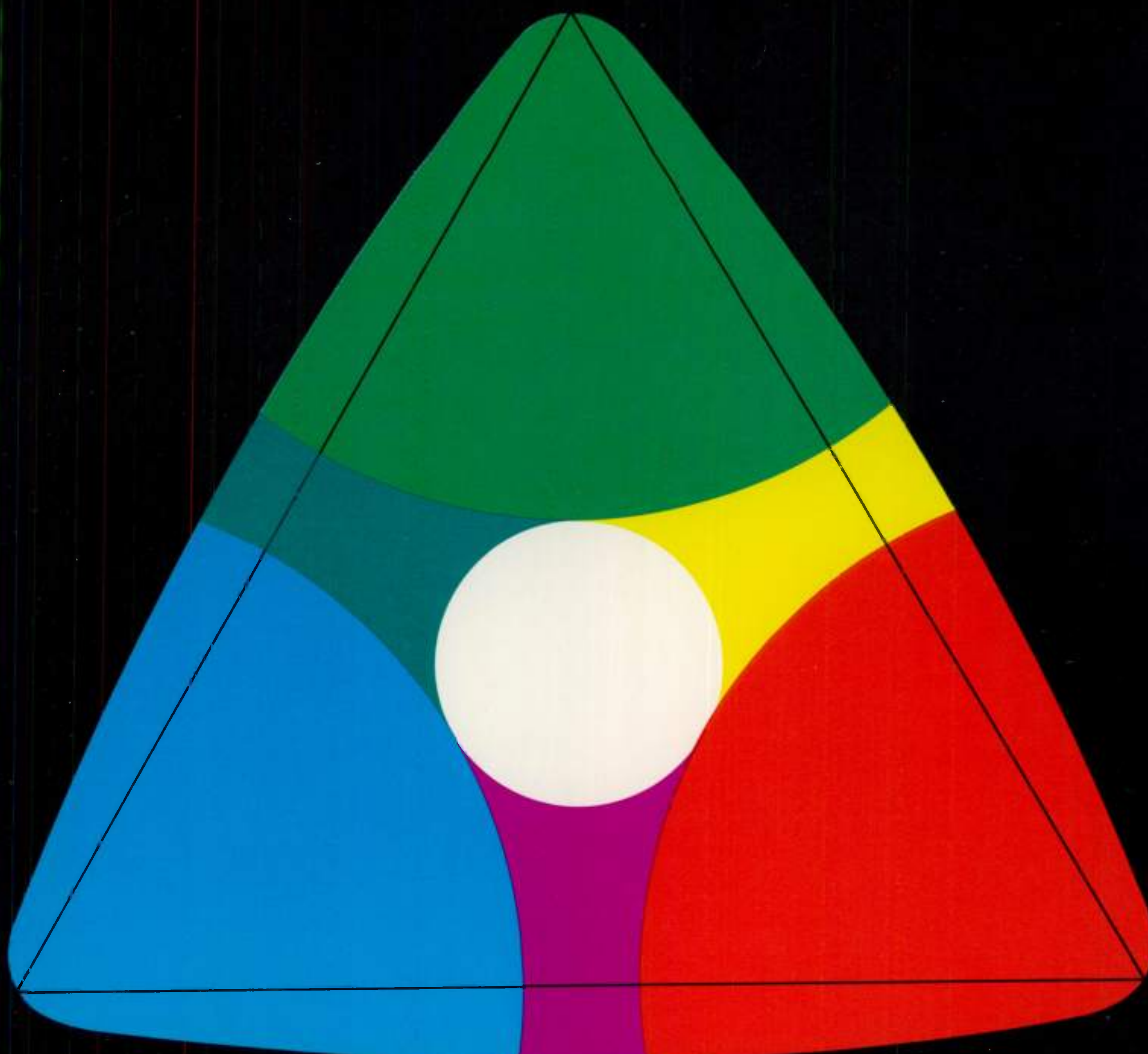
Westinghouse ENGINEER

November 1971



Modular Interior Subsystems Speed Housing Construction

An increasingly effective method for constructing various kinds of housing rapidly is industrialized housing, which means taking most of the construction processes off the jobsite and putting them into a factory where they can be approached in a systematized production-line manner. Industrialized housing has been applied mainly to building the frame and exterior modules; the shell goes up fast, but then finishing the interior living spaces can take months. Now, however, *interior* subsystems to complement other industrialized residential building components are being designed and manufactured by the Westinghouse Home Systems Department.

The interior subsystems include galley and U-shaped kitchens; preassembled HVAC units that combine the heating, ventilating, and air conditioning functions; and Service Support Modules, which are assemblies containing kitchen, bath, utility, and laundry facilities. Each is made in a variety of capacities, sizes, and options to meet a wide range of needs. A line of separate bathroom modules will be introduced soon.

The kitchens are complete with wiring, plumbing, appliances, cabinets, ceiling, and lighting. Appliances are hung on the walls, and the sides of the kitchen form a shipping carton that also serves to protect the unit during construction of the building (Fig. 1). When the unit has been installed, the appliances are released for conventional placement on the floor.

Construction of a Service Support Module begins with assembly of a steel frame (Fig. 2). Use of jigs assures that all frames are assembled exactly alike. Another jig, for plumbing, fixes the exact size and position of each pipe in the system (Fig. 3).

The largest of the Service Support Modules combine complete mechanical and electrical cores (HVAC unit, electrical load center, hot-water heater) with a kitchen and dinette (Figs. 4 and 5). They also include a full bath with tiled or fiber-glass tub and shower, and a combination half bath and laundry room (Fig. 6). In addition, a connecting hallway has an FHA-approved 2- by 5-foot closet.

Finished modules are shipped to the building construction site and lifted into place (Fig. 7). Installation is completed by making simple connections to electrical, water, and sewage utilities.

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Front Cover: A stylized version of one conventional way of representing a white light composed of three colors is featured as the cover design. Combining those three particular colors has been found to provide the best combination of brightness and color-rendering capability; the article beginning on the following page tells why.

Improving the Performance of White Light

W. A. Thornton

The performance, and therefore the usefulness, of white light is measured by the light's brightness and its color-rendering capability. Performance of white lights of the same apparent color can be excellent or disastrous, depending on the distribution of colors (wavelengths) composing them.

Improvements in artificial lighting, from the campfire to the modern lamp, have been aimed mainly at increasing the brightness, efficiency, and convenience of the lighting. Two other important properties, the color of the light and its ability to show objects in their proper colors, were largely uncontrolled because they were intrinsic properties of each kind of artificial illumination.

The advent of discharge lamps, however, especially fluorescent lamps, has given researchers wide choice and a great measure of control over the colors (wavelengths) composing the light. The distribution of wavelengths, known as the spectral power distribution (SPD), is what determines the color and color-rendering capability of the light and, together with the power and power efficiency of the lamp, its total luminous output. Therefore, the question for lamp researchers should now be what is the *optimum* SPD for artificial light.

The question has been answered at the Westinghouse Lamp Divisions, where white light composed of three sharply defined pure colors has been found to outperform conventional artificial light whenever the combination of high brightness and good color rendition is important. The discoveries rest on the characteristics of normal human color vision, so is seems safe to say that they are final and that the optimized SPDs are close to the ultimate in lighting performance.

For applications where either high brightness or good color rendition is considered more important than the combination, other SPDs can be chosen. (An example is street lighting, in which brightness usually has been considered more important than color rendition.) However, color discrimination is important for virtually all human activities, so the combination of good color rendition and high brightness probably will be widely used now that the way to optimize both has been found.

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Performance of White Light

"White light" is a subjective term applied to a rather large range of colors that includes the various daylight colors, from blue sky to yellowish sunlight, and also the colors of very hot incandescent bodies. White-light colors are often correlated to the temperature in degrees Kelvin of an incandescent body of the same color. Average daylight has about the same color as an incandescent body at 6700 degrees K, so its color temperature is said to be 6700K. A color temperature near 4000K is known as Cool White, and (paradoxically!) one near 3000K is known as Warm White.

White light of any of those colors may be composed of as few as two spectral (pure) colors or of an infinite number of them.

Any daylight, from blue sky to sunset, could serve as reference for the purposes of this article. The one used is average daylight, Illuminant C, an industry standard. Average daylight is composed of a fairly even distribution of power of various visible wavelengths (Fig. 1). Any daylight also contains ultraviolet and infrared radiation—wasted power so far as vision is concerned.

The generally used measure of brightness is luminosity. The luminosity of white light, or of light of any color, is determined from the wavelength sensitivity $\bar{y}$ of human vision (Fig. 2). For example, the luminosity η of average daylight is obtained by multiplying the curves of Figs. 1 and 2, wavelength by wavelength, and summing, then dividing by the area under the curve of Fig. 1:

$$\eta = \frac{\int P\bar{y}d\lambda}{\int Pd\lambda}, \qquad (1)$$

where P is the power of the light per unit wavelength interval (for example, watts per nanometer interval) and λ is its wavelength in nanometers.

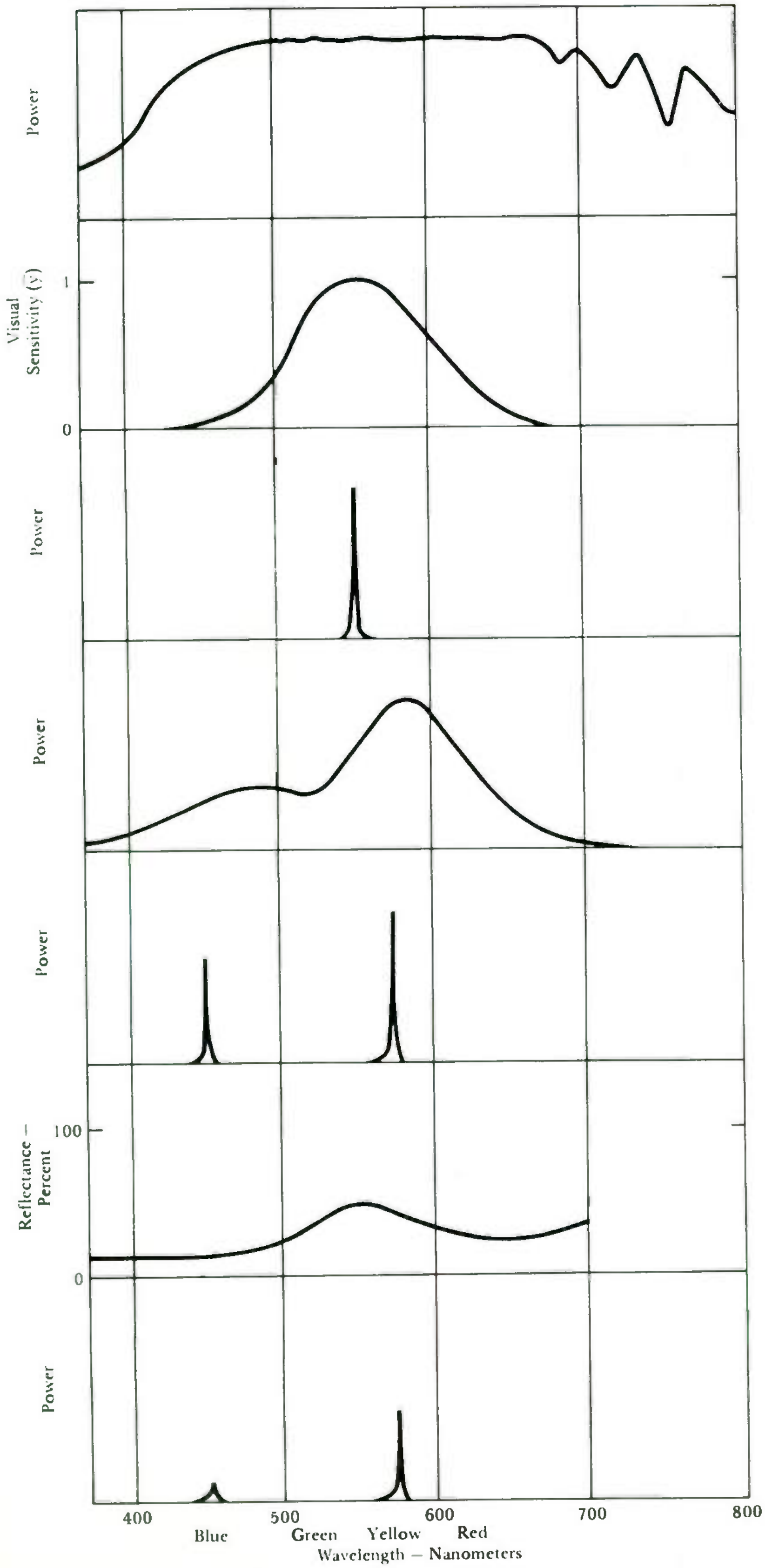
The luminosity of average daylight is about 0.2. For comparison, the luminosity of pure yellow-green light is about 1.0 (Fig. 3). The reason daylight often seems brighter than artificial light is its high power density, roughly 700 watts per square meter in average sunlight at sea level. The power density in artificial light is generally only about one percent as great.

Most people would agree that the color-rendering capability of average daylight is superb, but its luminosity is far too low for a commercial lamp. A 40-watt Cool White fluorescent lamp, for example, normally radiates about 3000 lumens, the universally used unit of visible light; if its SPD (Fig. 4) were changed to that of average daylight (Fig. 1), its output would drop to about 1000 lumens. As a result, its commercial value would all but disappear.

Light of the same color as average daylight, with the highest possible luminosity for that color, is composed of a mixture of pure blue and pure yellow light (Fig. 5). Its color cannot be distinguished by eye from that of Fig. 1, even though the SPDs are so strikingly different. A 40-watt fluorescent lamp with the SPD of Fig. 5 might radiate about 4000 lumens, but its color-rendering capability would be disastrously poor.

To understand what is necessary for acceptable color rendition, one must consider the reflectance of colored objects. The spectral reflectance of a head of lettuce, for example, is shown in Fig. 6. If the white light of Fig. 5 shines on the lettuce of Fig. 6, the reflected light seen by the eye (Fig. 7) is still composed of a mixture of pure blue light and pure yellow light, though in different proportion. There is no hint of the green color characteristic of the lettuce; it appears yellowish white. That appearance can be understood by considering next how the addition of colored lights is depicted in two-dimensional space.

A conventional type of two-dimensional color space is shown in Fig. 8. An area in its center includes those colors called white. Movement away from the center represents increasing color saturation (also called "chroma" and, by



1—Spectral power distribution (SPD) of average daylight is fairly even, consisting of a range of colors (wavelengths) at about the same power.

2—Wavelength sensitivity of the human eye is not at all even, and it spans only a part of the SPD of average daylight and of many other lights. Thus, the luminosity (brightness) of any light depends on the relationship of its SPD to the eye's wavelength sensitivity.

3—SPD of a pure yellow-green light is concentrated near the peak of the eye's wavelength sensitivity, so the luminosity of that light is high.

4—SPD of the Standard Cool White fluorescent lamp has higher luminosity than average daylight, although its color-rendering capability is not as good.

5—A light of the same color as average daylight is made by mixing only two wavelengths—blue and yellow. It has the highest possible luminosity for the average-daylight color, but its color-rendering capability is very poor.

6—Spectral reflectance of lettuce is the manner in which that estimable vegetable reflects light. It explains why lettuce looks green or yellow-green in any light with good color-rendering capability.

7—SPD of the light reflected from lettuce illuminated by the two-component light of Fig. 5 has peaks in the same locations as in that figure. However, their powers are reduced in proportion to the lettuce's reflectance at those wavelengths. The lettuce would appear yellowish white.

some, "intensity" or "purity"). The periphery of the diagram represents spectral (pure) colors. Every point in the color space represents a certain chromaticity, which is the "color" calculated from the SPD of the light.

In Fig. 9, the blue and yellow lights composing the white light of Fig. 5 are plotted on the periphery, and the average-daylight color *D* of the mixture on the line drawn between. One of the most useful characteristics of this type of color space is that the color of a mixture of any two colored lights, in any proportion, lies on the straight line connecting the colors of the two lights.

It follows that the light reflected from the lettuce (Fig. 7) is such that the apparent color *L* of the lettuce must lie on the same straight line, somewhat displaced toward the yellow because the yellow peak in Fig. 7 is proportionately higher than that in Fig. 5. Similarly, the apparent color of any object in this light—a lime, a tomato, a complexion—must fall on the same line and therefore appears either blue, bluish-white, white, yellowish-white, or yellow. Obviously, the color-rendering properties of the lamp of Fig. 5 would be intolerable, even though the light has an acceptable average-daylight color.

Optimum Distribution of Colors

The SPDs of both real daylight, with excellent color rendition but poor luminosity, and its look-alike (Fig. 5), with poor color rendition and excellent luminosity, are unacceptable for commercial lamps. The fluorescent lamp of Fig. 4 is a reasonably good compromise. But what is the *optimum* spectral power distribution of white light when both luminosity and color-rendering capability are important? In other words, what is the proper goal for the design of the white emission of commercial lamps, and how much is to be gained in performance when that goal is reached?

The trick is to add one, and only one, more component to the two color components considered above. When white light is composed of three spectral colors, as in Figs. 10 and 11, colored objects illuminated by it tend to take on truer

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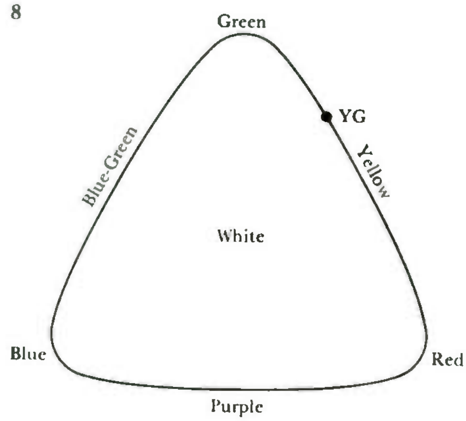

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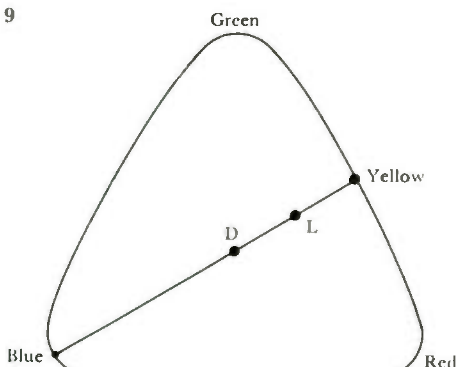

8—Addition of colored lights can be depicted by this conventional color space. White light is represented by the area in the center, and colors increase in saturation with distance from the center. Spectral (pure) colors are at the periphery; thus, the pure yellow-green light of Fig. 3 is represented by point *YG*.

