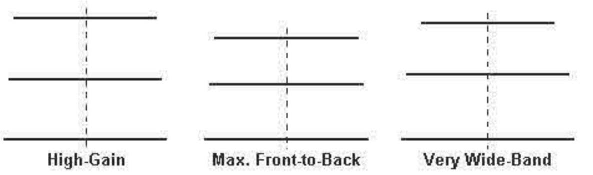

Fig 1—Relative proportions of the three 3-element Yagi designs based on 3/8 inch diameter elements.

Table 1
High-Gain Yagi Dimensions for Round Elements

Dimensions: L = Element half-length—double the L-value to obtain the full element length. Dimensions in inches—multiply by 25.4 to obtain dimensions in millimeters.

El. Dia.	*Ref L*	*Dri L*	*Dir L*	*R-Dr Sp*	*R-Dir Sp*
0.125	20.24	19.33	18.25	13.24	27.50
0.1875	20.18	19.23	18.08	13.34	27.51
0.25	20.00	19.15	17.90	13.95	28.10
0.375	19.95	18.97	17.66	14.30	28.25
0.50	19.88	18.85	17.43	14.40	28.35

munications. Alternatively, we may select a design with a very high 180° front-to-back ratio (F/B) for direction-finding uses. Finally, we may select a design that covers the entire 2-m band-with an exceptionally low 50-ohm SWR. For each design, there are trade-offs that we shall examine along the way.

Once we select a design, we need to select the material for the elements. If we choose to use rod or tubing for the elements, we may simply optimize the design for the element diameter we wish to use. In fact, the design information provided in the tables will cover most common 2-m rod and tubing sizes. However, my e-mail regularly poses questions about the use of non-standard materials, such as flat stock, L-stock, whips, and tape. Therefore, we shall spend a bit of time looking at a technique for determining what adjustments we might have to make for some of these materials. I shall provide some data that emerged from my own use of these techniques, but the techniques themselves will be your better guide to handling materials that I have not imagined.

Finally, we shall look at a few methods of overall assembly that are suitable for the element material, the overall size of the antenna, and the intended use. For such a short boom, there is no reason to avoid a non-conductive boom. In most cases, the choice will be between PVC and Fiberglass, with PVC being easier to find and somewhat more versatile.

In the end, these notes are just a sample of a thought process you can and should extend to other bands, other designs, and other operating purposes.

Part 1: The Three Yagi Designs

The first step in our *Tale of Three Yagis* is to describe the Yagis themselves. There is a high-gain, narrow-band version, a maximum F/B version, and a very wide-band version. A papa bear, mama bear, and chubby baby bear analogy in these characterizations is likely not accidental.

For each antenna design, the tables will provide detailed dimensions for a variety of element diameters from 1/8 up to 1/2 inch, in readily available rod and tube sizes. The material may be aluminum (recommended for its light weight and strength), brass, or copper. The performance figures are based upon aluminum, although changing the material will not alter the performance in any detectable way.

The tables also provide performance data from *NEC-4* models at the design frequency. All designs attempt to achieve a minimum of 20 dB F/B across the listed passband. The particular design, however, will reveal variations of where within the operating passband the maximum F/B occurs. All 3-element Yagi designs show a gradual increase in gain across the operating passband.

Fig 1 shows the relative proportions of the three Yagi designs, using the 3/8 inch diameter element versions as the basis for the sketch. The high-gain version has nearly equal spacing between elements and an almost uniform taper

Table 2
High-Gain Modeled Performance at the Design Frequency

Performance at 144.5 MHz

El. Dia. (Inches)	*Free-Space Gain(dBi)*	*Front-to-Back Ratio(dB)*	*Feed Impedance (R±jX ohms)*	*25-ohm (SWR)*
0.125	8.23	24.61	24.73–*j*0.77	1.033
0.1875	8.27	24.63	24.15–*j*0.57	1.042
0.25	8.31	24.64	24.65+ *j*0.30	1.019
0.375	8.31	24.71	24.77–*j*0.65	1.028
0.50	8.31	24.67	25.06–*j*0.04	1.003

Table 3
High-Gain Modeled Performance at the 1-MHz Operating Passband Edges

Passband Edge Performance: Values are free-space gain (dBi) / 180-degree F/B (dB).

