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Heat-Treat Rack Material Selection Based on Thermal Performance

The choice of heat-treat rack material is important for every heat-treat operation, whether independent or captive. The selection of rack-material composition is typically dictated by the operating conditions of the specific heat-treating process involved.[1] The furnace operator must select materials capable of performing within these conditions, and the decision often balances performance against purchase price.

Performance is typically characterized by a material's chemical and thermal stability as well as secondary considerations such as ease of fabricating structures using common techniques (e.g., welding). Chemical stability refers to a material's resistance to reaction with the process atmosphere, such as oxidizing and carburizing conditions. Thermal stability encompasses a range of temperature-dependent mechanical properties, including ductility, creep strength and fatigue characteristics.

Three common rack materials for heat-treat applications where temperatures exceed 815°C (1500°F) are heat-resistant steel alloys, molybdenum alloys and carbon-carbon composites. Table 1 displays a variety of relevant properties for these three materials.

RA 330 is a common wrought alloy (ASTM B536 or B512 or UNS NO8330) used in rack construction by the heat-treating industry. This iron-based alloy incorporates 18-20% Cr, 34-37% Ni, 1-1.5% Si and 0.4-0.8% C. Cast austenitic stainless steels (ASTM A297) that have very similar compositions are also used because of their good thermal-shock resistance, resistance to carburization and relative stability in thermal cycling. These materials are often known as HU, HR-5 or HR-15. Both the cast and wrought materials have very similar thermal properties. So, for the purposes of this paper, RA330 will be used as a representative high-temperature steel alloy for comparison to other materials.

Molybdenum alloy (aka "moly") typically refers to the TZM alloy of molybdenum. TZM contains Ti, Zr and carbon that form fine precipitates and give it high-temperature strength and durability. Moly can also refer to the Mo-La alloys, which are strengthened by fine La_2O_3precipitates instead of carbide precipitates. Again, for the purposes of this paper, TZM will be used to represent molybdenum alloys.

Carbon-carbon composite refers to a composite of carbon fibers with a carbon matrix, essentially fiber-reinforced graphite, which is growing in importance in the industry. It retains the thermal-shock resistance and conductivity of graphite as well as the tendency to increase in strength as temperatures increase. In addition, the fiber reinforcement adds fracture toughness and creep resistance to its benefits.

Total Cost of Rack Ownership

Once operating conditions for a heat-treating rack have been defined, the available list of rack materials can be narrowed to those capable of performing in this environment. This list is further refined by considering the cost of each material option. While a straightforward decision based on purchase price is certainly reasonable, there are additional dimensions of cost that can be missed by taking this approach. When one speaks of the “total cost” of a purchasing decision, care must be taken to include aspects such as rack lifetime, thermal responsiveness and part quality associated with each rack material. Each of these aspects can contribute to the overall cost of a rack solution.

The longevity of rack materials can be reduced by processes such as deformation, embrittlement and loss of strength. Alloy racks are often used near their natural thermal limit and distort or deform over time due to thermal fatigue. Typical alloy-rack lifetimes range from 12-18 months. If pushed beyond their useful life, there is a risk of fracture during processing, putting treated parts at risk of damage.

Moly racks suffer from reduced fracture toughness after high-temperature exposure, and care must be taken when handling them to avoid rack damage. Carbon-carbon composite racks have relatively stable fracture toughness, and their strength actually increases as temperatures increase. With these lifetime considerations in mind, the price of a rack solution should incorporate purchase price divided by the lifetime of the rack.

Thermal responsiveness is a design element often overlooked when selecting rack materials. The speed at which a rack construction can be taken to process temperatures as well as reduced in temperature (quenched) can have a large impact on the economics of a heat-treat operation.