9—When the blue and yellow lights of Fig. 5 are plotted on the periphery of the color space, the average-daylight color *D* that they form lies on the line between. (The resultant color of a mixture of *any* two lights can be so depicted.) *L*, the color of lettuce illuminated by this mixed light, also lies on the line, but it is displaced toward the yellow because of the characteristic spectral reflectance of lettuce (Fig. 6).

colors. Light reflected from the lettuce (Fig. 12) appears greenish, as it should, so the apparent color of the lettuce appears nearer its proper position in color space (Fig. 11).

This color improvement can be represented quantitatively. The present method of evaluating color-rendering capability of a light source is by means of the color-rendering index (CRI).[1] A set of eight object colors, each with an actual reflectance curve such as Fig. 6, has been chosen. When those eight colored objects are illuminated by some light source with superb color-rendering capability, say average daylight, their perceived colors are spaced roughly equally around the circle of hues (Fig. 13) and are roughly of the same saturation, or distance from the center point *D* representing average-daylight color. Under the two-component white light source of Fig. 5, however, the apparent colors of the eight test objects fall (Fig. 14) along the line of Fig. 9, even though their true colors include rich blue-green, red, and purple. CRI is a measure of the average vector distance (AVD) in color space between the apparent colors of the eight objects and their colors under the reference illuminant:

$$CRI = 100 - k(AVD). \qquad (2)$$

The reference illuminant is one of a series of differently colored daylight or incandescence SPDs. The one that most closely resembles the color of the test illuminant is chosen. For this article, the reference illuminant is average daylight, and the test illuminant is the white light composed of three spectral colors. If the test illuminant renders the eight colors as precisely the same chromaticities as does the reference illuminant, then AVD = 0.

The value of the constant *k* was arbitrarily chosen so that the CRI of the Warm White fluorescent lamp would come out 50. A CRI of zero has no special significance, and an illuminant can have a negative CRI.

Under a superb illuminant such as average daylight, the average vector difference is near zero and so the CRI is near 100. Under the light source of Fig. 5, which has average-daylight color

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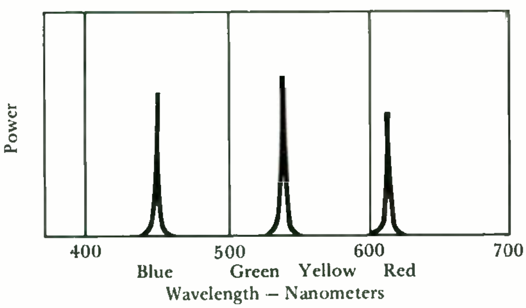

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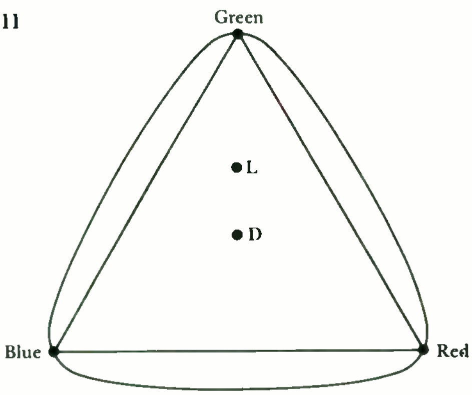

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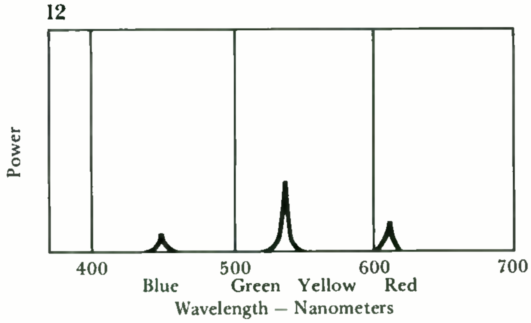

10—Another light of the same color as average daylight is illustrated by this SPD. It consists of blue, green, and red spectral colors with wavelengths, respectively, near 450, 540, and 610 nm.

11—The three-component white light of Fig. 10 is depicted here in the color space as *D*.

12—SPD of light reflected from lettuce illuminated by the white light of Fig. 10. The reflected light appears greenish because of the proportional manner in which the lettuce reflects wavelengths (Fig. 6). Thus, the apparent color of the lettuce is much nearer its proper position in color space (*L* in Fig. 11) than it is in Fig. 9.

but consists only of blue and yellow light, the average vector distance is large (Fig. 14) and CRI is about −20. The commercial Warm White fluorescent lamp, with its CRI of about 50, is usually judged to have rather poor color-rendering capability.

Four remarkable discoveries have been made[2] concerning white light composed of three spectral colors (Fig. 10):

1) For highest color-rendering capability, choice of the three colors is extremely critical (Fig. 15). The chosen wavelengths must be close to 450, 540, and 610 nm.

The procedure for identifying the three optimum colors began with picking a particular white color *W*; that is, a particular chromaticity in the central region of the conventional color-space diagram. Then any three spectral colors were chosen that formed a triangle, as in Fig. 11, enclosing chromaticity *W*. The triangle need not, of course, be isosceles. Two of the spectral colors were fixed and the wavelength of the third was varied; that is, two vertices of the triangle were fixed and the third allowed to move along the periphery of color space so long as chromaticity *W* fell inside the triangle. Then another vertex was allowed to move while the remaining two were held fixed, and likewise for the third vertex.

For each of those numerous triads of wavelengths (spectral colors), a certain three-way power ratio resulted in the same color *W* of white.* For each triad with its unique power ratio, CRI was calculated. Three particular wavelengths emerged by trial and error as those leading to highest CRI, depending slightly on choice of the white color *W*. Combination of those three most-effective wavelengths was found to compose color *W* with maximum CRI. When two of the three most-effective wavelengths near 450, 540, and 610 nm were chosen and the third allowed to vary, and average daylight was chosen as color *W*, the CRI dependence of Fig. 15 resulted.

*So many triads of components of so many arbitrary widths were necessary that the calculations would have taken the better part of a lifetime to do by sliderule; use of the digital computer shortened the job to a week or two of computer time.

2) White light composed of those three particular wavelengths renders colors better than do most commercial fluorescent and vapor lamps in use today. As apparent from Fig. 15, the CRI of white light composed of three wavelengths only—450, 540, and 610 nm— has a color-rendering index of about 80. That is so whether the color of the white light is bluer than average daylight, the same as average daylight, or so much "warmer" than average daylight that it is similar to the color of an incandescent lamp. For comparison, the CRIs of some commercial lamps are approximately as follows:

Warm White fluorescent	53
White fluorescent	56
Cool White fluorescent	66
Daylight fluorescent	74
Warm White Deluxe fluorescent	69
Cool White Deluxe fluorescent	89
Mercury vapor	20
High Output White vapor	36
Standard White vapor	43
Deluxe White vapor	45
High-pressure sodium	35

The luminous output of the special three-color lamp is 25 percent higher than that of the Cool White Deluxe fluorescent lamp, in an industry where heretofore even a 3-percent improvement has been significant.

3) The same three colors are optimum when *both* color-rendering capability and luminosity are important. When the data of Fig. 15 are plotted with both CRI and luminosity as parameters, the same wavelengths lead to best performance on both counts.

4) White light composed of those three particular pure colors cannot be surpassed appreciably in performance by any other SPD whatsoever, so long as color-rendering capability and luminosity are both important. In other words, that particular combination of wavelengths, when used to compose white light, apparently cannot be appreciably improved in performance by adding one or more additional wavelengths, by adding a continuum, or by broadening the power distributions of the three unique components.

There has been a long-standing belief that a discontinuous SPD cannot

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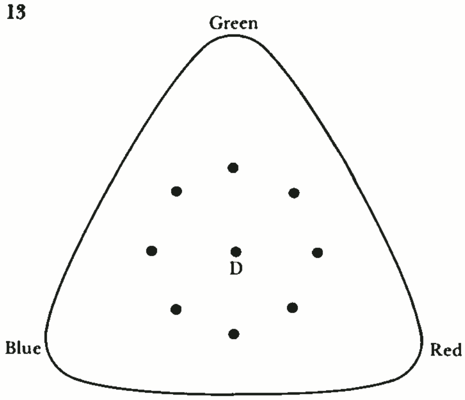

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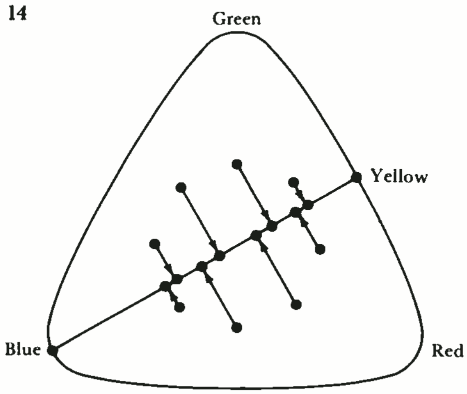

13—Color-rendering capability of a light is evaluated by the apparent colors of eight standard test objects as illuminated by that light. Here, the objects are illuminated by the real average daylight of Fig. 1; their perceived colors are spaced roughly equally around the circle of hues.

14—Under the two-component white light of Fig. 5, the perceived colors of the test objects are shifted to the line connecting the blue and yellow emissions of which that light is composed. Color-rendering index (CRI) of a light source is a measure of the average vector distance between the apparent colors of the eight test objects under the test illuminant and their apparent colors under a reference illuminant.

render colors adequately. These results show that substantially the reverse is true —that a discontinuous SPD composed of three spectral colors near 450, 540, and 610 nm is the ideal case, where luminosity and CRI are of roughly equal importance, and that it exceeds the performance of most commercial lamps.

The lamp and lighting industry tends to believe that commercial lamp colors must, for customer acceptance, lie on or near the black-body line near which daylight and incandescence colors lie. The same three approximate wavelengths lead to best performance in white light of chromaticity in this region, or anywhere in the central region of color space.

Some qualifying statements can be made to round out the picture. For example, the choice of the three wavelengths varies slightly with the relative importance of CRI and luminosity; it also varies slightly depending on the color of white light desired, e.g., blue sky, average daylight, sunlight, or a warmer white. Choice of any of these as the reference illuminant to calculate CRI does not appreciably affect the results. Broadening and shifting the three components somewhat can be tolerated, if necessary for practical reasons, but generally results in somewhat poorer performance. For example, phosphors for use in fluorescent lamps do not emit single spectral colors, nor is their emission usually positioned in wavelength precisely where desired.

The three lobes of Fig. 15 are a measure of the effectiveness of spectral colors of wavelength λ in a white-light mixture. They have been used separately as criteria for the effectiveness of blue, green, or red components of light to be combined later by some means into white light. For example, the red lobe has been used to evaluate the emission of 40 red-emitting phosphors for possible use in fluorescent lamps. There is excellent correlation between the "redness" of the phosphor SPDs, evaluated as in equation (1) but using the function from Fig. 15 instead of the $\bar{y}$ function, and the actual performance of the red phosphor blended with blue and green emitters in a white-emitting blend. The performance of blue and green phosphors is successfully evaluated in the same way.

The performance of white light can be plotted on a graph of luminosity versus CRI (Fig. 16). Performance of commercial fluorescent lamps of colors Cool White (CW) and Warm White (WW) is as shown; the performance of present mercury-vapor, high-pressure-sodium, and metal-halide lamps is poorer and is off the diagram to the right. Also shown (XCW and XWW) is the considerably better performance of light of Cool White and Warm White color composed of the proper proportions of the three spectral colors 450, 540, and 610 nm.

The goal for performance improvement with the new three-component approach is roughly 25 percent beyond present fluorescent lamp performance in luminosity, CRI, or a combination of both as in Fig. 16. By way of contrast, in the past 10 years industry-wide progress in performance along conventional avenues has averaged less than one percent per year at an annual expenditure, on the present lamp and phosphor, in the order of a million dollars.

For high-intensity-discharge lamps, such as vapor lamps, the potential improvement in performance over, for example, the present Deluxe White lamp is about 40 percent. The first step is the new Westinghouse Beauty Lite, a lamp in which blue emission near 450 nm has been added to the SPD of the Deluxe White vapor lamp. The addition makes a striking improvement in general color-rendering capability, and particularly in rendition of flesh tones, so it has served to bring the lamp indoors—into department stores, supermarkets, and other places where the appearance of people and produce comes under close scrutiny and must be pleasant and accurate.

The fluorescent lamp is especially adaptable to the needed shaping of its spectral power distribution because the blue-, green-, and red-emitting phosphors can be optimized individually and then blended to give the desired composition of white light. The components can be evaluated by functions similar to those of Fig. 15.

The basic color-matching functions,

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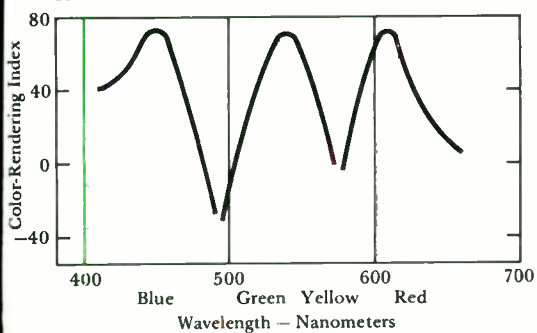

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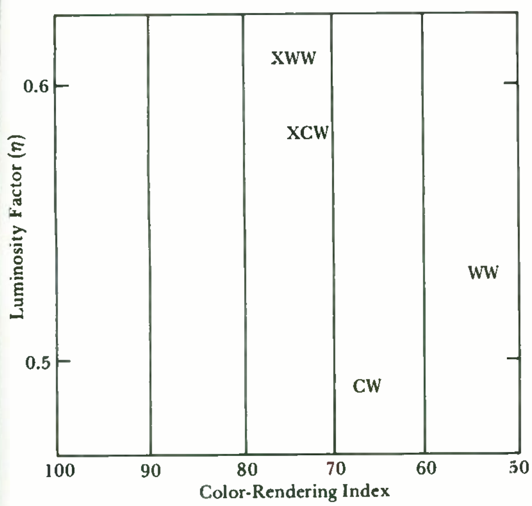

15—CRI of three-component white light varies as one component at a time is varied in wavelength in the neighborhood of its peak while the other two remain fixed at their peak values. Such experimental varying identified the wavelengths that produce the highest color-rendering capability when mixed.

16—Performance of white light can be indicated by plotting luminosity versus CRI. (The CRI scale starts at 100 and decreases in value to the right, so the direction of increasing performance is toward the upper left.) The performance of light of Warm White and Cool White colors (XWW and XCW respectively) composed of the three spectral colors of Fig. 10 is much better than that of light from standard Warm White and Cool White fluorescent lamps (WW and CW).

upon which world-wide colorimetry is based, represent normal human color vision. Their form depends on arbitrary choice of three fictitious primaries, which are chosen only for the purpose of controlling the form so that one of the functions becomes identical to the luminosity function of Fig. 2. If the color-matching functions are transformed to a different set of fictitious primaries, which may be done without altering their validity and applicability to colorimetry, they take on the form of the functions of Fig. 15. Hence those functions, and all our conclusions, are related to normal human color vision.

The three unique spectral colors—blue near 450 nm, green near 540 nm, orange-red near 610 nm—have the property of high visibility in a different sense from that described by the luminosity function of Fig. 2. Those three wavelengths, reflected from a colored object in proportion to its spectral reflectance, pull its apparent color most effectively toward its true value. As an illustration of what is meant by "pulling power," consider the SPD of any white light of a certain chromaticity *W*. To this SPD is added increments of power (say a watt), one at a time, at successive wavelengths through the visible spectrum. Chromaticity *W* is pulled farthest from its original position in color space when the power increments are added near 450, 540, or 610 nm.

Because the eye is particularly sensitive to those three wavelengths, it is a more efficient use of power to compose the illuminant from them and thus sample the reflectance spectrum of a colored object at those three wavelengths than it is to waste power in more insensitive regions of the spectrum. That such sampling is successful depends on the fact that the reflectance spectra of naturally colored objects are relatively broad and nonselective.

The effectiveness of these three colors is as stable as human color vision, so, in the next hundred years, one of two things should occur. Either the luminosity of white light will still be important and the spectral power distribution of all artificial light will have approached the optimum distribution of Fig. 10 asymptotically; or luminosity will no longer be important, because of greater availability of power and ease of distribution, and the composition of artificial light will have approached that of daylight with low luminosity and superb color rendition. Either way, for the immediate future there need be no doubt about research programs on the design of lamp emission: white light composed of three spectral colors near 450, 540, and 610 nm is the proper objective.

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Selecting Heat Rejection Systems for Future Steam-Electric Power Plants

R. J. Budenholzer
L. G. Hauser
K. A. Oleson

The combination of turbine, condenser, and heat sink should be tailored to fit the plant site. Careful evaluation of all the variables that will affect the heat rejection system selected, and detailed analysis of final equipment designs, can provide significant economic advantages over the life of the plant.

Many electric utilities are now confronted with the problem of how to properly dissipate unused heat from future electric generating steam power plants. The number of new installations of conventional once-through cooling water systems is decreasing because of the widespread adoption of federal and state water quality regulations. Some regulations make it virtually impossible to use natural lakes and rivers as heat sinks, so many utilities will have to use alternative methods to reject heat at future plant sites. Man-made cooling lakes, spray ponds, and wet (evaporative) cooling towers are presently the most desirable methods. Dry (nonevaporative) cooling towers are under consideration for application within the next ten years, primarily in areas where make-up water is unavailable for wet cooling towers.

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Cooling Systems, Turbine Exhaust Pressures, and Kilowatts

The function of any power plant cooling system is to reject the unused heat in the steam-condensing stage of the steam cycle. It is desirable to reject this heat at a low temperature, since the cooling system operating temperatures are closely related to the steam condensing temperature and turbine exhaust pressure, and a lower exhaust pressure means the turbine can produce more useful work. The factor that expresses the relationship between the steam condensing temperature and the temperature of the warm circulating water leaving the condenser is known as the condenser terminal temperature difference (TTD). This value is a measure of the heat transfer efficiency of the condenser.

