Selecting high-strength alloys for furnace hardware

The author outlines why components fail, and relative strengths and weaknesses of cast and wrought components, before concluding that "less consumable" consumables make sense in a quality heat treat shop.

by M. F. ROTHMAN

It should come as a surprise to no one that heat treating furnace hardware does fail. The surprise comes when the failure occurs at the worst possible time, like when the last batch of a critical order is due the next day. The point is that while such failures are not perfectly predictable, they can be anticipated. The anticipation can take the form of a more robust design, or it can mean building the component in question out of a more robust material.

To appreciate the factors that enter into selecting more robust materials of construction for furnace hardware and consumables, it is first necessary to understand why furnace components fail. Overlooking general abuse and mishandling, which unfortunately are not insignificant causes of failure, some of the common ways by which components fail include:

—distortion from overload or thermal cycling;
—thermal or environment-induced embrittlement; and
—loss of section thickness due to oxidation.

Distortion of high-temperature furnace parts such as retorts, muffles, baskets, grates, etc., occurs commonly. The source of the distortion can generally be traced to one or both of two factors: either the component is overloaded, or the component is designed in such a way that it is subject to high thermal stresses when heated and cooled.

In the first case, the problem is simple enough. If the component is overloaded, reduce the load, thicken the section size, or go to a higher strength material. When deciding to what degree the component is overloaded, it is important to remember the difference between short-term and long-term strength, as illustrated in **Fig. 1** (p. 24). Here, the short-term yield strength indicated that, for example, 230 alloy is about twice as strong as RA330 alloy at 1800°F. But for long-term rupture capability at lower, more meaningful stress levels, 230 alloy lasts more than 60 times as long as RA330 alloys.

Turning to the case in which distortion occurs as the result of thermal cycling, more often than not the problem can be the result of variations in cooling or heating rates experienced by different parts of the component. The parts either have different thicknesses or see different conditions. The point is that you can't develop thermal stresses without constraint on the component. No matter how fast you heat or cool a heat treat basket, for example, if all parts of the basket expand on heating or contract on quenching at the same rate, then little or no thermal stress will develop. In actual practice, however, such uniform heating or cooling is difficult to achieve. To minimize distortion from thermal cy-

	Ni	Fe	Co	Cr	Mo	W	Mn	Si	Al	N	C	Other
Haynes alloy No. 230	Bal.	—	—	22	2	14	.5	.4	.3	—	.10	.02 La
Haynes alloy No. 556	20	Bal.	18	22	3	2.5	1.0	.4	.2	.2	.10	.6 Ta, .02 La, .02 Zr
Alloy No. 601	Bal.	15	—	23	—	—	1*	.5*	1.4	—	.10*	—
RA330 alloy	35	Bal.	—	19	—	—	1.5	1.3	—	—	.05	—
Type 304	9	Bal.	—	19	—	—	2*	1*	—	—	.08*	—
Type 446	—	Bal.	—	26	—	—	1.5*	1.0*	—	—	.15*	—
HK alloy	20	Bal.	—	26	—	—	2*	2*	—	—	.40	—

*Maximum

Table I: Nominal composition of alloys

Financial criteria	Component performance requirements:
• Material cost • Fabrication cost	Adequate strength: Yield strength, stress rupture strength
• Maintenance cost • Downtime	Thermal cycling, thermal embrittlement: Tensile ductility, thermal stability, thermal expansion
• Product losses • Liability	Environmental degradation: Carburization resistance, nitriding resistance, oxidation resistance

Table II: Criteria for selecting material

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cling, designing with uniform component section thickness and using high-strength alloys with low thermal expansion characteristics is recommended.

Thermal and environment-induced embrittlement of furnace parts are important causes of failure. Few, if any, of the common heat-resistant stainless steels and alloys suffer environment-induced embrittlement in air or combustion environments that are not reducing; however, many of these same materials have intrinsic susceptibility to thermal embrittlement. Austenitic stainless steels, for example, will embrittle from sigma phase formation when exposed for prolonged times at intermediate temperatures. So will a number of the lower-alloy ACI casting alloys. Most of the higher nickel iron-nickel-chromium and nickel-base materials such as RA330, 800H, 600, 601, and 230 alloys do not exhibit such problems. Composition of some typical alloys used for furnace hardware are given in **Table I**.