El. Dia.	*144*	*145*
0.125	8.17 / 26.32	8.30 / 22.04
0.1875	8.21 / 26.40	8.34 / 22.17
0.25	8.24 / 24.48	8.37 / 23.29
0.375	8.25 / 25.23	8.38 / 23.10
0.50	8.25 / 25.06	8.38 / 23.30

Table 4
25-ohm SWR Performance

El. Dia.	*144*	*145*	*146*
0.125	1.19	1.14	1.61
0.1875	1.17	1.15	1.59
0.25	1.12	1.17	1.58
0.375	1.15	1.11	1.47
0.50	1.12	1.12	1.45

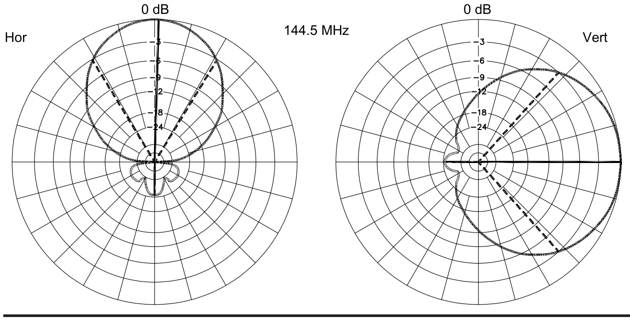

Fig 2—High-gain 3-element Yagi—typical horizontal and vertical patterns. Dashed lines are at –3 dB.

Table 5
Maximum F/B Yagi Dimensions for Round Elements

Dimensions: L = Element half-length—double the L-value to obtain the full element length. Dimensions in inches—multiply by 25.4 to obtain dimensions in millimeters.

El. Dia.	*Ref L*	*Dri L*	*Dir L*	*R-Dr Sp*	*R-Dir Sp*
0.125	20.21	18.78	18.02	11.79	23.85
0.1875	20.20	18.64	17.82	12.09	24.10
0.25	20.18	18.51	17.64	12.49	24.50
0.375	20.11	18.32	17.42	13.09	24.90
0.50	20.06	18.16	17.21	13.39	25.10

of the elements. The departure of the spacing and taper from uniformity is essential to achieving the performance. The maximum 180° F/B design preserves a similar driver-reflector structure, but shortens the length and spacing of the director to achieve the deep rear null. Both antennas have a feed-point impedance near 25 ohms. The very wide-band version requires a 50 ohm feed-point and therefore widens the reflector to driver spacing. Note also the relatively short director.

144.5 MHz High-Gain 3-Element Yagi

The high-gain Yagi is designed for maximum gain with a reasonable boom length and modest bandwidth. It will cover about 2 MHz of the 2-m band if the design frequency is moved from 144.5 MHz to 145 MHz. However, its present design recognizes that most point-to-point activity is in the first MHz of the band. So the design frequency is set at 144.5 MHz. Within the first MHz, the SWR is less than 1.2:1 for any listed element diameter. Although horizontal operation is the norm for the low part of 2-m, the antenna is equally operable horizontally or vertically.

The feed-point impedance is resonant at about 25 ohms. This arrangement is intentional to avoid the need for excessive mechanical connections at the antenna proper. A $^1/_4$ λ section of RG-83 (35-ohm) or a parallel section of RG-59 (or similar 75-ohm) coax will provide a match to the 50-ohm main cable. Cut the section for 144.5 MHz, allowing for the cable's specific velocity factor. Alternatively, one may modify the design to shorten the driver so that it shows about 25 ohms of capacitive reactance. Then, a hairpin or gamma match becomes applicable.

