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High Temperature Materials for Exhaust Manifolds

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1. ***Scope***—A subcommittee within SAE ISTC Division 35 has written this report to provide automotive engineers and designers a basic understanding of the design considerations and high temperature material availability for exhaust manifold use. It is hoped that it will constitute a concise reference of the important characteristics of selected cast and wrought ferrous materials available for this application, as well as methods employed for manufacturing. The different types of manifolds used in current engine designs are discussed, along with their range of applicability. Finally, a general description of mechanical, chemical, and thermophysical properties of commonly-used alloys is provided, along with discussions on the importance of such properties.

1.1 **Background**—Figure 1 provides a diagram of a typical fabricated exhaust manifold, in this case for one side of an eight-cylinder engine. Cast versions are similar in geometry. In simple terms, it provides a means of containing exhaust gases generated from each cylinder within the engine block, combining the volume, and passing the gas on to the catalytic converter.

FIGURE 1—FABRICATED MANIFOLD

Operating demands on exhaust manifolds, as with many other elevated temperature engine components, have increased significantly over the past decade. There are numerous reasons why this has occurred, including the usually-cited reasons of tighter emissions requirements, improved fuel efficiencies, and design toward higher specific engine power (kW/kg), with a cumulative end-effect yielding higher exhaust gas temperatures. Techniques used to meet emissions requirements, such as the addition of air injection systems and the use of controlled variations in air-fuel ratios, have changed overall hydrocarbon levels, and, under certain conditions, have increased the emissivity of the exhaust gas, further raising the manifold inner wall temperature. This has led to much higher elevated temperature strength, creep, and fatigue demands on

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exhaust manifold alloys. Radioactive heat shields that are now used to protect underhood electronics from high temperatures further exacerbate the issue by reflecting otherwise lost heat back on to the manifold.

Such thermal demands lead to reduced alloy strength simply from the higher temperatures, but perhaps more importantly higher internal stresses can also develop from the higher thermal gradients via thermal expansion mismatch considerations in the cylinder head - manifold interface. The cumulative effect then becomes higher temperatures in combination with higher cyclic stresses. Thermal fatigue, a condition in which time-dependent stress variations occur directly as a result of thermal expansion mismatch and mechanical constraint, becomes an important issue. Distortion, gas blow-by, and cracking of metal components result. To avoid such problems, designers have had to examine stronger alloys and employ alternate mechanical designs.

2. References

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein.

Charles F. Walton, *Iron Casting Handbook*, Iron Casting Society, 1981
Stephen I. Karsay, *Ductile Iron I Production*, QIT – Fer et Titane, Inc., 1992
Michael F. Burditt, *Ductile Iron Handbook*, American Foundrymen's Society, Inc., 1992

***3. Alloy Classes and General Properties*—**Before manifold design and use can be discussed in any detail, it is necessary to review some of the more basic issues regarding the material classes that are used to make them.

3.1 Cast Iron—Discussion of cast iron metallurgy will be brief, as excellent references are readily available.[1,2,3]. In very basic terms, cast irons are comprised of iron and large amounts (>1% by weight) of carbon (C), and contain two primary microstructural components, a free graphite phase and the surrounding matrix. "Gray" and "Ductile" iron, two of the most common types of cast iron in general, and certainly the most typical for exhaust manifolds, differ in the form of their free graphite. In gray cast iron, graphite is present in the form of clusters of thin, two-dimensional flakes, while in ductile (nodular) iron it is in the form of spheres, or nodules. A cast iron matrix can be ferritic, pearlitic, some combination of ferrite and pearlite, or, with addition of suitable amounts of austenitizing elements, entirely austenitic. Austenitic matrix irons are also known as Ni-Resist. The matrix of a cast iron can be varied independently of the graphite form, so both gray and ductile irons can be ferritic, pearlitic, or austenitic. The different graphite forms and matrix microstructures are created by using special alloying additions and inoculation practices. Silicon (Si) and carbon provide the primary influence on graphite type and amount. The combination of graphite form and matrix microstructure give each type of cast iron its characteristic mechanical and physical properties. For instance, flake graphite alloys (gray iron) typically exhibit the lowest toughness and resistance to crack growth of all the cast irons, but they are also the least expensive to make, and the graphite flakes very effectively dampen sound and conduct heat well. Nodular, or ductile irons exhibit better toughness, will conduct heat more sluggishly, and are more expensive to produce.