The product of specific heat capacity and weight is heat capacity, a measure of how much thermal energy must be input or removed to raise or lower temperature of the material. Rack materials with high heat capacity may have variation in temperature between top and bottom of the rack, which can lead to variation in the microstructure, hardness or dimensional stability of parts on the rack. Low-heat-capacity rack materials enable shorter cycle times and higher throughput due to their quick heating and cooling nature. In order to illustrate the impact of heat capacity on rack materials, a thermal model previously developed will be used here to compare three rack materials.[4]

Experimental Details

A numerical simulation of the heat-transfer environment consisting of one layer of a furnace rack system was constructed in order to compare the fixture materials. For purposes of this paper, a 24-inch x 36-inch (609 x 914 mm) rack was considered. The usual complex construction was simplified by flattening the rack into an equivalent thickness, which was determined by adjusting the thickness of the plate such that the volume of the plate multiplied by the material density equals the weight of a typical rack.

The furnace environment constructed for the purpose of simulation was a large, isothermal chamber that had already reached the heat-treat temperature and was unaffected by entry of the rack or fixture. The emissivity of rack materials is summarized in Table 2, as estimated from handbook values.[5,6] While this is a greatly simplified furnace and rack model, it allows the relative material performance to be evaluated.

A further simplification of the situation was to exclude the parts being heat treated because part geometry and loading are greatly variable in industry practice. The applied assumptions were consistent throughout each material and model result. Therefore, the limitations of the simplified model should not significantly alter the resultant trends.

For both heating and cooling simulations, the fixture was immediately placed into heat-treat or cooling conditions, respectively. In each case, the tray was assumed to have reached the previous temperature uniformly before changing conditions. The tray dimensions, as well as other simulation settings for these materials, are provided in Table 2.

Results

The simulation results indicate that carbon-carbon composite tray centers reach 870°C (1600°F) austenitizing temperature 29% faster than molybdenum fixtures and 76% faster than RA330 fixtures (Table 3). Also, the temperature profiles (Fig. 2) reveal a difference between the center and surface temperatures of the RA330 volume due to the low thermal conductivity of that material. Table 4 shows the model calculation for the energy required to heat the fixture materials, where it can be seen that both moly and carbon-carbon composite require significantly less energy to heat than RA330 does.

Similarly, the cooling profiles show that the RA330 fixture displays a difference in temperature from the surface to center due to the thermal conductivity. Moly and composite fixtures cool faster than the RA330 fixtures (Table 5).

Discussion

The simulation shows that both carbon-carbon and molybdenum fixtures reach austenitizing temperature and cool to tempering temperature significantly more quickly than RA330 fixtures. Speed to temperature has implications on the total cycle time for a heat-treat furnace run. The faster the racks get to temperature, the faster the parts get to temperature, allowing increasing ramp rates to improve productivity. In addition to the productivity aspect, higher-thermal-conductivity fixture materials will have more uniform temperature throughout the heat-treat cycle. In turn, this will reduce the microstructural variation and residual-stress-induced distortion in heat-treated product.

In terms of energy savings, assuming the rack system is about one-third of the total load in the furnace, switching to molybdenum racks could save as much as 6% of the energy input needed to heat the furnace, while switching to carbon-carbon composite racks could save as much as 20%.

Summary and Next Steps

Thermal-model results indicate that carbon-carbon composite heat-treating racks heat three times faster than moly-alloy racks and four times faster than heat-resistant steel-alloy racks. Carbon-carbon composite racks also provide energy savings while providing productivity increases. However, RA330 and moly racks are less reactive with carbon-sensitive compositions.

In order to take full advantage of carbon-carbon composite racking, heat-treat furnace operators currently must utilize specially tailored ceramic-tile inserts to isolate parts from the rack. These inserts can obstruct atmosphere flow during rapid gas-quench operations, as well as add complexity to load builds.

The need exists for development of eutectic-barrier surface treatments for carbon-based rack systems. While preliminary work on potential eutectic barriers has been completed,[7]successful demonstration of the durability and low reactivity of these coatings will enable the thermal advantages of carbon-carbon racks to be more widely utilized in the heat-treating industry.

