CONSIDERATIONS OF ALTERNATIVE MATERIALS
FOR PASSENGER RAIL CARBODY CONSTRUCTION

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(not completely original material)

Introduction

The following is not a definitive treatise on the relative merits of the use of any particular material(s) for use in the design and construction of railroad passenger vehicles, nor is the treatment of the various characteristics discussed below exhaustive. ***Recommendations for improvement are sought.***

Material choice is a very complex issue which must take into account planned service, structural and safety requirements, manufacturability, serviceability and numerous additional factors which are depicted in Figure 1. Designers understand these competing constraints and choose appropriate materials based on necessary trade-offs required in order to achieve their objectives.

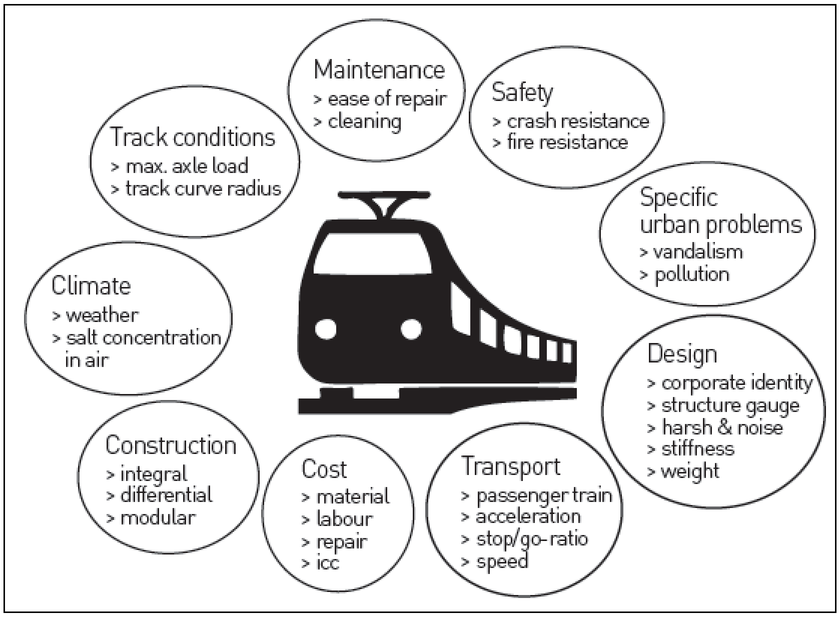

Figure 1. Passenger railcar design considerations [1].

Today stainless steel is used in a wide range of rail applications. Regional, commuter, metro, underground and light-rail train services all rely on stainless steel solutions. Each of these applications has particular operating characteristics. Design criteria and material selection are influenced by the specific operating conditions to which the rolling stock will be exposed during its service life. Many of these criteria are met by stainless steel. Stainless steel is a viable solution whenever corrosion resistance, durability, crash resistance, fire safety, ease of cleaning, maintenance and visual attractiveness are key requirements [1].

Experience with aluminum over the past several decades has resulted in numerous applications for the metal not only in freight cars, but also in light rail and inner city commuter trains, metros, and underground trains as well as in express, intercity passenger trains.

Building rail cars from aluminum is a tested and proven way to increase railroad efficiency. An excellent example is the third generation of the TGV Duplex, a French high speed train, converted from steel to aluminum to achieve a 20 percent weight savings, while also converting to two decks and keeping the axle load below 17 tons. The Japanese high-speed "Bullet" train and the Washington, DC Metro trains are also fabricated with aluminum [2]. There is also considerable use of aluminum in the advanced high speed trains such as the Acela, the Transrapid, Shinkansen, and Pendolino type trains, and magnetic levitation (Maglev) trains [3].

Typical Structural Materials

HSLA (LAHT) Steel

High-strength low-alloy (HSLA or alternatively low-alloy high-tensile, LAHT) steels are specified for the end underframes of the PRIIA bi-level and single-level cars at this time.

