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INNOVATIVE CLEAN AIR TECHNOLOGY (ICAT) PROGRAM

State of California

Air Resources Board

RFP 94-10

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PROJECT TITLE:	High-Efficiency Catalytic Converter Prototype Demonstration
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PROJECT DESCRIPTION

PROJECT SUMMARY

The proposed demonstration program will provide trade studies and quantify performance and cost improvements possible for catalytic aftertreatment devices using reticulated foam catalyst supports and thermally stable catalyst technology developed at Ultramet. Specifically, the funded investigation will develop detailed design and performance data using Ultramet's UltraCat™ converter technology. The basis for the UltraCat is the use of Ultrafoam$_{SiC}$™ reticulated silicon carbide foam as a catalyst support, allowing smaller, lower cost, lower pressure drop converters to be fabricated.

Using UltraCat technology, exhaust conversion kinetics are dominated by surface reaction kinetics as opposed to the mass transfer limited kinetics observed when honeycomb catalyst supports are utilized. This in turn allows 5-20x higher space velocities to be used, dramatically reducing the size, complexity, and cost of catalytic aftertreatment devices. For example, current automotive catalytic converters use two 3 x 6 x 3" 400-cpi cordierite honeycomb supports at a space velocity of 40,000/hr. Using Ultracat technology, equivalent conversion can be obtained at space velocities of 250,000/hr, requiring the use of one 3 x 6 x 1" 45-ppi reticulated SiC foam support having roughly half the backpressure of the two 400-cpi honeycomb supports. In addition to surface reaction kinetic control over mass conversion rate, a similar enhancement of heating rate is obtained, reducing lightoff time by a factor of 5-20 and reducing cold start emissions by at least 80%. As currently formulated, the baseline catalyst composition and support combination is immune to thermal poisoning, leading to improved reliability, especially when coupled to currently "dirty" pollution sources such as high-performance vehicles, off-road vehicles, two-stroke engines, and side-valve utility engines.

While the cost of the SiC supports is 3-4 times that of the cordierite honeycomb on a volume basis, only 1/6 the amount of material is required, resulting in a 1/3 unit cost reduction. Additionally, because the platinum group metal catalyst represents 2/3 of the total converter cost, a catalyst cost reduction of more than 50% should be obtainable, since the same surface area and catalyst loading are required per unit volume for both types of substrates. The combination of these two effects should provide a total cost reduction of some two-thirds.

ICAT funds will be used to develop improved catalyst formulations and low-cost methods for their application to SiC foam substrates; characterize catalyst samples; and construct, test, debug, and begin qualification of catalytic aftertreatment devices for high-performance auto and off-highway vehicles, as well as utility lawn and garden engines. Matching funds will be provided in the form of a portion of an SBIR Phase II program being performed for NASA Lewis Research Center, which will allow design, testing, and beginning of FAA STC procedures for noise- and pollution-reducing exhaust systems for general aviation aircraft. Matching funds will also be provided through waiver of all G&A expenses involved in the performance of the project, and waiver of fee.

TARGET APPLICATIONS

The proposed program is centered around the development of emission control products based on a new catalyst support technology, UltraCat™. This technology allows higher temperature, lower backpressure, faster lightoff, and smaller volume exhaust aftertreatment devices to be constructed. When the UltraCat support technology is combined with Ultramet's proprietary platinum group metal-based catalyst coatings, these devices become immune to thermal poisoning. Using radial flow and optimized converter flowpaths, combined with optimized catalyst loadings and surface areas, high performance, low backpressure, and sound attenuating aftertreatment devices can be made at a dramatically reduced cost compared to currently produced and envisioned aftertreatment technologies.

This new technology is uniquely positioned for potential adoption in the general aviation, ultralow-emission vehicle (ULEV), personal watercraft and marine engine, motorcycle, restaurant equipment, off-highway vehicle, and utility lawn and garden equipment (ULGE) markets. Each of these markets, previously unregulated (with the exception of automotive), has been targeted by ARB for emission reductions under previous and current state implementation plans (SIPs), as allowed by the California Clean Air Act (CCAA) and codified in Health and Safety Code (HSC) sections 43013 and 43018.

Specifically, the following applications/market areas are targeted for prototype development, demonstration, and qualification under the proposed program:

- Utility lawn and garden equipment (ULGE): Current and upcoming ARB and EPA regulations will require reductions in pollutants from ULGE engines. These engines fall into two general classes, two-stroke and four-stroke. Two-stroke ULGE engines have been estimated to emit 53 tons per day (tpd) of total exhaust hydrocarbons (THC), 164 tpd of carbon monoxide (CO), and 0.2 tpd of nitrogen oxides (NO_x) in California. Four-stroke ULGE engines are estimated to produce 17 tpd of THC, 331 tpd of CO, and 1.8 tpd of NO_x. This amounts to approximately 5% of the total statewide on-road mobile source hydrocarbon emissions and 4% of the CO, and is equivalent to the emissions from 3.5 million new 1991 model passenger cars driven 16,000 miles per year. Table I summarizes the current (1995-1998) and 1999 emissions standards for ULGE engines. To meet 1999 standards, a 75-80% reduction in CO and HC emissions will be required.

- Automotive catalytic converters: Future catalytic converters will operate closer to the engine and will require lower backpressure than current systems. The UltraCat support has much lower heat capacity than either metallic or ceramic honeycomb supports. This lower heat capacity, combined with 5-10x heat and mass transfer coefficients, results in the potential for up to a 90% reduction in lightoff time and allowing ULEV emissions standards to be met without the requirement for either close-coupled or electrically heated catalyst supports. This in turn will result in a significant cost savings for implementing ULEV standards (20%-80% cost savings compared to close-coupled and electrically heated catalysts). In addition, the isotropic nature of the UltraCat support allows optimized support flowpath designs, including radial and conical flow designs resulting in lower backpressure systems. Furthermore, enhanced surface area and higher mass transfer coefficients allow 3-5x the

Table I. Exhaustive Emission Standards for Utility Engines, 1994-98 (Top) and 1999 and Beyond (Bottom)

94-98

ALL ENGINES	Emissions Standards (g/bhp-hr) THC + NOx	CO	PM-diesels
< 225 cc[1] Displacement	12.0	300	0.9
>=225 cc Displacement	10.0	250	0.9

HAND HELD EQUIPMENT ENGINES	Emissions Standards (g/bhp-hr) THC	CO	NOx	PM
< 50 cc Engine Displacement	180	600	4.0	-
>=50 cc Engine Displacement	120	300	4.0	-

99->

	Emissions Standards (g/bhp-hr) THC + NOx	CO	PM-diesels
NON-HAND HELD EQUIP'T ENGINES	3.2	100	0.25

	THC	CO	NOx	PM
HAND HELD EQUIPMENT ENGINES	50	130	4.0	0.25

space velocity of current converters to be used, allowing smaller, lower cost converters to be used (65% of the cost is catalyst cost, which is 2-5x lower using UltraCat supports). Furthermore, low backpressure, very high flow and high temperature converter designs would be adopted by the on-road and track racing industries.

- Catalytic converters for piston-powered general aviation engines: The upcoming federal implementation plans (FIPs) for Southern California and Sacramento target general aviation airplanes with an imposed takeoff and landing fee designed to discourage the use of general aviation aircraft. Certified "clean" engines would be exempted from the new fees. Under a NASA-funded SBIR program, Ultramet will evaluate current emissions levels from horizontally opposed piston engines in 0-200 to 0-470 class engines and evaluate converter designs and other simple, retrofittable modifications resulting in a 30-75% reduction in emissions levels. Aircraft-specific requirements include very low backpressure, high temperature operation, low weight, and zero probability of clogging.

