

NASA/TM—1998–209004



# **High-Strength Aluminum Casting Alloy for High-Temperature Applications**

**(MSFC Center Director's Discretionary Fund Final Report,  
Project No. 97–10)**

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***December 1998***

## Acknowledgments

The author wishes to thank Dr. Po-shou Chen from IITRI in Huntsville, AL, for his assistance in the alloy development phase of this work, and Mr. Bob Natkin from Ford Motor Company in Dearborn, MI, for his helpful technical discussions and coordination meetings with Ford's piston vendors.

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## LIST OF ABBREVIATIONS AND SYMBOLS

Al	Aluminum
Al <sub>2</sub> Cu	Aluminum-copper binary compound
Al <sub>2</sub> O <sub>3</sub>	Alumina or aluminum-oxide compound
Al-Si	Aluminum-silicon alloy
Al-Te	Aluminum-transition
B <sub>4</sub> C	Boron-carbide compound
C/C	Carbon/carbon
CDDF	Center Director's Discretionary Funds
Cu	Copper
Fe	Iron
FeC	Iron-carbide compound
FMC	Ford Motor Company
HC	Hydrocarbon emission as air pollutants
Mg	Magnesium
Mn	Manganese
MMC	Metal Matrix Composites
MSFC	Marshall Space Flight Center
Ni	Nickel
NO	Nitric-oxide emission as air pollutants
PNGV	Partnership for the Next Generation of Vehicles
SAE	Society of Automotive Engineering
Si	Silicon
SiC	Silicon-carbide compound
Si <sub>3</sub> N <sub>4</sub>	Silicon-nitride compound
Ti	Titanium
TE	Transitional elements in the periodic table
TiB <sub>2</sub>	Titanium-boride compound
ThO <sub>2</sub>	Thorium-oxide compound
Zn	Zinc
ZrO <sub>2</sub>	Zirconium-oxide compound





## TECHNICAL MEMORANDUM

### **HIGH-STRENGTH ALUMINUM CASTING ALLOY FOR HIGH-TEMPERATURE APPLICATIONS (MSFC Center Director's Discretionary Fund Final Report, Project No. 97-10)**

#### **I. INTRODUCTION**

A new aluminum-silicon (Al-Si) alloy has been successfully developed at Marshall Space Flight Center (MSFC) that has a significant improvement in tensile strength at elevated temperatures (500 to 700 °F). For instance, the new alloy shows an average tensile strength of at least 90 percent higher than the current state-of-the-art 390 Al piston alloy at 500 °F. Compared to conventional Al alloys, automotive engines using the new piston alloy will have improved gas mileage, and may produce less air pollution in order to meet the future U.S. automotive legislative requirements for low hydrocarbon (HC) emissions from auto engines. Since 1995, as part of the Partnership for the Next Generation of Vehicle (PNGV) program, MSFC has worked with Ford Motor Company (FMC) in Dearborn, Michigan, to develop this alloy as a dual-use technology. From 1996-1998, MSFC independently developed this new alloy under sponsorship from MSFC's Center Director's Discretionary Funded (CDDF) program.

Presently, all commercially available Al-Si alloys are unable to meet a constant demand for higher mechanical strengths at temperatures above 450 °F. Hypereutectic Al-Si alloys offer a number of benefits in the area of a piston's operation such as corrosion resistance, hardness, low thermal expansion, and improvement in surface wear resistance. If such a high-strength, low-cost alloy were available, it would help solve many of the high-temperature, high-wear-resistance material-related problems facing NASA, and particularly the automotive industry. However, it must also be recognized that low material cost is an important factor for mass production in commercial industries. The new alloy is economically produced by pouring molten metal directly into conventional permanent steel molds or die casting. The projected cost for this new alloy is <\$0.95 per pound, and it readily allows the automotive components to be cast at a high production volume with a low, fully accounted cost.

## **II. AIR POLLUTION AND PISTON DESIGN**

### **A. Hydrocarbon Emission Sources**

Currently, the big three U.S. automakers are facing their worst environmental crisis since the oil embargo in the 1970's. Under the congressional Global-Warming Treaty, there is a pressing need for the automakers to meet the U.S. automotive legislative requirements for low HC emissions from gasoline- and diesel-powered vehicles. Combustion research conducted for gasoline engines in the early 1980's has shown that the causes for HC emission from the engine could be traced to the unburned fuel in the combustion chamber. Some of these compounds are strong-smelling, but their main importance is as precursors, with nitric-oxide (NO) as secondary air pollutants. Chemically triggered by sunshine, these pollutants are the products of atmospheric reactions that lead to the noxious mist called the "Los Angeles smog." Moreover, the unburned fuels that result in gasoline engine HC emissions also cause a significant engine performance loss.