HSLA steels have a higher strength-to-weight ratio than conventional low-carbon steels for only a modest price premium. Because HSLA alloys are stronger, they can be used in thinner sections, making them particularly attractive for transportation-equipment components where weight reduction is important [4].

Typically, high-strength, low-alloy (HSLA) steels are low-carbon steels with up to 1.5% manganese, strengthened by small additions of elements, such as columbium, copper, vanadium or titanium and sometimes by special rolling and cooling techniques. Improved-formability HSLA steels contain additions such as zirconium, calcium, or rare-earth elements for sulfide-inclusion shape control.

Since parts made from HSLA steels can have thinner cross sections than equivalent parts made from low-carbon steel, corrosion of an HSLA steel component can significantly reduce strength by decreasing the load-bearing cross section. While additions of elements such as copper, silicon, nickel, chromium, and phosphorus can improve atmospheric corrosion resistance of these alloys, they also increase cost. Galvanizing, zinc-rich coatings, and other rust-preventive finishes can help protect HSLA-steel parts from corrosion [5].

Stainless Steel

Stainless steels are steel alloys with a minimum of 10.5 or 11% chromium content by mass. Stainless steel does not stain, corrode, or rust as easily as ordinary steel. There are different grades and surface finishes of stainless steel to suit the environment to which the alloy is exposed. Stainless steel is used where both the properties of steel and resistance to corrosion are required.

Stainless steel differs from carbon steel by the amount of chromium present. Carbon steel rusts when exposed to air and moisture. This iron oxide film (the rust) is active and accelerates corrosion by forming more iron oxide. Stainless steels contain sufficient chromium to form a passive film of chromium oxide, which prevents further surface corrosion and blocks corrosion from spreading into the metal's internal structure.

Some grades of stainless (known as austenitic stainless steels) have a unique property: their strength increases when they are worked at ambient temperatures (called cold forming). This added strength enables manufacturers to reduce the thickness of pre-fabricated stainless steel structures for the body of a railcar, making them lighter and therefore more economical to operate.

A stainless structure provides excellent crash performance as it can absorb large amounts of energy in an accident. During deformation, the material gradually increases in strength while maintaining a high enough level of ductility to prevent brittle fractures. Austenitic stainless steels offer excellent weldability, but austenite is not stable at room temperature. Consequently, specific alloys must be added to stabilize austenite. The most important austenite stabilizer is nickel, and others include carbon, manganese, and nitrogen.

The current PRIIA specifications for bi- and single-level cars prescribe austenitic stainless steel for the carbody structure.

Aluminum

As a result of a naturally occurring tenacious surface oxide film, many aluminum alloys provide exceptional resistance to corrosion in many atmospheric and chemical environments.

The combination of relatively high strength with low density yields high strength efficiency (strength to density ratio) for aluminum alloys and many opportunities for replacement of heavier metals with no loss (and perhaps a gain) in load-carrying capacity. This characteristic, combined with the excellent corrosion resistance and recyclability, has led to aluminum's broad use in rail, containers, aircraft, and automotive applications.

Aluminum alloys have elastic moduli about one third those of steels (about 10,000 ksi vs. about 30,000 ksi), so they absorb about three times as much elastic energy upon deformation to the same stress. They also deflect three times more under load [6].

Aluminum alloys are identified by a 4-digit code the first of which defines the principle alloying element (the series) and the other digits identify the modification number and numerical position within the series. Aluminum alloys typically used in railcar construction include (but are not limited to):

- 3xxx series alloys which are suitable for secondary structure, e.g. roof skins.

- 5xxx series alloys are the most versatile for sheet and plate. These 5000 series alloys are available in different amounts of cold work hardening, as denoted by the suffix “H” temper. Cold working increases the strength but the trade-off is a reduction in ductility. The alloys in this series lose proportionally the least amount of strength in the welded condition. This series is difficult to extrude and generally is not available in the extruded form.
- 6xxx series alloys are heat treatable and are available in a number of ranges of mechanical strengths. The two basic tempers are the T4 (naturally aged) and T6 (artificially aged) tempers. 6061-T6 products outsell all other alloys combined. It has good corrosion resistance and can be easily welded, albeit with a considerable decrease in strength. This loss of strength can be recovered by reheat treating, on smaller parts [7].