Tables 1 to 3 provide a summary of important properties associated with nodular cast irons used in manifold production. Gray iron properties are not included since they are not of current interest.

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1. Charles F. Walton, *Iron Castings Handbook*, Iron Casting Society, 1981
2. Stephen I. Karsay, *Ductile Iron I Production*, QIT - Fer et Titane Inc., 1992
3. Michael F. Burditt, *Ductile Iron Handbook*, American Foundrymen's Society Inc., 1992

TABLE 1—COMPOSITIONAL AND MICROSTRUCTURAL CHARACTERISTICS OF DUCTILE CAST IRON

	Ferritic Ductile	Si-Mo Ductile Grade A[1]	Si-Mo Ductile Grade B[1]	Si-Mo Ductile Grade C[1]
Carbon	3.80%	3.45%	3.45%	3.45%
Silicon	2.70-3.00%	4.00%	4.00%	4.00%
Sulfur	<0.015%	<0.02%	<0.02%	<0.02%
Magnesium	0.020% min	0.020% min	0.020% min	0.020% min
Molybdenum	N/A	0.80-1.0%	0.50-0.70%	0.40-0.60%
Copper	<0.10%	<0.10%	<0.10%	<0.10%
Manganese	0.20-0.40%	0.20-0.40%	0.20-0.40%	0.20-0.40%
Phosphorus	<0.04%	<0.04%	<0.04%	<0.04%
Chromium	0.10% max	0.10% max	0.10% max	0.10% max
Nickel	<0.10%	<0.10%	<0.10%	<0.10%
Ferrite	Balance	Balance	Balance	Balance
Pearlite[2][3]	10-15%	10-15%	10-15%	10-15%
Carbides	0-1%	2-3%	1-2%	0-1%
Graphite Nodularity	95% +	95% +	95% +	95% +

1. Difference in grades is primarily in the Molybdenum content.
2. Amounts vary depending on section size and presence of heat treating (process dependent), or as required by customer.
3. Area percent of matrix excluding graphite area; total matrix constituents = 100%, excluding graphite.

TABLE 2—ELEVATED TEMPERATURE MECHANICAL PROPERTIES OF DUCTILE CAST IRON

	Ferritic Ductile	Si-Mo Ductile Grade A (0.8-1.0% Mo)	Si-Mo Ductile Grade B (0.6-0.8% Mo)	Si-Mo Ductile Grade C (0.4-0.6% Mo)
Elongation	16-20%	10-14%	12-16%	14-18%
Tensile Strength	MPa	MPa	MPa	MPa
22 °C (72 °F)	565	601	592	588
316 °C (600 °F)	490	535	524	518
427 °C (800 °F)	386	414	407	404
538 °C (1000 °F)	248	293	282	276
649 °C (1200 °F)	90	123	115	111
704 °C (1300 °F)	61	83	78	75
Yield Strength	MPa	MPa	MPa	MPa
22 °C (72 °F)	331-365	468	462	459
316 °C (600 °F)		409	404	401
427 °C (800 °F)		379	370	366
538 °C (1000 °F)		263	253	249
649 °C (1200 °F)		92	83	79
704 °C (1300 °F)		71	66	63
Elongation 22 °C (72 °F)	16-20%	8-12%	10-13%	11-14%
Compressive Strength (MPa)	234	356	354	353
Modulus Elasticity	170 GPa	145-170 GPa	145-170 GPa	145-170 GPa