Combustion analysis from gasoline engines have shown that the unburned fuel comes mostly from a ring-shaped crevice that is formed between the combustion's cylinder wall surface, the piston outside wall, and the top of the piston ring.<sup>1-3</sup> This piston crevice is sometimes called the piston top-land clearance. When an engine is under normal operation cycles, the gasoline-air mixture supplied to the combustion chamber is compressed into the piston's ring crevice in the compression stroke. The combustion of gasoline is initiated at the spark plug and the flame propagates throughout the combustion chamber. If the flame in the combustion chamber cannot travel to the piston's wall and enter the inside of the crevice, the unburned fuel is exhausted out of the combustion chamber in the expansion stroke as the main source of HC emissions.<sup>4-5</sup> Experimental results from Adamczyk<sup>6</sup> have shown that the piston's crevice volume produced  $\approx 80.5$  percent of the total HC emission, while the heat gasket and spark plug threads produced  $\approx 12.5$  and 5 percent, respectively. All other HC sources produce  $< 2$  percent of the total scaled HC emission from an auto engine. Thus the piston's crevices significantly increase the HC emissions from the auto engine, and there is a direct relationship between the volume of the crevices and the amount of HC emission. When the flame arrives at the piston crevice, it cannot usually propagate into the crevice and burn the contained fuel.

### **B. Current Piston Design and Materials**

Since there is a correlation between the piston's crevice volume and the amount of HC emission from a gasoline engine, several piston redesign efforts were taken by the auto industry in the early 1990's as a way to reduce the HC emission. One way to reduce the crevice volume was to reduce the vertical thickness of the piston top-land clearance by machining off parts of the piston crown, making it have a thinner section. Another similar way to minimize the piston's crevice volume is to move the top piston ring groove upward in relationship to the piston's crown. Figure 1 depicts a recent approach that is taken by FMC to reduce the piston top land which is an origin of a substantial HC emission. In this design, the top piston ring groove is moved upward, very close to the crown of the piston, in order to

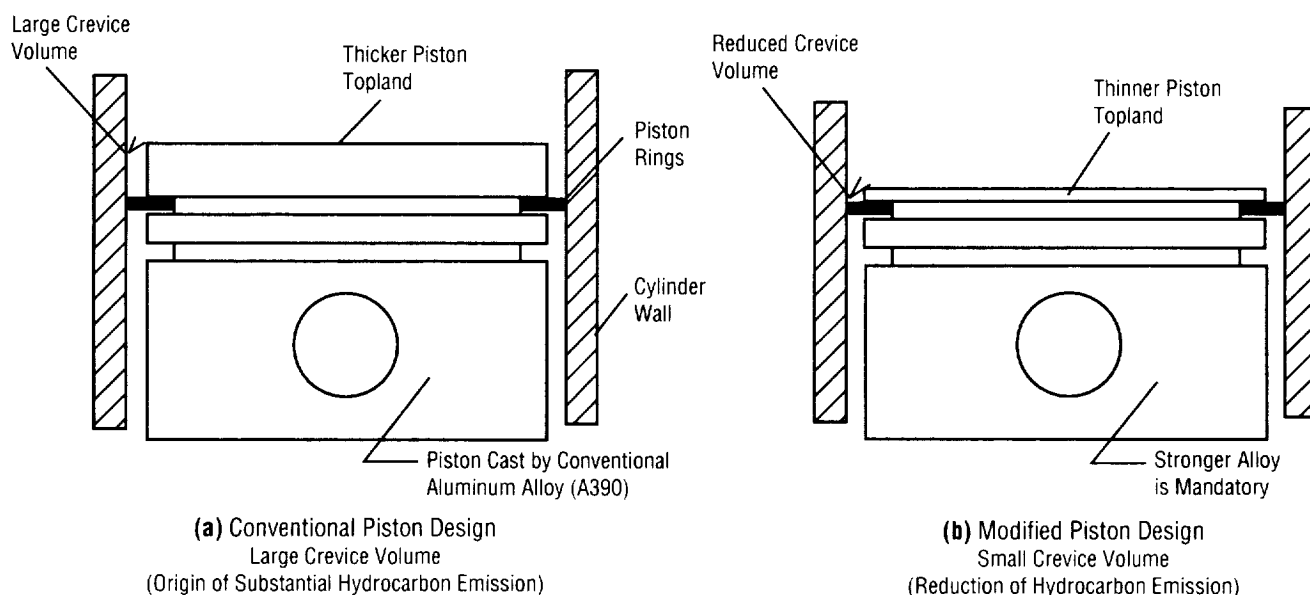


Figure 1. Piston design modifications for HC emission reduction.

reduce the vertical length of the piston top land. However, in this design, the piston top land above the piston ring must have sufficient wall strength across the bendable zone as the piston moves up and down in the combustion chamber. The pistons lie at the heart of the internal combustion engine and their reciprocating motion will generate severe stress on the piston crown, sidewall, and the piston's top rings.<sup>7</sup> Thus if the piston top land is made to be very thin, then a stronger piston alloy is mandatory to permit such design modification in order to reduce the HC emission.