- Motorcycles, spark-ignited marine engines, and recreational vehicles: This class of vehicles covers mopeds, dirt bikes, all-terrain vehicles (ATVs), jet skis, and outboard engines. This class of vehicles is dominated by low-cost two-stroke and side-valve four-stroke engines and has previously been unregulated. Practically, these engines and the converter requirements are very similar to the ULGE engines and require small size, low cost, temperature insensitivity, elimination of ignition (flameout), and very low backpressure.

TECHNOLOGY BASIS

The technological basis for the proposed program is the recent development of a highly porous, high-strength reticulated SiC foam material tradenamed $Ultrafoam_{SiC}^{TM}$. This cellular material, originally developed for structural reentry insulation under Air Force SBIR sponsorship, has a number of distinct advantages over conventional honeycomb monolith supports and alternate porous and cellular solid materials when used as a catalyst support. Figure 1 illustrates the structure of the $Ultrafoam_{SiC}$ catalyst support. This material has numerous advantages over alternate materials for catalytic converter application:

- Very high strength at low densities: Figure 2 shows the mechanical properties of the $Ultrafoam_{SiC}$ catalyst support. Because of its unique method of manufacture, the strength of the SiC foam material is an order of magnitude higher than other foam materials at equivalent density.

- Very high heat and mass transfer rates: Figure 3 shows the conversion, at equivalent catalyst loadings, for C_{20} hydrocarbons in 45-ppi $Ultrafoam_{SiC}$ supports and 400-cpi honeycomb supports. The 45-ppi foam and the 400-cpi honeycomb have equivalent geometric surface area. Similar enhancements in heat transfer rates are obtained. Theoretically, the foam substrate can be modeled as a series of stacked screens, and friction factor and Colburn modulus as a function of foam geometry are shown in Figure 4.

- Very low thermal mass: Figure 5 compares the thermal mass and specific surface area of $Ultrafoam_{SiC}$ and metallic honeycomb (Emitec data). Because there is no limitation on ligament thickness, and because SiC has very low thermal mass, the $Ultrafoam_{SiC}$ supports can be fabricated with very high surface area/thermal mass ratios.

- Flow isotropy: The $Ultrafoam_{SiC}$ structure, which is the heart of the UltraCat converter system, is isotropic in nature. This allows optimized converter structures to be used that maximize the cross-section to flow in a given volume.

- Low induced backpressure: Because of the high heat and mass transfer rates, high surface area, and flow isotropy of the UltraCat converter system, equivalent conversions can be obtained at one-third to one-half the induced backpressure of honeycomb monolith-based converter systems. This reduced pressure drop is illustrated in Figure 6.

In addition to the technical benefits of the UltraCat catalyst support, Ultramet has developed a method for applying catalysts to the $Ultrafoam_{SiC}$ structure which eliminates the need for a washcoat (and its associated thermal mass, mass transfer limitations, and thermal instability). Ultramet has discovered a method of bonding platinum group metal crystallites directly to the substrate, eliminating the requirement for a washcoat to distribute the platinum group metal while obtaining highly dispersed platinum group metal crystallites. The application method is currently being held proprietary, but Figure 7 illustrates the dispersion obtained. The direct application and bonding of the catalyst crystallites eliminates the thermal poisoning mechanisms associated with sintering, pore closeout, and solution of the catalyst metal while providing a much reduced thickness with equivalent catalyst loading.

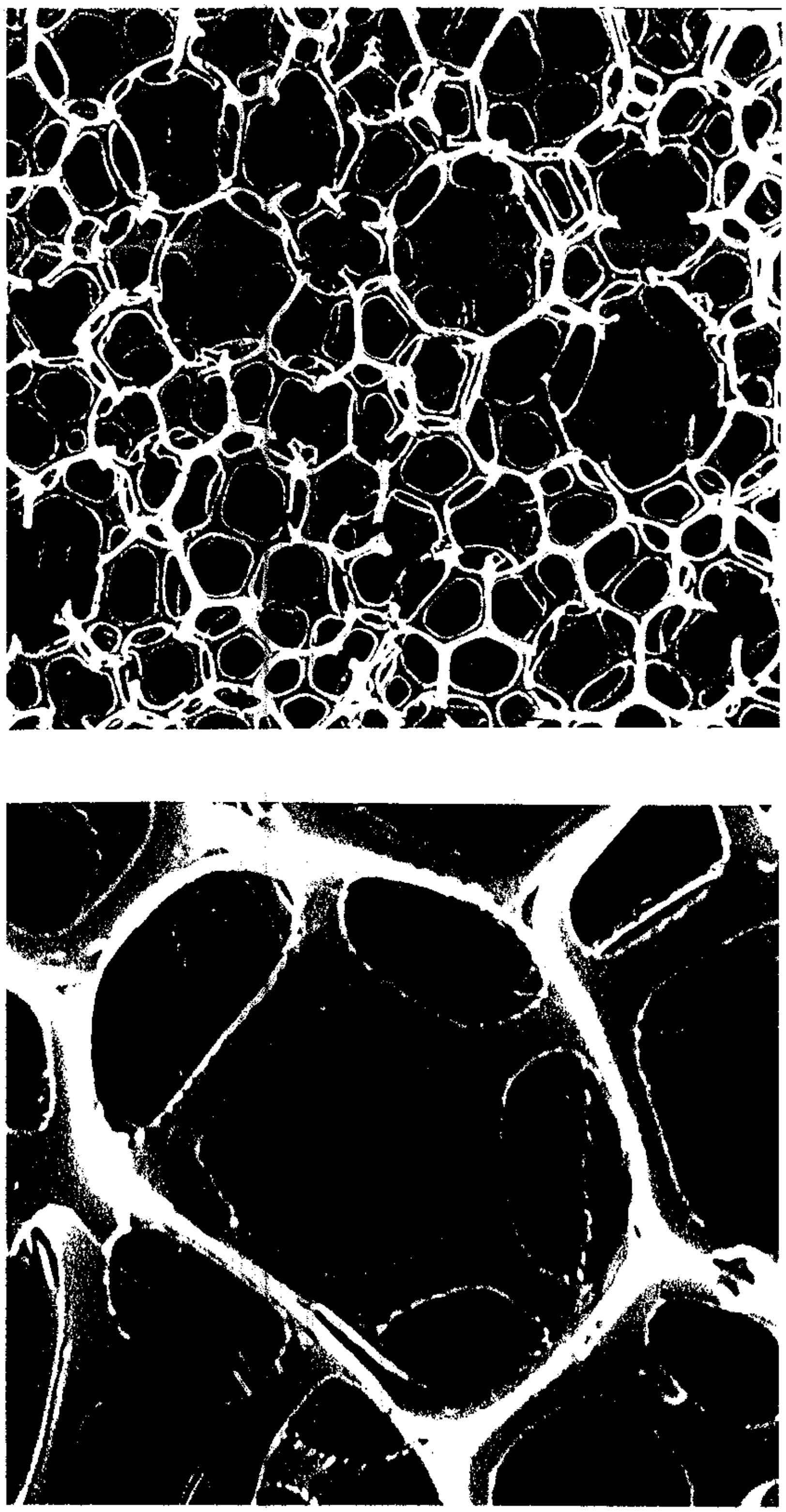


Figure 1. SEM micrographs showing structure of Ultrafoam$_{SiC}$ catalyst support (top: 24x; bottom: 75x)