Aluminum's galvanic potential is high, while that for steel is low. When aluminum and steel are in direct contact, accelerated corrosion is evident. There are barrier technologies available to help with this condition when mixing metals, but at a significant cost impact [8].

Comparison of Selected Properties

Table 1 below presents selected mechanical and physical property data for materials typically used in the construction of railroad passenger cars.

Table 1. Comparison of selected mechanical and physical properties of materials used in passenger railcar construction.

Property	MATERIAL		
	HSLA/LAHT Steel (e.g., A588) [9]	Stainless Steel (e.g., A304) [10]	Aluminum (e.g., 6061-T6) [11]
Density (lb/in^3)	0.284	0.290	0.0975
Yield strength (ksi)	50 (min)	42	40
Ultimate Strength (ksi)	70 (min)	90	45
Modulus (ksi)	29,700	28,000	10,000
Ductility (% elongation)	18% (min)	55%	12-17%
Fracture toughness (ksi√in)		80	26.4
Fatigue strength (ksi)	*(est.)* 35	*(est.)* 45	14
Melting point (°F)	~2500	2550°-2640	1080°-1205

The PRIIA bi- and single-level specifications specifically require A301 stainless, A304 (as described in Table 1) may be acceptable as its lower work hardening rate (increased ductility) may facilitate forming.

Weight Considerations

Given that the density of aluminum is approximately one-third that of steel, the notion that the weight of a structure constructed of aluminum will be substantially less that of a comparable steel structure is widely contended. Clearly, this is not the case since more aluminum is required to construct a structure of equivalent strength to that of steel and it is may not be practical (based on design constraints) to build a rail car which is 100% aluminum (or 100% steel). Items such as windows and seats for example contribute substantially to the total car weight. Trucks and truck components (wheels, axles) are always constructed from steel. Lighter weight materials can have the most significant impact on the total car weight when used for the car shell and structural members as shown in Figure 2, below.

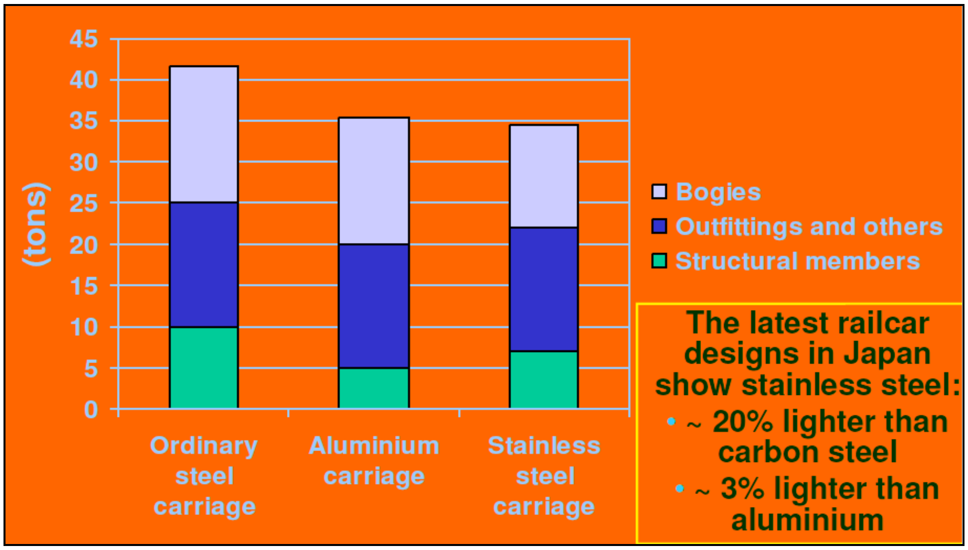

Figure 2. Relative railcar weight based on construction material [12].