As for environment-induced embrittlement, the two common modes of failure relate to carburizing and nitriding. Exposed to the same environments being used to treat parts, furnace hardware will eventually crack due to cumulative carburizing or nitriding coupled with loading or thermal-cycling-induced stresses. The only real choice here involves material selection for the exposed components.

In much the same vein, furnace components fail due to oxidation in air or combustion gases, evidenced in the form of section thinning. This usually proceeds until either a perforation-type failure occurs in, say, a retort, or the thinning of a structural member causes an overload failure, as in a basket. Again, the only choices in terms of minimizing this type of failure are to use a thicker section or select a more oxidation-resistant material.

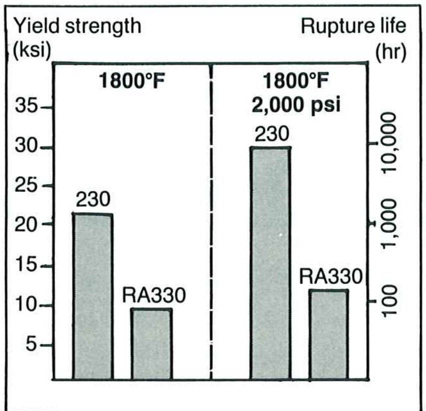

Fig. 1: Comparison of the yield strength and stress rupture life capabilities of RA330 and 230 alloy at 1800°F

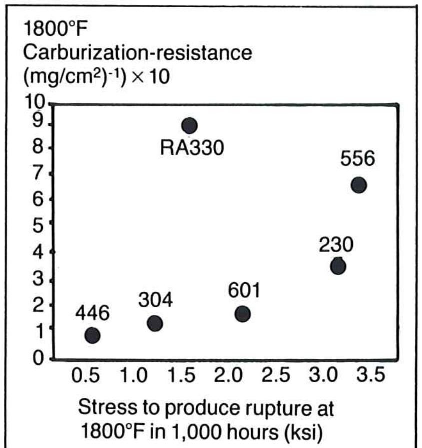

Fig. 2: Carburization-resistance vs. stress rupture strength at 1800°F. Resistance plotted as inverse of carbon absorption per unit area for 55 hour exposures in Ar–5%H_2–5%CO–5%CH_4. Resistance for types 446 and 304 estimated based upon composition.

In selecting a more oxidation-resistant alloy, the type of test data you look at can lead to different conclusions. Oxidation is often equated only with scaling of materials. Indeed, steels and stainless steels are normally characterized by "scaling rates," which rank weight change per unit area per unit time. This is not a good way to judge the performance of materials, since it does not address the issue of internal attack. As will be discussed later, oxidation-resistance measurements that include evaluation of internal damage (which does serve to reduce effective metal thickness) can be quite damning to what otherwise might be considered very resistant alloys. Also, cyclic combustion environments prove to be much more severe than would be predicted from simple flowing air tests.

Typical components/service needs

Regardless of the type of use any heat treating furnace hardware may be subjected to, the two common requirements for the material employed are high-temperature strength, and either castability for cast components or good fabricability for wrought ones.

Beyond that, it comes down to specifics. In the case of baskets, the strength must be supplemented with resistance to thermal shock and/or repeated thermal cycling. This means the material must have good ductility and maintain it in the face of thermal

	230		556		601		RA330		304		446	
Temperature (ºF)	UTS (ksi)	YS (ksi)	UTS (ksi)	YS (ksi)	UTS (ksi)	YS (ksi)	UTS (ksi)	YS (ksi)	UTS (ksi)	YS (ksi)	UTS (ksi)	YS (ksi)
70	125	57	116	55	108	35	79	37	84	37	77	51
1000	103	40	90	31	84	23	70	26	59	19	52	35
1200	98	40	83	31	74	26	56	22	46	17	24	14
1400	88	43	69	29	45	27	34	19	29	14	12	6
1600	63	37	49	28	23	19	19	16	18	7	6	—
1800	35	21	31	19	12	10	11	9	—	—	3	—
2000	20	11	16	9	7	5	—	—	—	—	1.5	—

Table III: Typical tensile and yield strength for various materials (Bar and plate)

amounts of internal penetration and void formation, with consequent loss of load-bearing capability. Alloy 230 provides the best resistance of the alloys tested, being about twice as resistant as 556 alloy, which is in turn about twice as resistant as RA330 alloy.