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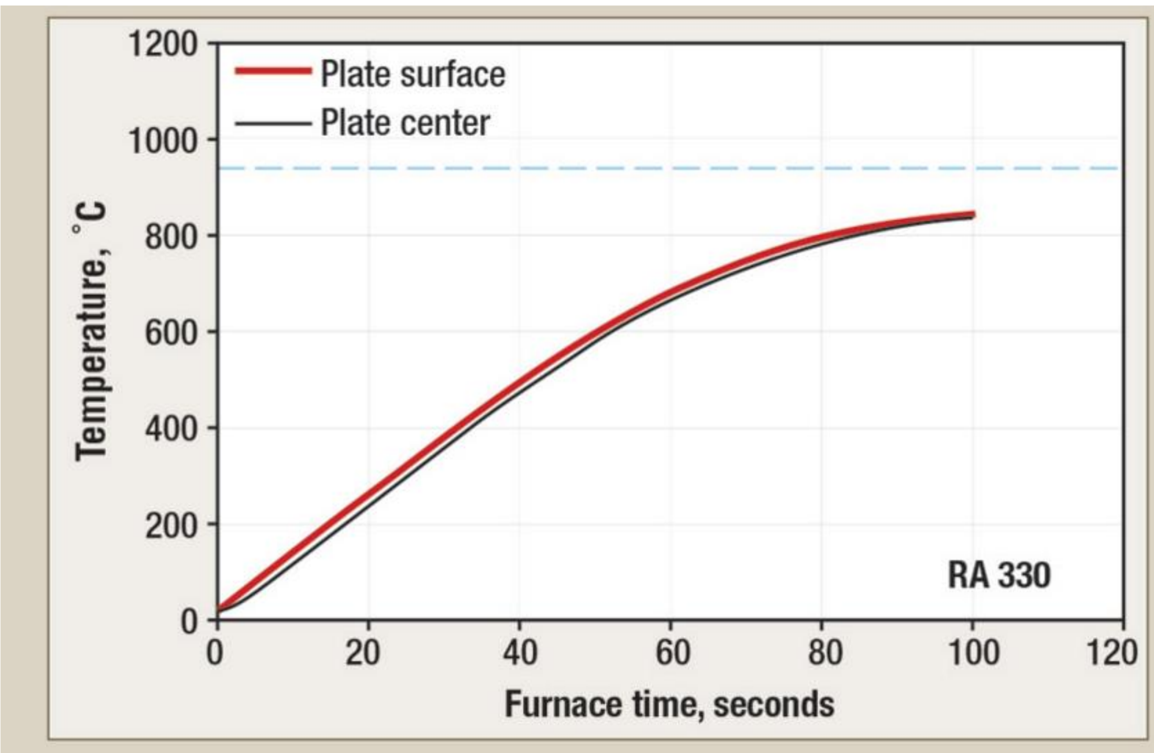