Car weight is an important consideration in train operations, especially when propulsion systems are challenged as may be the case for the envisioned PRIIA 125 mph diesel locomotive. In a train, the total weight that must be moved divided by the number of passengers yields a "pounds per passenger" factor which is directly proportional to the amount (and cost) of the energy required to move that passenger. Minimizing the “pounds per passenger” factor can translate into substantial savings for transportation authorities. In almost all cases, the "pound per passenger" factor is lower in trains comprised of aluminum cars, since aluminum cars are generally somewhat lighter.

Figure 3 presents a survey of Bombardier-made products for the subway market [13]. The survey was performed to compare certain characteristics of aluminum and stainless steel cars for this service application. Although dissimilar to the subject PRIIA bi- and single-levels cars this information is of particular interest here.

The upper portion of Figure 3 describes the weight per inch of car length and suggests that as cars increase in length the weight reduction benefit achievable with an aluminum design diminishes. The

PRIIA cars for which specifications have been developed are to be 85 feet (~1000 inches) in length and the data in Figure 3 suggest (if it is assumed that the trends remain when scaled for longer, heavier vehicles[1]) rather modest weight savings. This is corroborated by the data presented in Figure 2.

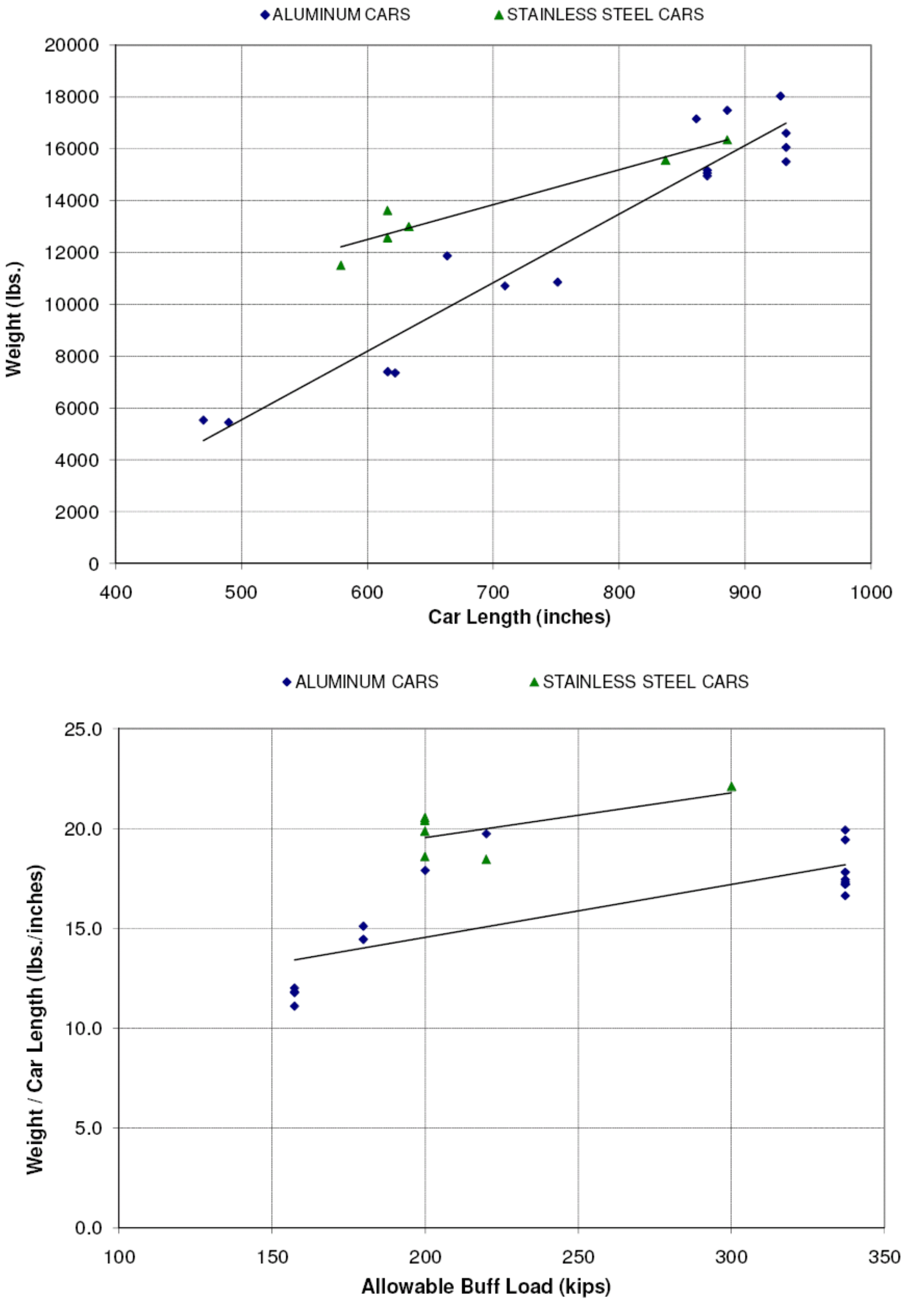

Figure 3. Comparison of relative weight and buff strength for aluminum and stainless steel SUBWAY vehicles [13].

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[1] The PRIIA bi-level car estimated gross weight is approximately 150,000 lb and the single-level car is on the order of 104,000-111,000 lb.