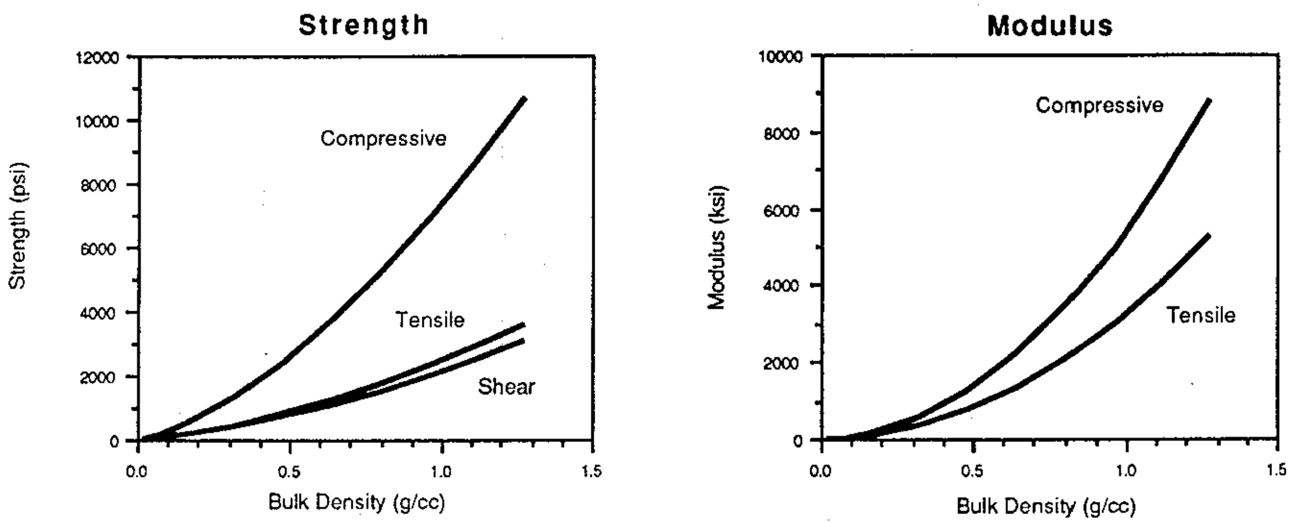


Figure 2. Mechanical properties of Ultrafoam$_{SiC}$ catalyst support

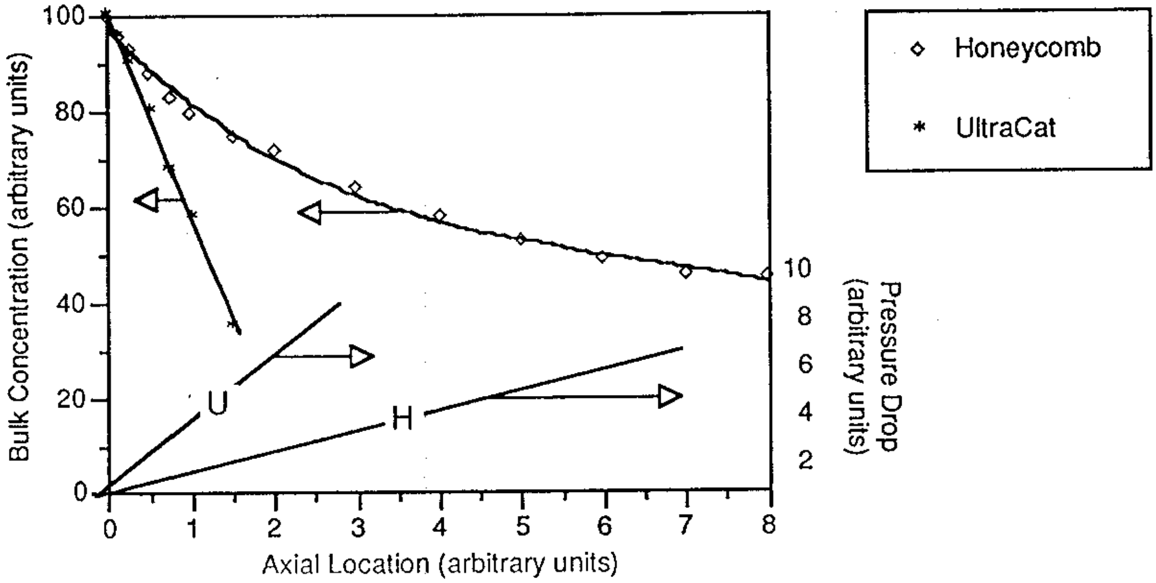


Figure 3. Relative conversion and pressure drop vs. axial location for UltraCat and conventional honeycomb supports ($C_{20}H_{42}$ basis)

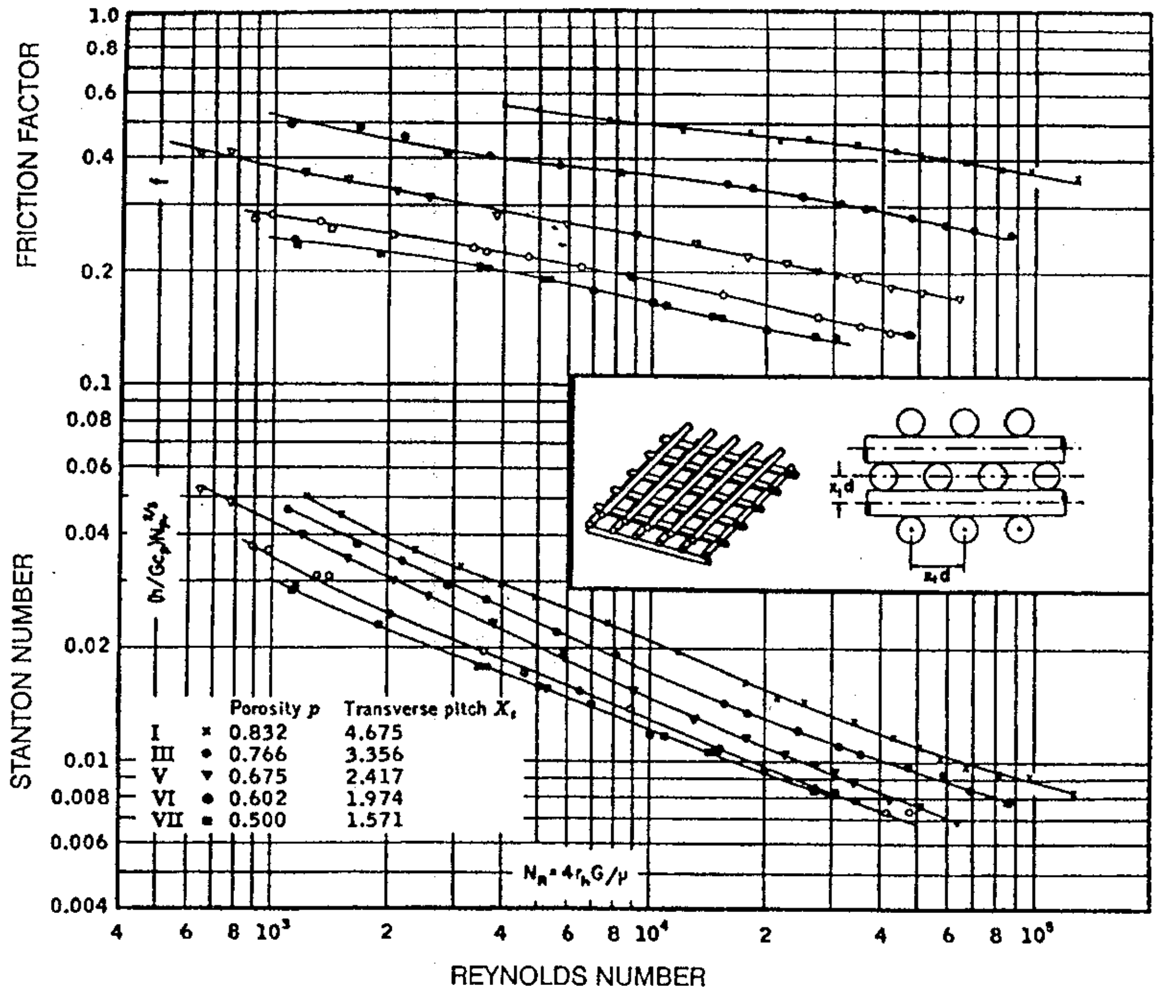


Figure 4. Convective heat transfer coefficient and friction factor in cross-rod matrices and screens