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TABLE 3—PHYSICAL PROPERTIES OF DUCTILE CAST IRON

	Ferritic Ductile	Si-Mo Ductile Grade A	Si-Mo Ductile Grade B	Si-Mo Ductile Grade C
Thermal Conductivity (W/K x cm)				
20 °C	0.33	N/A	N/A	N/A
100 °C	0.40	0.25	0.25	0.25
400 °C	0.33	0.27	0.27	0.27
1000 °C	0.24	0.25	0.25	0.25
Coefficient of Thermal Expansion Temp (°C)	$x10^{-6}$/°C			
20-100	11.2			
20-200	12.2			
20-300	12.8			
20-400	13.1			
20-500	13.5			
20-600	13.7			
20-760	14.8			
20-871	15.3			
Density (at 20 °C)	6.9 g/cc	6.9 g/cc	6.9 g/cc	6.9 g/cc
DBTT[1] Charpy Impact Properties	At 22 °C notched 13.5–19.0 j	N/A	N/A	N/A
Notched: –10 °C to –65 °C as tensile increases	notched, ductile fracture: 16.3-21.7 j			
	un-notched, ductile fracture: 94.9-135.6 j			
Un-notched: –60 °C to –10 °C as tensile increases	un-notched, brittle fracture: 2.7-4.0 j			
Creep Strength Temp °C	MPa @ 0.0001%/h rate	N/A	N/A	N/A
427	96.5			
538	27.7			
649	3.09			
Hardness (HB)	143-217	192	192	192
Fatigue Strength Endurance Limit				
Un-notched	193 MPa	N/A	N/A	N/A
V-notched	117 MPa	N/A	N/A	N/A
Poisson's ratio	0.28	0.28	0.28	0.28

1. Ductile to Brittle Transition Temperature

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3.2 Stainless Steel—Stainless Steels are selected for elevated temperature applications because of their excellent strength and resistance to oxidation and corrosion. Both cast and wrought versions are available. Additions of Chromium (Cr) to iron in amounts greater than approximately 12% will result in an alloy that will naturally form on its surface a tenacious chrome oxide passive film (chromia, Cr_2O_3). This film tightly adheres to the base alloy (in contrast to “red rust” on carbon steel which easily cracks and spalls) and protects the underlying metal from further oxidation at high temperature, or corrosion from other factors such as sulfur-bearing gases or chloride containing aqueous solutions.

Iron with the addition of 11% to 30% Cr comprises a host of ferritic stainless steels. These alloys are primarily characterized as having a BCC structure, are ferromagnetic, and are less expensive than their austenitic counterparts. High temperature oxidation resistance tends to be very good to excellent, partly because the thermal expansion coefficient of the alloys and chromia are similar, limiting scaling of the chromia during cyclic thermal conditions. While considering the ferritics for welded fabrications, it is important to maintain extremely low levels of carbon and nitrogen so that matrix chromium levels are not depleted by the formation of chromium carbonitrides. Improved weldability, formability, and corrosion resistance will result when these interstitial elements are controlled to low levels. Ferritic stainless steels are preferred in fabricated exhaust systems due to their cost advantage over the nickel (Ni) containing austenitics. Another important advantage is the low coefficient of thermal expansion (~40% less than austenitics) which minimizes stresses generated from thermal growth at operating temperatures.

Nickel, when added to stainless steels in percentages ranging from 6% to as high as 35%, will lead to an FCC or austenitic structure at room temperature. These austenitic stainless steels typically possess much better deep drawability, weldability, and elevated temperature strength than the ferritic grades. The austenitic alloys with moderate additions of other refractory elements, e.g., Molybdenum (Mo), Niobium (Nb), Titanium (Ti), exhibit even better corrosion resistance and further enhanced elevated temperature properties. Austenitic stainless steels exhibit superior elevated thermal mechanical properties in comparison to ferritic, pearlitic, and martensitic cast irons, as well as ferritic stainless steels.

Both ferritic and austenitic stainless steels are susceptible to the formation of internal chromium rich carbides at high temperature by a reaction between the chromium and carbon/nitrogen in the alloy. This is otherwise known as sensitization. Sensitization can lead to severely reduced corrosion resistance, because the local concentration of chromium near these carbide particles can be reduced to well below the nominal alloy level. If time and temperature are insufficient to allow back diffusion (or “healing”) into the area near the carbides, chromium-depleted regions will exist adjacent to the carbide network. If the network is continuous, a path of lower corrosion resistance will exist through the material. Sensitization can also lead to reduced strength and fracture resistance, particularly with the ferritic stainless grades. A common means of mitigating sensitization is by employing “stabilization” of the base alloy. This term refers to the addition of small levels of refractory elements, that are more reactive with carbon and nitrogen than chromium, e.g., Ti and Nb, to tie up the interstitial carbon/nitrogen, thus preventing further reaction with Cr. Thus, the chromium carbide formation that could occur during high temperature exposure is minimized. This is the primary method used to address the sensitization of ferritic stainless steels which are put into service in the as-welded condition.