It is not possible to let the maximum F/B of the high-gain, narrow-band design coincide with the design frequency for all element diameters. The smaller the element diameter, the more likely the maximum F/B is to fall below the design frequency. However, the F/B exceeds 22 dB from 144 to 145 MHz for all versions of the design.

Table 1 provides dimensions for the design using round elements from $^1/_8$ inch up to $^1/_2$ inch in diameter. Table 2 shows the modeled free-space performance at the design frequency, 144.5 MHz, for each size material. Simplified values for the edges of the 1 MHz operating passband appear in Table 3, while Table 4 suggests the usable operating bandwidth with 25-ohm SWR values at 144, 145, and 146 MHz. If the builder uses a $^1/_4$ λ matching section for a 50-ohm coaxial

Table 6
Maximum F/B Yagi Modeled Performance Across 2-m

0.125 inch Diameter Elements.

Freq. (MHz)	*Free-Space Gain (dBi)*	*Front-to-Back Ratio (dB)*	*Feed-point Z R±jX (ohms)*	*50-ohm (SWR)*
144	7.60	20.23	72.49+*j*11.74	1.519
145	7.66	26.36	62.15+*j*4.33	1.260
146	7.74	50.67	50.92–*j*0.30	1.019
147	7.84	26.42	39.62–*j*1.78	1.266
148	7.97	20.14	29.34–*j*0.38	1.704

0.1875 inch Diameter Elements.

Freq. (MHz)	*Free-Space Gain (dBi)*	*Front-to-Back Ratio (dB)*	*Feed-point Z R±jX (ohms)*	*50-ohm (SWR)*
144	7.61	21.34	69.70+*j*10.70	1.459
145	7.67	27.61	60.42+*j*4.18	1.226
146	7.75	54.07	50.28–*j*0.01	1.006
147	7.85	26.89	39.98–*j*1.48	1.254
148	7.98	20.80	30.44–*j*0.46	1.643

0.25 inch Diameter Elements.

Freq. (MHz)	*Free-Space Gain (dBi)*	*Front-to-Back Ratio (dB)*	*Feed-point Z R±jX (ohms)*	*50-ohm (SWR)*
144	7.62	22.01	68.20+*j*10.91	1.435
145	7.68	28.25	59.77+*j*4.83	1.220
146	7.76	52.26	50.47+*j*0.79	1.018
147	7.86	27.61	40.92–*j*0.90	1.223
148	7.98	21.51	31.91–*j*0.30	1.567

0.375 inch Diameter Elements.

Freq. (MHz)	*Free-Space Gain (dBi)*	*Front-to-Back Ratio (dB)*	*Feed-point Z R±jX (ohms)*	*50-ohm (SWR)*
144	7.65	22.96	67.13+*j*9.41	1.399
145	7.72	29.33	59.22+*j*3.58	1.199
146	7.80	51.05	50.35–*j*0.29	1.009
147	7.90	27.90	41.19–*j*1.91	1.219
148	8.02	21.97	32.52–*j*1.37	1.540

0.5 inch Diameter Elements.

Freq. (MHz)	*Free-Space Gain (dBi)*	*Front-to-Back Ratio (dB)*	*Feed-point Z R±jX (ohms)*	*50-ohm (SWR)*
144	7.66	23.34	65.90+*j*8.24	1.364
145	7.72	29.42	58.47+*j*2.95	1.180
146	7.81	56.80	50.17–*j*0.60	1.012
147	7.90	28.96	41.60–*j*2.14	1.209
148	8.02	22.82	33.41–*j*1.76	1.500

