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Released for general publication upon presentation

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
29 West 39th Street, New York 18, N. Y.

Printed in U.S.A.

Meramec 3 Steam Electric-Generating Unit

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This paper describes the principal design features of a 250,000-kw steam electric-generating unit for the Meramec 3 power plant. Basic economic factors, such as fixed charge rate, fuel cost, load factor, thermal performance, and cost of unavailability are dealt with briefly, and the design is viewed largely from the standpoint of such economic considerations.

PLAINTIFF'S EXHIBIT

RS-266

Contributed by the Power Division for presentation at the Semi-Annual Meeting, St. Louis, Mo., June 14-18, 1959, of The American Society of Mechanical Engineers. Manuscript received at ASME Headquarters, March 31, 1959.

Written discussion on this paper will be accepted up to July 20, 1959.

Copies will be available until April 1, 1960.

RS-000281
1/17/02
NUECES

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Meramec 3 comprises a 250,000-kw electric-generating addition to the Union Electric system in the St. Louis area, placed in commercial operation January, 1959. It is neither nuclear nor supercritical, but it typifies in many ways the design philosophy behind much of the generating capacity being added to this nation's utility system. The present paper will make no attempt at covering the plant design in detail. Rather, it will attempt to cover the highlights of the design from the viewpoint of economic-engineering considerations.

A project of this type has its inception in a prediction that a utility, some 4 years later, will require additional generating capacity to meet the load demands of its customers. There is no economic choice here. The decision is inherent in the utility's obligation to its customers and to the communities that it serves. But there is economic choice involved in the type of equipment that should be installed to meet the stated load requirement. And it is in this area of the engineering that various designs may be utilized to fulfill various economic requirements. Basically, engineering must begin with a plant design having minimum cost, in dollars per kilowatt, to provide for reliable service together with safe operation, and with adequate provision for maintenance. Additional design features, in general those design features that increase investment cost but reduce operating cost, are then adopted as they are shown to be individually attractive.

Somewhat paradoxically, it can be shown that for large units the lowest initial cost plant for a given electrical output, that is, the cheapest plant on a dollar per kilowatt basis, is also a remarkably efficient plant. It will utilize five or more stages of extraction feedwater heating, it will employ the reheat cycle, and it will incorporate considerably more than the minimum required condenser surface. This is so because the low-efficiency plant entails large steam and water flows, large quantities of fuel, and high cost of all associated equipment (pumps, feedwater heaters, piping, boiler, fuel handling and preparation, and so on). In all but the smallest units, the lowest investment cost per kilowatt requires the use of reheat, entirely

aside from the fuel saving that use of reheat additionally provides.

ECONOMIC ANALYSIS

In the case of Meramec 3, over-all project cost was in the order of \$40,000,000. The range in cost between a moderately efficient lowest cost plant¹ and a higher efficiency, higher cost plant² was in the order of \$2,500,000. It is this latter amount that becomes the subject of engineering-economic analysis as the design is worked out. In making such an analysis, there must be established a number of factors, representing not eternal and immutable relationships, but best judgement at the particular time as applied to the particular utility and the particular project. And since these factors are different depending on economic, geographical and other conditions, it follows that individual plant designs will be different.

There follows a discussion of some of these basic relationships for the Meramec 3 addition:

Fixed Charge Rate on investment was set at 15 per cent. This is to say that a \$100 investment in plant requires \$15 per year in revenue to cover corporate income tax on the revenue, depreciation, and insurance on the equipment, and 6 per cent net return on the investment. However, instead of \$15 annual revenue, a \$15 annual reduction in an operating expense, such as fuel or labor, will support the investment just as well.

If, for example, \$100 additional investment in a specific feature can be expected to reduce operating expense by \$15 a year, the investment requires no additional revenue to support it. If reduction in operating expense is more than \$15, the investment is attractive in that it reduces total revenue requirements. Fifteen per

¹ Taken as 1800 psi, 1000F/1000F, 5-stage feedwater heating, 130,000--sq-ft condenser, tandem turbine-generator.