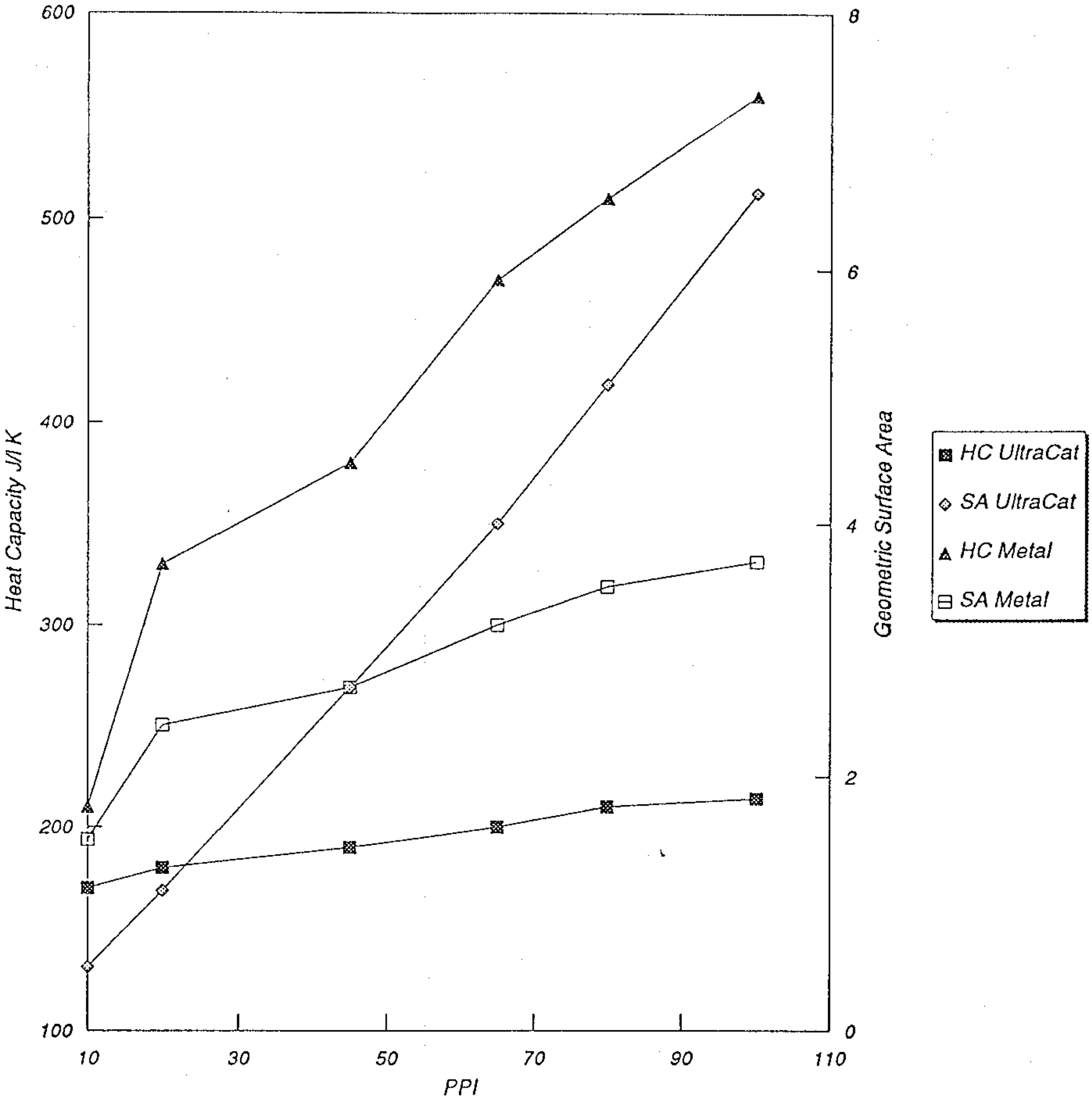


Figure 5. Heat capacity vs. surface area for UltraCat and conventional honeycomb supports

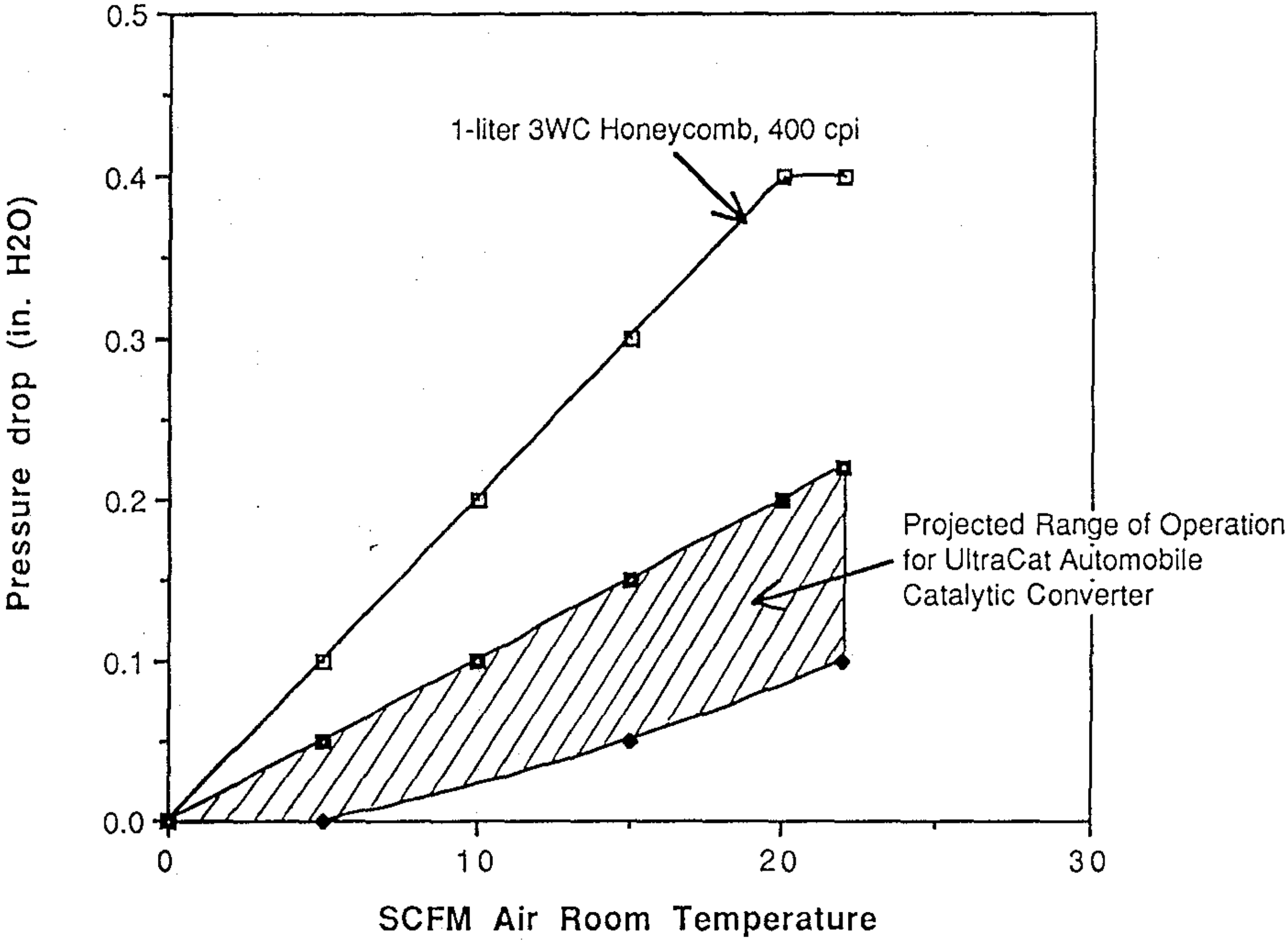


Figure 6. Pressure drop vs. flow rate for UltraCat and conventional honeycomb supports