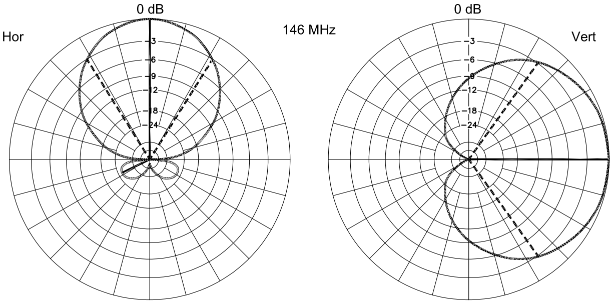

Fig 3—Maximum F/B 3-element Yagi—typical horizontal and vertical patterns. Dashed lines are at –3 dB.

feed line, the 50-ohm SWR at the junction of the matching section and the main feed line will be similar. Fig 2 shows free-space E-plane and H-plane patterns for the array at the design frequency. These patterns replicate the pattern shapes when the antenna is used over ground in the horizontal and vertical positions, respectively.

The charts show clearly that the bandwidth for any particular characteristic tends to increase with an increase in element diameter. However, note that each increase in element diameter requires a change in element spacing as well as element length to sustain the performance curves over the 144-145 MHz passband. Most of the change in element spacing occurs with respect to the driver and reflector, since this spacing, relative to a given element diameter, largely determines the feed-point impedance of the array, once we have set the performance values with the spacing and length of the director.

To change the design frequency, scale both element lengths and element spacing. Take the ratio of the old (144.5 MHz) frequency to the new frequency and multiply or divide all dimensions in the tables by the result. If the scaling is within the 2-m band, no element diameter adjustment is necessary. If the frequency ratio is greater than about 1.2:1 or less than 0.8:1, then element diameter scaling is necessary to retain the performance characteristics.

146 MHz Maximum F/B 3-Element Yagi

The applications for a high-gain design are obvious. A maximum F/B design has more limited application, for example, in the field of Amateur Radio direction finding. The antenna should have sufficient gain to locate the desired signal and a sufficiently sharp and deep rear null to provide a reliable bearing toward the target transmitter. Although the horizontal pattern for any parasitic beam will include rear quartering lobes, the vertical pattern will show a clear single null. Most direction-finding activities use vertical polarization.

I have set the design frequency for the maximum F/B at 146 MHz, because there is no absolute standard for direction-finding frequencies. However, for operation within the 2-m band, one may scale the dimensions according to previously given principles without concern for scaling the element diameter. However, for scaling outside the limits of the 2-m band, one should also scale the element diameter.

Table 7
Very Wide-Band Yagi Dimensions for Round Elements

Dimensions: L = Element half-length—double the L-value to obtain the full element length. Dimensions in inches—multiply by 25.4 to obtain dimensions in millimeters.

El. Dia.	*Ref L*	*Dri L*	*Dir L*	*R-Dr Sp*	*R-Dir Sp*
0.125	20.80	19.23	17.25	13.79	26.00
0.1875	20.45	19.17	17.15	14.80	26.50
0.25	20.44	19.16	17.05	15.60	27.00
0.375	20.42	19.15	16.90	17.10	28.05
0.50	20.46	19.15	16.80	18.10	28.60

Table 8
Very Wide-Band Yagi Modeled Performance Across 2-m

0.125 inch Diameter Elements.

Freq. (MHz)	*Free-Space Gain (dBi)*	*Front-to-Back Ratio (dB)*	*Feed-point Z R±jX (ohms)*	*50-ohm (SWR)*
144	6.93	18.84	49.77–*j*9.65	1.213
145	6.93	19.51	50.09–*j*5.01	1.105
146	6.96	19.96	49.97–*j*0.25	1.005
147	7.00	20.16	49.43+*j*4.69	1.100
148	7.06	20.07	48.49+*j*9.87	1.224

0.1875 inch Diameter Elements.

Freq. (MHz)	*Free-Space Gain (dBi)*	*Front-to-Back Ratio (dB)*	*Feed-point Z R±jX (ohms)*	*50-ohm (SWR)*
144	7.10	18.16	49.78–*j*8.88	1.195
145	7.11	19.73	49.92–*j*4.88	1.103
146	7.13	21.26	49.58–*j*0.72	1.017
147	7.17	22.61	48.80+*j*3.67	1.081
148	7.23	23.48	47.61+*j*8.35	1.195

0.25 inch Diameter Elements.