The universal acceptance of Al pistons by worldwide manufacturers can be attributed to the piston's light weight that would enhance the engine. In the use of Al alloys for pistons, several traditional Al-Si alloys, such as the Society of Automotive Engineering (SAE) 332 and 390 alloy, have been proposed. However, their tensile strengths are not suitable for high-temperature applications of  $>450^{\circ}\text{F}$ . Higher tensile strength must be achieved in order to permit such piston design modification to reduce the HC emission. Over the years, the most versatile and economical way to produce an Al piston is through conventional casting methods. The hypereutectic Al-Si alloys are the most popular piston alloys because they can offer a number of benefits in the area of a piston's operation such as corrosion resistance, hardness, low thermal expansion, and improvement in surface wear resistance.<sup>8,9</sup> However, the current alloys have inadequate strength to pass the required 100-hr piston and gasket test for the higher output four-valve engine for the new piston design to operate at a temperature of  $\approx 500^{\circ}\text{F}$ .

Some material solutions identified to date would include the piston top land's reinforcement with nickel (Ni) welding, Ni foam, or ceramic ring carriers that are produced using squeeze casting.<sup>10</sup> These solutions are generally adequate to improve the piston performance. Unfortunately, they would also add significant cost and weight to the pistons. Another material approach is to use ceramic fibers or particulates to reinforce conventional Al alloys to produce the so-called ceramic-reinforced metal matrix composites (MMC's). However, the MMC's materials and processing costs are considered as prohibitively expensive for industrial piston production levels.<sup>11-14</sup>

### III. ALLOY DEVELOPMENT

#### A. Aluminum-Silicon Systems

Al casting alloys are the most versatile of all common foundry cast alloys in the production of gasoline pistons. The universal acceptance of Al pistons by worldwide manufacturers can be attributed to the piston's lightweight and high thermal conductivity. A lightweight Al piston would enhance the engine performance by permitting the engine to run at a higher engine speed and with lower crankshaft counterweighting. Virtually all Al pistons are made from a family of Al that is alloyed with Si. The Al-Si alloy systems used in pistons fall into three major categories: Eutectic, hypoeutectic, and hypereutectic. Following is a brief explanation of these categories.

Si additions to Al are very similar to the sugar addition to iced tea. Si can be made to dissolve completely into solid Al at room temperature, and this process is called forming a solid solution of Al and Si. However, there is a saturation point that limits how much Si can be dissolved into Al to form a solid solution. When Si is added above this particular saturation point, it will precipitate out in the form of hard, small Si particles. This phenomenon is very similar to the excess sugar that could not dissolve further in the iced tea. For an Al-Si system this saturation point is  $\approx 12$  percent Si. Therefore, Al alloys with  $<12$  percent Si are referred to as hypoeutectic, those with close to 12 percent Si as eutectic, and those with  $>12$  percent Si as hypereutectic. In general, hypereutectic is more difficult to cast and machine than the hypoeutectic because of its high Si content of  $>12$  percent. In hypereutectic Al-Si alloys, the Si grain refinement by using a phosphorus addition is very essential to obtaining a good cast and improve product performance.

Hypoeutectic and eutectic Al pistons have been the auto industry standard for many years, but they are being phased out in favor of the hypereutectic versions. For example, the SAE 332 and 356 alloys were the standard hypoeutectic and eutectic piston alloys for the auto industry, respectively. By the late 1980's, the production of hypereutectic Al-Si pistons had dominated the manufacture of Al pistons. Presently, the standard hypereutectic Al-Si alloy for the industry is the A390 alloy. Table 1 shows the typical compositions for piston Al-Si alloy 332, 356, and 390.<sup>15</sup> The current worldwide annual consumption of 390 alloy is estimated to be  $\approx 150,000$  ton. However, the usage of 390 alloys is limited to a maximum temperature of  $\approx 450$  °F.

Table 1. Composition for SAE 332, 356, and 390 piston alloys.

Piston Alloy	Compositions (% wt.)							
	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti
332	8-10	1.2	2-4	0.5	0.5-1.5	0.5	1.0	0.25
356	6-7	0.6	0.25	0.35	0.2-0.5	0.5	0.35	0.25
390	16-18	1.3	4-5	0.1	0.4-0.6	0.1	0.1	0.20

## B. Strengthening Mechanisms

In this section the basic concepts for strengthening the tensile properties of Al-Si alloys will be based on the theory of dislocations. Dislocations are very small lines of imperfection that exist within a material from the misalignment of atom arrays in the crystal lattice. All cast metals and alloys contain a large number of dislocation lines as defects. The density of dislocations is defined as the number of dislocation lines that intersect a unit area in the crystal. There are four important ways of increasing the tensile strength of an alloy, based on the dislocation's production and movement within the crystal lattice: (1) Mechanical blocking of dislocation motion, (2) pinning of dislocations by solute atoms in a solid solution, (3) impeding dislocation motion by short-range order, and (4) increasing the dislocation density so that tangling of dislocations results. All four strengthening mechanisms depend upon impeding dislocation motion for their success. In the development of the Al-Si alloy, we utilize two major strengthening mechanisms: Mechanical blocking and impeding dislocation motion by short-range order. These techniques are briefly explained below.