² Taken as 2400 psi, 1050F/1050F, 7-stage feedwater heating, 160,000--sq-ft condenser, cross-compound large exhaust turbine-generator.

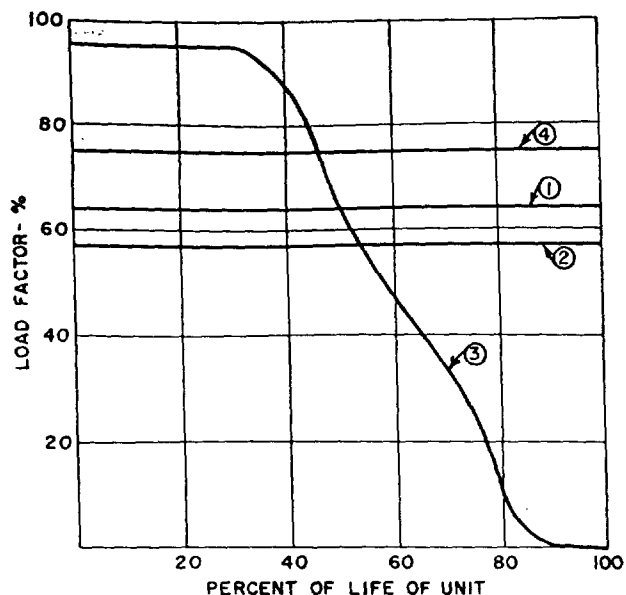


Fig.1 Analysis of load factor.

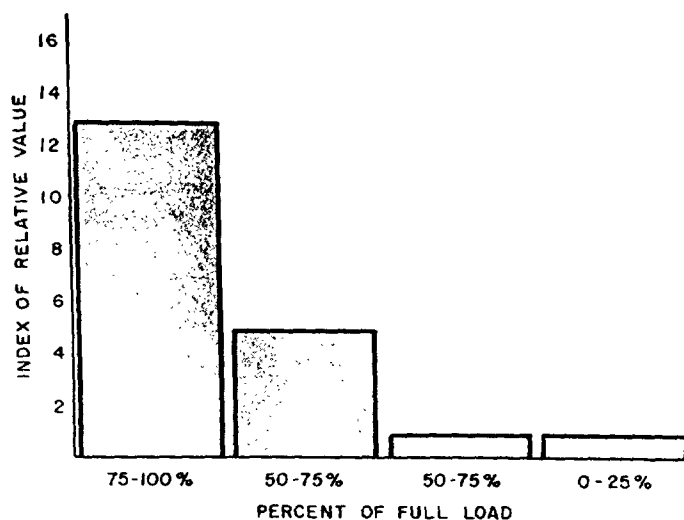


Fig.2 Relative value of a given percent improvement in thermal performance.

cent represents an approximate break-even point.

Fuel Cost 22¢ per million Btu, estimated over the life of the unit. Meramec is close to a relatively ample and low-cost supply of bituminous coal, in which continued mechanization of mining and availability of both rail and water transportation may very well hold fuel cost close to today's level over a period of some time.

Load Factor was considered equivalent to 75 per cent of capability over the useful life of the unit, for purposes of evaluating fuel savings. This figure may be derived in a number of ways; Fig.1 illustrates one approach. Average load factor of the Union Electric system over a period of years has been approximately 64 per cent (curve 1). After taking into account system reserve and generating-equipment availability, this means the load factor, or capacity factor, on all generating equipment of the system has been approximately 57 per cent (curve 2). However, it is recognized that during early years of operation, load factor on the Meramec 3 unit will be high since it will be one of the most efficient units available to the system; on the other hand, Meramec will be relegated to peaking service in later years of its life, and load factor will be low (curve 3). The "present worth" of fuel savings effected during early years of operation is greater than the same savings during later years, and as a consequence added weight attaches to the high load factors that are expected during early years of operation. The result of taking into account present worth of future fuel savings, therefore, is to increase the load factor arrived at arithmetically for

the unit throughout its life to an equivalent load factor of approximately 75 per cent (curve 4). This, then, is the figure used for calculations involving fuel consumption of the equipment.