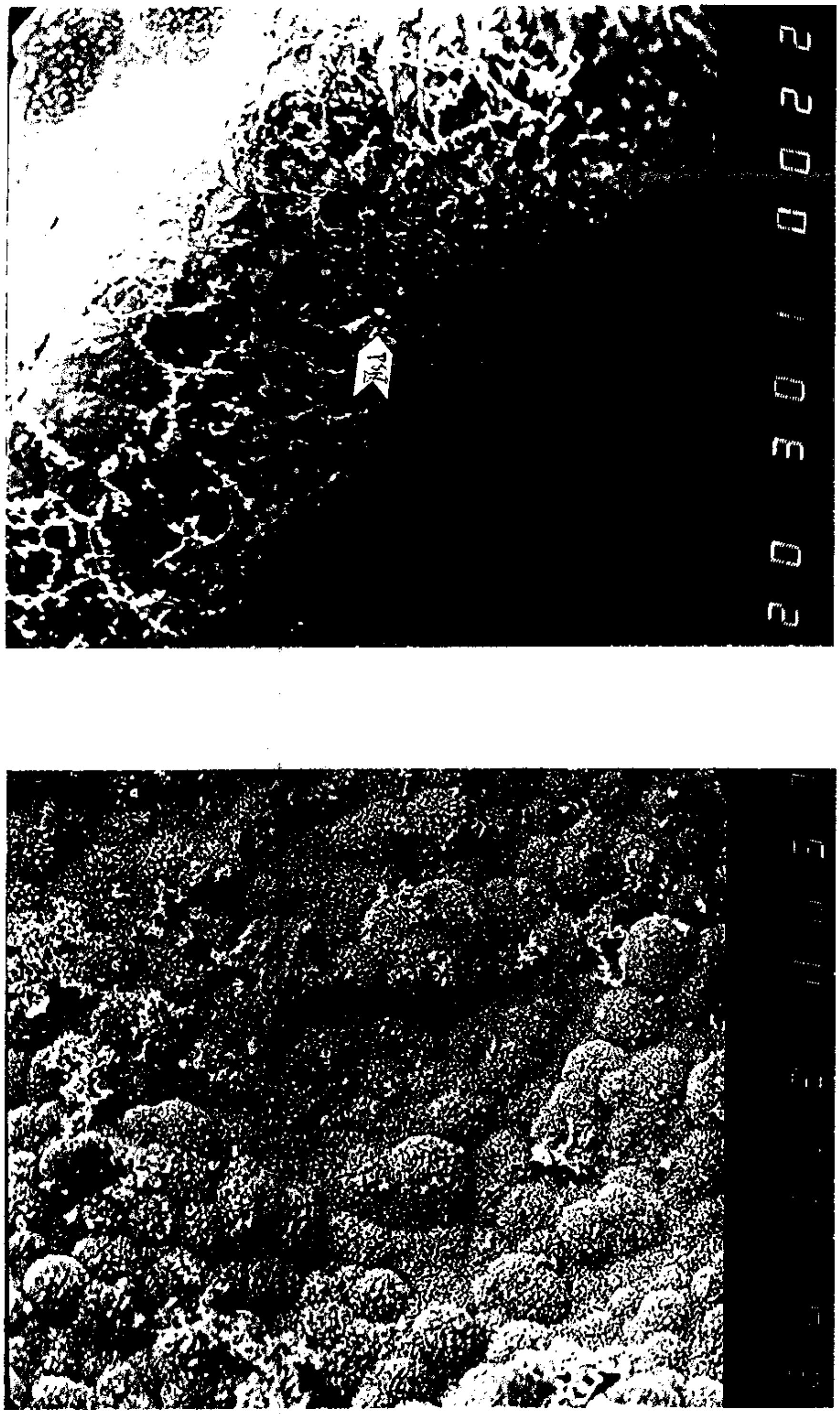


Figure 7. SEM micrographs showing catalyst dispersion at low (top, ≈0.2 g/L, 300x) and high (bottom, ≈3 g/L, 1000x) loadings

PROJECT GOALS

The overall goal of the proposed program is to quantify, through bench testing, prototype fabrication, and application demonstration, the economic and performance advantages of the UltraCat converter system in each of the four target applications. In doing so, the design limits (space velocities, optimal cell size and catalyst loading, optimal geometry, and mounting/canning requirements) will be developed which can be extrapolated to additional applications/markets. By quantifying the performance and identifying the minimum size requirements, detailed costing can be derived which will allow competitive market analyses to be conducted, leading to the obtaining of venture capital to complete scaleup and commercialization of the UltraCat technology.

Specific program goals include the following:

- Demonstrate prototype designs resulting in simultaneous >10-dB noise reduction and >75% reduction in THC and CO at less than 1-inHg induced backpressure for small two-stroke and side-valve four-stroke engines in the 2-10 HP ULGE and 10-50 HP spark-ignited marine, recreational, and motorcycle engine classes.

- Demonstrate prototype designs resulting in a >80% reduction in bag 1 (cold start) THC and CO emissions using passive converter technology for ULEV automotive applications and determine design limits (space velocity, exhaust gas temperature, etc.) that result in meeting ULEV emissions standards.

- Develop an emission inventory for propeller-driven piston-engine general aviation aircraft (in terms of grams of pollutants per passenger mile) for O-200 to O-470 class engines, and develop a prototype converter capable of satisfying continued airworthiness (FAR parts 23 and 36) requirements.

- Resolve key technical risk issues to enable the obtaining of outside risk capital for scaleup and commercialization of the UltraCat technology.

- Determine packaging, cooling, and insulation requirements to enable converter designs to meet all applicable state and federal regulations concerning durability, surface and exhaust temperatures, and product packaging and integration requirements.

TECHNICAL OBJECTIVES

Consistent with the goals of the program, the overall objective of the proposed effort is to resolve the key technical risks involved in the design and application of SiC foam monolithic catalyst supports (UltraCat) to a range of pollution control applications through bench and prototype testing in order to secure the required financing for scaleup and commercialization of UltraCat converter technology. Two objectives will be pursued. First, detailed design data necessary for UltraCat application to generic pollution control applications will be generated in laboratory bench testing using simulated gas compositions. Second, actual performance data will be generated on prototype converters fabricated and tested for four target market applications consistent with scheduled and proposed ARB and EPA regulations.

While significant work has already been conducted in order to demonstrate the technical basis and feasibility, it is necessary to generate the detailed design and performance data required to size and cost UltraCat products for specific applications. The proposed objectives and technical approach are designed to accomplish exactly this.

The specific objectives of the proposed program include the following:

- Develop a design database by characterizing the THC and CO conversion efficiencies obtained as a function of time, gas temperature, gas composition (simulated engine mixture ratio), flow rate, gas residence time, catalyst loading, catalyst surface area, and catalyst formulation.

- Determine the lightoff kinetics to develop a cold-start converter design.

- Evaluate the effects of thermal aging and engine exposure on conversion efficiency to identify any poisoning mechanisms and degradation factors.

- Conduct design and sizing of a converter system for 1, 10, and/or 35 HP two-stroke engines, construct prototypes, and measure performance including pressure drop, conversion efficiencies and emissions, performance and fuel penalties expected, and the effect of mixture ratio/engine retuning which may be required to meet emissions regulations.

- Design, fabricate, and evaluate the performance of passive and close-coupled fast-lightoff converters capable of meeting ULEV emissions standards.

- Conduct an emissions survey of piston-powered light aircraft, and construct and evaluate a prototype converter capable of meeting FAA part 23 and 36 standards.

TECHNICAL APPROACH

The technical approach to be taken in the proposed program is to develop prototype aftertreatment devices based on the use of a low-density SiC foam monolithic catalyst support and demonstrate its performance in selected target applications. Additionally, laboratory bench testing will be conducted in parallel to develop a detailed design database allowing extension of this technology to additional pollution control applications ranging from diesel engine catalytic converters to flue gas cleanup of restaurant equipment and coal-fired boilers.