Fig. 1a. Calculated heating temperature profiles of the tray materials

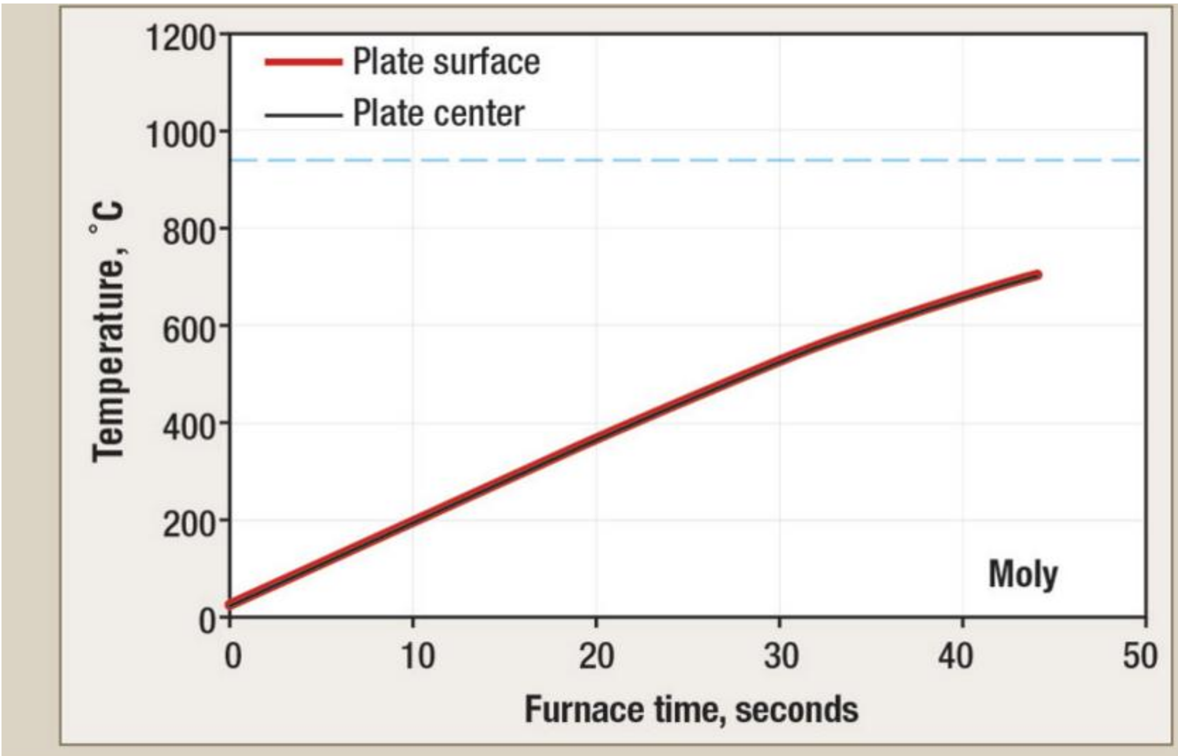

Fig. 1b. Calculated heating temperature profiles of the tray materials

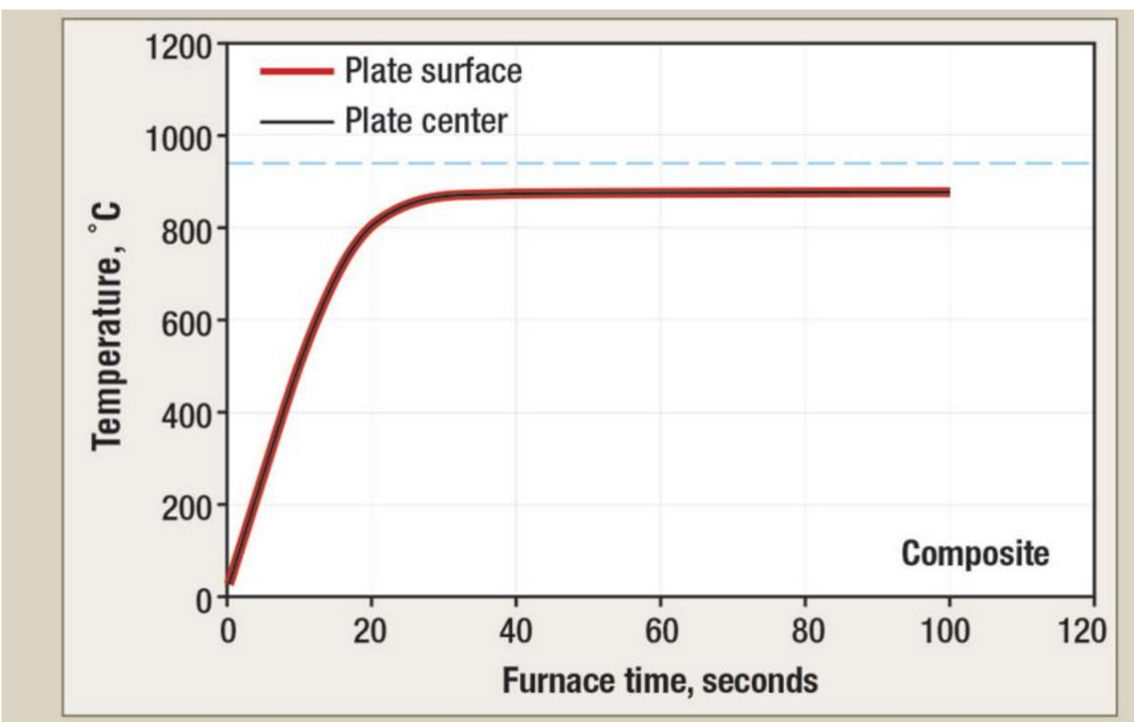

Fig. 1c. Calculated heating temperature profiles of the tray materials

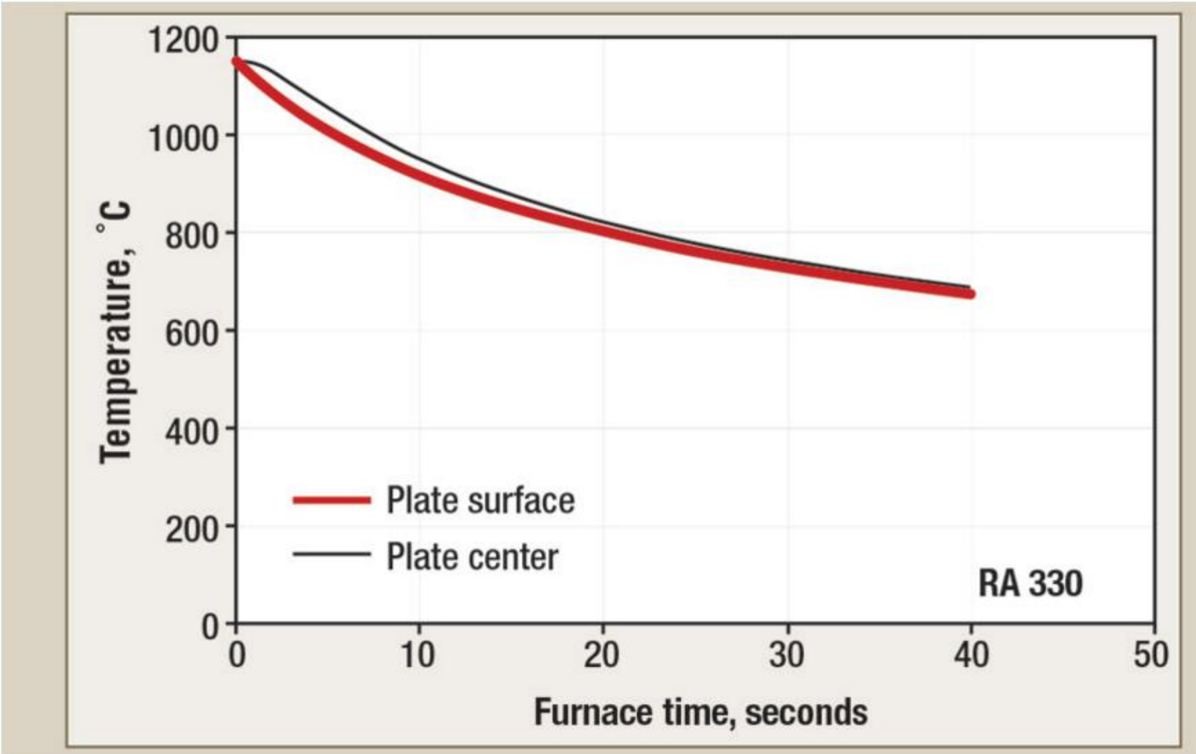

Fig. 2a. Calculated cooling temperature profiles of the tray materials

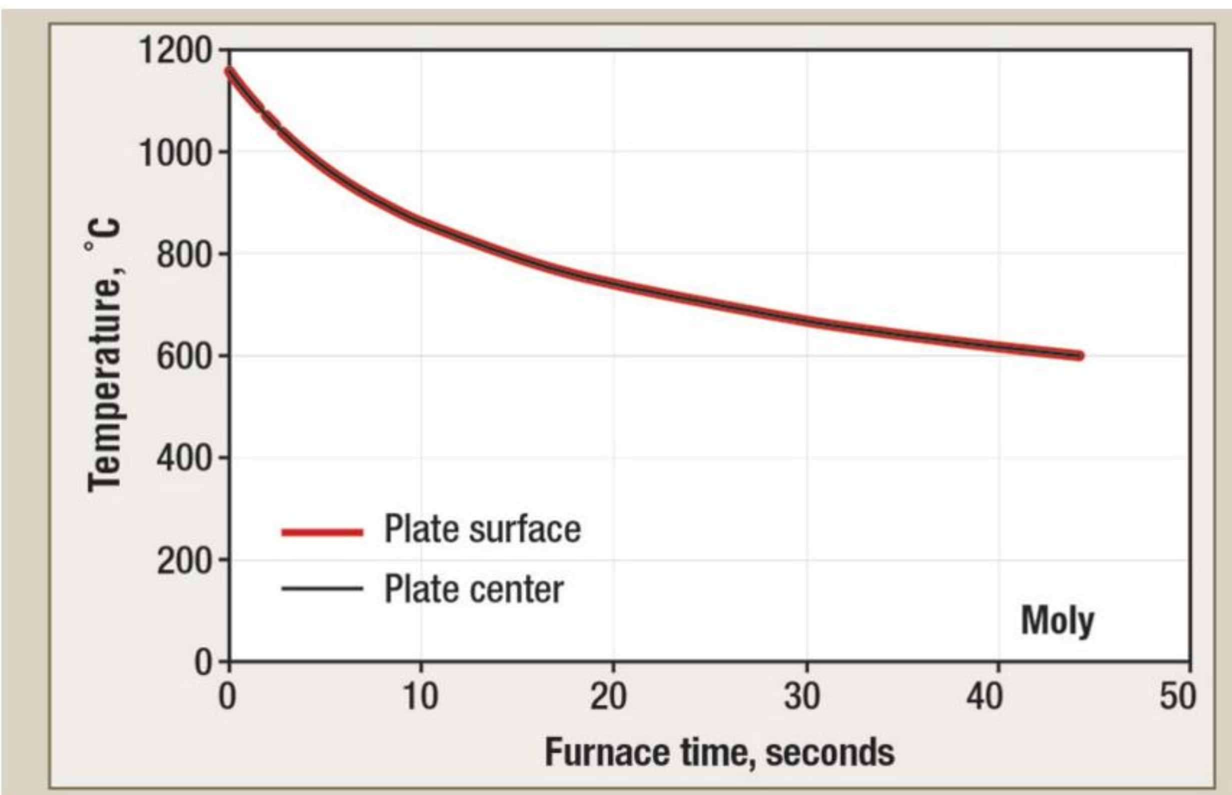

Fig. 2b. Calculated cooling temperature profiles of the tray materials