A plot of the steam-condensing line as a function of temperature and pressure is shown in Fig. 1, with typical cooling system temperatures superimposed.

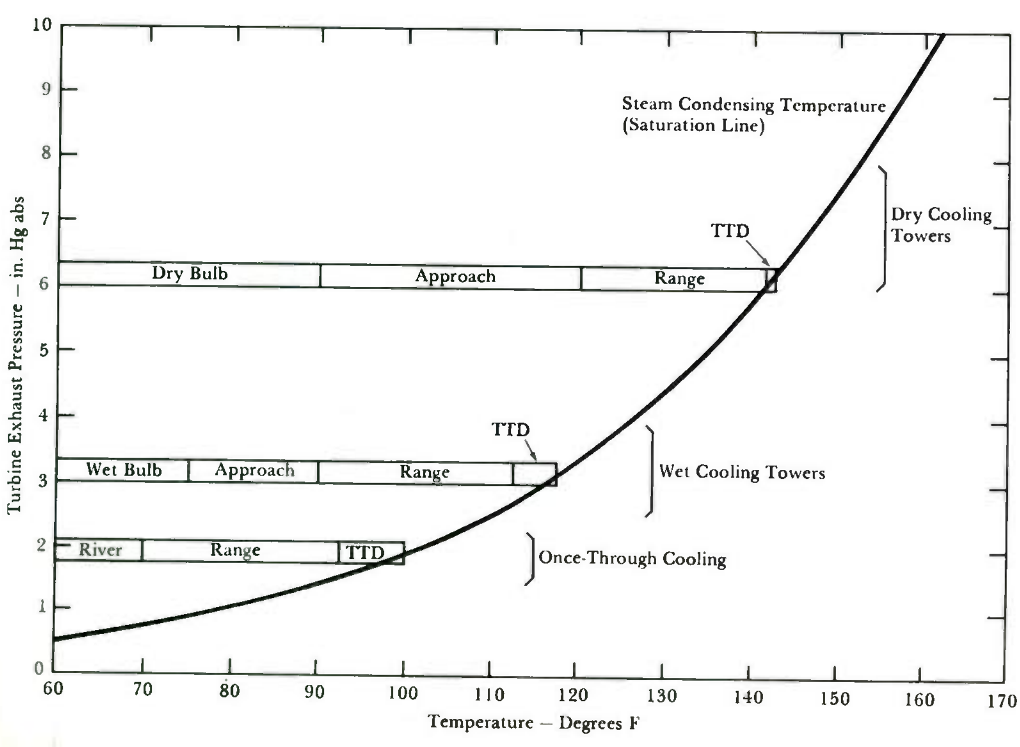
With once-through cooling systems, water is pumped from a natural body of water at temperatures normally below 75 degrees F, and warmed 15 to 25 degrees (the range) as it passes through the condenser. A typical TTD of 5 to 10 degrees F results in turbine exhaust pressures of 1.0 to 2.5 in. Hg abs.

A cooling-lake system resembles a once-through system, with the exception that it is a "closed system" and cooling water is recirculated. Since cooling lakes are much smaller than the once-through systems, rejection of a power plant's unused heat results in higher operating temperatures. Thus, turbine exhaust pressures are slightly higher, typically in the range of 2.0 to 3.5 in. Hg abs.

Wet cooling towers are also used in closed systems. In this design, most of the unused heat is transferred from the cooling water to ambient air by evaporation, so the limiting temperature for this cooling process is the ambient wet-bulb temperature. The "approach" measures how closely water is cooled to this temperature, with approach values of 14 to 22 degrees F most popular. Maximum wet bulb temperatures of 70 to 80 degrees F throughout the United States result in exhaust pressures of 2.5 to 4.5 in. Hg abs.

Interest has recently grown in the use of spray ponds for power plant applications. The spray nozzles may be placed in a small cooling lake or cooling canal to increase convective and evaporative heat transfer rates and thus allow a much smaller area to transfer a power plant's unused heat. Such a system has performance characteristics similar to those of wet cooling towers, rather than cooling lakes.

For economic reasons, the application of dry cooling systems has been very limited in the United States. With heat transfer dependent entirely on convection, the ambient dry bulb temperature



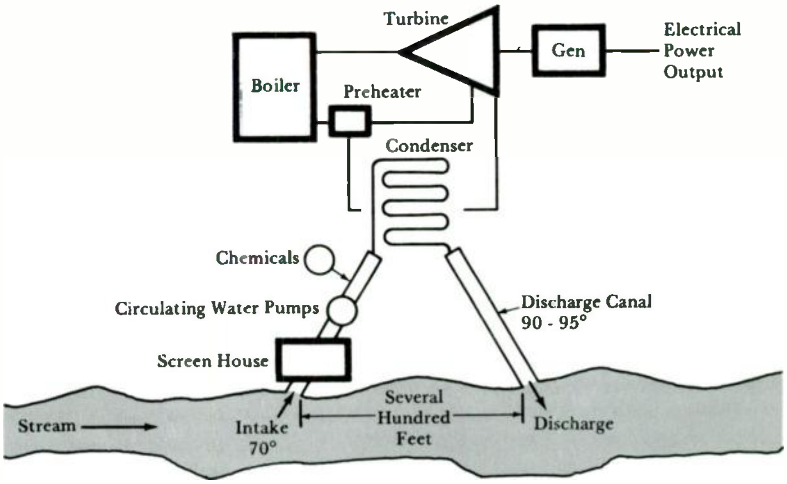
1—Cooling system temperatures determine turbine exhaust pressures along the steam condensing line. Ranges of exhaust pressures are indicated for basic types of cooling systems.

Once-Through Cooling Systems

Once-through cooling takes water from a lake or river at temperatures of about 70 degrees F, heats it 20 to 25 degrees F in the condenser, and discharges it at a point downstream from the plant.

Advantages: Normally the simplest and most economical method; minimum water consumption.

Disadvantages: Limited availability of large supplies of cooling water; may violate water quality standards.

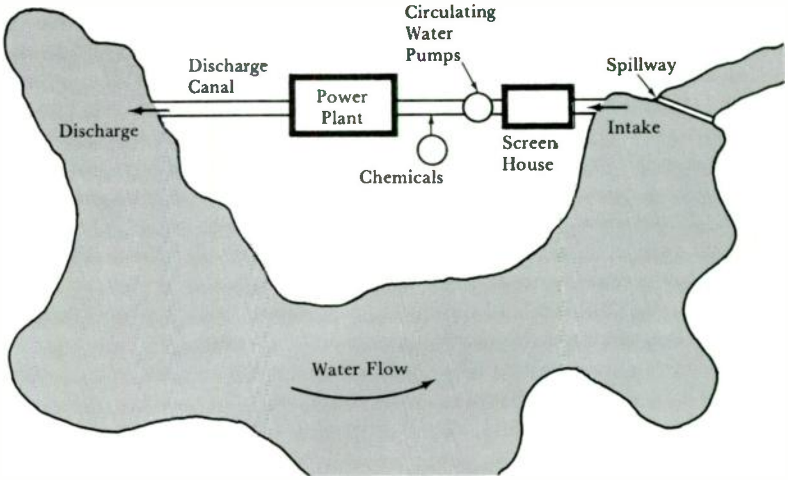


Cooling-Lake Systems

Cooling-lake systems resemble once-through systems except that cooling water is recirculated in the lake. However, if lake size is in excess of 2 acres/MW of nameplate rating for a fossil plant (3 acres/MW for nuclear), surface water temperatures will closely approximate those of once-through systems.

Advantages: Construction costs are reasonable where soil conditions permit; provides a settling basin; can operate for extended periods without makeup water; may be beneficial for other purposes such as recreation; evaporative losses may be compensated by collection of rainfall and runoff.

Disadvantages: Requires large land area; requires soil basin of low permeability; may cause fogging and icing in the area; concentrates dissolved solids in the lake, which will require proper blowdown disposal.

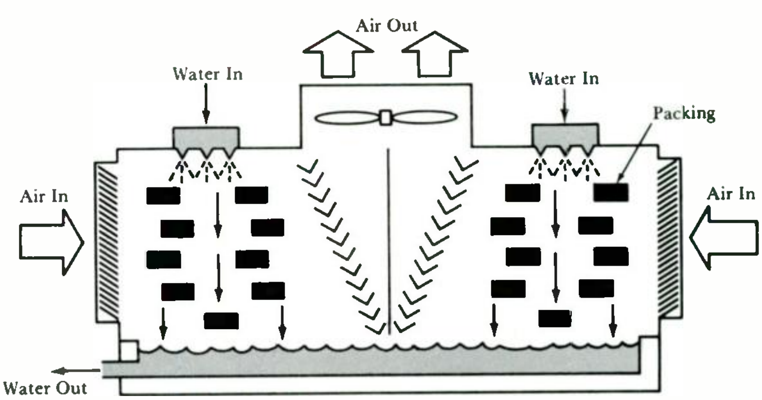


Mechanical-Draft Wet Towers

Mechanical-draft wet cooling towers have fans to move cooling air past water as it descends through the tower. The cross-flow arrangement shown is most widely used in the electric utility industry, with air drawn horizontally across the packing, which breaks water into small droplets for increased heat transfer. Air is moved by induced-draft axial-flow fans. Drift eliminators are placed beyond the packing to separate water droplets from the main air stream.

Advantages: Positive control over air supply; close control of cold-water temperature; generally low pumping head; ambient relative humidity has a minimal effect on tower performance; lower capital cost than a natural-draft tower.

Disadvantages: Subject to mechanical failure; subject to recirculation of the humid exhaust air; operation and maintenance costs high; high evaporative losses; exhaust air may cause localized icing and fogging; blowdown disposal problem; possible troublesome mixing of vapor with stack gases from fossil plants.



Induced-Draft Cross-Flow Tower

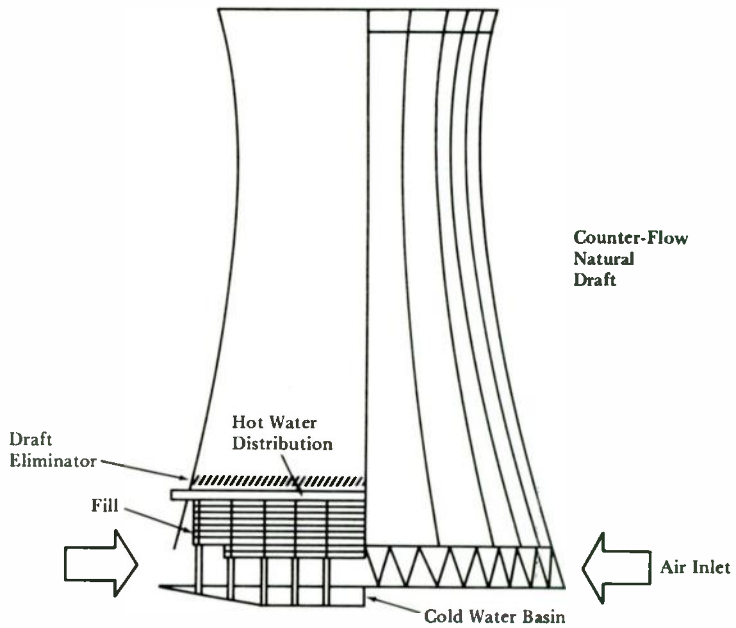
Natural-Draft Wet Towers

Natural-draft cooling towers use tower height to produce a "chimney effect" to move air.

Natural-draft towers now in service or on order range in size from 250 to 400 feet in diameter, with heights from 325 to nearly 500 feet. Both cross-flow and counter-flow (shown) designs are popular; the cross-flow design has a lower air pressure drop, but more efficient heat transfer is obtainable with the counter-flow design. Natural-draft towers are most efficient in areas where the ambient relative humidity is high, such as the northeastern United States.

Advantages: No mechanical or electrical components; low maintenance costs; excellent availability; large water loading capacity; comparatively small ground area requirements; high-level plume discharge reduces local icing problems.

Disadvantages: Internal resistance to air flow must be kept minimal; great tower height necessary to produce draft; exact control of outlet water temperature difficult; higher capital cost than mechanical draft towers; towers may be aesthetically undesirable in some areas; high evaporative losses; blowdown disposal problem; possible troublesome mixing of vapor with stack gases from fossil plants.

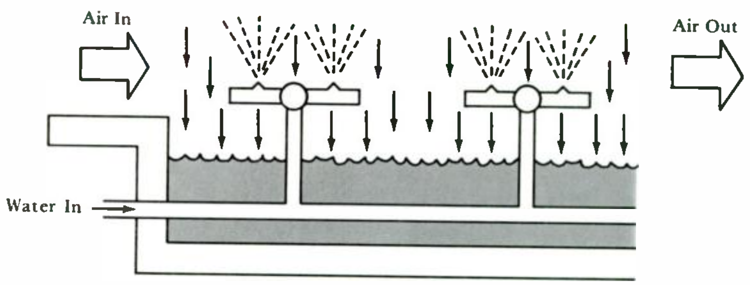


Spray-Pond Cooling

Spray ponds have performance characteristics very similar to cooling towers. Heat is rejected by direct contact of ambient air with warm discharge water from the condenser. The spray nozzles atomize the droplets into fine sprays, thereby increasing the heat transfer area per unit volume of spray so that heat-transfer packing material and fans are not needed.

Advantage: Reduces required land area compared to cooling lakes.

Disadvantages: Increased water losses due to drift; performance strongly dependent upon wind speed and direction; may cause localized icing and fogging.

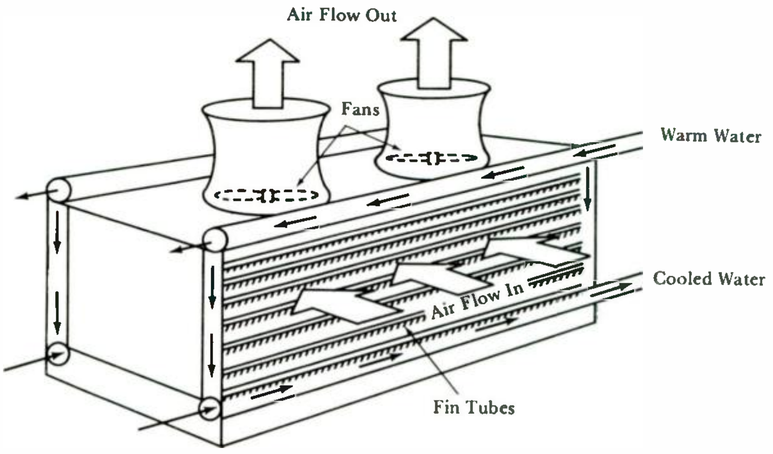


Dry Cooling Towers

Dry cooling towers operate on the same principle as an automobile radiator; cooling water never comes in direct contact with air, and all heat is rejected through finned tube exchangers. Another type of dry cooling system, known as an air-cooled condenser, condenses steam directly inside the finned tubes. The flow of cooling air, in either dry cooling design, can be promoted by fans (induced-draft design shown) or by a natural-draft stack.

Advantages: Avoids problems of fogging, mist, and icing; eliminates water problems such as availability, evaporative losses, blowdown, and thermal pollution.

Disadvantages: High capital costs; high maintenance costs; must circulate large volumes of air; larger land area requirement than wet towers; conventional low turbine exhaust pressures are not economically achievable.



is the lowest temperature to which the water could be cooled, and exhaust pressures in excess of 6 to 8 in. Hg abs would be common. The consequent loss of turbine capability at these high pressures is one reason that makes dry cooling uneconomical, but future applications may be necessary in some areas due to unavailability of cooling water, such as at mine-mouth generating stations in desert regions.

The power plant designer has this variety of cooling methods available to him, and an infinite number of possible equipment designs for any one of these methods. In addition, he must choose a turbine low-pressure-end size that is most economically matched to the year-round fluctuations in load requirements and exhaust pressures that the turbine will encounter. It is apparent that the turbine, condenser, and cooling system are all intimately related in determining both the performance and the cost of a generating unit. Optimum equipment selection must focus on the turbine, condenser, and cooling system as a whole, operating in the realistic economic environment of the electric utility system. Only such an integrated system optimization can result in true economy of operation over the life of the generating unit.

Environment Influences Choice of Method

In recent years, the environmental effects of the various heat rejection methods have become an important consideration in the design of cooling systems as well as the choice of new plant sites. Each of the methods has its unique advantages and disadvantages, some of which are referred to in the accompanying figures.

Recently, there has been a growing concern for the amount of water being consumed in the heat rejection process. Calculations of evaporative losses (termed *water rates*[1]) are based on the amount of water evaporated per net kilowatt-hour of plant output. Some areas have costs on the consumptive use of water, as well as costs for non-evaporative water usage. Such a situation puts the water rates of the various cooling methods into the scope of economics and possible optimization. Water availability and cost will continue to grow in importance in the selection of future plant sites and cooling methods.

Aside from environmental concern, several physical limitations can influence the choice of cooling systems for a given plant site. High soil permeability might result in excess seepage from cooling lakes or spray ponds. Although this problem can be remedied by lining the lake or pond with clay or plastic, the cost could be excessive. The large size and weight of a natural-draft cooling tower requires firm foundation soil, or the added cost of pilings or other foundation supports may be prohibitive. Also, these towers are not suitable for use in areas of low relative humidity because this hampers the natural draft effect.

Economic Comparison for Alternate Methods of Cooling

A generalized economic comparison of different methods of rejecting waste heat for a 1000-MWe nuclear plant is shown in Table I[2]. The additional generation costs incurred for cooling ponds and wet and dry cooling towers result from higher capital costs, increased fuel requirements, replacement of capability lost due to higher turbine exhaust pressures, and increased auxiliary loads. The correlation of transmission tradeoffs shown in Table I indicates that a 1000-MWe nuclear plant employing once-through fresh water cooling could be located up to 320 miles from the load center and still be economically competitive with a dry-cooled plant of the same size located directly at the load center. Similarly, the transmission trade-offs, over once-through cooling, for cooling ponds and wet cooling towers are 35 miles and 80 miles, respectively.

It should be noted that this analysis is general in nature and cannot be considered accurate enough for actual system planning, although it does indicate relative magnitudes of cost differentials for nuclear plants in average situations. Specific site parameters could cause the results to vary significantly.