Freq. (MHz)	*Free-Space Gain (dBi)*	*Front-to-Back Ratio (dB)*	*Feed-point Z R±jX (ohms)*	*50-ohm (SWR)*
144	7.09	18.49	51.18–*j*7.89	1.171
145	7.11	20.05	50.93–*j*4.17	1.088
146	7.14	21.64	50.26–*j*0.24	1.007
147	7.19	23.16	49.20+*j*3.95	1.085
148	7.25	24.21	47.77+*j*8.45	1.196

0.375 inch Diameter Elements.

Freq. (MHz)	*Free-Space Gain (dBi)*	*Front-to-Back Ratio (dB)*	*Feed-point Z R±jX (ohms)*	*50-ohm (SWR)*
144	7.08	19.10	52.56–*j*7.34	1.163
145	7.11	20.67	51.75–*j*3.87	1.087
146	7.15	22.36	50.61–*j*0.13	1.012
147	7.22	24.07	49.15+*j*3.92	1.084
148	7.29	25.29	47.41+*j*8.31	1.195

0.5 inch Diameter Elements.

Freq. (MHz)	*Free-Space Gain (dBi)*	*Front-to-Back Ratio (dB)*	*Feed-point Z R±jX (ohms)*	*50-ohm (SWR)*
144	7.04	19.78	52.58–*j*7.78	1.173
145	7.09	21.40	51.40–*j*4.92	1.096
146	7.14	23.20	49.95–*j*0.76	1.015
147	7.22	25.10	48.24+*j*3.23	1.078
148	7.30	26.42	46.30+*j*7.58	1.191

Although not radically finicky, the maximum F/B frequency for a Yagi design is a narrow-band phenomenon. Hence, one should construct the antenna for the frequency of intended use. As the performance tables will show, the F/B decreases steadily off frequency until the design shows no distinct null. However, the design has sufficient gain and F/B to make it a useful performer for other purposes.

The feed-point impedance for this design is set for about $25 - j25$ ohms. The models all use an identical shorted transmission line stub across the feedpoint to simulate a hairpin match. Hence, the SWR curves are for 50 ohms. The modeled feed-point resistance is actually close to 27 ohms, and the required inductive reactance of the hairpin is 54 ohms. You may construct a U-shaped hairpin for the antenna by calculating the characteristic impedance for the spacing and wire diameter used. Then the length follows standard shorted-transmission line equations found in *The ARRL Antenna Book*, Chapter 24. A normally good construction method for the hairpin is to choose a distance between the parallel lines that is equal to the spacing between the driver terminals.

As an example, AWG #14 wire (0.0641 inch diameter) has a 400-ohm characteristic impedance at a center-to-center line spacing of 0.901 inch. A shorted stub or hairpin made from this line would need to be 1.73 inch long to achieve 54 ohms inductive reactance at 146 MHz. The final adjustment requires care, since the terminal structure at the feed-point normally introduces some reactance that may add to or subtract from the amount provided by the hairpin. Lower characteristic impedances yield longer stubs for the same reactance. Narrowing the line spacing or fattening the conductor will lower the characteristic impedance. The goal is a hairpin that is short enough to be sturdy in field use but not so short as to make the final feed-point adjustment too finicky.

If you build this design for its intended purpose, general field adjustment also requires care. Contrary to most received wisdom, the reflector is not chief source of the F/B in the design. The reflector is relatively insensitive and serves primarily to establish the feed-point impedance by virtue of its length and spacing from the driver. The most sensitive element relative to establishing the ideal F/B will be the director. The director length will be more sensitive than its spacing from the driver, although both dimensions deserve the label "sensitive."