Incidentally, curve 3 of Fig.1 points up the important requirement that the unit must be capable of both base-load operation in early years and cycling or peak-load operation in later years.

Heat rate finally realized affects fuel consumption and in certain cases affects net output of the unit. It is clear from information already given that average fuel consumption of Meramec 3 may be considered in the order of \$4,000,000 a year. Thus, a 1 per cent fuel saving represents \$40,000 a year, which is the annual carrying charge on an additional investment in the plant of slightly over a quarter-of-a-million dollars. For a 1 per cent reduction in heat rate, a quarter-of-a-million dollars initial investment would be considered "marginal" or "break-even" for Meramec 3.

Where an improvement in heat rate is non-uniform over the load range, other factors come into play. Fig.2 is an attempt to indicate the relative importance of the fuel savings resulting from an improvement in performance in various load ranges; note that a given percentage gain in the 75-100 per cent load range is worth 13 times as much as the same percentage gain in the 0-25 per cent or the 25-50 per cent load range. If, in addition, the improvement at top load is reflected in increased output from the unit, an even greater value must be given it.

Estimated cost of unavailability of the

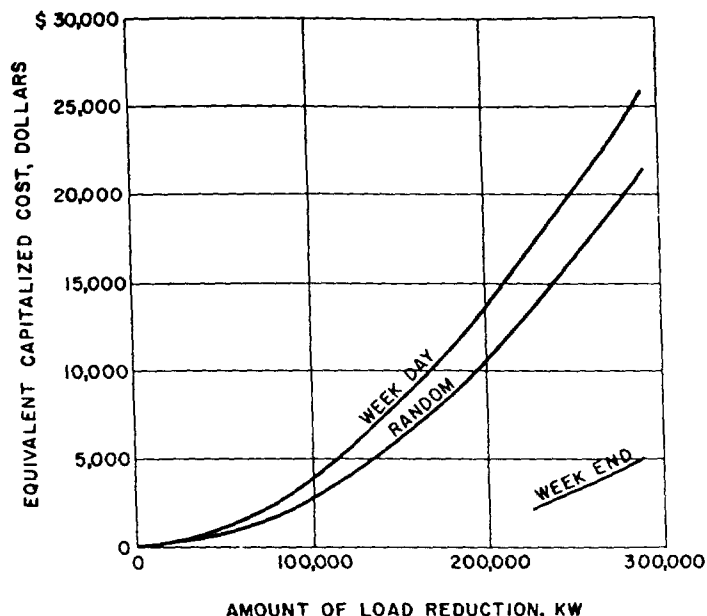


Fig. 3 Equivalent capitalized cost of one day per year outage.

unit is shown in Fig. 3, representing differential cost of generation by the Meramec 3 equipment and by other less efficient equipment of the system. Equivalent capital cost of a one-day outage per year on an unscheduled or random basis is in the order of \$20,000. Taking into account the long-range effect on system reserve requirements, unavailability may cost more like double the amount shown by Fig. 3, if it is a forced or random type, rather than a type that can be scheduled off-peak.

So much for the economic backdrop against which the Meramec 3 design was carried out. More could be said, but it is hoped that the foregoing gives a sufficiently clear picture of the general relationships involved. Let us now consider the design itself.