Preparing for Optimization Studies

Before a specific turbine cooling system optimization study can begin, an extensive list of variables must be examined. In identifying these variables, it is convenient to group them into six categories: economics, site data, turbines, condensers, heat-rejection systems, and water distribution systems. An extensive list of design variables under these categories, typical of those required for an optimization study, is shown in the accompanying insert, *Input Data for a Cooling System Optimization Study*. It is apparent that the quantity of input data should be clearly specified and accurately compiled. The important point to recognize is that the cooling system is the prime interface between a plant designed by man and the site parameters provided by nature. Since a standard cooling system design cannot accommodate all the environmental variables, each plant and site should have an optimized cooling system design.

Table I—Evaluated Cost Additions and Equivalent Transmission Distances for a 1000-MWe Nuclear Plant

	Total Cost Additions (mills/kWh)	*Equivalent Transmission Distance (miles)*
Fresh Water	Base	Base
Cooling Ponds	0.0871	35
Sea Coast	0.0336	15
Wet Cooling Towers	0.2097/0.1986	80
Dry Cooling Towers	0.8168	320

Ground Rules for Cooling System Evaluation

There are several methods in use today for the evaluation of cooling systems. Differences occur not only in the detail to which performance and costs are calculated, but also in the interpretation of how performance affects the overall economy of a generating unit operating in a complex electric utility system. The method of evaluation which the authors have chosen is to establish a "firm power rating" that must be achievable at all times, regardless of ambient weather conditions. The exact value of this rating is in a sense arbitrary, but it is chosen such that all generating unit designs require supplements of capability and energy to achieve the "firm power rating" and produce power under a realistic loading schedule over the life of the unit. Capability and energy penalties are then assessed to reflect the true cost of meeting these supplementary capability and energy requirements, by the addition and use of alternate generating capacity.

A common fault in evaluating capability penalties is to assess capability losses at the cooling system *design temperature*, rather than the *historic maximum temperature*. The reasoning behind this typically relies on the utility's reserve margin to supplement unit capability under less favorable generating conditions. In many cases, design conditions are based on temperatures that on the average are not exceeded for more than five percent of the hours during the summer months. This five-percent figure represents a total of 146 hours. As the ambient temperature increases beyond the design point, turbine exhaust pressure will increase with cooling system temperature and generating capability will be reduced.

For system planning purposes, unit ratings and capability penalties should be assessed for each cooling system design under the least favorable ambient conditions, especially since these conditions would be expected to coincide with the maximum system demand. In this way, the reduction of capability which is likely to occur coincidentally among many generating units (even gas turbines) on hot days is accounted for by unit ratings. The reserve margin is then left to account for the statistical probability of unit outages whose occurrences are either random or scheduled.

Whether this practice is accepted or not, the underlying factor is that capability deficiencies must be paid for either by more conservative unit ratings or higher reserve margins.

Evaluation of System Operating Costs

Of paramount importance in any turbine-cooling system optimization study is the careful consideration of local weather conditions, future loads and their durations, and future costs for fuel to operate the unit over its entire life. Since this part of an optimization study can be complex, it is usually treated in an over-simplified manner. In many cases, cooling system design and operating conditions are based on monthly or seasonally averaged weather conditions, and averaged load factors and fuel costs are used. This procedure may be satisfactory for small units, but for larger units requiring larger expenditures, a more detailed analysis is justified. Such an analysis is outlined below.

Climatalogical data may be obtained from the U.S. Weather Bureau for a city or airport close to the plant site. These data are recorded on magnetic tape and consist of hourly observations of wet- and dry-bulb temperatures, wind speeds and directions, cloud cover, precipitations, etc. for periods of over five years. These data are then processed to yield hourly average conditions and historical maximum values for each month of the year. For example, diurnal variations in average wet-bulb temperatures for the month of August at a location in the northeastern United States are shown in Fig. 2; historical maximum wet-bulb temperatures for the same site and period of time are also shown. Dry-bulb temperatures, wind speeds and directions, and other variable weather conditions can be plotted in a similar fashion.

The next step in utilizing these weather conditions is to correlate them with future anticipated loading on the turbine-generator unit. Since the unit will operate at different capacity and load factors

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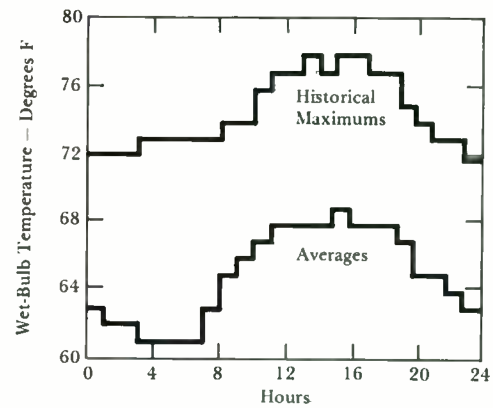

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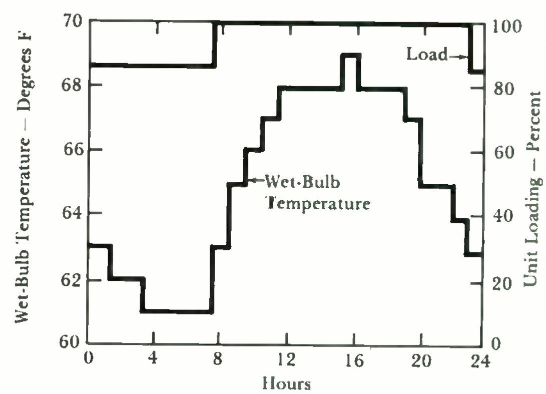

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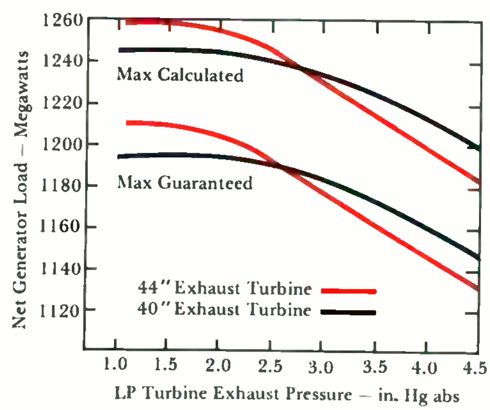


2—Wet-bulb average temperatures and historical maximum temperatures are shown for an average August day in a northeastern location in the United States.

3—Averaged daily wet-bulb temperature (Fig.2) is shown with typical unit loading.

4—The maximum calculated and guaranteed turbine-generator performance is a function of the low-pressure turbine exhaust pressure.

throughout its life, and since it is possible to forecast these factors with reasonable accuracy, the procedure for correlating the weather data and unit loading is not extremely difficult. Fig. 3 shows how this can be accomplished for one period of time, possibly the first 8 to 10 years of operation; in this example for the month of August, the anticipated loading of the unit is 100 percent between the hours of 7 a.m. and 11 p.m., and 86 percent for the remaining hours. Finer adjustments can be made with these temperature durations to account for different modes of operation, such as weekends, when the unit may be operated at a reduced rating during the daytime hours. Allowance can also be made for the actual periods when the unit will be shut down for scheduled maintenance.

Use of similar loading information for each month of the year and for each year of service allows an accurate accounting of coincident plant load requirements, turbine exhaust pressures, and cooling system auxiliary loads, which can be used to assess annual plant operating costs.

Cooling System Optimization Program

The increased use of cooling towers and other supplementary devices to reject waste heat will involve significantly higher capital costs for cooling equipment. The projected costs for fuel will also increase,[3] placing greater economic value on high generating cycle efficiency. (The price of coal is expected to double by 1980; in fact, the electric utility industry has already begun to experience sharply rising coal prices.[4]) The large expenditures that will be involved make the most exact calculating methods desirable. To satisfy this need, a computer program has been developed[5] to conduct a complete and accurate cost analysis for selecting (as a system) the most economic combination of turbine, condenser, and heat sink for specific site parameters.

In many cases, there is a choice of more than one turbine design. For example, two large nuclear-steam turbines that have similar performance characteristics are compared in Fig. 4. At approximately 2.5 in. Hg abs exhaust pressure, both turbines produce the same amount of

Input Data for a Cooling System Optimization Study

Group 1—Economics

1) Interest Rate
2) Fixed Charge Rate
3) Escalation Rate for Labor
4) Escalation Rate for Materials
5) In-Service Date
6) Construction Schedule
7) Forced-Outage Rate
8) Scheduled-Outage Rate
9) Service Life
10) Fuel Costs
11) Required Capability
12) Future Unit Operating Schedule—The desired generating schedule for the unit over its entire life.
13) Auxiliary Power, Less Circulating Water System
14) Capability Penalty
15) Replacement Energy Penalty
16) Water Costs

Group 2—Site Data

1) Historical Weather Data
2) Site Elevation (Longitude and Latitude)
3) Surrounding Land Environment
4) Soil Conditions
5) Air Contaminants
6) Labor Rates
7) Accessibility

Group 3—Turbines

1) Installed Prices
2) Heat Balances
3) Exhaust Losses
4) Exhaust Pressure Corrections to Load
5) Exhaust Pressure Corrections to Heat Rate
6) Steam Generator Efficiency vs. Load
7) Dimensions

Group 4—Condensers

1) Installed Prices
2) Space Limitations
3) Configurations
4) Exhaust Pressure at Varying Heat Load and Inlet Water Temperature
5) Pumping Head
6) Condensate Storage
7) Material Specifications
8) Tube Length Constraints
9) Tube Velocity Constraints

Group 5—Heat Rejection Systems

Cooling Lakes
1) Water Cost and Availability
2) Land Cost and Availability
3) Lake Development Cost
4) Legal Temperature Limits
5) Water Temperature for Varying Heat Loads and Ambient Conditions
6) Water Consumption
7) Water Quality Requirements
8) Maintenance Costs

Spray Ponds
1) Water Cost and Availability
2) Land Cost and Availability
3) Pond Development Cost
4) Installed Spray System Prices
5) Water Temperature for Varying Heat Loads and Ambient Conditions
6) Pumping Head
7) Water Consumption
8) Water Quality Requirements
9) Replacement Component Prices
10) Maintenance Costs

Wet (Evaporative) Cooling Towers
1) Water Cost and Availability
2) Installed Cooling Tower Prices
3) Cooling System Layout
4) Water Temperature for Varying Heat Loads and Ambient Conditions
5) Pumping Head
6) Fan Power
7) Water Consumption
8) Water Quality Requirements
9) Replacement Component Prices
10) Maintenance Costs

Dry (Nonevaporative) Cooling Towers
1) Installed Cooling Tower Prices
2) Cooling System Layout
3) Water Temperatures for Varying Heat Loads and Ambient Conditions
4) Pumping Head
5) Fan Power
6) Replacement Component Prices
7) Maintenance Costs
8) Installed Drain System Prices

Group 6—Water Distribution Systems

1) Installed Pipe Prices
2) Installed Pump Prices
3) Installed Valve Prices
4) Installed Pumphouse Price
5) Installed Water Treatment Facility Price
6) Water Treatment Costs
7) Make-Up and Blowdown Water Facility Installed Prices
8) Pump Head

power; however, the turbine with 44-inch last-row blades produces more power than the 40-inch design at lower exhaust pressures, and less power at higher exhaust pressures. When cooling towers are used, turbine exhaust pressures range from 1.8 to possibly 5.5 in. Hg, depending upon the choice of tower design. In this case, there is no obvious conclusion as to which turbine design is the better economic choice, so other factors must be considered. These factors include capital costs for the turbine and cooling system, penalties for fan and pump power, make-up water costs, fuel costs, cost of money, taxes, depreciation, and other pertinent factors.

Since expenditures take place over different periods of time, and since money has time value, the best and most accurate method for comparing alternatives is by present-worth evaluation. If the current published price lists for equipment are used in selecting equipment that will be purchased three or four years later, an escalation factor must be applied to make equipment costs more realistic. Also, after the equipment has been purchased, it takes time to install the various components. During this time, an additional cost is incurred because the investment is not yielding a return. The factor for this cost is known as *interest during construction*. Once the plant becomes operational, the fixed charge rate can be applied to give an annual expenditure for the entire life of the equipment. These costs can then be multiplied by appropriate present-worth factors so that all costs can be evaluated at the same point in time for comparative purposes.

Each year during the life of the plant, there may be different or variable operating costs, such as fuel costs, capability penalties, auxiliary power, maintenance, and so on. By multiplying these various costs by their respective present-worth factors, an equivalent amount can be obtained that is comparable with the capital expenditures. Thus, the total evaluated cost for any combination of equipment becomes the sum of present-worth revenue requirements for both capital and operating costs.

Infinite choices in possible and feasible equipment designs exist for each cooling method, or combination of methods; however, it is both impractical and unnecessary to evaluate all possible combinations. For example, the choice in cooling equipment designs for any large power plant requiring cooling towers could be approached by considering the design parameters listed in Table II. This array of 198,000 combinations would provide sufficient data to make a preliminary economic evaluation of all possible combinations. However, numerical methods are available which allow an automated search of the infinite variety of cooling system designs to select that which is economically optimum. Such an automated pattern search technique has been incorporated in the turbine, condenser, and cooling system optimization program, and it has been highly successful in determining an optimum design without an unreasonable number of system design evaluations.

Typical Results of Optimization Studies

The differences in evaluated costs for single-pressure and multiple-pressure condensers used in conjunction with mechanical-draft cooling towers for a large two-unit nuclear power plant are shown in Figs. 5a and 5b. Among the feasible cooling systems with single-pressure condensers (Fig. 5a), there is a range of almost $27 million in evaluated costs, with the 40-inch turbine and the 22-degree-F-approach, 27-degree-range cooling tower being the most economic combination; similarly, there is a $14-million evaluated cost range with the multiple-pressure condenser (Fig. 5b). In both cases, the evaluated costs between alternate turbine designs are nearly $6 million.

Since the multiple-pressure condenser with the 40-inch turbine (Fig. 5b) is almost $1 million lower in evaluated costs than any combination for the single-pressure condenser, further refinement for the multiple-pressure condenser and the 40-inch turbine is indicated. That combination is the apparent optimum.

The final result—the optimum design based on minimum present worth of future revenue requirements—is shown in Fig. 5c. This design calls for 21 degrees approach and 35 degrees cooling range.

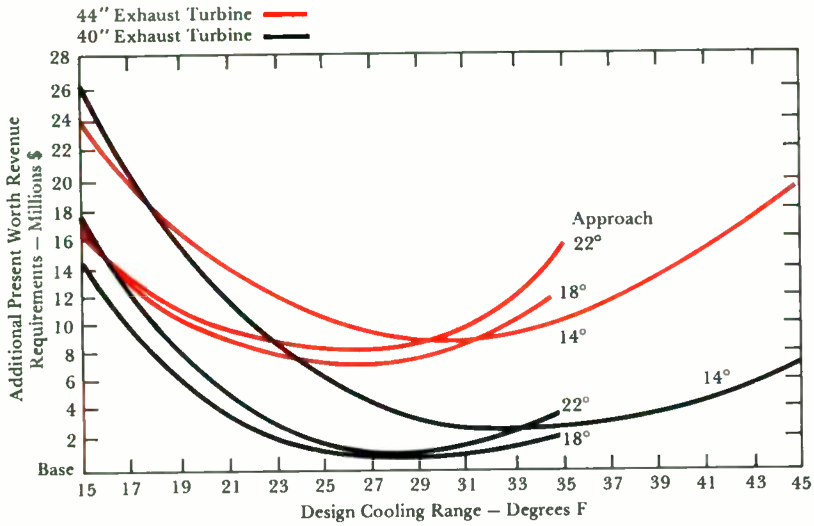
*Table II—Possible Condenser and Cooling Tower Designs for a Tandem Compound Six-Flow Turbine**

Single-Pressure Condenser Designs	*Cooling-Tower Designs*
5 Tube Diameters 6 Tube Velocities 5 Tube Lengths 2 Number of Passes	6 Approaches 5 Cooling Ranges 2 Natural- and Mechanical-Draft Towers
(300 designs)	(60 designs)
Multiple-Pressure Condenser Designs	*Cooling-Tower Designs*
5 Tube Diameters 6 Tube Velocities 125 Tube Lengths 1 Pass	6 Approaches 4 Cooling Ranges 2 Natural- and Mechanical-Draft Towers
(3750 designs)	(48 designs)

*A Total of 198,000 Possible Combinations of Condenser and Cooling Tower Designs for a Single Turbine Design.

5—The additional present-worth revenue requirements are shown for: (*a*) optimized single-pressure condensers with both 44- and 40-inch-exhaust-end turbines over cooling-tower approach temperatures of 14 to 22 degrees F; (*b*) optimized multiple-pressure condensers with 44- and 40-inch-exhaust-end turbines over approach temperatures of 14 to 22 degrees F; and (*c*) final optimization of multiple-pressure condenser with 40-inch-exhaust-end turbine.

5a



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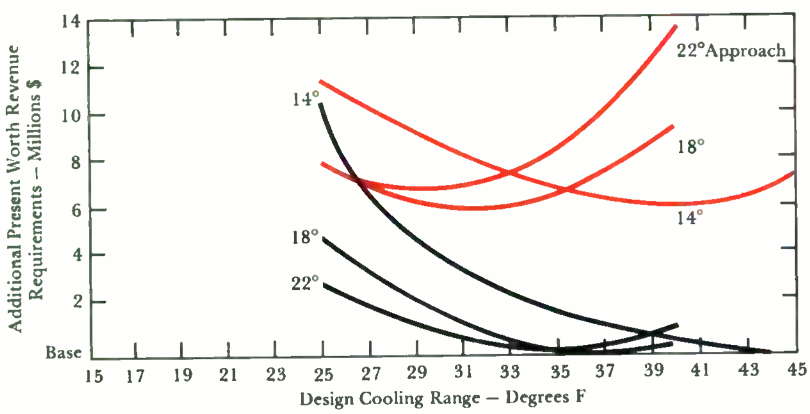

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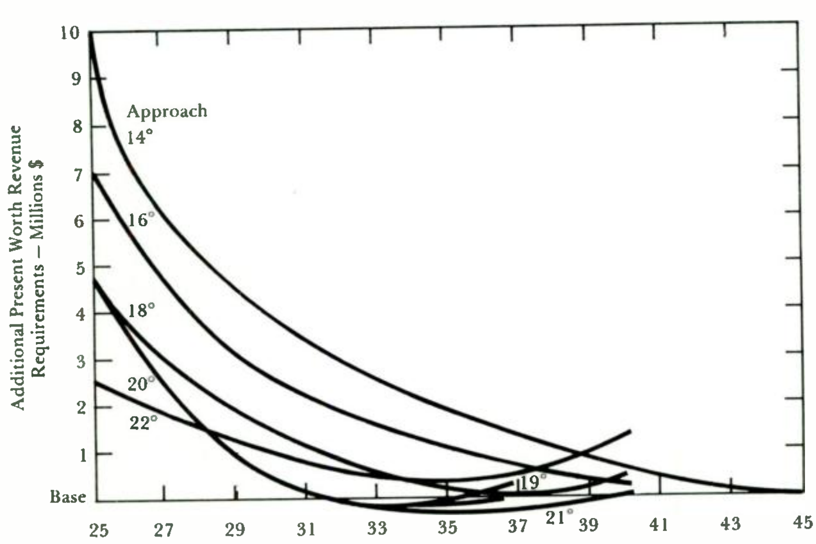

The magnitude of the evaluated cost differences shown in Fig. 5 certainly emphasizes the importance of detailed analyses.