The carburization data in **Table V** was generated by exposing samples in flowing Ar-5%H_2-5%CO-5%CH_4 (unit carbon activity, low oxygen partial pressure) and measuring the actual carbon absorption per unit area by chemical analysis and weight change determinations. Unfortunately, the stainless steels were not included in the test; but they can be expected to exhibit fairly poor resistance. Alloy RA330 displays very good resistance to carburization, based largely upon its silicon content. Alloy No. 556 is not very far behind, displaying about twice the resistance of 230 alloy, which in turn is about twice as good as alloy 601.

Nitriding resistance has always been equated with high nickel content in alloys, and the results of tests conducted at 1200ºF in cracked ammonia shown in **Table VI** confirm this. Iron-base materials, such as 556 alloy, RA330 (not shown), type 304 stainless and type 446 stainless (not shown) all will exhibit significant nitriding attack in comparison to the nickel-base alloys. In these tests, 230 alloy is marginally better than alloy 601, while both far outdistance the iron-base alloys in resistance to nitriding.

Wrought vs. cast materials

The two principal driving forces for using cast heat-resistant materials for furnace components are their high strength and relatively low cost. The penalty one pays for using these

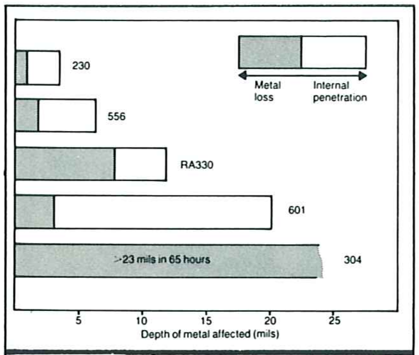

Fig. 6: Oxidation damage measured for 1,000 hour exposure to 1800°F combustion gases with severe cycling to lower temperatures

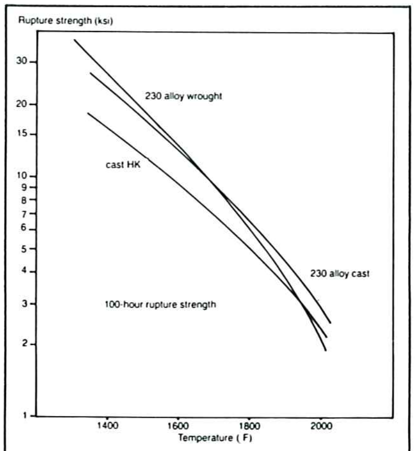

Fig. 7: Comparison of 100-hour stress rupture strengths for wrought and cast 230 alloy vs. cast alloy HK

materials is their intrinsic low ductility, with related thermal cycling problems.

An interesting comparison between the strengths and ductilities of a typical cast alloy, type HK, and both the wrought and cast versions of a high-strength material, 230 alloy, are given in **Fig. 7** and **Table VII**. As can be seen from **Fig. 7**, the strength levels exhibited by wrought 230 alloy are superior to type HK cast properties up to about 1900ºF, and slightly less at higher temperature. On the other hand, when 230 alloy is prepared as a casting, superior strength is evidenced to temperatures at least as high as 2000º-2100ºF.

Interestingly enough, 230 alloy as a casting does not display the lower tensile ductility commonly associated with cast alloys at lower temperatures. As may be seen from **Table VII**, 230 alloy has significant ductility advantages, and thus presumably thermal cycling resistance advantages, over alloy HK. This same behavior will likely be observed for other solid-solution-strengthened alloys that do not depend largely upon carbon for strength at high temperature.