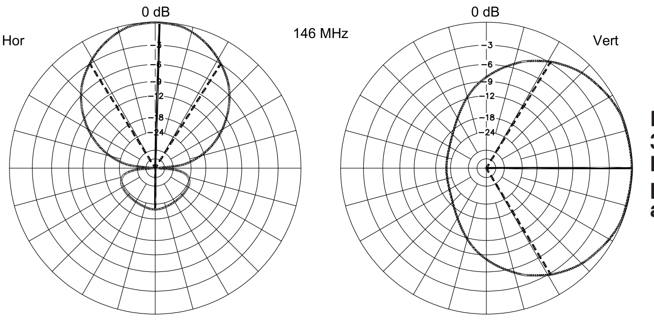

Fig 4—Very-wide-band 3-element Yagi—typical horizontal and vertical patterns. Dashed lines are at –3 dB.

Table 5 provides dimensions and Table 6 supplies performance values based on *NEC-4* models for element sizes ranging from $^{1}/_{8}$ inch to $^{1}/_{2}$ inch. In all of the designs in these notes, the dimension values presume a non-conductive boom or the use of mountings that insulate and isolate the elements from the influences of a conductive boom. See "Scaling and Adjusting VHF/UHF Yagis" at my Web site for notes on adjusting element lengths for insulated through-boom construction (**www.cebik.com/scales.html**). However, for boom lengths under 30 inches or so, and for direct-feed drivers, there is little reason to use a conductive boom.

The performance values show the increasing performance—although very gradually increasing—as we increase the element diameter and also adjust both element length and spacing to optimize performance for each new element size. This clear picture emerges largely because the design aligns the design feed-point impedance and the maximum F/B at the same frequency. The only performance figure for which variations make no difference is the 146 MHz F/B—I ceased optimizing when this value exceeded 50 dB.

Fig 3 shows free-space E-plane and H-plane patterns, which replicate the patterns you will obtain when using the antenna in a horizontal or vertical orientation, respectively. Over ground, expect the vertical pattern to have less gain but a wider beamwidth than the horizontal pattern. However, when used vertically, the rear quadrants will show a single deep, sharp null.

146 MHz Very Wide-Band 3-Element Yagi

The third design stresses smooth performance over the entire 2-m band with a 50-ohm SWR of less than 1.2:1. The design achieves this goal by using a variation of a W6SAI design from the 1980s, modified for 2-m and for the full range of rod and tube diameters. Although the gain is about a full dB less than the high-gain model, the wide-band Yagi will provide roughly equal performance anywhere in the band. Thus, it is fit for flipping from horizontal to vertical and back again as we change to and from point-to-point and FM repeater operations.

The Yagi uses a direct 50-ohm feedpoint with no matching network required—although common mode current suppression measures are advisable. The need to establish the SWR curve as the primary design goal has consequences as we increase the element diameter. The F/B shows improvement with each larger element, but the low end of the band does not quite make the 20 dB level. Very quickly in the sequence, the gain ceases to increase with increasing element diameters. Although not clearly apparent in the performance figures, both the peak gain and the peak F/B occur at ever higher frequencies. Above the smallest element size, the peak F/B occurs above the upper end of 2-m.

Nevertheless, the very wide-band 3-element Yagi is a true general utility antenna for use anywhere in the band. Table 7 provides the dimensions for elements ranging from $^{1}/_{8}$ inch to $^{1}/_{2}$ inch in diameter. Table 8 supplies the modeled performance figures. Fig 4 gives the shape of patterns when we use the antenna horizontally and vertically. All previous notes about scaling this antenna to other frequency bands are applicable with the very wide-band Yagi.

The very wide-band version of the 3-element Yagi completes the family of designs that we shall consider. Other variations may be possible, but these three cover the major performance parameters with which amateurs are most concerned: gain, F/B, and operating or SWR bandwidth. One might further optimize the designs, but the level of optimizing used here gets the most out of each design that we can for each size element. The next step—assuming that one of these designs will meet an operating need—is deciding upon the element material. We shall explore those options next time. □□