The lower portion of Figure 3 compares the compressive (buff) strength of stainless and aluminum subway cars (in terms of the car weight per inch of length) and indicates that (albeit with somewhat sparse data) equivalent buff strength can be achieved with a 25% lighter aluminum car with the same weight/unit length ratio.

Appearance and Maintenance

ALUMINUM: Highly appealing initially; tends to accumulate dirt and requires washing with potentially environmentally unfriendly cleansers. Aluminum carbodies require more care to last as long and look as good as stainless steel carbodies.

STAINLESS STEEL: Highly appealing with very little care required to maintain appearance.

Fatigue Performance

Typical useful service of rail vehicles has been estimated as follows [12]:

Carbon steel:	20 to 40 years
Aluminum:	25 to 40 years
Stainless steel:	up to 80 years

For such lengthy anticipated service lives, structural fatigue becomes a concern. Steels possess a more or less defined endurance limit as shown in Figure 4 (and see Table 1). The endurance limit defines a stress level below which fatigue damage does not accumulate.

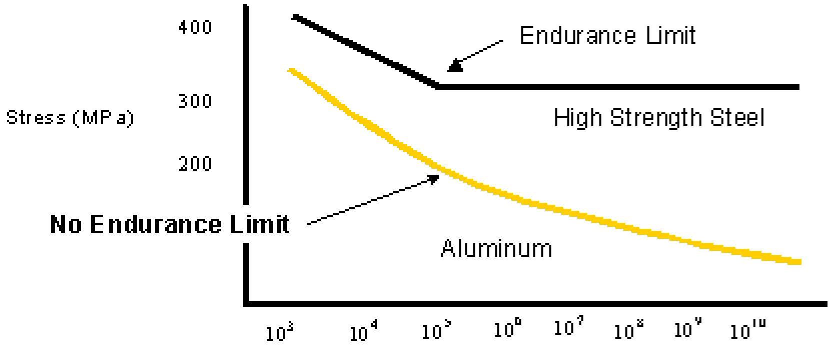

Figure 4. Typical stress/number of cycles curves for steel and aluminum [Error! Bookmark not defined.**].**

Aluminum fatigue performance is less than half that of steel. This is a very important advantage for steel in terms of vehicle life durability. From testing, it was found that structural aluminum grades (5XXX series) do not possess an endurance limit, but continue to accumulate fatigue damage as the number of applied cycles increases [8].

However, many aluminum alloys are exceptionally tough and excellent choices for critical applications where resistance to brittle fracture and unstable crack growth are imperatives [6].

Fatigue issues can be addressed by judicious design which controls the stress level to which aluminum components are subjected.