The temperature ranges in which austenitic alloys become susceptible to sensitization are different than the ferritic counterparts. In the as-welded form, corrosion resistance in austenitics can be achieved through the use of low carbon chemistries (e.g., 304L) or by stabilization (e.g., 321 or 347). Applications in which austenitic stainless steels are put into service at sensitization temperatures require additional consideration.

Physical, chemical, and mechanical properties of some of the more commonly-used wrought stainless steels are shown in Tables 4 to 6. Additional elevated temperature properties are listed in Table 7.

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TABLE 4—PHYSICAL PROPERTIES AT ROOM TEMPERATURE

Product Designation	Density g/cc	Young's Mod. GPa	Therm. Cond. W/m/K	CTE[1] cm/cm/°C	Cost $/lb
409	8	206	25	14	1
439	8	196	24	13	1
444	7			13	1.75[2]
441	8	206	24	12	1
468	8	200	25	14	1
304	8	193	16	20	2
309	8	200	16	20	3
321	8	193	16	20	2
601	8	207	11	17	8

1. Coefficient of thermal expansion.
2. Indicates estimated value.

TABLE 5—CHEMISTRY OF COMMONLY-USED STAINLESS STEELS

Product Designation	Composition, Weight Percent C	Composition, Weight Percent Ni	Composition Weight Percent Cr	Composition Weight Percent Fe	Others	Type
409	0.08 max	0.5 max	11	88.4	Ti = 6 x C min to 0.75 max	Ferritic
439	0.07	0.5	18	Balance	Ti = 0.20 + 4(C+N) min to 1.0 max	Ferritic
444 (18Cr 2Mo)	0.02	0.4	18	Balance	2Mo, 0.02N	Ferritic
441	0.02	0.3	18	Balance	0.7Nb, 0.3Ti	Ferritic
468	0.009	0.22	18.25	Balance	0.25Cb, 0.1Ti	Ferritic
304	0.03	10	19	Balance	2Mn, 1.0Si, P, S	Austenitic
309	0.06	13	23	Balance	1.75Mn, 0.5Si, 0.02P, 0.002 S	Austenitic
321	0.08 max	10	18	72	Ti = 5xC min to 0.7 max	Austenitic
601	0.05	60.5	23	14.4	1.4Al	Ni Base

TABLE 6A—ELEVATED TEMPERATURE MECHANICAL PROPERTIES OF STAINLESS STEELS—YIELD STRENGTH

Grade	409	439	444	441	468
Temp. (°C)	YS (MPa)	YS (MPa)	YS (MPa)	YS (MPa)	YS (MPa)
21	255	290	358	345	290
260	172	255	262		
538	117	193	207	175	152
649	83			145	117
760	28			47	
816	24	41	34	40	62
871	17	28	34	29	34

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TABLE 6B—ELEVATED TEMPERATURE MECHANICAL PROPERTIES OF STAINLESS STEELS—TENSILE STRENGTH

Grade	409	439	444	441	468
Temp. (°C)	**TS (MPa)**	**TS (MPa)**	**TS (MPa)**	**TS (MPa)**	**TS (MPa)**
21	407	455	476	510	476
538	241	262	338	372	276
649	159	124	283	303	207
704	76	69	241	145	159
760	41	41	145	62	83
816	28	28	83	48	48
871	21	21	69	34	41

TABLE 6C—TENSILE STRENGTH DATA: (300 AND 600 SERIES STAINLESS STEEL)

Grade	304L	309	321	IN601	IN625
Temp (°C)	**TS (MPa)**	**TS (MPa)**	**TS (MPa)**	**TS (MPa)**	**TS (MPa)**
21	676	620	586	0	931
204		528	459		862
427		517	457		820
538	434	483	444		
649	324	393	385	538	765
704	248				
732			286		
760	193			290	
816	145	207	179		
871	114			138	276
982		76		76	138
1093		48		48	