Mechanical blocking of dislocation motion can be produced by forming tiny particles of a second phase material into a crystal lattice.<sup>16,17</sup> For example, when small particles of iron-carbide (FeC) compound are precipitated into iron, the iron's strength is drastically increased. For Al alloys, the particles of Al-copper (Al<sub>2</sub>Cu) compound are precipitated into the Al matrix to increase the strength of Al by pinning of a dislocation's movement. This mechanism would work well if these particles are very small and evenly distributed within the alloys. However, if the alloy is held at a high temperature for a certain period of time, the thermal energy will make these particles dissolve and grow even larger through thermal diffusion, and therefore decrease the effectiveness of the mechanical blocking of dislocation.

Dislocation motion can also be impeded by a short-range order solid solution. The passage of a dislocation across a slip plane in a perfected ordered crystal lattice does not alter the binding energy across the plane after the dislocation is gone. Most cast metals and alloys are considered as disordered solid solutions in long-range but tend to have short-range order solid solution. The short-range order means that atoms of different species are not arranged at random on the lattice sites, but tend to have an excess or a deficiency of pairs of unlike atoms. This is called ordered crystal structure at the short range. Thus in ordered alloys, dislocations tend to move in pairs and the second dislocation reorders the local disorder left by the first dislocation. This action impedes the dislocation motion by short-range order structure.

All strengthening mechanisms by impeding dislocations begin to break down at sufficiently high temperatures where material diffusion can occur at an appreciable rate. When diffusion is rapid, most tiny precipitated particles dissolve or become larger in size. The short-range order in solid solution repairs itself behind slowly moving dislocations, and annealing at high temperature will decrease the dislocation density. In this program, the search for a higher strength Al-Si alloy for use at very high temperatures is a search for reduced material diffusion rates, so that these four strengthening mechanisms will survive to high temperature in order to impede the dislocation movement.

### C. Key Alloying Elements

This section does not contain any confidential commercial information nor does it disclose an invention for which a patent has been applied. There are two key alloying elements which are commonly used for all hypereutectic-Al alloy systems: Si and Cu.<sup>15</sup> Si is the major alloying element added to the Al. For hypereutectic Al, Si has a typical range from 16 to 20 percent by weight. Additions of Si to pure Al dramatically improve the fluidity and feeding characteristics. Moreover, Si offers a number of benefits in the area of a piston's operation such as corrosion resistance, hardness, low thermal expansion, and improvement in surface wear resistance. Perhaps the major advantages of using Si are its high heat capacity and wear-resistant properties. The Si particles, being a nonmetallic material, act as small islands of insulators, keeping the heat in the combustion chamber and preventing heat loss through conduction, allowing the rest of the piston area to run cooler.

Cu is added to the Al mostly for improvement in tensile strength. Alloys containing 4 to 6 percent Cu will respond strongly to heat treatment in T5 and T6 conditions. The major step is to control the Al-copper (Al<sub>2</sub>Cu) compound particle size which is made to precipitate uniformly into the Al matrix to increase strength by pinning the dislocation's movement. This mechanism would work well if these particles are very small and evenly distributed within the alloys. However, if the alloy is held at a high temperature for a certain period of time, the thermal energy would make these particles dissolve and grow even larger through thermal diffusion, and decrease the effectiveness of the mechanical blocking of dislocation. When thermal diffusion is rapid, most tiny precipitated particles of Al<sub>2</sub>Cu will dissolve or become larger in size. In this program, additional Al-transition element compounds must be used to slow down the diffusion rate of Al<sub>2</sub>Cu compound.

The alloy development strategy is to reduce the Cu<sub>2</sub>Al diffusion rates, so that the mechanical blocking and short-range order solid solution strengthening mechanisms from the Cu<sub>2</sub>Al particles will survive to high temperature in order to impede the dislocation movements. The key is to make Al-transition (Al-TE) element compounds to precipitate in submicron-size particles (<0.3  $\mu\text{m}$ ), and evenly distribute throughout the Al matrix. Surprisingly, the total amount of transition elements required to form the Al-TE is usually not >2 percent by weight. The key is to select a certain transitional element to react with Al at a relatively low temperature (<1,400 °F) during casting to form the Al-TE compounds. This is why any preformed metal-oxide powders (i.e., non-Al-TE forming) added to Al, such as zirconium-oxide (ZrO<sub>2</sub>), thorium-oxide (ThO<sub>2</sub>), titanium-boride (TiB<sub>2</sub>), and even Al-oxide (Al<sub>2</sub>O<sub>3</sub>), are ineffective as strengthening mechanisms for blocking dislocations because they are very large in size (5–20  $\mu\text{m}$ ). Second, most of these preformed metal-oxide particles do not form a short-range order solid solution because their solubility limits at room temperature with Al is practically zero. Third, the insolubility of these metal-oxides with Al means that they generally do not form a strong chemical bond with the Al atoms in order to enhance the cohesive strength or the tensile strength of the alloy. Adding preformed metal-oxide powders may enhance the alloy strength only in some rare instances that usually require high cost process conditions and high volume percent of powders.