Conclusions

The recent widespread adoption of federal and state water quality regulations will result in an increased use of methods other than conventional once-through cooling to reject unused heat at future plant sites. Since these methods will be costly, the various alternatives should be carefully evaluated for each application. Although simplified methods for evaluating cooling system design specifications could be used, only a detailed evaluation considering both capital and operating costs can insure real savings over the entire plant life. The apparent capital cost savings of many feasible combinations may be more than offset by other costs when all the important factors are evaluated.

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A New Study Technique Helps Improve Elevator Service

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The performance of a proposed elevator installation in terms of passenger service can be estimated by simulation. A mathematical model generates passenger traffic while other computer programs describe the building, elevator configuration, and system operation.

An important item in the planning of any successful passenger transportation system is a valid evaluation of performance. In an elevator system, one measure of performance is vehicle operation, such as the ability of the motion controlling mechanism to provide the passengers a smooth comfortable ride. Another is passenger service, most directly found by measuring the waiting times. (Waiting time is the time it takes an elevator to answer a call initiated by someone pressing a call button.)

A simulation technique to determine what elevator configuration will provide the best passenger service for a given building has been developed by the Westinghouse Research Laboratories. The simulation involves a mathematical model that generates passenger traffic and computer programs that describe the building, elevator scheme, and system operation.

Elevator Service

Waiting times vary widely, depending on the type of installation and the time of day sampled (Fig. 1). The figure also shows that there are random fluctuations in waiting time from a slowly varying average.

Randomness of passenger demands, which causes random waiting times, has a natural tendency to degrade service, a tendency that can be explained by the following simplified example. Suppose passengers arrive at the rate of one every second to use a 20-passenger elevator that arrives empty at the rate of once every 20 seconds. If these rates are maintained with perfect regularity, each arriving car picks up all waiting passengers. However, if the arrival times are staggered by some random increments, even though the average rate remains fixed, some cars depart only partly filled, others completely filled, and some passengers have to wait for (at least) a second car. Thus, the measured service has deteriorated.

The responsibility of providing good service despite demand variability is that of the elevator's supervisory system. Its logic monitors all incoming calls, determines the locations of the cars, and then assigns cars to calls and calls to cars. Some logic systems, such as that used in Westinghouse Mark IV elevators, can even recognize shifts in average demand and alter their strategy accordingly to improve efficiency. However, since demands are generally unpredictable, no supervisory system can always provide optimal service. The problem is alleviated, though, by classifying demand configurations into particular categories and providing the logic with specific instructions for each. Therefore, service is best evaluated by separately studying each demand category.

Waiting times during a typical day in a high-rise office building are usually distributed as in Fig. 1, which shows peaks at starting, noon, and quitting times. Of the three periods, the morning "up peak" is the most easily analyzed because certain simplifying assumptions can be made that convert the activity from a random process to one that can be analyzed deterministically. The major assumption is that all traffic originates from the main floor of the building and all cars leave with a known equal load. Mathematical models are then used to compute the expected number of stops and the expected highest floor reached for each car as a function of its capacity and the number of floors served. The average round trip time for each car is also computed and used to determine the "interval," which is the average time between successive arrivals of cars at the main floor. Another quantity called the system's "capacity" is computed; it is the rate at which passengers are distributed within the building. A system is considered satisfactory if the interval is respectably small while the capacity is comfortably large.

The down-peak period is the opposite of the up peak and requires a different strategy. For instance, the down peak finds cars loading at a variety of floors and having a common destination at the main floor. Some cars automatically return to the top of the building for reloading while others, if guided by the Mark IV type of strategy, begin reloading at intermediate floors. Cars that have become loaded at upper floors bypass further calls and take their passengers directly to the main floor. Thus, there is much more car-to-car variability than in the morning up-peak period. In addition, the up-peak service is rather insensitive to supervisory strategy, while the down-peak service depends critically on the details of that strategy.

The noon period presents the severest test of all to an elevator supervisory system because, although traffic intensity is generally less than at starting or quitting times, the travel is simultaneously heavy in both directions.

Between the three peak demand periods are midmorning and midafternoon off peaks. Those are times when traffic demands are fewest but interfloor travel can be greatest, as with secretaries transferring papers between various floors. The periods are called *balanced* off peaks because the number of persons entering the building about equals the number leaving.

While the up-peak period can be adequately studied with deterministic models, the noon-, down-, and balanced off-peak periods all have such complex traffic

1—Waiting time (the time it takes for an elevator to answer a call) for a typical office building is greatest when elevator demands are greatest: at starting, noon, and quitting times. Other characteristic demand periods are the "off peaks" that occur during midmorning and midafternoon. The service provided by a proposed elevator system is determined by simulating the system and studying the average waiting times of each demand period.

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patterns that the only currently available tool for analyzing service during those times is computer simulation.

Simulation not only provides a convenient method for studying complex random processes, but it permits some studies that would not be possible even on a real elevator system. For example, it is possible to study the effect of varying only the intensity of arriving traffic without disturbing the origin-destination mix. Or the passenger list can remain fixed while variations in the logic or installation are studied. While changes in logic and installation could be implemented on a real elevator system, simulation allows experimentation without the expensive hardware, considerable time, and user inconvenience that otherwise would be required.

Simulation Package

Three computer programs in sequence describe the operation and estimate service of a proposed elevator installation for a 10- to 15-minute interval of any demand period. The programs are the passenger generator, the elevator system processor, and the statistical summary program.

The passenger generator is basically a mathematical model that produces a stream of passenger traffic to simulate the random demands placed on a real elevator system. The model is general in that it can generate traffic for any demand period of the day for a wide variety of buildings. For example, it can generate morning up-peak traffic in an insurance company's home office as easily as evening down-peak traffic in a multi-occupant office building. The passenger list produced by the model includes an identification number for each passenger, the time that he pushed a call button, his floor of origin, and his floor of destination. The list also reflects the variability of times between demands and of the passengers' origins and destinations.

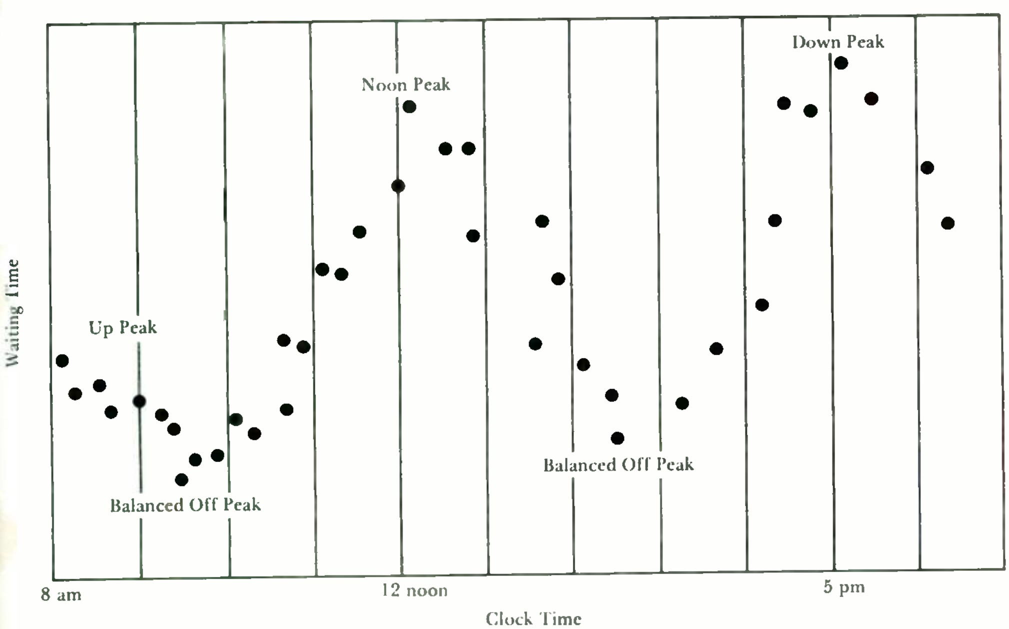
Input data for the passenger generator include: (a) each floor's population, (b) number of major tenants and their locations, (c) relative elevator use by each floor's occupants, (d) traffic intensity expressed as the percent of total building population that makes calls in a five-minute period, (e) percent of passengers with main-floor origin, (f) percent of passengers with main-floor destination, and (g) percent of interfloor traffic. Particular traffic patterns for the various demand periods of the day are created by selecting appropriate values for items (d) through (g). For example, characteristic morning up-peak traffic occurs at the rate of about 15 percent of the building's population in a 5-minute period with virtually 100 percent of all passengers originating on the main floor. During the off peak at midmorning, traffic is lighter (usually five percent or less) and is typically divided so that 40 percent of all passengers originate at the main floor, 40 percent have the main floor as destination, and 20 percent are interfloor travelers.

The elevator system processor simulates the action of elevators picking up and discharging the passengers provided by the generator program. An elevator installation in almost any type building can be represented with the system processor by adjustment of certain logic and physical parameters. The Mark IV control logic, which is the basis of the system processor program, has certain fixed strategy features. Other features, however, can be set to meet the requirements of a particular installation. They include the time doors are kept open while passengers are admitted and discharged; the number of cars that automatically return to the main floor to await passengers during an up-peak period; and a quantity, t, called the timed-out time. If an elevator call has remained unanswered after t seconds, it becomes "timed out" and is given a priority response. (When two or more timed-out calls are simultaneously in the system, the order of response is one of the things determined by the fixed logic.)

Adjustable physical parameters of the system processor include those that concern the elevator cars, such as their number, maximum speed, and passenger capacity. Others involve building features such as the number of floors served, the highest floor served, the number of floors served beneath the main floor, and the distance between successive floors.

The output of the system processor is a travel history for each passenger. It lists his floor of origin and destination, the time he placed a corridor call, the time his call was answered, the answering car, and the time he entered and departed the car.

The statistical summary program prepares a record of the elevator system's service during the simulation run (Fig. 2). Of



Waiting-Time Summary—Above Main Floor

Average Waiting Time: 11.3 Seconds
Maximum Waiting Time: 55.8 Seconds
Number of Calls: 116
Number of Passengers: 124

Time Period (seconds)	*Calls Answered*	*Percent of Calls Answered*	*Cumulative Percent of Calls Answered*
$0 \leq W \leq 5$	42	36.21	36.21
$5 \leq W \leq 10$	23	19.83	56.04
$10 \leq W \leq 15$	22	18.97	75.01
$15 \leq W \leq 20$	7	6.03	81.04
$20 \leq W \leq 30$	14	12.07	93.11
$30 \leq W \leq 40$	3	2.58	95.69
$40 \leq W \leq 50$	4	3.45	99.14
$50 \leq W \leq 60$	1	0.86	100.00
$60 \leq W \leq 70$	0	0.00	100.00
$70 \leq W \leq 80$	0	0.00	100.00
$80 \leq W \leq 90$	0	0.00	100.00
$90 \leq W$	0	0.00	100.00

Waiting-Time Summary—At Main Floor

Average Waiting Time: 14.0 Seconds
Maximum Waiting Time: 44.1 Seconds
Number of Calls: 37
Number of Passengers: 76

Time Period (seconds)	*Calls Answered*	*Percent of Calls Answered*	*Cumulative Percent of Calls Answered*
$0 \leq W \leq 5$	15	40.54	40.54
$5 \leq W \leq 10$	3	8.11	48.65
$10 \leq W \leq 15$	6	16.22	64.87
$15 \leq W \leq 20$	5	13.51	78.38
$20 \leq W \leq 30$	1	2.70	81.08
$30 \leq W \leq 40$	3	8.11	89.19
$40 \leq W \leq 50$	4	10.81	100.00
$50 \leq W \leq 60$	0	0.00	100.00
$60 \leq W \leq 70$	0	0.00	100.00
$70 \leq W \leq 80$	0	0.00	100.00
$80 \leq W \leq 90$	0	0.00	100.00
$90 \leq W$	0	0.00	100.00

2—The statistical summary program of the simulator determines passenger service in terms of the waiting time rendered by a particular elevator installation under given traffic conditions. The program determines the average and maximum waiting times at the main floor as well as at floors above main. In addition, the program records the number, percent, and cumulative percent of calls that were answered within each time period, *W*.

primary interest in the printout are the average and maximum waiting times above the main floor, and the number of calls that become timed out. The program also computes the calls that were answered within particular time intervals. From that data, the cumulative distribution of waiting times can be plotted, telling the probability of a call being answered within a given waiting time. In addition, the number of stops each car made during the simulation run can be determined.

While simulation data for the installation and logic are usually well defined, passenger traffic data are frequently incomplete and require the infusion of previous experience and careful judgement to produce the required simulator input. This incompleteness is especially apparent when studying installations for proposed rather than existing buildings. Much of the difficulty with inadequate traffic information, however, is relieved by performing "comparative" as opposed to "absolute" system studies.

The objective of an *absolute* study is an accurate estimate of service for a particular installation under specified logic-parameter settings. A valid service estimate depends critically on the passenger generator producing a passenger list that would be typical in the building being simulated. If the list does not properly reflect either the origin-destination mix or intensity, the resulting service estimate could be meaningless.

In a *comparative* study, the services rendered by two or more variations in logic or installation are compared—for example, a bank of six 3000-pound-capacity cars versus a bank of five 3500-pound cars. Passenger traffic data is not so critical in this type of study because even if the service estimates are in error due to unrealistic traffic data, the better configuration would most likely show the better service.

As described earlier, traffic intensity, as well as distribution of origins and destinations, varies widely for the different demand periods in a day. In addition, the average waiting time in any particular demand period varies from day to day, mostly due to minor variations of traffic intensity. Recent observations at Pitts-

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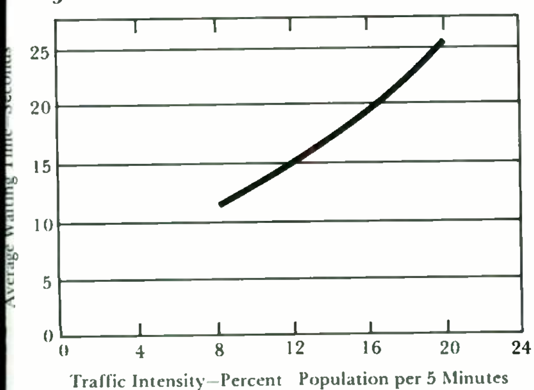

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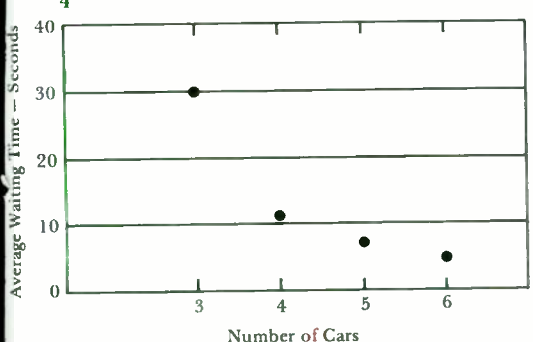

3—Simulation runs with several different traffic intensities were made for a typical elevator installation during the down-peak period. Traffic intensities of 15 percent are common in many office buildings.

4—The effect of one or more cars out of service on average waiting time was determined through several simulation runs during the balanced off-peak period. The simulation was run for a building normally served by a six-car bank.

burgh's Grant Building, for example, revealed an average waiting time of 11 seconds during a particular time interval on one day and 15 seconds during the same interval on the next day. Similarly, different simulation runs for the same configuration and demand period yield different average waiting times because of the variations in the stream of traffic produced by the passenger generator. Each simulation produces an average waiting time analogous to that observed on a single day. By averaging the results of several runs for each demand period, the accuracy of waiting-time estimates is improved.

Simulation Example

The balanced off-peak and down-peak periods were studied for a hypothetical 15-story multiple-occupant office building. The building has a population of 75 people per floor and an elevator system consisting of a bank of six 3000-pound cars operating at a maximum speed of 700 feet per minute. For the balanced period, traffic intensity was set at the typical rate of four percent of total population in a 5-minute period and distributed so that, on the average, 45 percent of the passengers originate at the main floor, 45 percent have the main floor as destination, and 10 percent are interfloor passengers. For those conditions, the simulation yielded an average waiting time of 6.0 seconds. When the traffic intensity was increased on subsequent simulation runs to eight and 12 percent, average waiting times increased to 13.4 and 22.9 seconds.

During the down-peak simulations, all traffic had the main floor as destination. The effect different traffic intensities had on average waiting time is illustrated in Fig. 3. As stated earlier, waiting time refers to the time it takes an elevator car to answer a call and not necessarily to an individual passenger's waiting time. While the waiting time generally increases as traffic becomes heavier, it does not increase without limit: after a call has been answered, anyone left behind because the car is too full has to place a new call, and he thereby starts a new waiting time.

Average waiting time in the down-peak simulation runs decreased slightly between 25 and 27 percent traffic intensity because, at 25 percent, not all cars were becoming full on the upper floors. At 27 percent they did become full and since fewer calls were then placed on upper floors, more cars were available to serve lower floors, which reduced the round trip time and thus the average waiting time. Above 27 percent, upper floor calls began increasing again, so the average waiting time resumed its increase.