TABLE 6D—YIELD STRENGTH DATA: (300 AND 600 SERIES STAINLESS STEEL)

Grade	304	309	321	601	625
Temp (°C)	**YS (MPa)**	**YS (MPa)**	**YS (MPa)**	**YS (MPa)**	**YS (MPa)**
21	241	290	216		469
204	159	241	162		296
427	131	207	134		283
538		165	131		
649	107	152	131	172	283
732			131	193	
760					
816	90		117		
871		128		131	276
982				62	138
1093				28	

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TABLE 7—ADDITIONAL MECHANICAL PROPERTIES

Product Description	Hardness HRB	Charpy Impact Toughness[1] Joules	Stress Rupture MPa 100 h 816 °C	Stress Rupture MPa 1000 h 816 °C	Stress Rupture MPa 10 000 h 816 °C
409	68	44	10.3	6.2	
439	73			6.2	
444	95 max				
441	80				
468	78		13.7		
304	88 max	203		20.6	10.3
309	95 max			41.3	24.1
321	80	144		31.0	20.6
601	81	139		44.8	27.5

1. Dependent on materials processing history. Sources: Allegheny Ludlum and Armco product Literature.

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3.3 Weldability—The chemical makeup, microstructure, mechanical, and physical properties of ductile irons can vary greatly. A correspondingly large number of welding electrode compositions are available for welding ductile irons, such as pure nickel, iron-nickel alloys, and stainless steel. Electrode selection is just one important factor in specifying an appropriate welding process to produce a high strength weldment. Heat treatment before and/or after welding may be specified to prevent possible microstructure changes. For example, formation of martensite or iron carbide will adversely affect the ductility and strength of the heat affected zone of the weldment. Maintaining thermal expansion compatibility between the filler metal and base alloy is also an important consideration. Historically, many foundries have used welding as a method of repair to recover otherwise scrap castings as salable product.

Both ferritic and austenitic stainless steels can be welded. To limit contamination of the molten weld metal with interstitial carbon, nitrogen, extremely clean practices and the use of shielded welding methods such as Gas Metal Arc Welding (GMAW) or Gas Tungsten Arc Welding (GTAW) are preferred. When employing filler metal welds on austenitic alloys, it is common practice to use alloys richer in chromium and nickel than the base alloy. For ferritic stainless alloys, high nickel fillers with similar thermal expansion coefficients are sometimes used.

Due to stringent emission requirements and vehicle packaging constraints, current designs favor the positioning of the catalytic converter as close as possible to the exhaust manifold. Welding a fabricated stainless steel exhaust manifold to a stainless steel converter shell is a common and well understood practice. Cast iron manifolds have several advantages over fabricated manifolds, not the least of which is cost. Unfortunately, a method of welding cast iron to stainless steel has not yet been developed. Thus, a weld joint between these two dissimilar metals continues to pose a challenge for manufacturing in high volume.

3.4 Machinability—As cast iron alloys become more highly alloyed (usually with matrix strengthening elements such as Mo, Nb, and Si) to achieve their desired microstructure and properties, unique machining challenges arise. Machine tool selection becomes critical as the increased alloying promotes carbides and decreases tool life. This creates quality and cost problems for tooling selection and machining parameters. In addition, machining equipment must be more robust in order to handle the higher clamping force and torque required to machine these alloys. Austenitic alloys, both Ni-Resist cast iron and cast stainless steels, are known to be very difficult to machine. Figure 2 summarizes relative machinability of some manifold alloys.