DESIGN CONSIDERATIONS

Size. The company's Cahokia power plant, built during the '20s, has as its largest unit, one of 75,000-kw size. Venice, built during the '40s, has a 100,000-kw unit. The first two units at Meramec were installed in 1953 and 1954, respectively; each is rated 125,000 kw. But Meramec 3 with its 250,000 kw capacity, had suddenly jumped to double the size of the preceding units. Why? The answer lies in the fact that between Meramec units 2 and 3, Union Electric had become part of an operating pool including the Illinois Power Company and the Central Illinois Public Service Company, a pool having a capacity of roughly twice that of the Union Electric Sys-

tem alone. The attraction of the large-size unit, of course, lies in its reduced cost per kilowatt of capacity, reduced fuel consumption per kilowatthour produced, and reduced labor and maintenance costs per kilowatthour of output. Additions to the transmission system, the pooled reserves, and associated interconnections made the 250,000-kw size feasible.

General arrangement of major equipment, Meramec plant, is shown in Fig. 4. Exclusive of general plant service areas, units 1 and 2 occupy 215 sq ft of plant area per 1000 kw of rated output, exclusive of general plant service areas; unit 3 occupies only 164 sq ft per 1000 kw; while unit 4 will require still less, or only 134 sq ft. These figures illustrate one of the advantages of larger units.

Meramec 3 follows the basis "kilowatthour factory" approach of the earlier Meramec units, with a minimum of ornamental and architectural treatment, use of corrugated siding for building walls, pipe railings, and so on.

Fig. 5 illustrates the essential features of the steam and water cycles, Meramec 3. Steam at 2000 psi and 1000 F is supplied to the turbine, is reheated to 1000 F, and flows to the condenser through a diffusing section in the turbine exhaust and condenser neck. (More about the turbine exhaust arrangement later.) Feedwater heaters number six, of which one is a deaerator. Boiler feed pumps are motor driven, taking their suction from the deaerator and discharging through regulating valves for control of flow.

Steam conditions of 2000 psi and 1000 F/1000 F were about as low as the turbine manufacturers wanted to go for a unit of this size and type. On the other hand, still higher steam conditions showed inadequate return; namely, 6 per cent gross return for 2400 psi over 2000 psi, and also only 6 per cent for 1050 F main steam temperature over 1000 F. Recall that 15 per cent gross return on an incremental investment is considered the breakeven point.

Number of feedwater heaters, that is, number of stages of extraction heating, is a design variable; additional stages of feedwater heating increase initial cost and maintenance cost, but likewise increase plant efficiency. For Meramec 3, the total of annual investment charges on equipment and operating costs appeared minimal with six heaters. The additional equipment cost of seven heaters more than outweighed the savings in fuel afforded by the more efficient cycle; similarly, the additional fuel cost of a five-heater arrangement more than outweighed the concomitant savings in equipment cost. Or to put it another way, going from a five to a six