Crashworthiness Performance

The performance of steel and aluminum alloys as structural materials is a subject of great debate. There are two main failure mechanisms by which structures may collapse and survival space may be lost. The first is by material failure, where the load exceeds the strength capacity of the material. The second mode of failure is by buckling. In this case the material remains largely intact but the structure collapses by folding up or crumpling.

Modern steel vehicle bodies are formed by skin-on-frame monocoque construction. The main structure comprises a thin skin supported by a framework of formed steel sections. When overloaded failure is usually initiated by local buckling, which then progresses to gross structural collapse and some local fracture.

An aluminum alloy structure built in the same manner as a steel one will tend to fail in a similar manner if it is overloaded. However, the most viable method of producing vehicle bodies in aluminum alloy is to manufacture them from large multicell extrusions joined lengthwise to form the main tubular structure. A structure formed in this way has double skins with close-spaced continuous internal bracing. When overloaded this structure will maintain its stability and fail predominantly by fracture, starting at the weakest point(s) [14]. The use of closed cell double-skinned longitudinal aluminum extrusions that can be welded to form the vehicle body has enhanced the efficiency of the manufacturing and assembly methods and at the same time resulted in highly rigid rail vehicle bodies. Such sections (shown schematically in Figure 5) have an inherently excellent resistance to impact loading that contributes to the crashworthiness of modern rail vehicles. This construction technique is enabled by a relatively new process called friction stir welding (FSW) [3]. In fact, it has been found that a double-skinned train car made of aluminum longitudinal hollow extrusions behaves like a “rigid body” during a collision.

For this reason, impact energy absorbing zones are introduced at either end of the car to absorb the impact energy that would otherwise be transferred to the passengers, crew, and equipment.

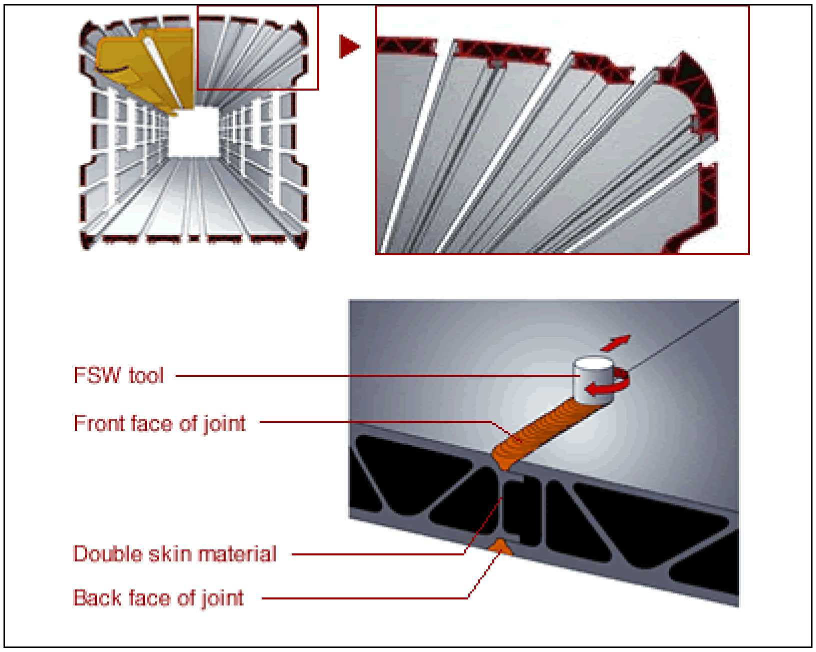

Figure 5. Double-skinned closed-cell concept for car shell construction [15].

Recent rail accidents (such as that which occurred in Eschede, Germany in 1998) have revealed a critical failure mode in aluminum rail vehicles in which the longitudinal welds joining the extruded sections, which form the vehicle body, appear to fail by fast fracture along the heat affected zone (HAZ)/weld metal (WM) interface. The term “weld unzipping” is commonly used to describe this type of failure.