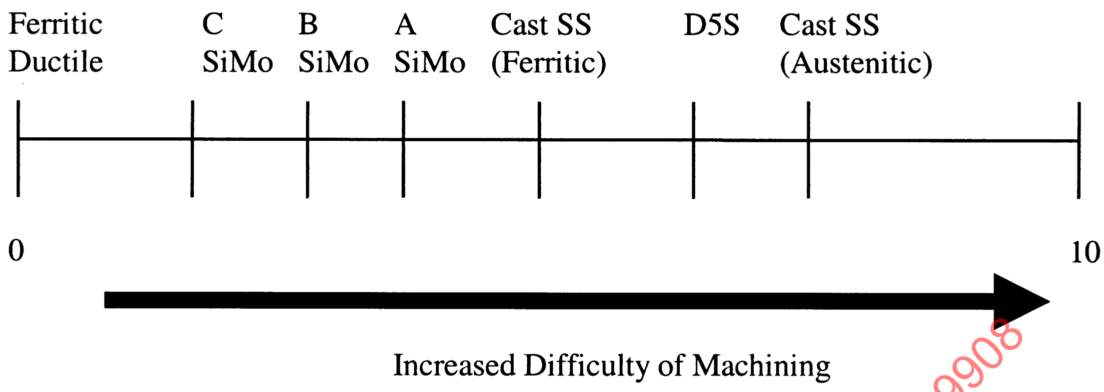

FIGURE 2—RELATIVE MACHINABILITY IN VARIOUS MATERIALS

4. ***Alloy Selection for Manifold Design***—Gray cast iron was the material of choice in exhaust manifold design for many years. In the 1970s, the first applications of air injection systems (AIR) were used to reduce hydrocarbon and carbon monoxide emissions from engines by oxidizing the HC and CO to CO_2 and H_2O. However, the exothermic nature of these oxidation reactions increased the temperature of the exhaust gas. Gray iron was unable to meet the design criteria for service life in this environment, in terms of both strength at temperature and scaling resistance. Designs began incorporating alloys with higher maximum use temperatures, including compacted graphite and ferritic ductile irons, high silicon, and Si-Mo ferritic ductile irons, and austenitic ductile iron. High silicon ductile iron and austenitic ductile iron are two of the casting alloys formerly used to produce exhaust manifolds. High silicon ductile irons are essentially alloys of the Ferritic D4512 type, but with a silicon content of 4 to 6%. The silicon addition increases the ferrite-to-austenite transition temperature, extending the service temperature at which a manifold can be used to 900 °C. Increased silicon imparts good high temperature scaling resistance and serves as a ferrite strengthener, but beyond 5%, Si significantly degrades impact strength and ductility between room temperature and 450 °C. The resulting casting brittleness makes higher silicon ductile irons undersirable for high volume production.

Austenitic ductile irons, also known as Ni-Resist ductile irons, are a family of ductile irons displaying an austenitic matrix at room temperature by alloying with large amounts of nickel. The grade most commonly used for exhaust manifolds, D-5S, contains 36% nickel and 2% chromium. D-5S can be used at service temperatures to 925 °C, and has excellent scaling resistance and thermal stability. However, Ni-Resist ductile irons require special foundry practices and tooling, due to their austenitic matrix, and are significantly more expensive than conventional ductile irons because of their high nickel content.

The microstructures of gray irons used in the past for exhaust manifolds were typically all pearlitic, and thus, high strength. This was possible because operating temperatures were well below that which causes the cementite phase to either coarsen to a spheroidal structure or decompose to ferrite + graphite. The microstructure of current D4512-type ductile iron is essentially ferritic, because this is the stable phase at application temperatures. High silicon-molybdenum ductile iron is basically D4512 type with added silicon and molybdenum for improved high temperature properties. Its microstructure is also essentially ferritic.

The exhaust manifold is the only major engine component that is not actively cooled. Therefore, alloys used for this application must withstand high heat loads and should absorb as little heat as possible from the exhaust gas during start up, to avoid delays in catalytic converter warm up and function. Manifold alloys should be dimensionally stable at high temperature. They should also attenuate noise as efficiently as possible, yet be light to limit vehicle weight. For these reasons, thermophysical properties are of equal importance as mechanical properties when considering alloys for manifold use.

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More recently, wrought and cast stainless steels have been used. Figure 3 illustrates generally accepted maximum temperatures of use for these various alloys.