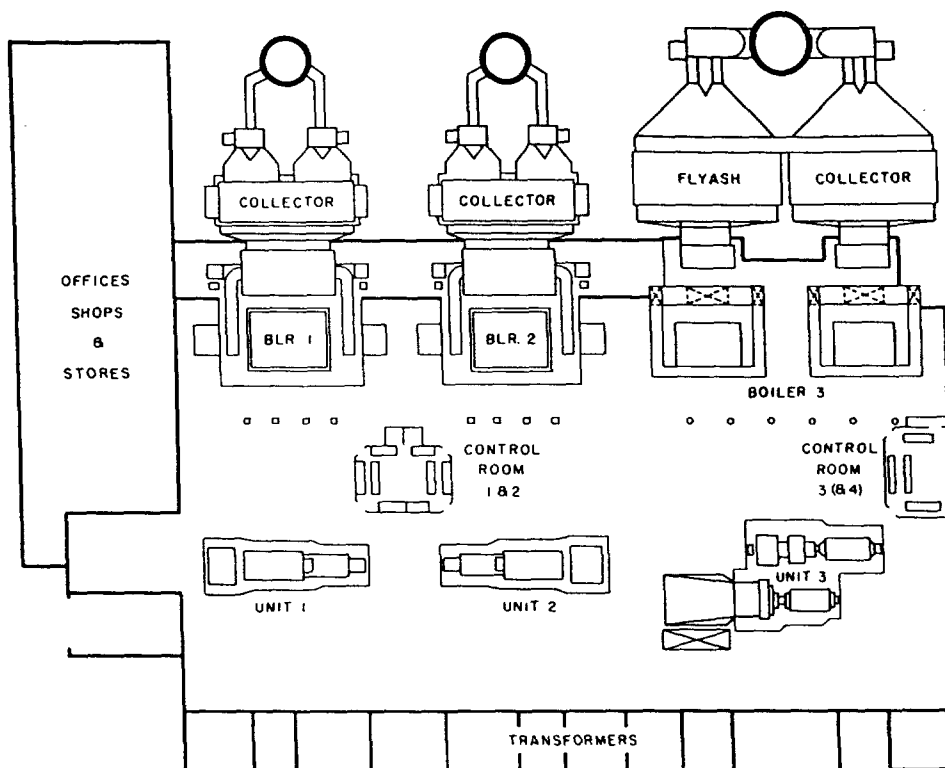


Fig. 4 Meramec 3 floor plan.

TABLE 1 BOILER FEED PUMP DATA

Type Pump	Hp	Plant	Year	Availability
Split-case. .	1750	Venice	1943	96.0
Barrel. . . .	1750	Venice	1948	98.0
Barrel. . . .	1500	Meramec	1953	99.1

heater arrangement showed an attractive return of over 20 per cent on the additional investment required, while going from a six to a seven heater arrangement showed only 13 per cent return on the additional investment. While of course this is an oversimplification of the analyses which had also to take into account disposition of drains, terminal temperature differences, degrees of approach to be used in the feedwater heaters, and placement of pumps in the cycle, it nevertheless correctly demonstrates the method which pointed to a six-heater arrangement for the particular conditions for which this plant was designed.

A deaerator is included in recognition of the great cost of oxygen corrosion in modern units, and in an attempt to minimize this cost to whatever extent possible. Not only is a deaerator provided, but, in addition, the con-

denser is fitted with a deaerating-type hotwell. Positive venting of the deaerator to the atmosphere at all loads from minimum (20 per cent) to full load is accomplished by connecting it to an extraction point of the turbine which is under positive pressure throughout this load range.

Boiler feed pump. Reliability and availability record was summarized in 1955 for recent feed-pump equipment installed in the Union Electric system. The purpose was to develop information to guide in the selection of the size and number of pumps required for Meramec 3. The findings are given in Table 1.

It seemed clear that improvements in design and metallurgy had significantly bettered the reliability of the boiler feed pump.³ However, during recent years both capacity and pressure had increased, so that the boiler feed pump and its supporting electrical installation was becoming a more and more important consideration in the over-all power-plant cost picture. Avail-

³ See "A Qualitative Evaluation of Equipment Reliability," by I. J. Karassik, presented at ASME Semi-Annual Meeting in St. Louis, June 15-17, 1959.