Similarly, using preformed powder of nonmetal-oxide and carbide particles such as Si-carbide (SiC), Si-nitride (Si<sub>3</sub>N<sub>4</sub>), and boron-carbide (B<sub>4</sub>C) will be ineffective as strengthening mechanisms for the same reasons stated above. In fact, it has been shown that all Al MMC's, reinforced with particulates (nonfibers) such as SiC, B<sub>4</sub>C, Al<sub>2</sub>O<sub>3</sub>, etc., are rarely able to achieve a higher strength level than their

nonreinforced alloys. Even when the volume fraction of these MMC reinforcements are relatively high (i.e., up to 60 percent), particulate reinforced MMC's are developed for higher stiffness (modulus of elasticity) components rather than for higher tensile strengths.

#### **D. Foundry Practices**

This section does not contain any confidential commercial information nor does it disclose an invention for which a patent has been applied. Hypereutectic Al-Si alloys are among the most difficult Al alloys to cast using conventional gravity-poured casting because of the high Si contents. Controlling the material compositions and fine-grain microstructures are important keys to producing successful Al-Si cast parts.<sup>15</sup> There are three important casting parameters for hypereutectic alloys that foundrymen have to understand in order to produce a good cast: (1) Grain refinement for the primary Si particles, (2) controlling the "fluidity" of the molten metal pouring into permanent molds due to the broad solidification range, and (3) providing a rapid cooling rate to control the high heat of fusion from Al-Si alloys. These basic foundry techniques for hypereutectic alloys are briefly explained below.

Si grain refinement is very important for producing a sound cast and obtaining product performance, particularly in the areas of high hardness and wear resistance. The unique feature in every hypereutectic alloy's microstructure is the primary Si phase that appears as large black "cuboids" particulates. These are hard Si particles that provide a hypereutectic alloy with its exceptional performance in wear resistance. In fact, these Si particles are so hard that diamond tooling is routinely required to machine the alloys for making pistons. However, the wear resistance is effective only when these Si particles are precipitated in very small sizes.<sup>9</sup> One of the key steps for making very small Si particles is to provide appropriate nucleation sites for small Si particles to precipitate out of Al. It is found that phosphorus addition to Al would be sufficient in forming extremely small Al-phosphide crystals to act as nucleate sites for the primary Si particles to precipitate in small sizes.<sup>15</sup>

The fluidity is an important property indicating how far a molten metal can flow in a mold to fill out all fine details before it becomes too solid to flow any further. The heat of fusion for Si is several times greater than that of Al. When Si is alloyed into Al it adds a large amount of heat capacity that must be removed from the alloy to solidify it. The heat of fusion is what provides Al-Si cast alloys with their unique characteristic "fluidity." This is why adding a small amount of Si to pure Al can dramatically improve the fluidity and mold feeding characteristics. However, when the Si content for hypereutectic is between 18–20 percent by weight, these Si primary crystals, upon precipitating rapidly out of the Al matrix during cooling, may "mechanically" impede the flow of the alloy within the mold. This is due to the uneven solidification temperatures within the molds. This broad range of solidification temperature equates to poor castability in certain types of mold geometries. In fact, hypereutectic Al-Si has a very broad solidification range of  $\approx 250$  °F. The broad solidification range is directly related to the amount of Si content alloyed in the Al. The optimum molten metal temperatures for pouring, gate and riser design for permanent molds, and mold temperatures must be carefully measured and designed to optimize casting parameters. For hypereutectic alloys, the casting parameters change with each change in Si concentration. The exact conditions which yield good castings for a 16-percent Si level will not yield an equally good casting at a 20-percent Si level. Presently, it is a common practice to keep the Si content to <18 percent.<sup>8,9</sup>

Since Al-Si alloys have very high heat of fusion, a large amount of heat from the molten metal is absorbed by the molds and other surrounding parts. This excess thermal energy must be removed from the alloys rapidly in order to solidify the cast and achieve optimum fine-grain structures. A system of rapid heat removal technique that operates in a cyclic cooling schemes for molds or dies must be designed as parts of the casting production lines. The optimum molten metal temperatures for pouring and the preheated temperatures for permanent molds and dies must be carefully measured and designed to optimize casting parameters. If possible, rapidly cooling the molds is one of the key steps in producing fine Si grains in submicron sizes and evenly distributing them throughout the Al matrix. After casting, using permanent molds, the mechanical properties can be further improved by using heat treatment in the standard T5 and T6 conditions.



## IV. RESULTS AND DISCUSSION

### A. Mechanical Properties

A new Al-Si alloy has been successfully developed at MSFC that has a significant improvement in tensile strength at elevated temperatures (500 to 700 °F). For instance, the new alloy shows an average tensile strength of at least 90 percent higher than the current state-of-the-art 390 Al piston alloy at 500 °F. Compared to conventional Al alloys, automotive engines using the new piston alloy will have improved gas mileage, and may produce less air pollution in order to meet the future U.S. automotive legislative requirements for low HC emissions from auto engines. The alloy development strategy is to reduce the Cu<sub>2</sub>Al diffusion rates, so that the mechanical blocking and short-range order solid solution strengthening mechanisms from the Cu<sub>2</sub>Al particles will survive to a high temperature in order to impede the dislocation movements. The new alloy is economically produced by pouring molten metal directly into conventional permanent steel molds or die casting.