Another study illustrates the sensitivity of average waiting time to the number of cars in service (Fig. 4). Balanced off-peak traffic conditions were used with four-percent traffic intensity. As an additional car was taken out of service on each successive simulation, the waiting times increased significantly, with the greatest increase occurring after three cars were removed.

Conclusions

Simulation has great potential as an economical means of designing elevator installations that can be counted on to provide first-class service. The Westinghouse elevator simulator is probably the most general of its type.

In addition to computer simulation of elevator systems, Westinghouse has done extensive simulation of production lines for products as diverse as distribution transformers and steam irons. Those two simulations were performed to optimize the output of new production facilities by determining the number of carrying devices and the number and location of waiting areas between work stations. In the nuclear reactor field, computer simulation has been used to estimate the reliability of various components in a complex reactor system.

A Demonstration Power Plant Design for the Liquid-Metal Fast Breeder Reactor

W. M. Jacobi

The Atomic Energy Commission has embarked upon a Fourth Round Program aimed at the development, design, construction, test operation, and power operation of a Liquid-Metal Fast Breeder Reactor Demonstration Power Plant (LMFBR). Westinghouse recently completed its part in the first phase of the program, the Project Definition Phase, the purpose of which was to perform any necessary design and analyses and develop further various aspects of the contemplated demonstration plant, including: (1) the magnitude of the technical and economic risks associated with the proposed plant design; (2) investigation of alternate sites to help insure meeting siting criteria, to minimize the financial and technical risks, and to help obtain regulatory approvals; (3) the supporting research and development, component development, and proof testing that will be required; (4) trade-off studies required for design decisions; (5) identification of codes and standards required for the design and construction phases; (6) site and safety analyses; and (7) technical coupling between the project and the on-going and planned development programs.*

The demonstration plant proposed by Westinghouse is the subject of this article.

*Work partially performed under AEC contract AT (30-1)-4200.

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Construction of the 300-MWe fast breeder demonstration plant designed in the Project Definition Phase of the LMFBR Program would permit accurate assessments of the various components and systems required for commercial breeder plants. The sodium coolant and the steam conditions in the demonstration plant design are the same as those deemed necessary for a commercial plant, the reactor core and internal structure are designed to accommodate modifications that could provide larger ratings, fuel-handling and other mechanical systems are similar to those projected for a commercial plant, and the plant components are large enough to minimize extrapolations required for an economic commercial plant.

The construction and operation of an LMFBR demonstration plant is a vital step to achieving the commercial breeder plants so necessary to the maintenance of economic electric power production in the years ahead.[1]

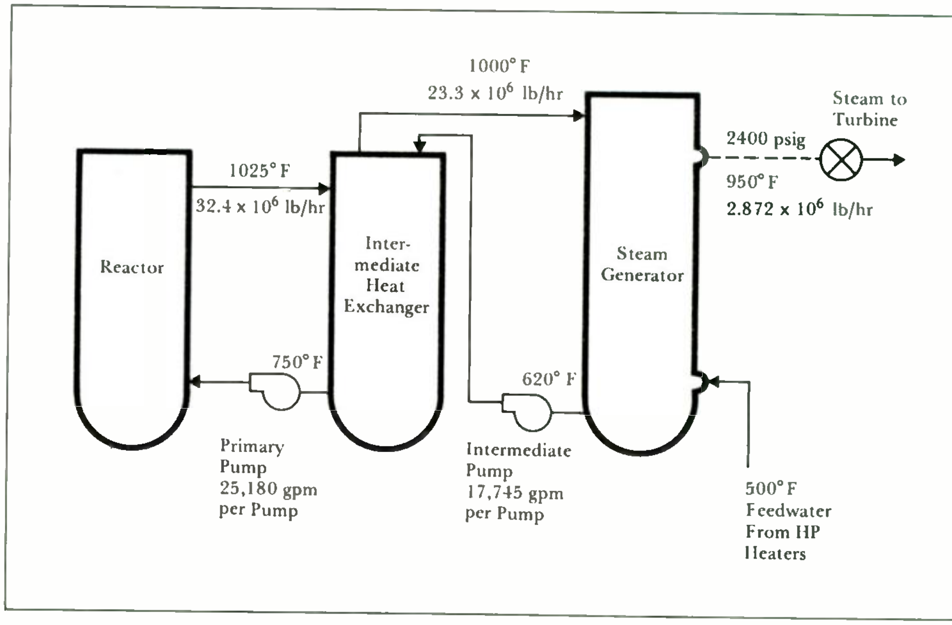
A Three-Loop System

In the proposed demonstration plant, three primary sodium loops transport heat from the reactor core to three intermediate heat exchangers and corresponding intermediate sodium loops. The simplified plant schematic shown in Fig. 1 depicts only one of the three identical loops but indicates flows for the total plant. Heat is transported from intermediate heat exchangers to once-through steam generators. The steam generators supply superheated steam to a three-casing, tandem-compound turbine. The regenerative steam cycle has five stages of feedwater heating and external moisture separation between the high- and low-pressure cylinders of the turbine. Heat rejected to the condenser is dissipated to the atmosphere with an induced-draft wet cooling tower.

At full power, primary sodium is pumped to the reactor vessel inlets at a temperature of 750 degrees F. It flows upward through the core and exits at a mean outlet temperature of 1025 degrees F. Sodium flows from the reactor vessel to the intermediate heat exchanger where it travels down the shell side and discharges to the cold-leg sump suction pump. Basic plant parameters are shown in Table I.

In the intermediate system, the cold-

[1]J. C. Rengel, "Only High-Gain Breeder Reactors Can Stabilize Uranium Fuel Requirements," *Westinghouse ENGINEER*, Jan. 1968, pp. 3-7.



1—Heat transfer system schematic shows total plant flow (pounds/hour) and the flow in each of the three identical loops (gallons/minute).

leg pump directs 620-degree sodium through the tube side of the intermediate heat exchanger and returns 1000-degree sodium to the shell sides of the steam generators. Pressure in the intermediate system is maintained above that in the primary system so that any sodium leakage would be from the nonradioactive intermediate system to the radioactive primary system.

Feedwater enters the once-through steam generators at 500 degrees F and is discharged as 2400-psig, 950-degrees F superheated steam. After passing through the turbine and moisture separators, steam is discharged to the condenser at 2½ inches of mercury back pressure. Rejected heat is dissipated through cooling towers.

Under conditions of reactor shutdown, core decay heat is also removed by way of the primary and intermediate sodium systems. Dc-powered pony motors are provided for each of the sodium pumps to drive them at 10 percent rated speed for decay heat removal. This heat is transferred across the steam generators to separate decay heat removal loops, one for each steam generator. Heat exchangers in these loops transfer the decay heat either to the cooling tower circuit for dissipation to the atmosphere, or directly to river water systems, providing complete redundancy. To accommodate short-term emergency conditions, a redundant supply of water is maintained in an emergency tank to supply water for injection into the steam generators.

Plant Description

The reactor building is a double containment design (Fig. 2): the inner containment houses the reactor refueling system and includes the reactor hot cell and the fuel-storage tanks; the outer containment is a steel cylinder 105 feet in diameter and 100 feet high from the operating floor to the spring line, with a hemispherical top head. The reinforced-concrete-lined containment structure extends completely around the equipment vaults, which are below floor level. The reactor building and its equipment are designed to satisfy seismic Class I design criteria, which require that structures and equipment withstand the conservatively selected design-basis earthquake without failure.

The elevation view of the reactor building shown in Fig. 3 indicates the major equipment in the primary systems. The reactor vessel extends from the operating floor to the bottom of the lower vaults. The vessel is supported at the top flange by the reactor operating floor and is surrounded by an external guard vessel and external shielding. Above the vessel, the fuel-handling manipulator and reactor plug removal machine are shown in the refueling hot cell. Removal of the reactor plug by means of the plug removal machine opens up the entire vessel for refueling.

The intermediate heat exchangers are of vertical, shell-and-tube, counter-flow design. The primary sodium pumps are single-stage sump suction centrifugal units with the pump motor mounted above the operating floor. The motors are vertical squirrel-cage induction units, driving through vertical fluid couplings for speed control.

The fuel service hot cell is shown (Fig. 3) to the left of the reactor containment. It is connected to the hot cell by a fuel transfer lock (Fig. 2). Spent fuel is stored in three storage tanks in the hot cell. All equipment containing radioactive sodium is located in vaults below the level of the operating floor.

The arrangement of the equipment in the reactor building just below the level of the operating floor is shown on the plan view in Fig. 4. The reactor vessel, intermediate heat exchangers, and primary sodium pumps rest on fixed foundations, with sufficient flexibility designed into the piping system to accommodate thermal expansions.

Each of the three primary system loops is located in a compartment isolated by appropriate concrete vaults, thus allowing the inert-gas atmosphere to be removed from single cells without affecting the atmospheric conditions in the other vaults. Each loop is provided with isolation valves to permit it to be drained for maintenance without the need to drain sodium from the reactor vessel, or to permit the vessel to be drained without draining the loops. Guard vessels around the intermediate heat exchangers, pumps, and reactor vessel contain the primary sodium in event of a primary system break in order to keep the core submerged under sodium at all times.

Intermediate sodium system piping

Table I—Westinghouse LMFBR Demonstration Plant Parameters

Thermal Output of Reactor	790 MWt
Net Electrical Power	301 MWe
Net Station Heat Rate	8956 Btu/kWh
Net Station Efficiency	38.1%
Steam Pressure at Turbine Throttle	2415 psia
Steam Temperature at Turbine Throttle	950 Degrees F
Reactor Coolant Inlet Temperature	750 Degrees F
Reactor Coolant Outlet Temperature	1025 Degrees F
Fuel	PuO_2-UO_2
Average Burnup	75,000 MWD/tonne (initial)
Maximum Burnup	103,000 MWD/tonne (initial)
Refueling Cycle	6-Monthly (initial)
Breeding Ratio	1.30 First Core 1.21 Equilibrium Core
Compound Doubling Time	12.0 Years (first core)

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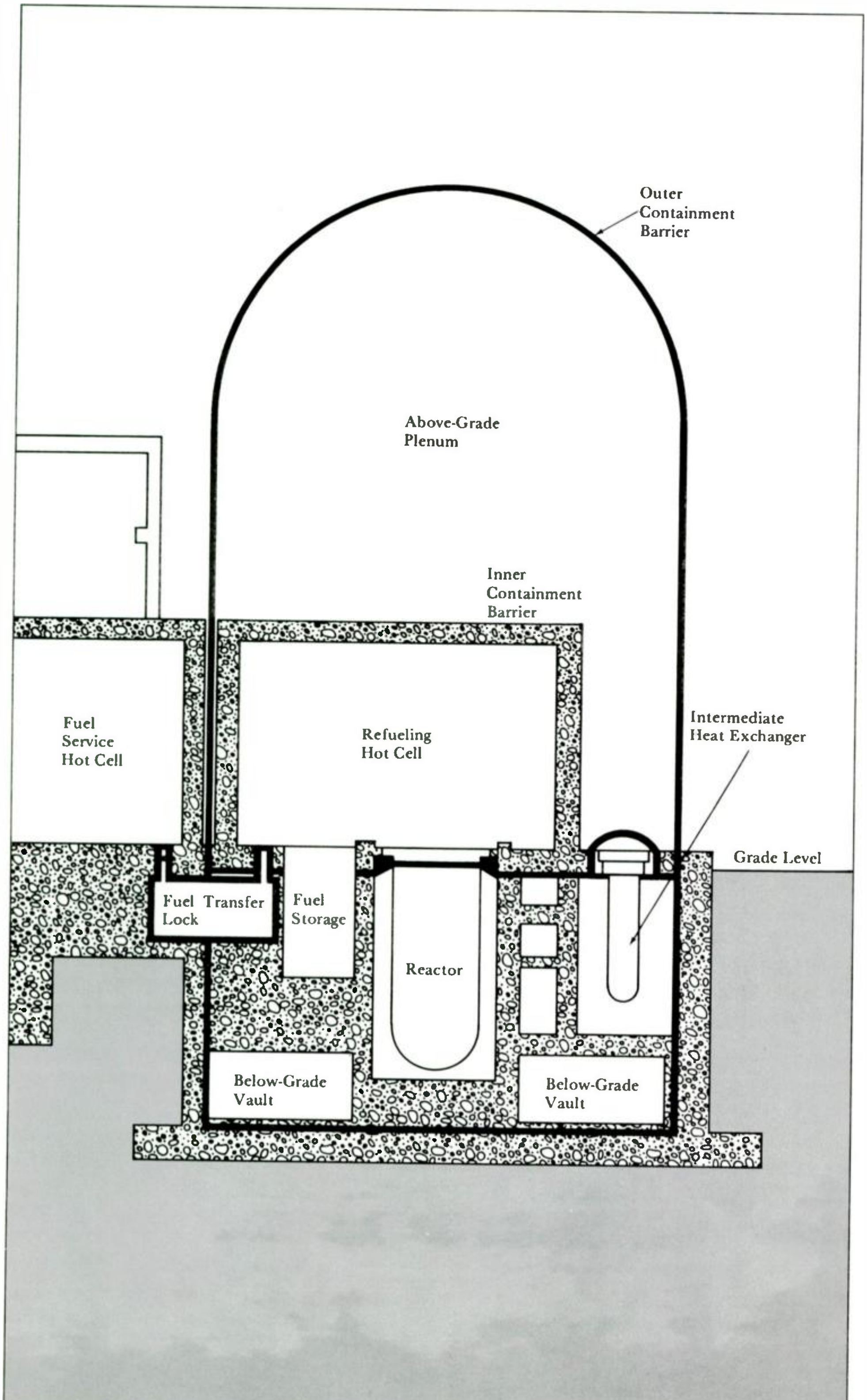

penetrates the containment wall to enter the steam generator building. Intermediate system piping that is inside the containment building is routed through the operating floor and is sealed from the atmosphere above and below the level of the operating floor.

The steam generator building (Fig. 5) is a separate concrete structure which houses steam generators and intermediate sodium pumps. Also housed in this building are the decay heat removal heat exchangers and pumps and the emergency water storage tanks.

Reactor Vessel

A bottom-inlet design was selected for the reactor vessel. The location of the primary coolant inlet nozzles is not a factor in guarding against a loss-of-coolant accident, but it is a major consideration in vessel and internals design. With this arrangement and the type of seal selected, pressure differential across the core barrel is minimized, thereby keeping its thickness to a minimum. This design can be readily extrapolated to the larger sizes that will be required for future commercial plants without requiring core barrels of excessive thickness.

The reactor vessel is surrounded by a close-fitting guard vessel to prevent the sodium level from dropping below the minimum level required for maintaining emergency cooling in the unlikely event of a reactor vessel leak or a pipe rupture. The guard vessel is supported by a bottom skirt and has no penetrations.

The temperature of the reactor vessel walls and outlet nozzle penetrations is controlled by core bypass coolant flow. Approximately 1.5 percent of the total sodium flow bypasses the core between the vessel wall and the core barrel to maintain a maximum vessel wall temperature of 800 degrees F under normal operating conditions. The outlet nozzles

2—The reactor building containment system consists of inner and outer containment barriers.

3—Reactor building elevation view indicates primary system equipment. All sodium-containing equipment is located below grade level.

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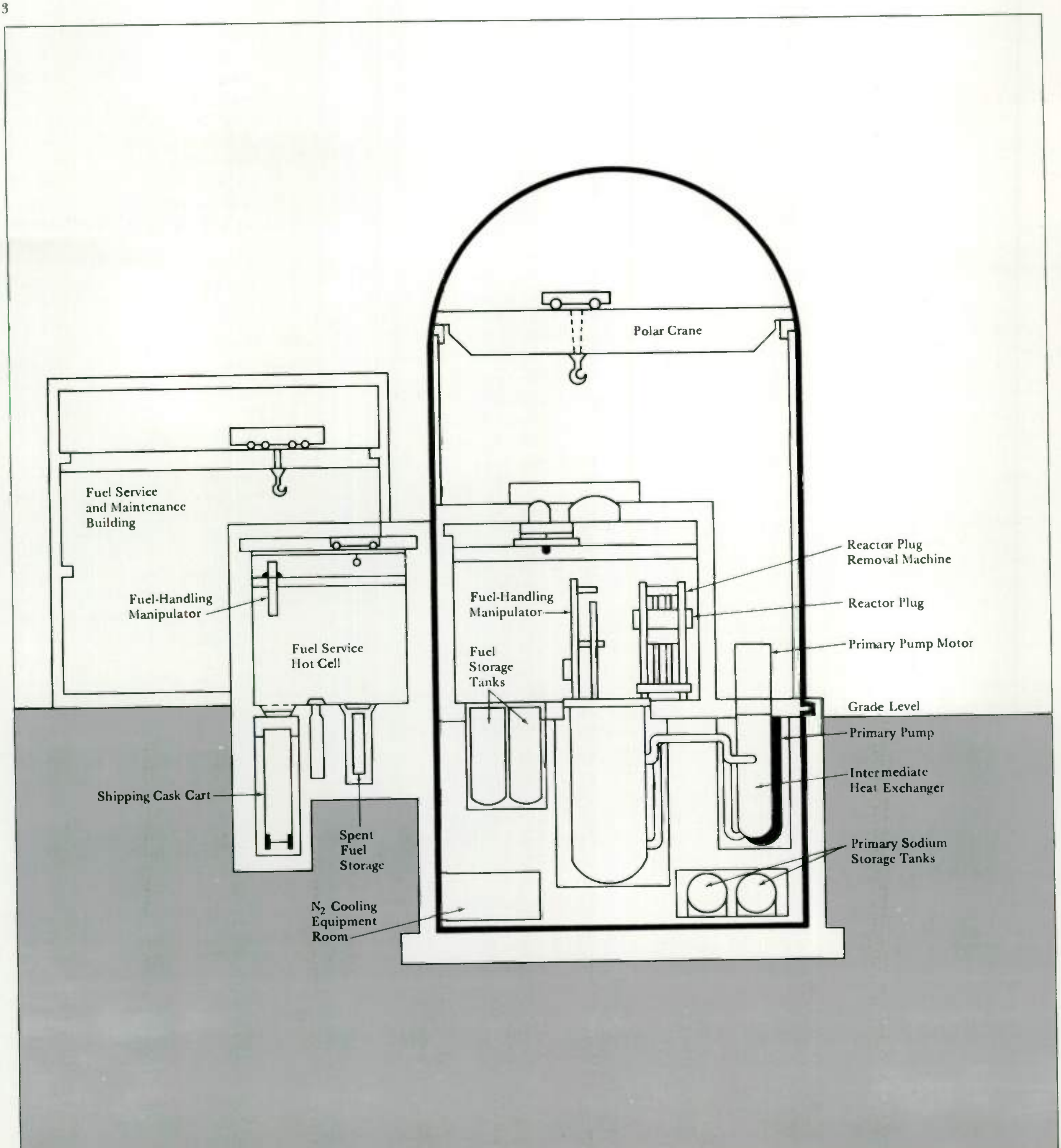
Polar Crane
Fuel Service
and Maintenance
Building
Fuel-Handling
Manipulator
Fuel Service
Hot Cell
Fuel-Handling
Manipulator
Fuel
Storage
Tanks
Reactor Plug
Removal Machine
Reactor Plug
Primary Pump Motor
Grade Level
Primary Pump
Intermediate
Heat Exchanger
Primary Sodium
Storage Tanks
Shipping Cask Cart
Spent
Fuel
Storage
N_2 Cooling
Equipment
Room

are cooled by controlled sodium flow from the bypass flow region into the vessel discharge streams.