Summary and conclusions

It has been shown that the case for selecting high-strength materials, such as 230 alloy or 556 alloy, for long-lived heat treating furnace components can make both technical and economic good sense. Although up-front costs may be significantly higher than traditional short-lived alloys, the performance advantages of these high-strength materials in virtually all properties of interest make for lower costs over the life of the components. This becomes more evident as focus shifts from consumable items, such as baskets, trays and fixtures, to more important components such as retorts and muffles, and critical parts such as furnace fans. In addition, the potential for use of these materials is not limited to the wrought form. Castings in such solid-solution-strengthened alloys can exhibit significant advantages in performance compared with traditional casting materials. HT

Alloy	Nitrogen absorption for 168-hour exposure in cracked ammonia (mg/cm^2)
230	0.7
601	1.1
556	4.9
304	9.7

Table VI: Nitriding resistance of alloys at 1200ºF

Temperature (ºF)	230 alloy wrought	230 alloy cast	Alloy HK cast
70	48	38	14
1000	45	36	17
1200	45	35	14
1400	48	36	20
1600	66	30	28
1800	71	40	46
2000	70	47	70

Table VII: Tensile ductility of alloys

and environment-induced embrittlement from exposure to temperature and whatever atmosphere is involved.

The same requirements are applicable for furnace fixtures cycled in and out of the furnace, such as trays, spacers, chains, hooks, etc. Static components, such as grates or insulation studs, are somewhat less demanding, as they are in the furnace essentially all of the time, and are not subject to severe cycling. But even these will eventually be subject to the same criteria.

A diagram outlining the important criteria involved in the selection of a material for a typical furnace hardware application is presented in **Table II**. In the case of the financial criteria, it is tempting to stop after the first two items when dealing with most consumable items like baskets and fixtures, or thermocouple protection tubes. Considering component performance criteria becomes somewhat academic if one looks only at these up-front costs. But in a quality shop, where the limiting factor in the life of a basket is not when it gets run over by the forklift, there are real savings to be realized when the rest of the financial criteria are considered and an appropriately long-lived material is selected for the job. Some heat treating shops have taken this perspective, and "less consumable" consumables are becoming more common.

Attention to the "downstream" financial criteria in selecting materials for components such as retorts and muffles is a more well-established practice than in the case of consumables. Here, the initial engineering and fabrication costs are much more significant relative to material costs, and maintenance/downtime issues are readily quantifiable. Again, the criteria for materials performance listed in **Table II** apply; however, as these are retorts and muffles, the resistance to air or combustion gas environments on the outside always applies in addition to the material requirement for resisting the process environment on the inside.

Even more emphasis should be placed on the product loss and liability considerations when dealing with such components as high-speed furnace fans, where the failure of the component in service can mean a ruined batch, or worse. Reliability is a key