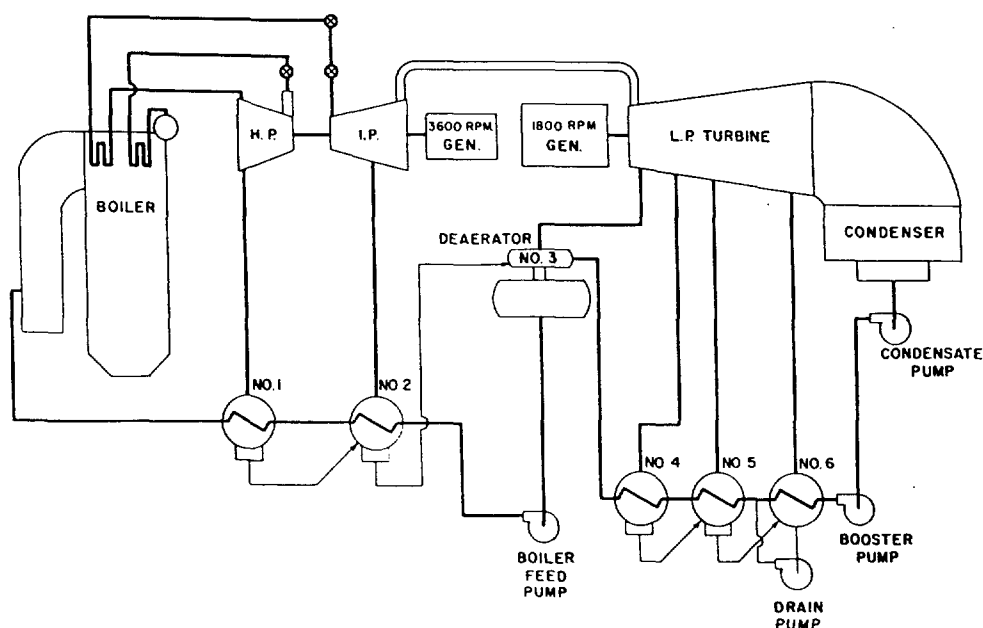


Fig. 5 Meramec 3 flow diagram.

ability figures given in Table 1 for the latest pumps installed at Meramec indicate that a third (spare) half-size pump could not be justified. Nevertheless, at the time this portion of the Meramec 3 design had to be crystallized, it was felt that there was insufficient experience in our own plants, or, for that matter, industry-wide, upon which to omit the spare boiler feed pump. Three half-size pumps, with 5000-hp motor drives, were installed.

As the design of Meramec 4 developed, it appeared that the use of a single full-size turbine-driven boiler feed pump offered attractive savings. However, there was concern for the risk involved during the break-in period, the "infant mortality" type failure during this period jeopardizing the entire output of the 300,000-kw unit. In the meantime, the generally high reliability on the modern boiler feed pump was verified with additional operating experience. The decision was made, therefore, to use the spare pump during the initial year's operation of Meramec 3, until start-up problems could be ironed out, and then to make the pump available as a back-up for the large turbine-driven pump of the Meramec 4 unit. And somewhat surprisingly, it proved considerably less expensive as well as providing a simpler installation, to move the pump physically into the fourth unit area, and disconnect it entirely from the third unit. This was found to be the case despite the value of slightly higher availability of unit 3 if the spare pump were piped into that unit as well as unit 4. So the Meramec 3 unit is now operating

with three half-size feed pumps, although a year or so from now it will have but two such pumps.

Feedwater Cycle. It may be of interest to mention the fluid velocities being used in the feedwater and steam-piping system. For the feedwater cycle, water velocities are about 20 fps at full load and in the main steam piping, 275 fps, both figures somewhat higher than generally used. Here again, these velocities represent an attempt to achieve the best economic balance, using the relationships described, between cost of piping on the one hand, and cost of pressure drop on the other. Pressure drop in these systems adversely affects pumping power, resulting in an increase in net plant heat rate and a decrease in net plant output.

The turbine-generator's principal feature is its axial-flow exhaust. This type design together with a related condenser design, has been described.⁴ In a conventional turbine, steam exhausting from the last-stage buckets is collected and turned downward into the condenser. In the axial-flow design, the exhaust section of the turbine and the condenser inlet hood are pro-

⁴ "Design Features and Development of the Cross Compound Single Flow Turbine with Axial Exhaust," by J. E. Fowler and C. Matney, ASME paper 57-PWR-6.

Also, "Condenser at Portland - With Axial Exhaust Turbine, Introduces New Horizons in Turbine-Condenser Operation," by G. T. Jones, ASME paper 57-PWR-14.

TABLE 2 SILICA DATA

	<u>Meramec 1, 2</u>	<u>Meramec 3</u>
Silica in steam, ppm	0.01	0.01
Drum pressure, psi	1450	2300
Max. silica in boiler water, ppm . .	1.3	0.24
Blowdown, per cent of output	0.25	1.3

portioned so as to convert a substantial portion of the steam's leaving velocity into static pressure. This results in the paradox of steam flowing from the low pressure (but high velocity) area in the last stage exhaust to the high pressure area in the condenser inlet. For a given exhaust pressure at the last stage, then, temperature of condensate returned to the feedwater cycle is higher than for a conventional turbine, improving cycle efficiency. Or stated conversely, for a given pressure in the condenser, steam is expanded in the turbine to a somewhat lower pressure and develops more work than in a conventional turbine.