Reactor Core Design

The reactor core system consists of a hexagonal array of 439 assemblies (Fig. 6). The 153-assembly core has two radial enrichment zones—81 fuel assemblies in the center zone and 72 fuel assemblies with higher enrichment in the outer zone. Sixteen control assemblies and guide assemblies are dispersed throughout the core. The core is surrounded by 132 radial blanket assemblies which, in turn, are surrounded by 138 reflector and restraint assemblies.

The plutonium fuel has an isotopic composition typical of the plutonium discharge from a pressurized-water reactor: 61 percent Pu-239, 22 percent Pu-240, 13 percent Pu-241, and 4 percent Pu-242. The uranium fuel in the core and blankets is depleted uranium with an isotopic composition of 0.2 percent U-235 and 99.8 percent U-238.

To meet its long-term objective as a commercial power producer, the reactor is designed for 12-month refueling intervals. Early in plant life, however, the reactor will be refueled at 6-month intervals to better study the expected behavior of a 1000-MWe LMFBR plant and to enable more frequent inspection of fuel assemblies.

The average residence time of the fuel in the core will be 2.5 calendar years, with approximately 30 fuel assemblies and 13 radial blanket assemblies replaced every 6 months. Space will be provided in the reactor for three additional control assemblies and for any necessary additions to the control logic system; these will be added when annual refueling is initiated. Reactor internals and cable runs will be designed for annual refueling.

The fissile loading of the first core is 971 kg of plutonium. Fissile plutonium will be produced at the rate of 58 kg per year in the first core, which corresponds to a simple doubling time (without losses) of 16.7 years for the first-core loading. The corresponding breeding ratio is 1.296.

The reactivity loss between refuelings for the first core will be compensated for by tantalum burnup control assemblies. Startup to 20-percent power is achieved by withdrawal of four boron-carbide startup control assemblies. Transition from 20-percent to full-power operation is achieved with load-follow control assemblies. A completely independent secondary shutdown capability exists with five boron-carbide safety assemblies.

Fuel management consists of scatter reload in the core and shuffling (repositioning) in the radial blanket. The radial blanket shuffling involves discharging assemblies from the outer row of the blanket and replacing them with blanket assemblies removed from the core/blanket interface. New radial blanket assemblies are loaded into these vacant positions.

The Doppler coefficient of reactivity is negative in all regions of the core, thus contributing an inherent feedback mechanism which helps provide a large safety margin during expected plant disturbances. In addition, this negative coefficient is large enough to provide a significant reduction in the energy release from the hypothetical core disruptive accident, thereby increasing the design safety margin provided by the containment system.

Fuel Assemblies—A typical core fuel assembly contains 217 fuel rods, each filled with fuel pellets and initially charged with helium. The fuel column consists of a 9-inch stack of depleted UO_2 pellets that serve as the lower axial blanket, a 35-inch stack of $(U\text{-}Pu)O_2$ pellets in the core region, and a 15-inch stack of depleted UO_2 to provide the upper axial blanket. The pellet stack is restrained axially by a spring system.

Radial Blanket Assemblies—Each radial blanket fuel assembly contains 37 blanket rods filled with depleted UO_2 pellets. The pellet stack is restrained by a hold-down spring similar to that used for the core fuel rod.

A trade-off study was made to determine the optimum thickness of the radial and axial blankets to minimize fuel-cycle costs, and to determine the radial reflector thickness required to meet specified fluence requirements. Higher breeding ratios can be obtained with thicker radial and axial blankets, but this increases fabrication and reprocessing charges. It was found that the optimum radial blanket thickness is three rows; the optimum upper and lower axial blanket thicknesses are 15 inches and 9 inches, respectively; and the minimum required reflector thickness is one row.

Reflector Assemblies—The reflector assemblies provide shielding for the core barrel and reactor vessel. Also, they must transmit radial loads with a minimum of attenuation. Each assembly is composed of closely fitting Type 316 stainless steel plates, machined to a 5-inch flat-to-flat hexagonal cross section and stacked around a central column. In their relatively remote radial position, the reflector assemblies receive little gamma heating. Therefore, they do not require internal cooling and do not need to be ducted to the radial blanket coolant plenum.

Peripheral Radial Restraint

The integrated fast neutron flux experienced by many core components is greater than 10^{23} nvt. Experiments and evaluations have shown that stainless steel irradiated to these high fluence levels experiences swelling and creep. Because of these effects it is necessary to restrain the core system to control the distortion of assemblies. Because of its simplicity and positive location aspects, a mechanical hold-down system with radial restraints was incorporated into the design to control distortion.

Plant Control

Overall plant control strategy is based on maintaining a nearly constant steam temperature and pressure at the high-pressure turbine inlet, and maintaining a nearly constant temperature differential across the reactor and heat exchangers under all significant loads. To do this, sodium and feedwater flows and reactor power must be controlled to programmed values, which are functions

4—Plan view of reactor building below grade level shows the three-primary-loop layout.

5—The steam generator and turbine building houses all major auxiliary equipment.

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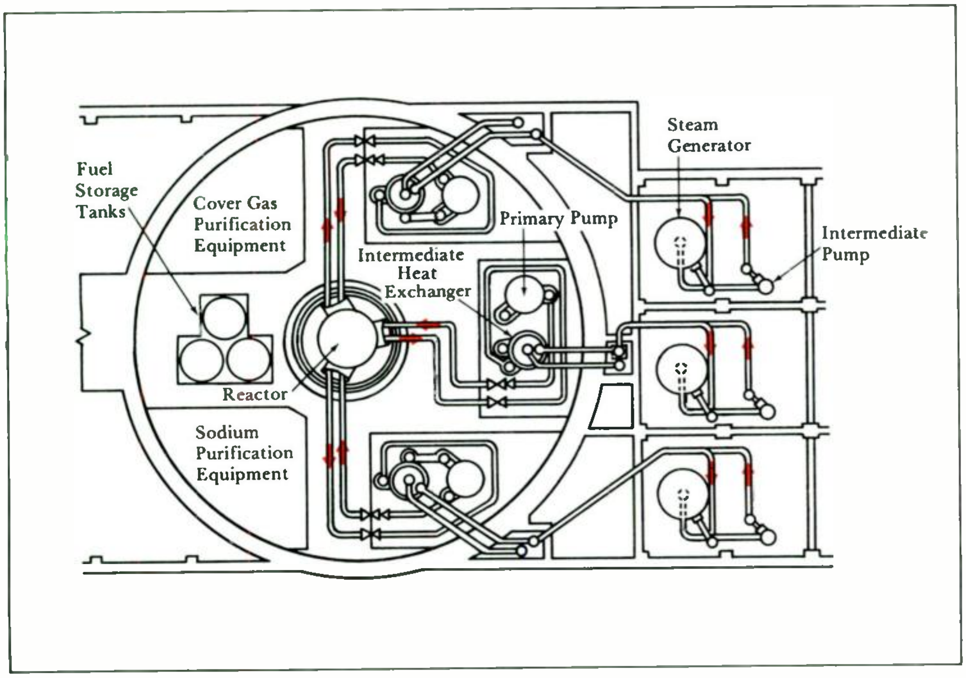

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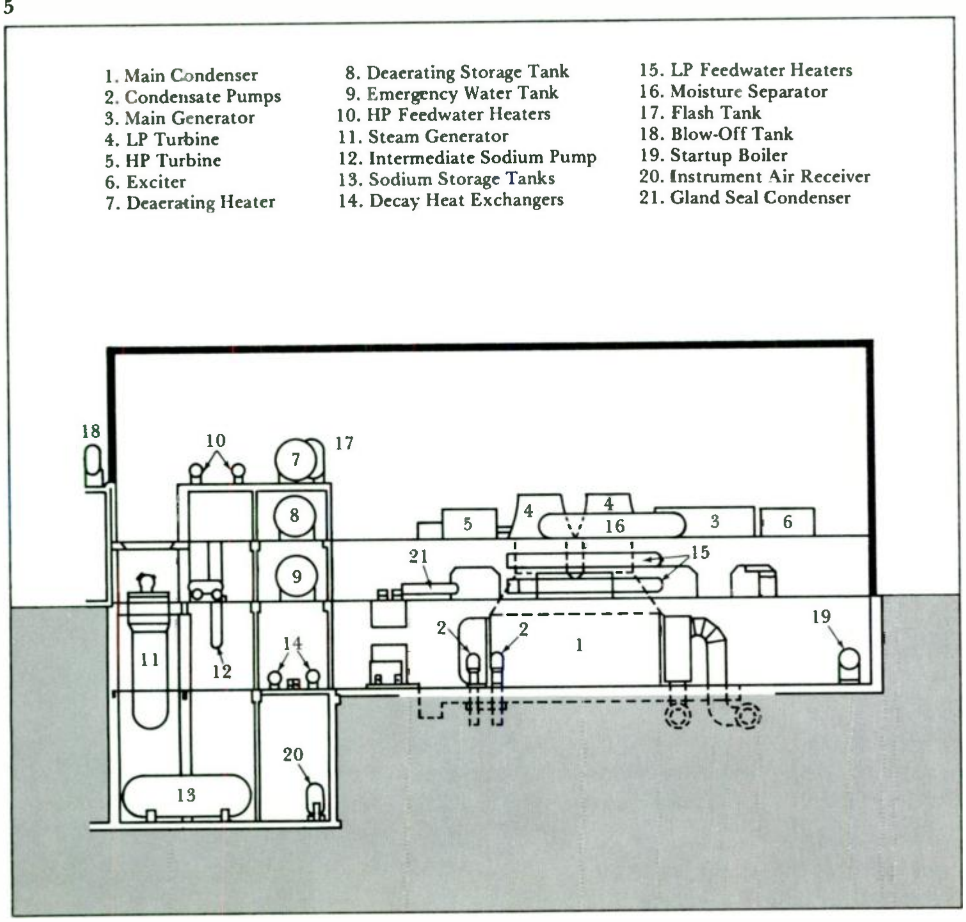


of load demand. Temperature difference across the reactor is controlled by positioning movable absorber rods; primary and secondary sodium flows are controlled by varying pump speed.

The feedwater flow-control system regulates the steam generator feed supply by controlling coarse and fine feed valves between the feed pump and the steam generator. Since the once-through steam generator has a small liquid capacity, equivalent to only a few seconds output at full power, this system is of particular importance. Signals from output-steam flowmeters and from pressure sensors are used in the feed-valve position regulating system.

Turbine-generator output is controlled by a steam-governing valve. This valve is positioned by a speed-governing mechanism actuated by signals from the overall control system.

Fuel Handling

The reactor refueling system is designed to: transfer nonirradiated and irradiated reactor core assemblies (fuel, blanket, control rod, and reflector) to, from, and within the reactor vessel; store irradiated core assemblies under sodium in a subcritical array; and prepare the reactor for power operations upon completion of fuel-transfer operations.

The reactor refueling machine is a "wet" or "valved-bucket" type. Core assemblies are withdrawn into a transfer tube immersed in the reactor sodium. A valve at the bottom of the tube is closed, trapping sodium, and the contained core assembly is transported to the fuel storage tanks. The three cylindrical fuel storage tanks can store 1.25 core-loads of fuel and blanket assemblies under sodium. Fuel assemblies are supported within the tanks by racks that provide criticality control by a combination of spacing and boron-carbide poisoning.

A shield plug and internals handling machine is used to remove and replace the reactor shield plug and upper internals package for refueling.

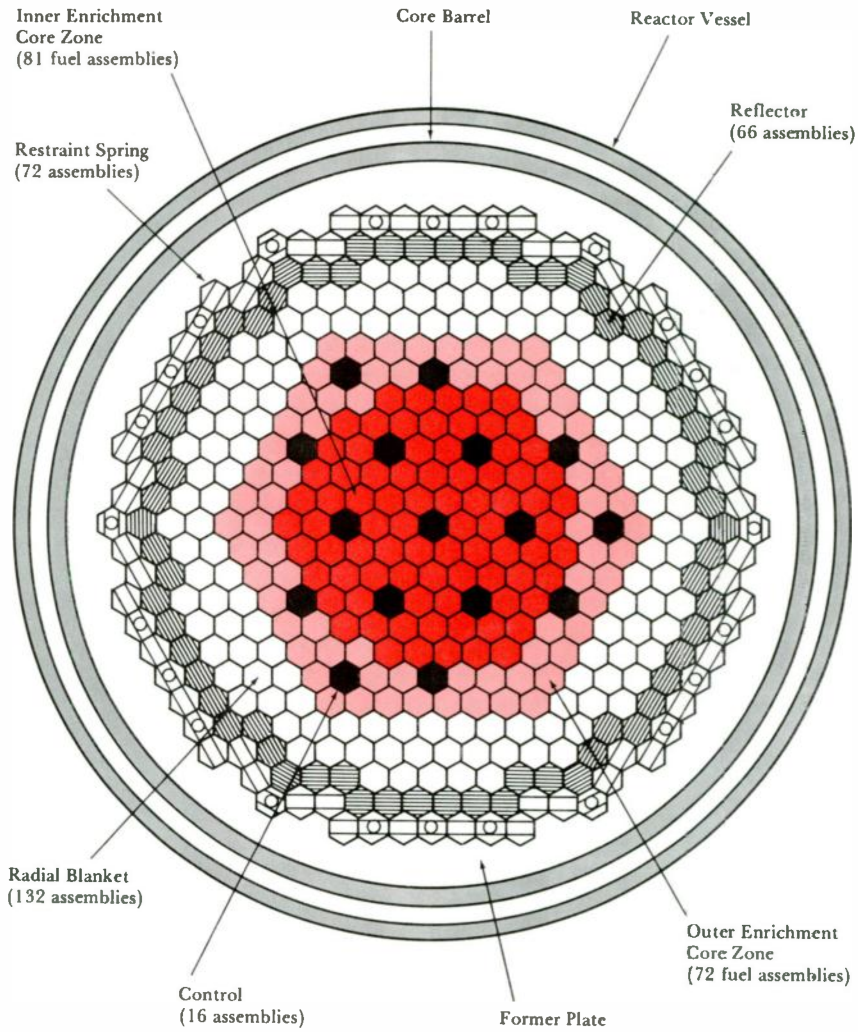
All reactor refueling system components are controlled and monitored from outside the refueling hot cell. Cell walls are of reinforced concrete approximately 6 feet thick for shielding purposes. A $^3/_8$-inch steel liner inside the cell provides alpha particle containment and sodium spillage protection, as well as containment for the hot cell inert atmosphere. Five shielded windows in the walls permit direct viewing of refueling, fuel handling, and reactor maintenance operations.

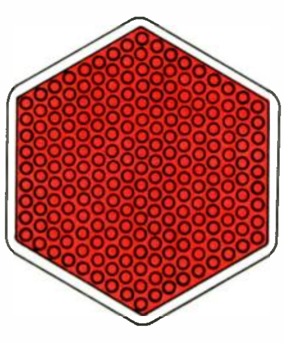
Inert Gas Systems

Inert-gas blankets are employed over all liquid sodium surfaces to prevent undesirable reactions at the liquid/gas interface under all operating conditions. Helium is used in the primary sodium system, argon in the intermediate sodium system, and nitrogen in the fuel-storage tanks. Helium was selected for the primary system because it does not become radioactive and because it is more easily separated from fission gas products. Argon was chosen for the intermediate sodium system because it is less expensive than helium, no fission gas is present, and it does not interfere with steam generator leak detection by mass spectrometer or thermal conductivity methods. Nitrogen was selected for the fuel-storage tanks because they operate at low temperatures where nitriding will not occur, and because during fuel-handling operations the storage tanks are exposed to the pure nitrogen atmosphere of the cell in which they are located. The atmosphere in this inner containment of the reactor building is nitrogen with less than 10 parts per million oxygen to prevent the potential hazard of a radioactive sodium fire.

The dry nitrogen environment required for the refueling hot cell and the fuel services hot cell is provided by two similar but separate systems, which permits de-inerting one cell independently of the other.

A compartment inerting system is provided to maintain a nitrogen atmosphere in the various below-floor equipment vaults within the containment during reactor operation. This atmos-





6—Reactor cross-section view shows the core, blanket, and reflector sections.

phere precludes a radioactive sodium fire in event of a leak or other breach in the sodium coolant boundary.

Nitrogen in the below-floor chambers contains one to two percent oxygen (depleted air) to inhibit nitriding of the components.

Each of the cover gas subsystems is fed from a pressure controlled gas supply. Helium is stored as a high-pressure gas, and argon and nitrogen are stored as liquids which are vaporized on demand.

For all of these inert gas systems, the gases are recirculated through cleanup and purification systems and are reused, resulting in essentially zero release of radioactive gas to the environment.

Safety Analysis

Plant safety is best guaranteed by technically sound design based on a thorough understanding of the system measured against general and specific safety-related design criteria, and by good quality control during design and construction. In addition, the performance of the plant in response to all credible occurrences must be evaluated to verify that it will respond safely.

In the LMFBR demonstration plant, a core disruptive accident, resulting from the complete loss of pumping power followed by a failure to trip the reactor, was determined to be the worst potential design-basis accident. Because this accident has the greatest potential for an uncontrolled release of radioactivity, it was used to assess the design safety margins of the reactor vessel and the containment barriers around the vessel.