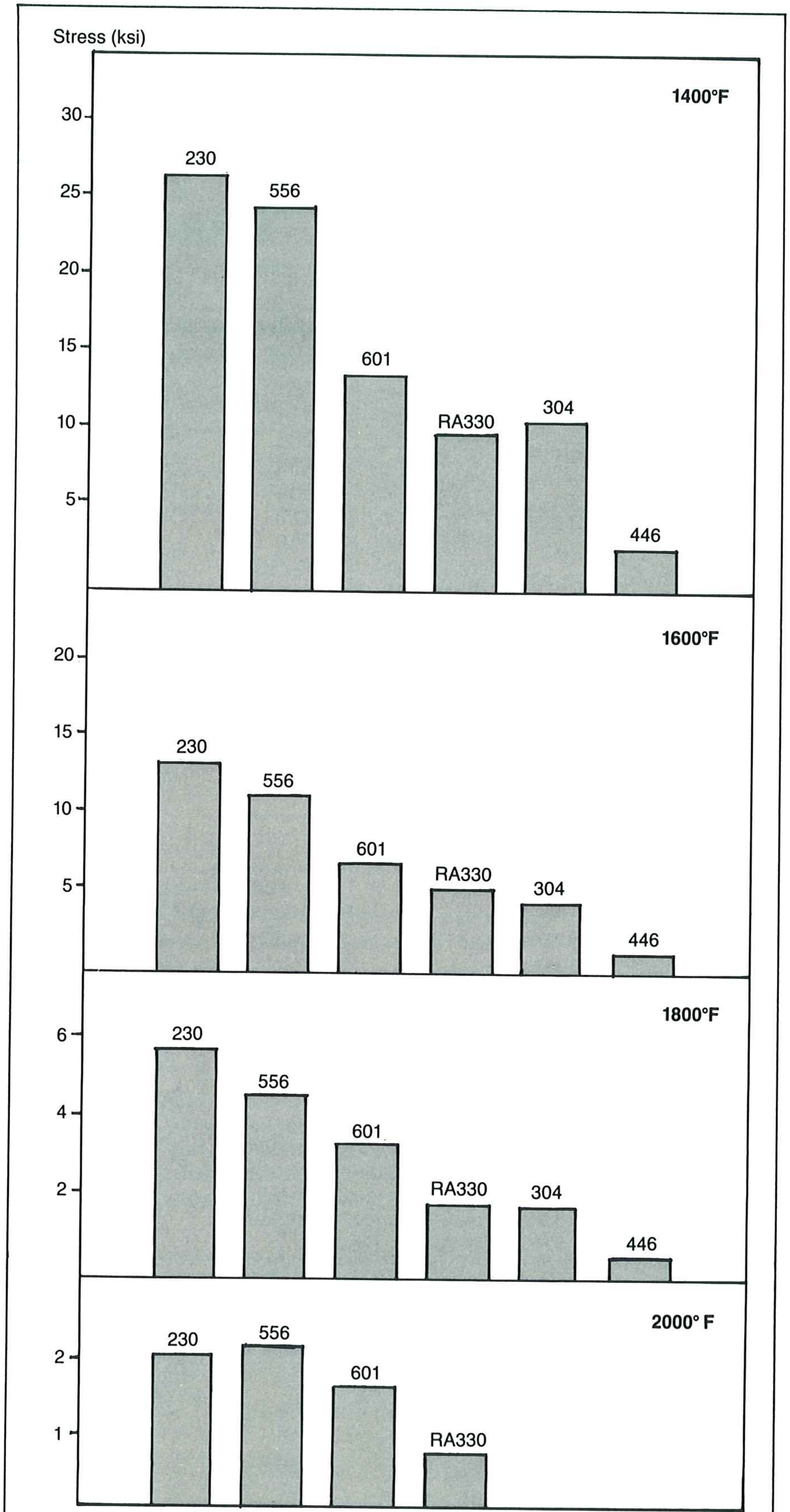

Fig. 3: High-temperature 100-hour stress rupture strengths for various heat-resistant alloys

High-strength

concern, since failures will be sudden. All of the performance criteria given in **Table I** apply, with special emphasis on resistance to thermal cycling under high stress conditons, as might be encountered in gas quenching operations. But of all the applications for furnace fans, the ones involving carburizing are the most demanding. These fans must resist carburization and have high strength to cope with high rotational speeds. This is in addition to handling the repeated thermal cycling. Not many materials can resist carburization and exhibit high strength at carburizing temperatures up to 1800°F, let alone handle the cycling. **Fig. 2** illustrates this well.

Wrought alloy properties

As mentioned earlier, the key properties of interest are tensile yield strength and, more importantly, stress rupture strength. The ultimate tensile and yield strengths as a function of temperature are given in **Table III** for several alloys for temperatures up to 2000°F. Corresponding 100-hour stress rupture strength data is given in **Fig. 3**. Tensile and yield strength advantages of about 2:1 are apparent for 230 and 556 alloys in comparison to the well-known alloy No. 601 once temperatures reach 1600°F or more. In turn, alloy No. 601 exhibits a slight advantage over RA330 alloy, which is significantly stronger than type 304 stainless steel past 1400°F. Type 446, a common ferritic stainless, is easily the weakest material in tensile strength above 1200°F.