In all other applications of the axial-flow turbine to date, the condenser has been mounted at about the same level as the turbine itself. However, in the present instance, circulating-water requirements established the elevation of the condenser, and the desire to have No. 3 turbine-generator at the same operating level as No. 1 and 2 established its elevation. As a result, the condenser is located at the basement level, 35 ft below the operating floor.

The better performance of the axial-flow turbine tended to favor it over the single-shaft tandem, although the latter required less expenditure for auxiliaries, foundation, and installation. The axial-flow arrangement also involved use of two fairly conventional generators in place of the tandem's single large generator for which there was no operating experience. In a comparison with a conventional double-exhaust cross-compound unit with significantly greater exhaust area, the higher cost of the latter could not be justified. However, for the larger 300-mw size Meramec 4, the double rather than single 1800-rpm exhaust is required.

Silica deposition on turbine blades has been, industry-wide, one of the more important operating problems. A recent estimate⁵ placed cost to the electric utility industry of resulting loss in efficiency at \$20,000,000 a year. In the recent experience of the authors' company,

it is indicated that if silica in steam can be kept to no more than 0.01 ppm, significant deposits do not form. Further, the ratio between silica in steam to silica in the water from which steam is formed has been established by several investigators, and is known to increase markedly with increase in boiler drum pressure.

An analysis of Meramec 1 and 2 experience and extrapolated requirements for Meramec 3 boiler are given in Table 2.

For Meramec 3, the total average annual cost of blowdown, in terms of heat loss, operating and maintenance charges on demineralizer, and fixed charges on demineralizer and heat-recovery equipment, came to a total of \$20,000 as estimated. This was the expected, and accepted, cost of preventing or minimizing turbine blade deposits. The dual-circulation feature of the Meramec 3 boiler is expected to reduce this boiler blow-down by some 80 per cent.

The dual-circulation design itself is described in a companion paper. Briefly, the design separates the circuit from which steam is supplied to the turbine and the circuit from which blowdown is taken. A higher concentration of silica can be tolerated in the secondary (blowdown) circuit while still holding very low concentrations in the primary (steam-producing) circuit. The reduction in blowdown thus achieved made the increased cost of the dual-circulation feature attractive for this boiler.

Coal handling is entirely from river barges, with the capacity of the coal-handling system such that two-shift operation is required to supply the three units, Natural gas is available on a "dump" basis to carry load on units 1, 2 and a portion of unit 3 load.

Instrumentation and control is an important area of design in which the "economic tools" described at the outset have little application, and yet is of such importance that it must be at least mentioned. We face a perplexing dichotomy: (1) We must keep the central operator's job from becoming too complicated, while at the same time (2) we must give the central operator enough information and control to handle unusual and emergency conditions. At least, most emer-

⁵ "Observed Effects of Deposits on Steam Turbine Efficiency," by J. Angelo, ASME paper 57-A-116.

gency conditions. Under some conditions we accept the proposition that the operator does not have sufficient information or control, or cannot act rapidly enough. In such cases the equipment is designed to shut itself down in a safe manner.

In developing the control board designs, it has been found of value to build full-scale mock-ups of the boards as they will appear in the central control room of the plant. This was done for Meramec 3, and a number of improvements

and consolidations were effected in the dry-run operation of these mock-up boards. Operating, design and manufacturers' engineers all participated in this development.

Much of the Meramec 3 design remains untouched by this paper. However, it is hoped that features of particular interest has been covered, and in a way that has served to illustrate some of the basic economic considerations involved in the design of a modern steam-electric power plant.

RS-000268
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