Figure 2 is a chart showing a comparison of this new alloy with conventional piston alloys. The chart shows the ultimate tensile strength, tested at 500 °F, after exposure of the cast specimens to a temperature of 500 °F for at least 100 hr. Similarly, figures 3 and 4 show a comparison of this new alloy with conventional piston alloys exposed to similar testing conditions at 600 and 700 °F, respectively.

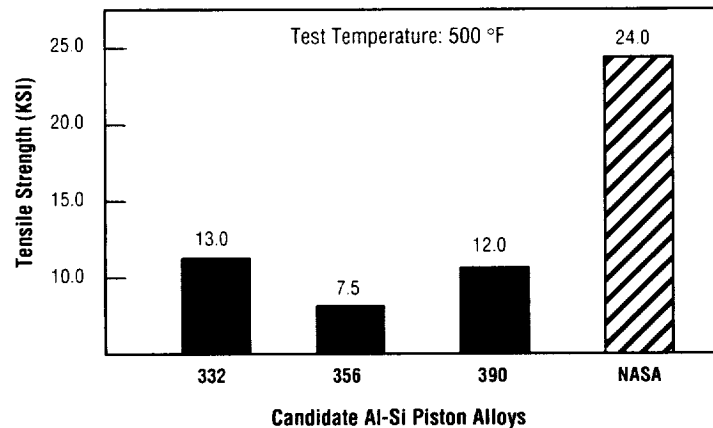


Figure 2. Ultimate tensile strength for piston alloys at 500 °F.

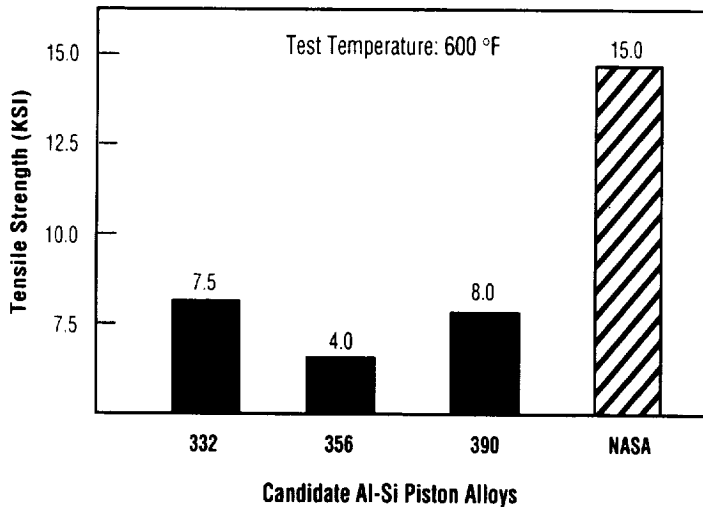


Figure 3. Ultimate tensile strength for piston alloys at 600 °F.

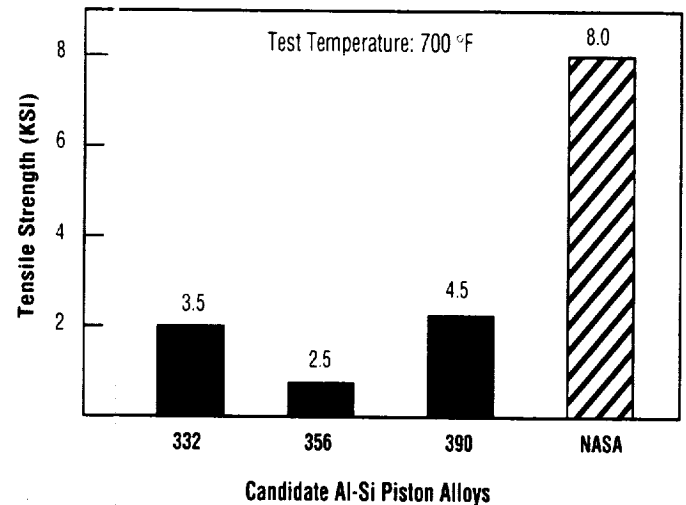


Figure 4. Ultimate tensile strength for piston alloys at 700 °F.

## B. Material Performance Versus Cost Trade-Study

The auto industry consumes roughly 23M ton of materials annually and 16 percent of this is Al. However, there are some key requirements that control the implementation of a new material in the auto industry. In recent years, there are many advanced materials developed for the aerospace industry that have outstanding properties but are considered as prohibitively expensive for the auto industry production levels.<sup>13</sup> Concerning the materials and its processing costs, table 2 shows a list of new materials implementation requirements for the auto industry. The manufacturing rates are very high for mass production in the auto industry. The high costs of a new material usually derives from low production volumes and immature processing technology for component productions. The low production volume usually comes from the problem of a worldwide raw material supply limitation or the manufacture's production capability for raw materials. For example, there is always a high demand for gold in our society, but the price of gold is never cheaper than Al because the supply of gold as a raw material is not plentiful. Furthermore, over the centuries the production capability for gold, whether through mining, processing, or recycling, has never been a low-cost process for the manufacturers. To some extent, a similar argument can be applied for advanced metal-oxide materials such as boron-carbide, Si-nitride, carbon/carbon composites, ceramic-reinforced MMC's is, etc. in which they do not exist plentifully in nature as raw materials.