The proposed approach will utilize a low-density SiC foam catalyst support with direct application of platinum group metal catalysts, which results in a catalyst system having very high heat and mass transfer coefficients, very low thermal mass, and the ability to operate at very high space velocities (small, low-cost units). This technical approach addresses the major drawbacks of current and developmental catalyst supports when applied to current and planned pollution control applications.

Ultrafoam$_{SiC}$ Catalyst Support and UltraCat Catalyst System

The UltraCat converter substrate consists of a low-density silicon carbide foam, tradenamed Ultrafoam$_{SiC}$. This reticulated foam structure, fabricated by chemical vapor deposition (CVD), presents an extremely high surface area per unit volume compared to honeycomb supports, approaching that presented by packed powder beds but at a much lower pressure drop (10% packing density vs. 50-60%) and thermal mass. This structure negates the requirement for high surface area "washes" which lead to thermal degradation of the catalyst.

Previous studies have demonstrated that equivalent conversions can be achieved, at constant cross-sectional areas and equivalent pressure drops, between a foam support (in those studies, a 30% packing volume cordierite foam) and the through-flow monoliths used in automobile converters, but in as little as one-sixth the converter length. Figure 8 shows a comparison of the conversion, at 1,290,000/hr space velocities, of a 45-ppi UltraCat substrate compared to a conventional two-way catalyst on a 400-cpi Celcor substrate.

Because the foam is isotropic, and requires a much smaller conversion length (gas residence time) to achieve equivalent levels of conversion, radial flow and other high cross-sectional area designs can be used to advantage, resulting in a better performing system. In addition, because of the unique method of fabrication, higher surface area (higher ppi) foams can be constructed with a much reduced thermal mass penalty compared to honeycombs, which have a limitation with regard to minimum wall thickness, leading to increased thermal mass and weight at higher surface areas. With CVD fabricated foams, material strengths are constant with density, and equivalent densities (and thermal masses) can be fabricated with pore diameters ranging from 0.005-0.010", allowing a 20x range of geometric surface areas to be obtained.

The SiC foam support is fabricated using a state-of-the-art ceramic manufacturing process, chemical vapor deposition (CVD)/infiltration (CVI). The material to be fabricated (in this case, SiC) is deposited onto the ligament surfaces of a

Similar Specific Surface 26cm2/cm3
Similar Space Velocity 1,290,000 hr ^ - 1
Test ramped to 600C
Total gas 8.3 SCFM nominal
1pc at 1.25" dia. x .85"

Substrate	Conversion %CO	Conversion %HC
45 PPI UFSiC	93	40-70
400CPI	68	32

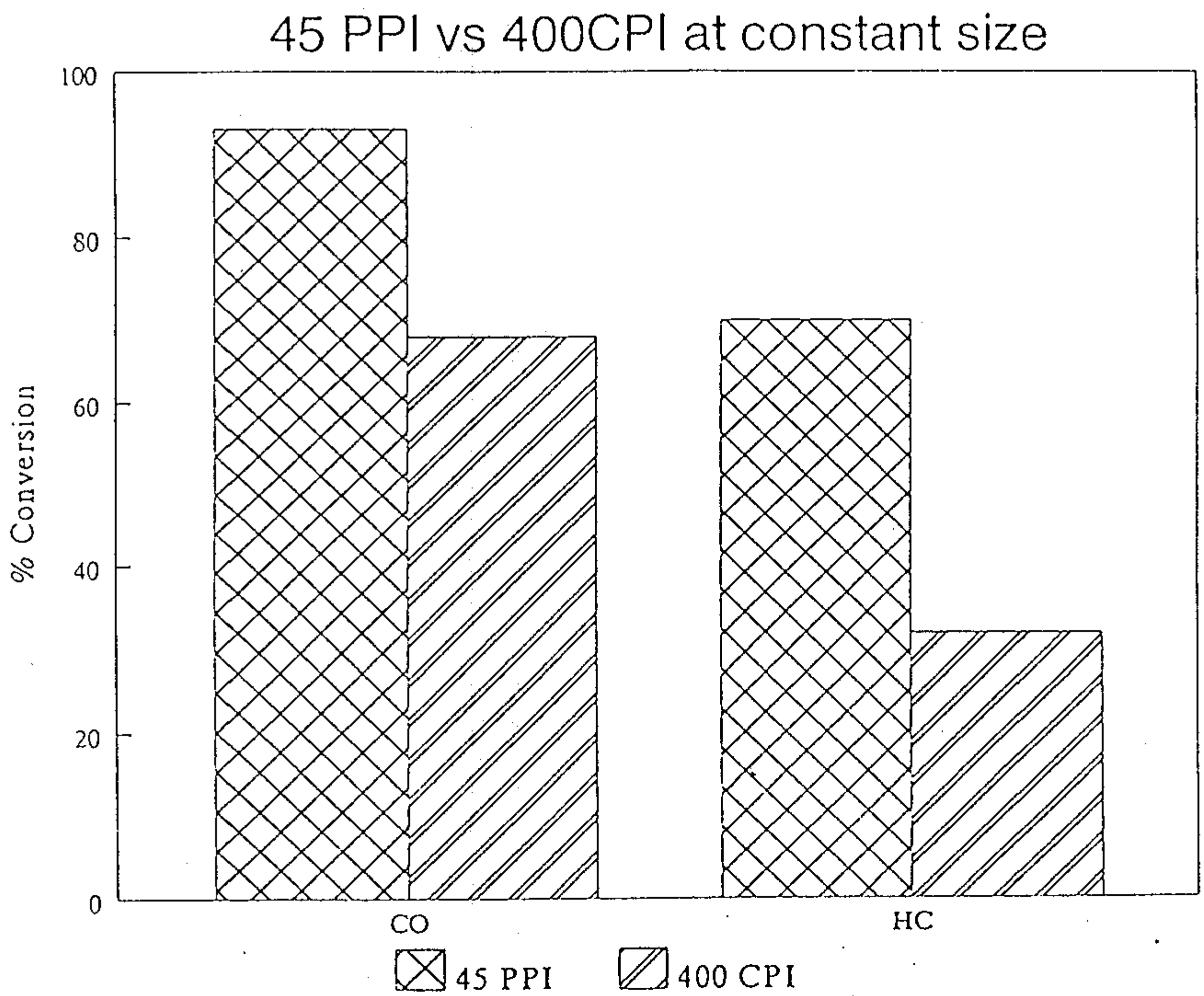


Figure 8. CO and HC conversion for UltraCat and conventional honeycomb supports

pyrolyzed polymer foam (typically used for furniture packing) in a process analogous to electroplating. The process allows fully dense, fine-grained high temperature materials to be formed. This method of fabrication results in a roughly 10- to 20-fold increase in mechanical properties compared to extruded or slurry-cast materials, the means by which other foams and monoliths are fabricated. This is evidenced by the fact that SCS6, a SiC fiber fabricated by CVD, has a strength on the order of 500-650 ksi, while bonded or sintered SiC has a strength on the order of just 50 ksi. This allows a 10% dense foam (i.e., 10% packing density) to have higher mechanical properties than a 30% dense extruded honeycomb or slurry-cast foam monolith, while having equivalent surface area at dramatically lower backpressures otherwise approachable only with metallic monoliths at a much higher projected cost.

The proposed approach addresses the following limitations of current and developmental systems through the use of the UltraCat catalyst support and catalyst system:

- <u>High heat transfer rates and low thermal mass</u>: Currently, over 80% of the emissions from automotive engines are released during startup before the catalyst unit has a chance to reach lightoff temperatures. The UltraCat system has 5-10x the heat transfer coefficient of equivalent honeycomb supports and 2-8x lower thermal mass, resulting in an order of magnitude reduction in time to lightoff.

