1 In order that circular tube surfaces can become competitive with extended surfaces of the plate-fin type with respect to volume, weight, and shape, it is necessary to resort to small diameters of the order of $^1/_4$ in. Even then the plate-fin surface will have the advantage of a smaller nonflow dimension.

2 Units fabricated from small-diameter tubular surfaces in high-alloy material will probably have a higher material and labor cost than the plate-fin surface, provided that methods of furnace-brazing fabrication can be developed for the latter.

3 If compact regenerators have to be realized, mechanical cleaning methods cannot be employed. In this respect the plate-fin-type of surface appears to be more cleanable and will probably show less tendency to foul as compared to $^1/_4$-in. tube or similar surfaces.

4 It is believed that these conclusions justify a considerable developmental effort devoted to plate-fin surface fabrication for high-temperature service.

5 The geometric advantages of true counterflow as compared to n-pass cross-counterflow arrangements in many cases may warrant the difficulties of header design.

6 Conceivably, other superior types of compact surfaces are available or can be developed. Firm conclusions regarding each surface can be made only after their basic heat-transfer and flow-friction characteristics are determined. The lack of such data has tended to restrict current regenerator thinking to the shell-and-tube-type surface.

7 In all probability experience will demonstrate that there is no one best surface for the regenerator application and that the designer will need information on a number of surfaces so that the best solution may be made for the particular cycle and machinery arrangement.

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Discussion

D. Aronson.[4] A realistic comparison between tubular heat exchangers and extended-surface plate-fin types is extremely difficult to make. The characteristics of tube-and-shell design have been established as a result of years of experience, and manufacturing costs are readily estimated. In so far as this writer knows, only three models of a large-size plate-fin extended-surface exchanger for high-temperature service have been built. The cost of manufacturing these three pioneer models is several times higher than a tubular design for the same service due partly to high cost of development. However, there are no cost data on operations comparable to those involved in the fabrication of extended-surface regenerators to encourage the view that they will be cheaper than tubular units. Engineers have a tendency to look more favorably upon new designs whose full assortment of hobgoblins have not yet made an appearance.

There is a special field of application for each type. For small installations it is possible to obtain better performance with small-diameter tubing or with closely spaced fins than with larger-size tubing. As the size of the gas turbine increases, the need for small diameters diminishes. This arises from the fact that the effectiveness of a regenerator is a function of the length-to-diameter ratio of passages. In small units either length must be obtained by a multipass arrangement or small diameter must be employed. A comparison such as made by the authors on the basis of dimensions per shp is not strictly valid.

The need for further development of plate-fin surface fabrication is very real as regards brazing techniques, end connections, thermal stresses, fin effectiveness, and resistance to oxidation.

The superiority of plate-fin-type surface for minimum weight and volume mentioned in the text of the article is not borne out by the authors' own calculations as shown in Table 4. In every instance the weight and surface are least for $^1/_4$-in. tubes and in most instances the volume is just a little less for the tubular design. The comparison is as follows:

	Weight, lb	
	$^1/_4$-in. tubes	Best design plate-fin extended surface
Cycle A	1050[a]	1750
Cycle B	436[a]	475
Cycle C	526	1333
Cycle D	2450	5996
	Volume, cu ft	
Cycle A	29.3[a]	27.0
Cycle B	12.0[a]	7.05
Cycle C	14.5	20.6
Cycle D	67.5	86.3
	Surface, sq ft (total of both passages)	
Cycle A	4170[a]	8050
Cycle B	1705[a]	2150
Cycle C	2060	6250
Cycle D	9600	25,700

[a] The figures for the tubular design have been modified proportional to the ratio of the NTU of the tubular design to that of the extended surface so that the comparison will be somewhat closer to a fair picture.

The advantage of the plate-fin surface in having a smaller nonflow dimension is not quite clear from the authors' remarks. The virtue of the plate-fin surface can perhaps be better expressed in a different way. It possesses a greater degree of design flexibility in that the proportion of surface on the hot side to that on

[4] Elliott Company, Jeannette, Pa. Mem. ASME.

the cold side can be varied over a wide range. This flexibility makes it possible to fit the regenerator into any particular geometry with maximum effectiveness for a given pressure drop. Where volume of regenerator is the sole criterion the non-flow dimension should be made as large as possible.

The dimensions of a tubular unit often result in an inefficient ratio of heat-transfer coefficients on the cold side to that on the hot side, and since the surface areas on the two sides are related directly as the diameter ratios, there is no opportunity for improving the utilization of surface. As a result, it will often be found that for a particular geometry of available space for the regenerator the plate-fin design can give a higher effectiveness for the same pressure drop. The price to be paid for this better performance will be a greater surface area, possibly a greater weight, and a greater cost.

The writer of this discussion presented at the ASME Annual Meeting, December, 1949, a method of designing for optimum performance, which includes consideration of some of the foregoing factors.

Authors' Closure

The authors agree with Mr. Aronson that a realistic comparison of general validity between tubular and extended surface gas-turbine regenerators is next to impossible to make. Even for a particular application, a comparison made now would not be valid at some later time because of rapidly changing conditions with respect to costs, methods of fabrication, and the development of new surfaces. Nevertheless, if limited comparisons can be made they should be made with as complete a realization as possible of the limitations. These are the "hobgoblins" referred to by Mr. Aronson. If engineers fail to look ahead, that is, "look favorably on new designs," the gas-turbine development will not overcome the advantage of the entrenched position now occupied by the conventional prime mover systems.

The comparison of regenerator geometry on the basis of non-flow dimension per 1000 shp will allow ready visualization of the size of heat exchanger required for any plant capacity, large or small. Mr. Aronson's objection to this basis is not clear to the authors.

There is no disagreement between the authors' text and the comparisons presented by the discusser regarding the "superiority of plate-fin-type surfaces." However, it was perhaps not emphasized that $^1/_4$ in. tubes probably represents the most compact circular tube surface that is practical while it is quite probable that more compact and more effective plate-fin surfaces exist or can be developed. As a matter of fact, current studies (12) confirm this view.

It is obvious from the first of Equations [7] that an increase of volume brought about by a change of surface will tend to decrease the nonflow dimension. It should be pointed out, however, that for a *given surface* the minimum volume design will also be very close to the minimum nonflow-dimension design. The increase of volume which produces a smaller nonflow dimension comes about from the use of a less compact surface. Thus the use of compact heat-transfer surfaces tends to yield small-volume heat exchangers but with large nonflow dimensions, as can be seen by an examination of the various designs for Cycle (A). If small volume is the only criterion then a large nonflow dimension will have to be accepted, as Mr. Aronson points out. It seems to the authors, however, that both "good" shape and "small" volume and "high" effectiveness are criteria which have to be in some measure mutually compromised in the usual design.