The immature component processing technology refers to an inadequate understanding of the relationship between material properties, process conditions, equipment design, and microstructures to the properties of the finished products. For example, when dealing with advanced ceramic and MMC's, experimental data are often too expensive to obtain and usually cover only a small part in the total process-material space. The issue of affordability cannot be reliably addressed when "critical" data needed for a mass production program are often lacking. This lack of information, regarding the novel materials and processes, often leaves little more than guesswork when down-selecting among competing material technologies or formulating a corporate research and development investment strategy for mass production in a near-term basis.

Table 2. New materials implementation requirements for auto industry.

Plentiful supply of raw material
– Readily available from natural resources
– Inexpensive to process and can be recycled
Low accounted cost at subsystem level
– Materials cost
– Fabrication cost
– Tooling and facilities cost (amortized)
High reliability
– Superior material properties
– Materials database is available
– Proven performance through experimentations
Existing supplier infrastructures
– Mass production capability
– Minimum supplier's equipment modifications

The low cost of new material is a key factor for mass production in commercial industries, achievable because the new alloy is economically produced by pouring molten metal directly into conventional permanent steel molds or die casting molds. The mass production capability for Al alloys and the worldwide supplier infrastructure for cast Al alloy remain unchanged. In comparison, the Al-Si piston alloy 390 costs  $\approx \$0.87$  per pound; our new material projected cost for this new alloy will be  $< \$0.95$  per pound. The new alloy readily allows the piston to be cast at high production volume with a low, fully accounted cost. Figure 5 shows the comparative cost analysis for the new Al-Si alloy. Projected cost for MMC would range from \$10–\$30 per pound, and for carbon/carbon ceramic composite from \$100–\$300 per pound. Obviously, these advanced composite materials and their processing costs are considered as prohibitively expensive for piston mass production levels at the present time.

### C. Potential Commercial Applications

Presently, the production of hypereutectic Al-Si pistons has dominated the manufacture of Al pistons in the U.S. The standard hypereutectic Al-Si alloy for the industry is the A390 alloy. The current worldwide annual consumption of 390 alloy is estimated to be  $\approx 150,000$  ton. However, the usage of 390 alloys for pistons is limited to a maximum temperature of  $\approx 450$  °F. Thus the intention of this new alloy is to systematically replace the 390 alloy for piston production in the near term. Other potential commercial applications are listed as follows: Rotary engine side housings, air compressors, master brake cylinders, and chain saw cylinders. It can also be used for the variable-speed drive sheaves and pulleys, freon compressor pistons and cylinder bodies, automatic transmission pump bodies, pump covers, and clutch input housings.