- <u>Thermal stability</u>: In "dirty" engine applications such as motorcycle, high-performance automotive, and two-stroke ULGE engines, exhaust gas temperatures in the converter can reach 1000°C. Current cordierite supports and alumina washcoats poison due to sintering and fail structurally due to a loss in strength. Likewise, metallic units have limited life due to oxidation at these temperatures. The combination of a SiC support (80% retention of room temperature strength at 1200°C) and direct application of the platinum group metal catalysts provides a thermally stable structure capable of surviving temperatures in excess of 1000°C. Enhanced temperature capability also allows the converter to be located closer to the engine.

- <u>Performance/backpressure effects</u>: High-performance, general aviation, and two-stroke engines are extremely sensitive to backpressure, losing approximately 2% of engine power for each 1-inHg increase in backpressure. The use of a radial or conical flowpath and the high space velocities achievable because of the elimination of boundary layer mass transport and the isotropic nature of the UltraCat catalyst support allow near-zero backpressure converters to be developed.

- <u>Cost</u>: Approximately 70% of the cost of a catalytic converter is due to the platinum group metal loading. With the UltraCat system, only one-fourth to one-half the volume of catalyst is required due to enhanced mixing, reducing the platinum group metal cost component by 50-75%. In addition, since nearly all of the catalyst applied is accessible to exhaust gases, it is possible to reduce the catalyst loading even further.

- <u>Size</u>: Many converter applications, such as ULGE, personal watercraft, and general aviation engines, have very little space and weight available for the converter unit. Because the UltraCat system is only one-fourth to one-half the volume of honeycomb-supported units, and of lower average density, it is uniquely suited for these applications.

Ultramet's demonstrated catalyst system has several unique features offering advantages over current autocatalyst formulations. First, utilization of a ceramic or metallic foam substrate, as opposed to a honeycomb structure, provides much greater surface contact and mixing at equivalent or reduced pressure drops. Pressure drop data for foams of various porosities are shown in Figure 9. Because of the much higher surface area and enhanced mixing which occurs in foam (or mesh) substrates, it is not necessary to utilize a high surface area washcoat to achieve the desired conversion efficiencies. If a higher surface area is desired, surface texturing of the foam surface can provide a 10-100x enhancement in surface area. Ultramet has demonstrated 10-100x enhanced catalytic efficiency using foams, due mainly to the greater exposure of catalytic surface to gas (i.e., the catalyst is located solely on the support surface, not embedded in a washcoat).

The primary objective of this project is to develop an exhaust aftertreatment reactor design capable of a >80% reduction in THC and CO emissions in four target applications representing industries/products impacted by upcoming environmental regulation. The system is based on the use of a catalyzed reticulated open-cell SiC foam which provides high surface area and noise reduction with low pressure drop and extreme thermal stability. The basic reactor consists of a muffler/converter can which acts as a plenum for noise reduction and contains the catalyst support structure.

The catalyst/support system to be pursued is designed primarily for oxidizing THC and CO to acceptable levels. NO_x reduction is a secondary consideration, since NO_x emissions are minor for two-stroke and side-valve four-stroke engines, and performance engines are tuned rich for peak power, placing the emphasis on THC and CO reduction, not NO_x reduction. Proper operation of the converter may require extra air addition (modifying the mixture ratio) or air injection to achieve low THC and CO and for cooling of exhaust gases.

Radial flow geometry has been selected for the baseline designs, since it offers the highest cross-sectional area to flow and hence the lowest backpressure per unit volumetric flow and reactant residence time. An overall schematic of the proposed aftertreatment reactor is shown in Figure 10. This reactor will be capable of reducing all hazardous emissions from the engine exhaust, and with minor engine modifications to each of the four candidate markets should satisfy upcoming watercraft, off-highway, recreational vehicle, ULGE, ULEV, and general aviation engine emissions regulations. The approach is to make the aftertreatment reactor and engine modifications retrofittable to existing vehicles, as well as applicable to new engines.

Bench-Scale Testing

Bench-scale (flowbench) testing will be conducted in parallel with prototype converter development and applications testing to develop a design database for optimizing converter designs (mainly in terms of cost, size, and performance, in that order) and to enable the extrapolation of designs to additional engine classes and applications. Bench-scale experimentation to be conducted during the proposed project will determine optimal noble metal catalyst loadings on the SiC

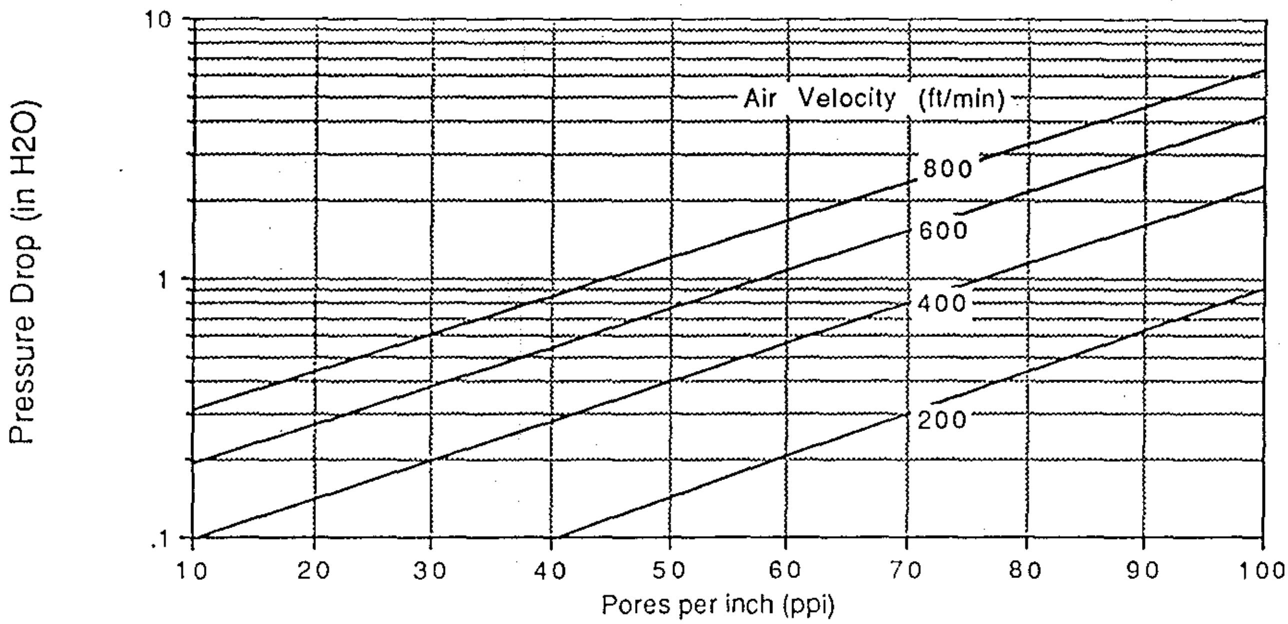


Figure 9. Pressure drop through Ultrafoam vs. porosity for several air velocities