In an aluminum alloy body, the welded joints joining the sidewalls to the floor are stronger in almost every respect than those in a typical steel-bodied vehicle. They have tended to fail in accidents because the surrounding structure is even stiffer and stronger, whereas in a typical steel body the sidewalls buckle before the attachment weld fails.

An inherent problem with fusion welding of heat treatable aluminum alloys, such as the 5000 and 6000 series used in train construction, is that the heat input during the welding process subjects the material to a localized solution treatment, which alters the microstructure adjacent to the weld, resulting in a reduction of the mechanical properties of the welded joint, as compared to those of the parent material. “Weld undermatching” is often used to describe this condition.

Numerical modeling performed to understand this “unzipping” phenomenon has shown good correlation with failure observed in an actual vehicle which was involved in a collision. Thickening of the aluminum sheet at the weld region is shown to eliminate the weld unzipping failure mode with the impact energy absorbed by controlled buckling of the structure [16].

Friction stir welding (FSW) has the potential to improve the crashworthiness performance of aluminum rail vehicles which may fail by “weld unzipping”. Sapa and Hydro Aluminium (Scandinavian aluminum extruders) pioneered the commercial application of FSW in the manufacture of single-wall aluminum roof panels for rail equipment [17].

Repairability

As stated previously, in a collision, both steel and aluminum cars generally fail by localized buckling followed by gross structural collapse if the impact event is of sufficient severity. In less severe accidents, the choice of material may not be an issue because crash energy-absorbing zones designed into the ends of passenger cars to protect the occupied volume (passenger seating area) are intended to be sacrificial and are designed this way.

For collisions in which damage to the car is substantial (gross buckling) repairability is of concern. It is contended that repair of collision damage to aluminum carbodies is complex, requiring specialized skills and techniques which are not currently available [18] or costly to acquire. Repair of stainless steel carbody structure can be equally complex.

The American Passenger Transportation Association (APTA) has developed standards for the repair of stainless steel and aluminum cars [19]. The relative costs of comparably extensive repairs to aluminum and stainless steel carbodies may be a relevant factor but is beyond the scope of this report.

Fire Performance

Aluminum and its alloys are good conductors of heat, and, while they melt at lower temperatures than steels, (about 1000°F) they are slower to reach very high temperatures than steel in fire exposure. Highly flammable materials (such as gasoline or kerosene) are generally not present on passenger trains. Diesel fuel is not easily ignited and train fires following passenger train collisions are rare [20].

Recyclability

Recycling is a closed-loop process by which a material moves from point-of-purchase to the consumer (end user), from the consumer (once discarded) to collection, sorting and re-processing to re-fabrication, and ultimately back to a consumer. Recyclability of a material alone is not sufficient. In order for true benefits to be derived from recycling, the material must eventually find its way back to a viable end use [21].

STAINLESS STEEL: Highly recyclable. There is a growing awareness of stainless steel's recycling properties. Stainless railcars are typically comprised of 304 and 301L austenitic grades which are easily reused. There is no deterioration in quality even when they are recycled [1].

ALUMINUM: Highly recyclable with the possible exception that trace metals added to improve strength (see earlier section) must be removed from the recycling stream. Series 5000, 6000 and 7000 grades are used to create aluminum railcars. These grades contain a quantity of iron to ensure rigidity. It can be time consuming and labor-intensive to remove them from the general aluminum waste stream. If they are recycled with other aluminum, the resulting material can only be reused for aluminum casting and similar applications [1]. All forms of aluminum can be recycled, but large items such as rail cars can yield impressive returns when scrapped. In one case when hundreds of all-aluminum railcars had been returned to a primary metals producer at the end of their 25-year lease in 1993, the ***value*** of the recycled metal was equal to 90 percent of the original manufacturing cost [21].

Conclusions

It is not appropriate to consider particular materials as more suitable for design than others. In most cases the construction style has a greater effect than the material alone on performance under extreme conditions. Designers are familiar with the characteristics of different materials and construction methods and use them intelligently to achieve the global vehicle prescribed requirements [14].

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