- Gray Iron **(1)**
- Compacted Graphite Iron **(2)**
- Ductile Iron (D4512) **(3)**
- Hi Silicon ductile Iron **(4)**
- Hi Silicon -Molybdenum Ductile Iron **(5)**
- Austenitic Ductile Iron (D5S) **(6)**
- Fabricated Stainless Steel **(7)**
- Cast Stainless Steel **(8)**

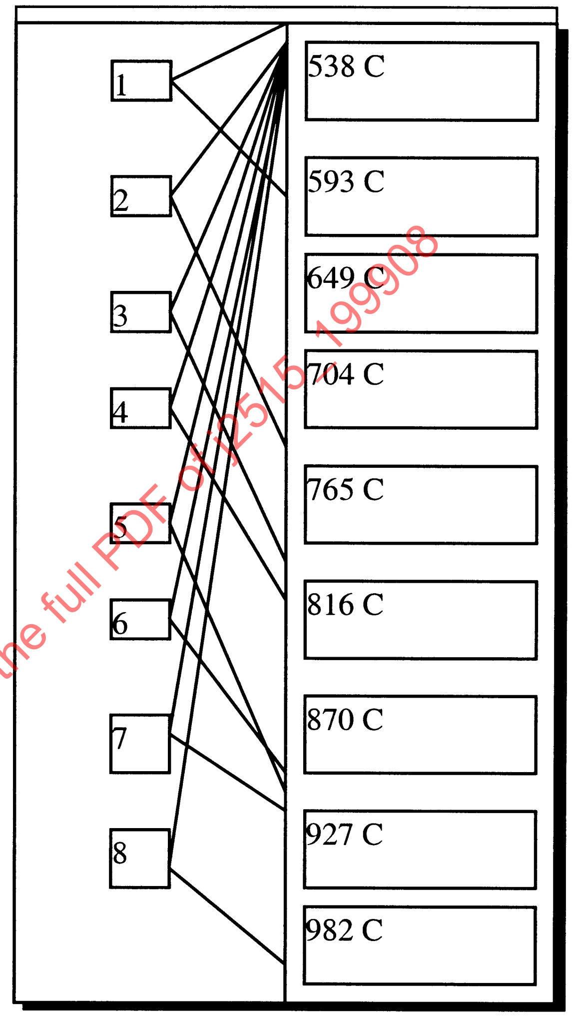

FIGURE 3—TEMPERATURE LIMITS OF THE VARIOUS EXHAUST MANIFOLD ALLOYS IN USE

Stainless steel fabrications and castings are used when exhaust gas temperatures exceed 870 °C, an increasingly common occurrence. Fabricated manifolds, both single wall and dual wall air-gap designs, typically use Ferritic or Austenitic grades. The increased emissions and performance requirements of future engines call for high temperature cast stainless steel manifolds. Properties of cast and wrought stainless steels are shown in Tables 4 to 7. Cast Stainless manifolds are made from Ferritic, Duplex, or Austenitic grades. The relative selection preference for selecting these materials, based on properties required in the application is shown in Table 8.

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TABLE 8—RELATIVE SELECTION PREFERENCE

	Austenitic	Ferritic
Cost		Preferred
Coefficient of Thermal Expansion		Preferred
Thermal Conductivity	Preferred	
Elevated Temperature Strength	Preferred	
Oxidation Resistance		Preferred
Fracture Toughness	Preferred	
Weldability	Preferred	
Formability	Preferred	
Hot Salt Corrosion		Preferred

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As shown in Figure 1, exhaust manifold alloy demand changes as the exhaust gas temperature increases. Future applications will likely see an increase in the use of thin-walled exhaust manifolds because of the following benefits:

a. Lower mass for improved fuel economy
b. Higher engine output through leaner, more controlled combustion
c. Increased exhaust gas temperature, due to more fuel-efficient engines
d. Turbocharging and Supercharging
e. Consumer demand for higher performance engines
f. More extensive shielding to protect under-hood components
g. Consumer demand for lower emissions

It is likely that future engines will require exhaust manifolds to operate at or above 900 °C. Current materials used to make exhaust manifolds, such as Si-Mo ductile iron, CB-30 duplex cast stainless steel or ferritic wrought stainless steels will not provide adequate life at these temperatures.