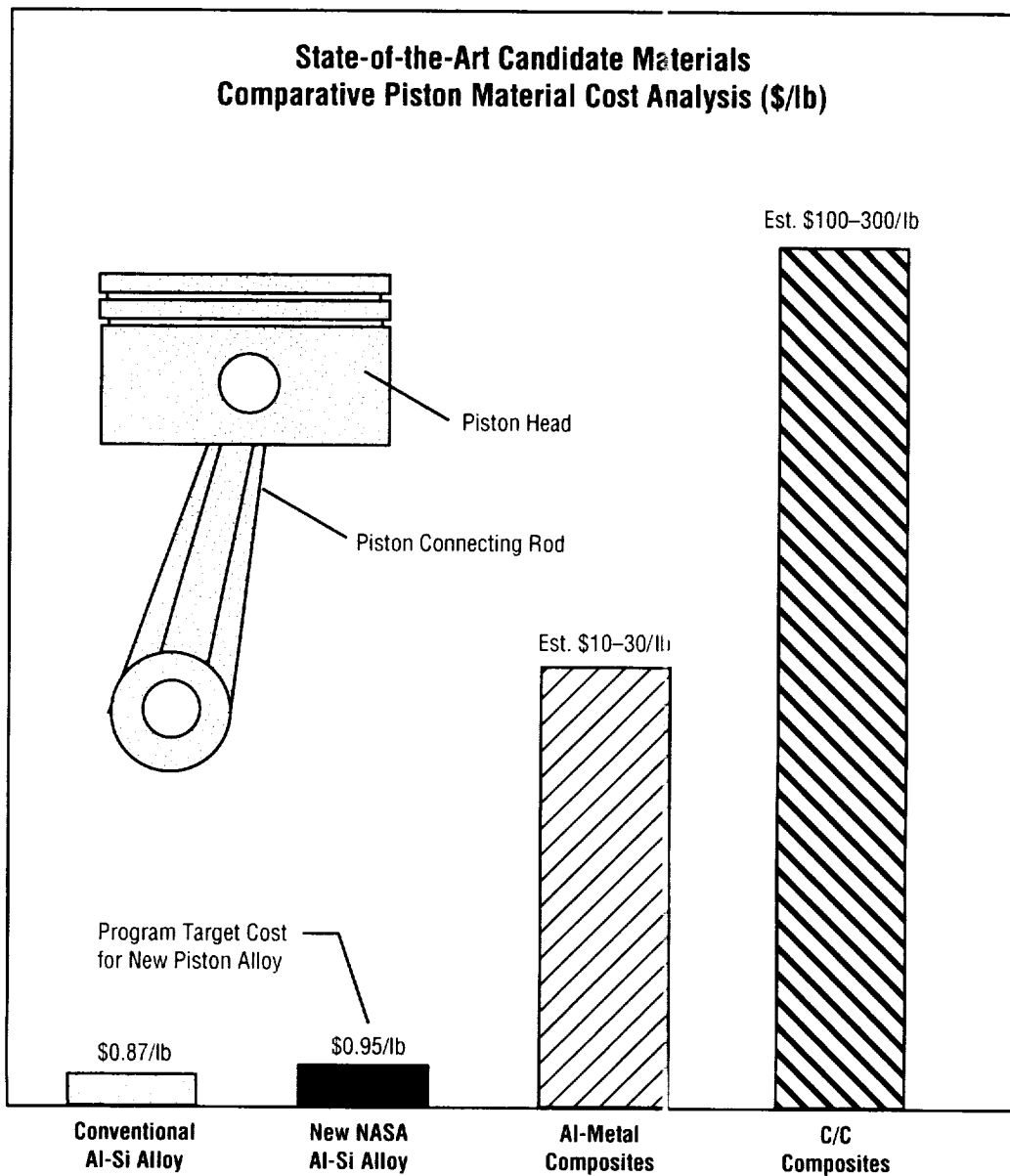


Figure 5. Candidate piston materials cost comparisons.

## **V. CONCLUSIONS AND RECOMMENDATION**

A new Al-Si alloy has been successfully developed at MSFC that has a significant improvement in tensile strength at elevated temperatures (500 to 700 °F). For instance, at 500 °F test temperature, the new alloy showed an average tensile strength of 24 KSI, which is at least 90 percent higher than the current state-of-the-art 390 piston alloy. With this remarkable performance in strength, it is anticipated that automotive engines using this new piston alloy will have improved gas mileage, and may produce less air pollution in order to meet the U.S. automotive legislative requirements for low air pollution emissions. It is also anticipated that the cost to implement this alloy for piston mass production is about the same level as the current auto industry's 390 alloy. The new alloy is economically produced by pouring molten metal directly into conventional permanent steel molds or die casting molds.

It is recommended that MSFC should conduct a proof-of-concept study phase with the U.S. piston vendors within the next 24 mo. This activity will serve as a focal point to bring together the unique material experiences from MSFC, U.S. automaker's experience in auto engine emission test, and piston suppliers for mutual benefits. Some of the major tasks to be accomplished are to (1) develop a material property database for the auto industry, (2) cast the alloy and fabricate the pistons, and (3) perform the piston-engine assembly and HC emission testings

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<b>REPORT DOCUMENTATION PAGE</b>			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operation and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503				
1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE December 1998		3. REPORT TYPE AND DATES COVERED Technical Memorandum
4. TITLE AND SUBTITLE High-Strength Aluminum Casting Alloy for High-Temperature Applications (MSFC Center Director's Discretionary Fund Final Report, Project No. 97-10)			5. FUNDING NUMBERS	
6. AUTHORS J.A. Lee				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812			8. PERFORMING ORGANIZATION REPORT NUMBER  M-902	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER  NASA/TM-1998-209004	
11. SUPPLEMENTARY NOTES Prepared for Materials and Processes Laboratory, Science and Engineering Directorate				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category 26 Nonstandard Distribution			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  A new aluminum-silicon alloy has been successfully developed at Marshall Space Flight Center that has a significant improvement in tensile strength at elevated temperatures (550 to 700 °F). For instance, the new alloy shows an average tensile strength of at least 90 percent higher than the current 390 aluminum piston alloy tested at 500 °F. Compared to conventional aluminum alloys, automotive engines using the new piston alloy will have improved gas mileage, and may produce less air pollution in order to meet the future U.S. automotive legislative requirements for low hydrocarbon emissions. The projected cost for this alloy is <\$0.95/lb, and it readily allows the automotive components to be cast at a high production volume with a low, fully accounted cost. It is economically produced by pouring molten metal directly into conventional permanent steel molds or die casting.				
14. SUBJECT TERMS aluminum-silicon alloy, hypereutectic, hydrocarbon emission, piston, permanent mold casting, dislocations, strengthening mechanisms, wear resistance, global warming, automotive engines, air pollution, 390 alloy, tensile strength			15. NUMBER OF PAGES 24	
			16. PRICE CODE A03	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	

**APPROVAL**

**HIGH-STRENGTH ALUMINUM CASTING ALLOY  
FOR HIGH-TEMPERATURE APPLICATIONS  
(MSFC Center Director's Discretionary Fund Final Report, Project No. 97-10)**

J.A. Lee

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

A handwritten signature in cursive script, appearing to read "A F Whitaker", is written above a horizontal line.

A.F. WHITAKER

DIRECTOR, MATERIALS AND PROCESSES LABORATORY