The maximum available energy for destructive effect on the reactor vessel for this accident was determined to be 102 MW-seconds. This magnitude of energy release would disrupt the core, damage the thermal shield, and distort the reactor vessel. However, the reactor vessel would not rupture. Transfer of thermal energy to sodium within and above the core would cause rapid vaporization and generation of a sodium hammer effect. The theoretical momentum transfer at impact would cause the shield plug to lift less than 2 inches and allow the escape of a moderate amount of sodium. Very little if any fuel would be ejected. Thus, the atmosphere of the refueling hot cell, located over the reactor, would rise in temperature and possibly become contaminated with radioactive fission products and with plutonium- and uranium-dioxide aerosol.

The structural design margin for the refueling hot cell was evaluated on the basis of 1000-degrees F sodium being ejected from the reactor when the vessel shield plug is lifted by the core disruptive accident energy release. In all cases, the design pressure of 10 psig and the temperature loads were determined to be conservative.

The structural design margin for the outer containment shell above the operating floor was evaluated on the basis of the conditions resulting from a sodium pool fire with a surface area of approximately 400 square feet. Again, the design pressure of 10 psig was determined to be conservative.

A series of spray and pool sodium fires was studied to assess the adequacy of a 10-psig design pressure for the vaults below the operating floor. Since these vaults have an inert atmosphere during operating and normal shutdown conditions, the evaluation assumed a 2-percent oxygen concentration. The temperature requirements for the floors and walls were also evaluated and found to be adequate.

Site Selection

Four sites, all on the Hanford Reservation, near Richland, Washington, were evaluated as candidates for the demonstration plant, considering such factors as safety, relative construction costs, licensability, and use of existing facilities. The prime site was chosen primarily because of the possibility of using existing facilities, and because of its nearness to the Hanford No. 1 Generating Station, which is already integrated into the Pacific Northwest Power System. All other considerations were relatively equal for the four sites.

Because of the availability of extensive information about the physical characteristics of the Hanford Reservation and past experience with nuclear facilities in the area, the financial and technical risks of locating the plant there will be small. Furthermore, local and state regulatory requirements regarding the siting of nuclear power plants are easily met since the demonstration plant will not adversely affect the ecology of the area, nor will it pose a risk to the health and safety of the public.

Program Schedule

The projected LMFBR plant construction schedule requires 78 months from the start of the program to the end of startup and test operations. The time allowed for plant construction is approximately 57 months from excavation to fuel loading, with the assumption of the standard practice that basic site improvement work and excavation will start six months prior to receipt of the AEC construction permit. This demonstration program is fully achieveable in the time span indicated—given appropriate support from the electric utility industry, the Atomic Energy Commission, and Westinghouse.

The need for timely introduction of the fast breeder as an economic and reliable source of power has been adequately documented elsewhere. It should suffice here to say that the earlier this occurs, the greater the financial return to the industry.

Industrial Noise Specialists Offer Sound Advice

The Occupational Health and Safety Law, which superseded the Walsh-Healy Act earlier this year, places limits on the sound levels to which workers in industry can be subjected. Its standards are presently the same as those in the Walsh-Healy act; one of the basic ones is a maximum allowable continuous sound level for an 8-hour work day of 90 decibels. However, the new law gives the U. S. Secretary of Labor authority to establish new limits.

Many larger companies have the resources to identify and solve their own noise problems, but medium-sized and smaller companies will often have to turn to outside sources for assistance in complying with the regulations. To help meet that need, the Westinghouse Electric Service Division is offering a new noise survey and analysis service.

Its service specialists "map" a plant by taking sound-level readings at all possible trouble spots, recording the data as they go. Then they analyze the cause of the noise and devise remedies. The most complex problems are referred to the Westinghouse Research Laboratories, where an acoustics laboratory is equipped to conduct detailed analyses of noise problems. (See photograph on back cover.)

Size of Ocean Waves Is Now Predictable

Oceanographers once thought that all waves are formed directly by wind, but now an international team of scientists has shown that wave growth is a much more complicated process. Small waves are most affected by the wind, and the motion of those small waves then causes large waves to form. A mathematical formula describing the process has been devised, so the accuracy of wave forecasts now depends only on how accurately weathermen can predict wind conditions. Improved wave prediction should permit steps to be taken in time to greatly reduce damage to ships and shore facilities.

Known as the Joint North Sea Wave Project (JONSWAP), the investigation involved cooperation of American, German, British, and Dutch scientists. It was begun in 1968. Measurements of wind and waves were made simultaneously at 13 stations near Sylt, one of the German Frisian Islands. Large oceanographic vessels occupied five of the stations, and a fleet of small ships serviced buoys and bottom-mounted masts at the others. The measurements included wave heights, directions, and frequencies; ocean currents; atmospheric temperatures and humidity; and fluctuations in wind speed and direction.

The United States effort was handled by the Westinghouse Ocean Research Laboratories and was supported jointly by the U. S. Office of Naval Research and the German Federal Republic. Other participating institutions included the German Hydrographic Office and Navy, the British National Institute of Oceanography, and the Netherlands Meteorological Institute.

Krypton Gives Light Bulb Triple Lifetime

A commercial light bulb with an average life of 3000 hours, about three times the life of ordinary bulbs, has been achieved without sacrificing brightness. The gain was made by filling the bulb with krypton, a rare and heavy gas.

A bulb's tungsten wire filament, when heated by an electric current, glows and produces light. It also slowly evaporates, causing the bulb to burn out when the filament eventually breaks. Within limits, manufacturers can control the rate at which the tungsten vaporizes but, generally speaking, it has been possible to make bulbs last longer only at the expense of brightness. Average life and brightness ratios have been set in an effort to give users the best product considering lighting requirements, economy, and convenience.

In the new Super Bulb, however, heavy krypton gas blankets the filament, retarding its evaporation and thus increasing its life expectancy without a corresponding decrease in brightness.

Although the advantage of using krypton in light bulbs was known to scientists at the Westinghouse Incandescent Lamp Division for years, it was not economically feasible to use the gas until recently because it was not available in any quantity. (It occurs naturally in air in only one part per million.) The cost has now been reduced as the result of expansion of steelmaking techniques that require huge amounts of oxygen; krypton is a byproduct of the air reduction process that produces industrial oxygen.

Combined-Cycle Power Plant Will Serve Oklahoma

The first PACE power plant, a predesigned combined-cycle unit, has been ordered by Public Service Company of Oklahoma to help meet the mushrooming power requirements of southwestern Oklahoma. The 240,000-kW plant will be located near Lawton, with initial operation scheduled for 1973.

The PACE (Power At Combined Efficiency) plant is a Westinghouse package consisting of two 60,000-kW gas turbines and a 120,000-kW steam turbine.* Though normally rated at 240,000 kW, it will be capable of peaking at 260,000 kW. Heat rate will be less than 9000 Btu per kilowatt-hour with natural-gas fuel (higher heating value) in most modes of operation. Start-up will require 30 minutes to half load and 1 hour to full load; in contrast, it takes about 4 hours to put a conventional steam plant on the line.

A basic advantage in combining the gas-turbine cycle and the steam cycle is utilization of the gas turbines' exhaust heat, otherwise wasted, to generate steam for the steam cycle. Thus, the combined cycle conserves natural gas. Moreover, the need to treat thermal discharge is drastically reduced because half of the plant output is in gas-turbine power, which requires no water. For cooling in the steam part of the plant, Public Service Company plans to use effluent from the town's sewage disposal system, purified and piped to a 200-acre lake.

*P. A. Berman and F. A. Lebonette, "Combined-Cycle Plant Serves Intermediate System Loads Economically," *Westinghouse ENGINEER*, Nov. 1970, pp. 168-73.

The combined-cycle power plant includes two Westinghouse model W-501 gas turbines, each exhausting into its own model 5000-F heat recovery steam generator. Steam from the steam generators is fed to a common header, which supplies a single-cylinder steam turbine with 28½-inch low-pressure end. The steam turbine has axial exhaust and generator drive from the high-pressure end to accommodate grade-level installation. The plant equipment consists largely of factory-assembled modules, so field construction effort is significantly reduced.

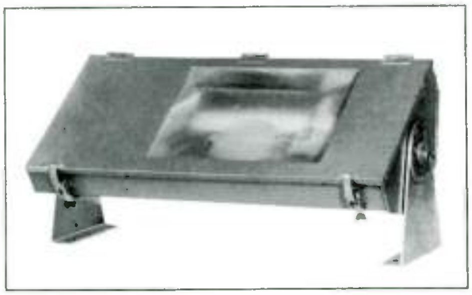
High-Voltage Electron Microscope Aids Fast Breeder Development

A one-million-volt electron microscope adapted for the study of radioactive materials is being used in support of breeder-reactor research at the Hanford Engineering Development Laboratory of the U. S. Atomic Energy Commission in Richland, Washington. The microscope will aid in development of materials for application in the Fast Flux Test Facility (FFTF) being constructed there.

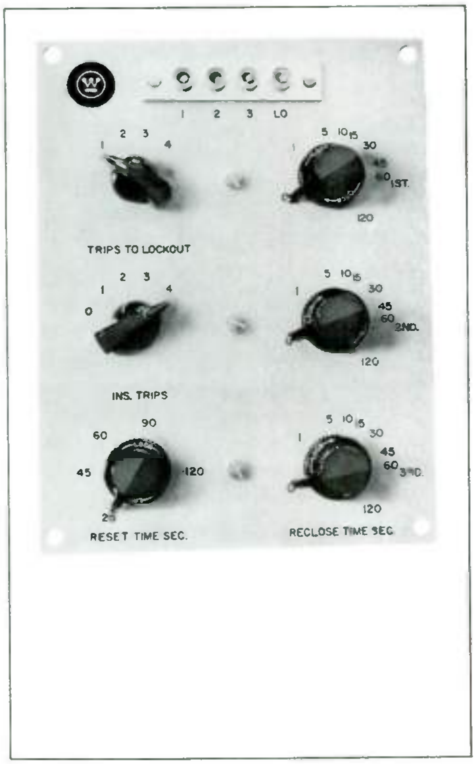
The high-energy beam of electrons produced in the microscope can penetrate specimens as much as ten times thicker than can be used with conventional electron microscopes. The instrument enables materials engineers to see imperfections in the atomic arrays of metals and alloys directly, an ability that will aid them greatly in developing improved materials for fast breeder reactors.

Initial applications include studies of the dynamic behavior of irradiated stainless steel, prediction of fuel behavior, establishing interaction between fuel and cladding, and providing insights into the microstructure and therefore the properties of a variety of materials used in reactor core components. Because most of the materials studied are radioactive after irradiation, the installation includes facilities for remote handling and preparation of specimens.

The Hanford Engineering Development Laboratory is responsible for the technical and administrative management of the FFTF construction project and will operate the facility. It is managed by WADCO Corporation, a Westinghouse subsidiary.



Mercury-Vapor Floodlight



Type RCS Relay

WSR Deuce Welder

Products for Industry

Mercury-vapor floodlight is designed for high performance in such illuminating applications as buildings, signs, billboards, roadway underpasses, tunnels, and parking lots. The APF all-purpose unit has a cast aluminum door, with a heat-resistant glass lens, hinged to the aluminum housing to simplify cleaning and maintenance. The ribbed lens directs light to the proper areas for efficient coverage. The floodlight includes a prewired integral ballast for a 175-, 250- or 400-watt mercury lamp. *Westinghouse Outdoor Lighting Department, 1216 W. 58th Street, Box 5817, Cleveland, Ohio 44101.*

Type RCS relay is now available as standard equipment on all relay-controlled reclosers. It provides complete reclosing flexibility through a panel-front adjustment of one through four trips to lockout and zero through four instantaneous trips. Reset times can be set between 25 and 120 seconds, with separately adjustable reclose settings between 0 and 120 seconds. The relay consists of a reclose timer, reset timer, integrator, and operations indicator. A cycle position indicator gives the recloser's exact position in each programmed cycle. *Westinghouse Distribution Apparatus Division, Box 341, Bloomington, Indiana 47402.*

WSR Deuce welder is a general-purpose manual dc type that can provide two 200-ampere arcs from a single unit of conventional size. It measures 20 by 31¼ by 22 inches high and weighs 330 pounds, and it can be stacked up to three high without auxiliary bracing. Power is rectified by silicon diodes guaranteed the life of the welder. Other standard features include transient voltage protection, primary breaker with thermal overload, weatherized construction, a fast response time, and polarity reversing switch. *Westinghouse Welding Department, P.O. Box 300, Sykesville, Maryland 21784.*

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Author Index

Author biographies appear on the inside back cover of each issue.

About the Authors

W. A. Thornton earned his BS degree in physics at the University of Buffalo in 1948 and his MS and PhD degrees in physics at Yale University in 1949 and 1951. He then joined General Electric and worked in the company's Research Laboratory.

Dr. Thornton came to Westinghouse in 1956 at the former Lamp Division. He worked first in electroluminescence, then in lamp phosphors, and in 1965 was made section manager of Phosphor Research. He is now Research-Engineering Consultant in the Fluorescent and Vapor Lamp Division, where his work consists of consulting and research in lamp design, luminescence, color, color vision, color standards, and color rendition.

Dr. Thornton has 17 patents to his credit, plus 13 in filing status. He has contributed to the development of many lamps including the new Beauty Lite, to the Division's Phosphor Advanced Development Section program, to development of phosphor-evaluation and lamp-evaluation techniques, and to understanding of color vision.

R. J. Budenholzer graduated from Illinois Institute of Technology with a BS in Engineering Science in 1969, and he earned an MSEE degree from Carnegie-Mellon University in 1971. He joined Westinghouse on the graduate student training program in 1969 and began work in the generation group of Power Systems Planning (now Power Generation Systems) shortly thereafter. His responsibilities have included work in generation forecasting, analysis of power-plant waste heat rejection systems, cooling tower design analysis, and computer optimization techniques. He is presently a Generation Engineer in Power Generation Systems.

L. G. Hauser is Manager, Fuels and Energy Systems, Power Generation Systems. He graduated from Carnegie-Mellon University in 1942 with a BSEE. After Army service, he joined Westinghouse as a design engineer for the Welding Division. He became a district representative and subsequently Manager of Application Engineering.

Hauser transferred in 1954 to the newly formed Atomic Equipment Division, created to supply nuclear apparatus for the atomic power industry. As Manager of Marketing, he participated in the phenomenal evolution and growth of nuclear power. In his present assignment, Hauser is responsible for technical, economic, and environmental evaluations of fuels and complete energy systems for electric power generation.

K. A. Oleson is also a Generation Engineer in Power Generation Systems. He has a BS in Engineering and an MS in Mechanical Engineering (1967 and 1968) from Southern Illinois University, and he joined Westinghouse in 1968 to work in the generation group of Power Systems Planning. His activities include cooling system design, dry cooling tower analyses, techno-economic evaluations of turbine back-pressure parameters, and optimization of turbine, condenser, and heat-rejection system combinations.

Bruce A. Powell graduated with a BS in mathematics from Denison University in 1963. At Case Western Reserve University he earned his MS in Operations Research in 1965 and his PhD, also in Operations Research, in 1967. After joining Westinghouse in 1967, Dr. Powell was first assigned to optimize the assembly line for the South Boston, Virginia, transformer plant. As a Senior Mathematician at the Research Laboratories, Dr. Powell has been involved in a number of projects including layouts for plants and for a new generation of military hospitals, production scheduling, and mathematical modeling of elevator systems.

Henry C. Savino earned a BSEE from Pennsylvania State University in 1942. He joined Westinghouse later that year on the graduate student training program and, after a few assignments, began work with the Control Engineering Department of the Elevator Division. Savino is currently Engineering Manager, High Speed Elevator Division, where his major responsibilities have been in design of complex elevator systems and controls, particularly the Mark IV System. He has 18 patents to his credit.

D. H. Shaffer attended Carnegie Institute of Technology, earning a BS degree in mathematics in 1950, his MS the following year, and his PhD in 1953. He came to Westinghouse in 1954 as a Senior Mathematician and has since participated in and directed the mathematical and statistical parts of many research and development programs. Three of those programs that illustrate the variety of Dr. Shaffer's contributions are development of a fusee-spring support system for medical X-ray units, reliability models for transmission cables, and evaluations of sensor and control units for home dryers. He is currently an Advisory Mathematician at the Research Laboratories. Dr. Shaffer has coauthored several books, taught mathematics, and presently lectures on statistics at Carnegie-Mellon University.

Donald P. Wei received his BSEE from Princeton University in 1960, and an MS in Numerical Analysis in 1963 from Brown University. He joined Westinghouse that year as a mathematician in the Computer Sciences Department at the Research Laboratories. Wei currently is Manager, Numerical Analysis and Programming, in that department. He provides consultation and programming services in both scientific and business areas.

Wei's other professional experience includes service as a Research Assistant in Electrical Engineering at Princeton University and at Forrestal Research Center. He was also Research Assistant in Numerical Analysis at Brown University.

William M. Jacobi is Manager, FFTF Engineering, in the Advanced Reactors Division. Among his responsibilities are design of the Fast Test Reactor and design of the major heat-transport system components associated with it. The Fast Flux Test Reactor to be completed at Hanford in 1974 is a key facility for the testing of fuels and materials in the national LMFBR program.

Dr. Jacobi earned his PhD in Chemical Engineering at Syracuse University in 1955, and he has also done graduate work in chemical engineering at the University of Delaware. He joined Westinghouse in 1955 at the Bettis Atomic Power Laboratory to work in heat-transfer analysis on the Nautilus and Nautilus-prototype reactor cores, and he later worked on the nuclear design of naval reactors. In 1958 he was made a scientist in charge of the S5W nuclear design, and in 1960 he became supervisor of the A1W Core 3 nuclear design.

In 1961, Dr. Jacobi joined the Nuclear Utility Services Corporation, where he did general consulting work on commercial nuclear power plants. He rejoined Westinghouse in 1963 at the Astronuclear Laboratory, where he was Manager of Advanced Reactor Design for the NRX-A6 and the NERVA II reactors. In 1968 he transferred to the Weapons Department as Manager of Design Engineering for the MK 48 Torpedo Program, later serving as Manager of MK 48/27 Follow-On Programs. He was appointed to his present position last year.

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Noise measured in an industrial plant is analyzed as part of a service that helps industries comply with government regulations. (See page 188.)