Cast ferritic stainless steels are currently undergoing development for thin-wall exhaust manifolds. These alloys have a low coefficient of thermal expansion compared with Si-Mo ductile irons or cast austenitic stainless alloys. They are weldable, and exhibit good oxidation resistance to about 940 °C. The nominal composition of this cast alloy is 12.0% Cr, 1.8% Si, and 0.03% C, with small amounts of Nb and Ti as stabilizers. Results of oxidation tests conducted in synthetic exhaust gas for this 12% Chromium cast alloy are compared to wrought 409 and 439 stainless steel in Table 9. Further development of these alloys is ongoing and some details of such materials are presented in Table 10.

TABLE 9—WEIGHT GAIN (g/m^2) AFTER 96 h OF OXIDATION AT VARIOUS TEMPERATURES IN SYNTHETIC EXHAUST GAS

Temperature °C	Type 409	Type 439	12% Cr 1.8% Si
650	3.9	1.9	1.3
700	6.1	2.4	1.5
750	7.8	3.3	1.8
800	11.5	4.3	2.8
850	18.3	6.1	4.6
900	149.8	20.6	9.0

TABLE 10—PROPERTIES OF DEVELOPMENTAL CAST STAINLESS STEEL - 12% Cr

Temperature °C	Yield Strength MPa	Tensile Strength MPa	Elastic Modulus 10^3 MPa	Poisson's Ratio	Specific Heat W/kg °K	Elongation %
21	233		20.6	0.28	451	5
93	200		19.4			
100					493	
148				0.29		
200					528	
204	172		18.9			5
260				0.29		
300					560	
315	168		18.3			
371				0.30		
400					602	
427	132		17.5			
482				0.30		
500					685	
538	110	241	16.4			5
593				0.31		
600					801	
649	86	157	15.4			6.5
700					990	
704				0.32		
760	30	42	11.4			
800						
816				0.33		
871	16	21	6.9			

5. Conclusion—The field of manifold development has been driven primarily by an increased heat load on the component brought about by stricter regulations on emissions. Not only have temperatures increased, but through thermal expansion and mechanical constraints, operational stresses have also increased, and often in a time-dependent manner. Demands on materials have become significant. Potential failure modes are numerous: creep or rupture from insufficient static strength at temperature, thermal fatigue, and alloy loss from static or cyclic oxidation are three of the major ones.

The goal set forth by the subcommittee writing this document was to provide an introductory and central reference of exhaust manifold design, manufacture, and alloy selection. Publication comes at a time of very active work in the field, and it would not be surprising if within a few short years it become somewhat incomplete. It is certainly not intended (at this point) to be an all-encompassing reference, although a very comprehensive bibliography is provided to guide the reader to further and more detailed work. Certainly as the document is revised in the coming years, newer and perhaps more detailed information will be added.

PREPARED BY THE SAE IRON AND STEEL TECHNICAL DIVISION 35—ELEVATED TEMPERATURE PROPERTIES OF FERROUS METALS

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APPENDIX A

BIBLIOGRAPHY
REFERENCE LISTING BY MATERIAL AND TOPIC

A.1 Cast Iron (Reference Number

a. Applications—#1, 8, 18, 36, 95, 96, 100, 101, 102, 143, 148, 149
b. Mechanical Properties—#2, 3, 4, 5, 8, 10, 13, 21, 25, 28, 29, 30, 31, 33, 35, 37 to 53, 55, 56, 57, 62, 65, 66, 67, 68, 70, 72 to 79, 81 to 100
c. Thermal Performance—#2, 4, 5, 21, 24, 28 to 33, 41 to 44, 68 to 70, 75 to 79, 82 to 87, 89, 90, 98, 104 to 133, 142, 152 to 157
d. Microstructure—#27, 40, 65, 74, 78, 81, 82, 85, 86, 89, 128, 135, 136

A.2 Cast Stainless Steel

a. Applications—#2, 6, 7, 15, 19, 20, 59, 144
b. Mechanical/Thermal Performance—#2, 7, 11, 19, 20, 58, 59

A.3 Stainless Steel

a. #2, 6, 7, 11, 12, 14 to 20, 22, 23, 27, 34, 58 to 61, 63, 64, 69 to 71, 80, 143, 144, 151, 152

A.4 Other Topics

a. Coatings—#1
b. Other High Temperature Applications—#22, 25, 54, 72, 73, 102

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TABLE A1—REFERENCE LISTING BY NUMBER

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