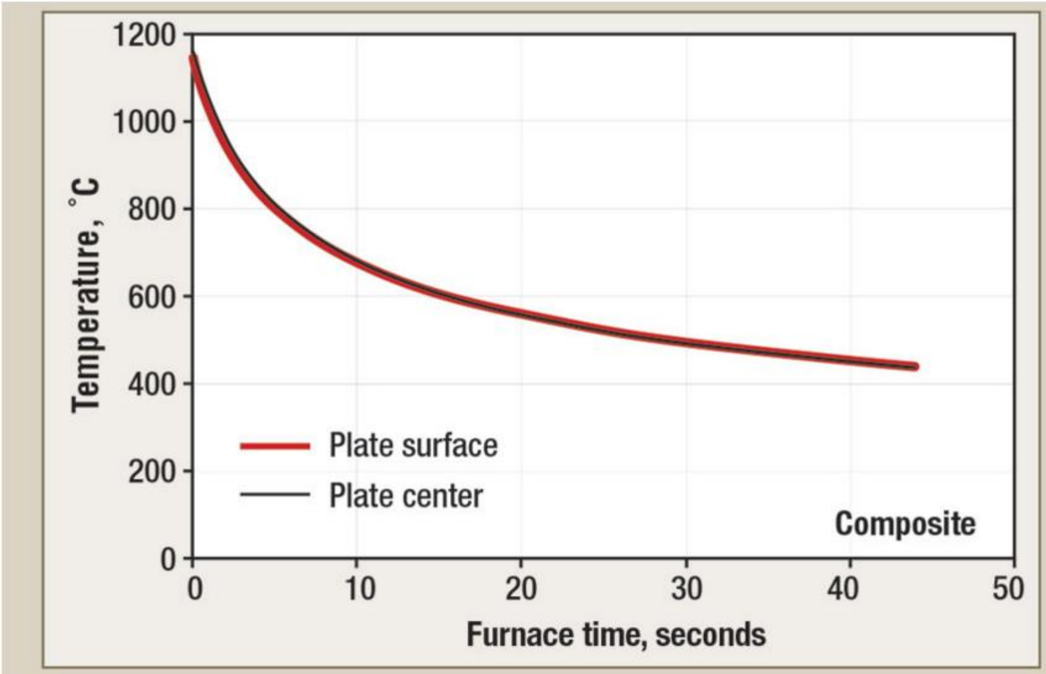

Fig. 2c. Calculated cooling temperature profiles of the tray materials

Table 1. Physical properties of rack materials[2,3]

Tray properties	RA 330	Molybdenum	C-C composite (Carlisle HL grade)	Units (SI units)
Specific gravity	0.29 (7.95)	0.37 (10.22)	0.059 (1.63)	pound/in^3 (g/cm^3)
Weight (24" x 36")	74	96	10	pound
Specific heat capacity	0.13 (0.55)	0.06 (0.25)	0.31 (1.30)	BTU/pound/°F (kJ/kg/K)
Heat capacity	9.62	5.76	3.10	BTU/°F
Thermal conductivity	12.8	125.0	50.0	W/m-K