In examining the stress rupture data, the same basic strength relationships are observed to exist between the various materials; however, as described in **Fig. 1**, the higher-strength alloys can exhibit more than a factor-of-10 advantage in time to rupture at the same stress level, as shown in **Table IV**. This means that the same component geometry in a strength-limited application can often be made to last as much as 10 times longer, simply by upgrading the material of construction.

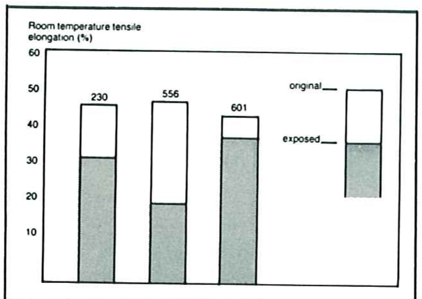

Fig. 4: Tensile elongation at room temperature before and after exposure for from 6,000 hours (601) to 8,000 hours (230 and 556) at 1400°F

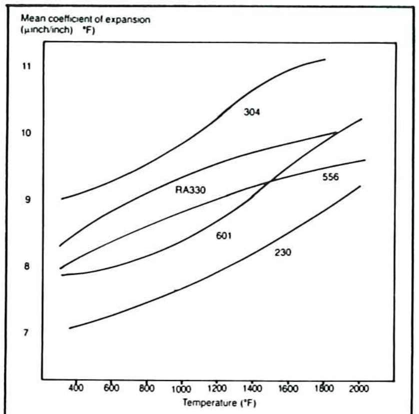

Fig. 5: Mean coefficient of thermal expansion for various alloys

The ductility and thermal stability of these materials, which relate to their ability to handle thermal shock and thermal cycling, are described in **Fig. 4**. The ductilities of these alloys are all quite good, and the thermal stability of 230 alloy is comparable to that of 601. Alloy 556, while still exhibiting good stability, is not quite as good as the other two alloys.

Thermal expansion coefficient is a relevant property when considering thermal fatigue of furnace components. The lower a material's expansion characteristics are, the less the stress build-up experienced by a component of that alloy during heating and cooling. Mean coefficient of thermal expansion data are plotted against temperature in **Fig. 5** for the alloys of interest. Clearly, the higher expansion characteristics of type 304 stainless and RA330 alloy do not speak well for their thermal fatigue performance. On the other hand, the low expansion characteristics of 230 alloy mean that it should display excellent thermal fatigue behavior, particularly when coupled with its high strength and ductility. The behavior of alloys 556 and 601 are intermediate, though 556 appears to tend lower above 1600°F.

Turning to environment-resistance properties, the carburization-resistance and nitriding-resistance properties of these alloys are described in **Tables V** and **VI**, respectively, while resistance to combustion gas environments is compared in **Fig. 6**. The 1800°F oxidation test results presented in this figure were generated by exposing samples to high-speed combustion gases produced by burning a mixture of No. 1 and No. 2 fuel oils at an air: fuel ratio of about 50:1, and cycling the samples to under 500°F every half hour by air blast.

Under these conditions, ordinary stainless steels such as type 304 are consumed very quickly. Alloy 601, while exhibiting reasonable resistance to thinning, displays significant

Test conditions	Time to rupture (hours) 230	556	601	RA330	304	446
1400°F & 10,000 psi	210,000	61,000	600	100	160	1
1600°F & 4,500 psi	51,000	29,000	1,200	230	100	1
1800°F & 2,000 psi	8,700	11,000	1,000	130	70	1

Table IV: Time to rupture for constant conditions (Bar and plate)

Alloy	Carbon absorption for 55-hour exposure in Ar-5%H_2-5%CO-5%CH_4 (mg/cm^2)
RA330	<1.0
556	1.3
230	2.5
601	4.8

Table V: Carburization resistance of alloys at 1800°F

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PROPERTIES DATA

The properties listed in this publication are average values based on laboratory tests conducted by the manufacturer. They are indicative only of the results obtained in such tests and should not be considered as guaranteed maximums or minimums. Materials must be tested under actual service conditions to determine their suitability for a particular purpose. All data represent the average of four or less tests unless otherwise noted.

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H-3076

Printed in U.S.A.