Coefficient of thermal expansion [RT-1000°C]	13.8	5.5	1.0	x10^{-6}/°C

Table 2. Simulation parameters			
Parameter	**RA330**	**Molybdenum**	**C/C composite**
Length, mm (inch)	914 (36)		
Width, mm (inch)	609 (24)		
Thickness, mm (inch)	7.6 (0.3)		5.1 (0.20)
Emissivity	0.6	0.5	0.8
Convection coefficient, $W/m^2/K$	100		
Simulation length	200 sec		
Heating simulation			
Rack initial temperature, °C (°F)	25 (77)		
Heat-treat temperature, °C (°F)	870 (1600)		
Cooling simulation			
Rack initial (heat-treat) temperature, °C (°F)	1150 (2102)		
Cooling-zone temperature, °C (°F)	180 (356)		

Table 3. Time required for center of fixture to reach 800°C on heating (seconds)

RA330	Molybdenum	C/C composite
84	60 (29% faster than RA330)	20 (76% faster than RA330)

Table 4. Energy to heat the fixture to 870°C (kJ)

RA330	Molybdenum	C/C composite
14,205	9,115 (36% savings over RA330)	5,135 (64% savings over RA330)

Table 5. Cooling data after 30 seconds (°C)

	RA330	Molybdenum	C/C composite
Rack temperature	743	668	495
Initial cooling rate (degrees/minute)	814	964 (18% increase over RA330)	1310 (61% increase over RA330)