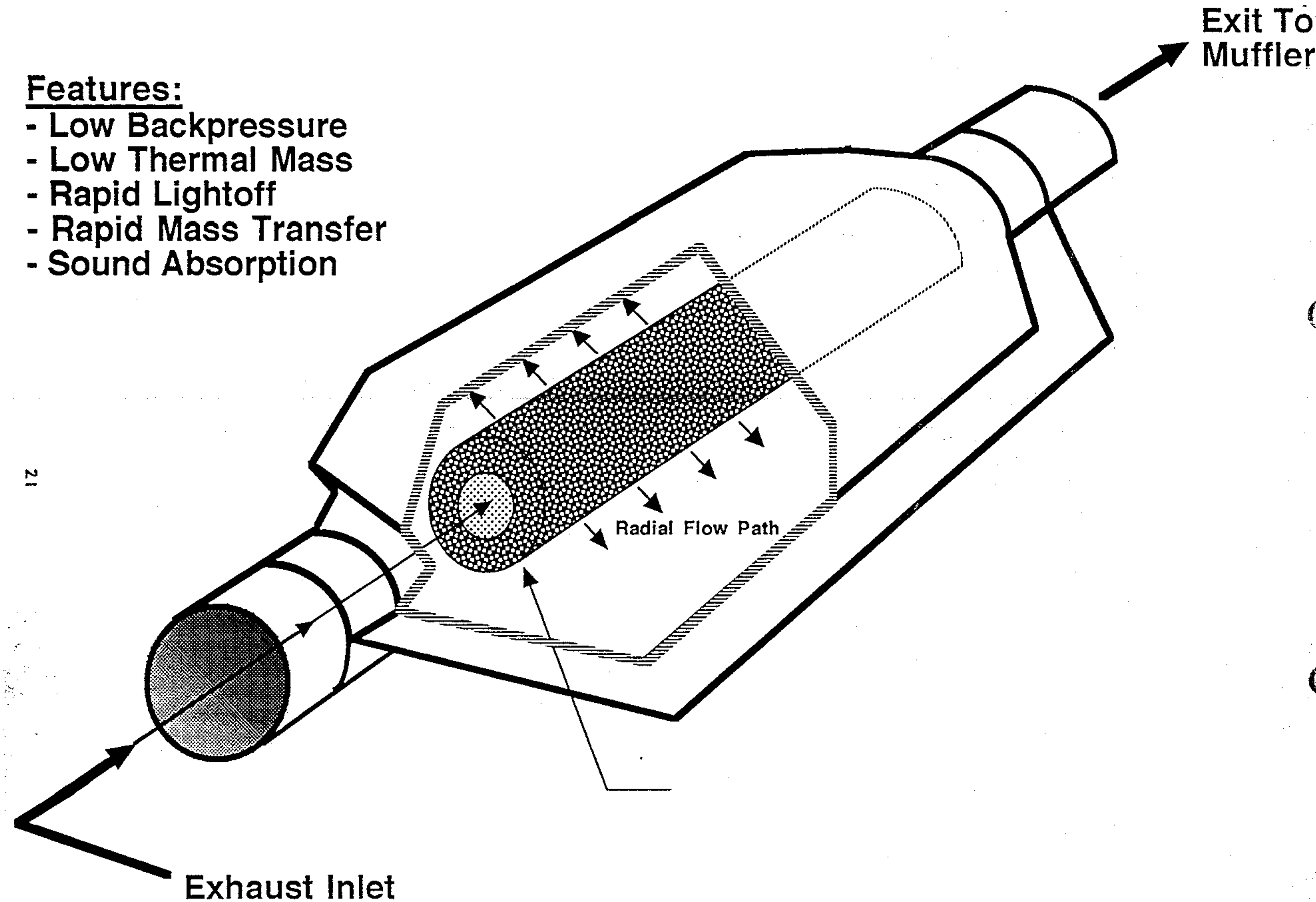


Figure 10. Schematic of proposed UltraCat aftertreatment reactor

foam structure, investigate performance enhancement additive (bench scale level) modifications (such as Al_2O_3, CeO_2, or NiO), and generate the design data (conversion efficiency of the catalyst/surface modifications) required to optimize the designs and extrapolate designs to additional application areas. Specific areas of bench-scale investigation will include the following:

- <u>SiC surface modification</u>: Little or no work has been conducted using SiC as a support for catalytic reactions. Current catalyst formulations and application techniques require a wetting or impregnatable surface for catalyst dispersion. Ultramet's catalyst is deposited directly onto the support surface. Bench-scale (simulated exhaust gas flow apparatus) testing will be used to evaluate the potential performance enhancement of NiO, CeO_2, and Al_2O_3 additions to the baseline platinum group metal catalyst formulations.

- <u>Catalyst design and performance data generation</u>: Using simulated exhaust gases (propylene + CO + N_2 + O_2), design data (conversion efficiency and pressure drop) for various catalyst/surface modification formulations will be determined as a function of catalyst loading, catalyst/surface composition, geometric surface area (foam ppi), foam density, gas residence time and flow rate, and gas composition.

- <u>Effect of catalyst aging</u>: The change in conversion efficiency will be evaluated as a function of exposure time and startup cycles through both simulated thermal exposure and engine exhaust exposure to identify potential poisoning effects and degradation factors, if present.

- <u>Design of the converter system(s)</u>: Analytical trade studies of pressure drop, conversion, fuel economy (effect on BSFC), and performance (horsepower) as a function of engine mixture ratio (gas composition), support geometry and size, excess air additions, and exhaust gas temperatures will be conducted and bench tested in order to verify design and sizing procedures.

Bench-scale testing will be conducted using a simulated exhaust environment, and THC, CO, and NO_x conversion efficiencies will be measured as a function of flow rate, gas composition, catalyst formulation, gas residence time, and gas inlet temperature. A flow-through microcatalytic reactor (2" diameter) connected to a five-gas analyzer will be used to measure exhaust gas compositions using the raw gas method. Gas mixing will be conducted through the use of mass flow controllers and high-purity research grade gases. Key gas composition variables will be oxygen, HC (simulated with propane), H_2O (inserted using a controlled temperature bubbler and saturating the gas), NO_x, CO, and CO_2. Raw gas testing will be conducted using a BAR 92 gas analyzer which uses FID for THC and chemiluminescence for NO_x observation. Instrumentation will consist of Honeywell microswitch pressure transducers and type K thermocouples.

To simulate thermal degradation, catalyst samples will be exposed to 800-1200°C temperature exposure for 10-400 hours, followed by retesting for conversion efficiency under one set of conditions for each gas (CO, HC, NO_x). Additional samples will be inserted into an engine exhaust stream from each of the four target market applications and exposed for 50-100 hours to evaluate the occurrence of any deposits (from soot or oil additives) and their effect on catalyst activity.

Prototype Development and Testing

Using design information gained during previously conducted feasibility studies and ongoing, internally funded development efforts, the converter system will be sized to provide minimum backpressure and maximum conversion using the radial flow design and integrated into an exhaust system package. Converter wall thickness, converter inner and outer diameter, and required converter length will be determined empirically through prototype fabrication and testing efforts. Prototypes will be fabricated for four target markets, consisting of side-valve four-stroke ULGE (10-HP Briggs & Stratton engine), two-stroke ULGE (28-cc McCulloch engine), ULEV and high-performance automotive (3.5-liter General Motors engine), and general aviation (O-360 Continental engine on a Piper aircraft platform). Time and funding permitting, a prototype will be scaled from the 28-cc McCulloch to a 25-50 HP off-highway or personal watercraft two-stroke engine (e.g. 450-cc Skee-Do or 500-cc Suzuki). The basic prototype design is shown in Figure 11, a preprototype operating on a 10-HP Briggs & Stratton engine on a portable generator platform.

The following five major areas will be addressed during prototype development and evaluation:

1. System performance
   - emissions reduction
   - induced backpressure
   - horsepower reduction, effect on BSFC

2. Degradation factors
   - thermal
   - chemical
   - deposit

3. Surface temperature and exhaust gas temperature controls
   - forced air cooling
   - dilution air cooling
   - natural convection cooling
   - airgap and cast insulation

4. Device durability
   - vibration
   - thermal
   - corrosion

5. Performance and cost
   - size
   - packing/insulation requirements
   - catalyst/support
   - complexity
   - ease of manufacture

A matrix of up to sixteen prototype iterations will be fabricated for use on each target engine class. Additionally, ULGE and two-stroke engines will be modified to provide air injection/convective cooling pumps/blowers to supply the required air injection and cooling/dilution air per the reactor design requirements. Candidate air pump designs include a diaphragm pump driven off the crankcase

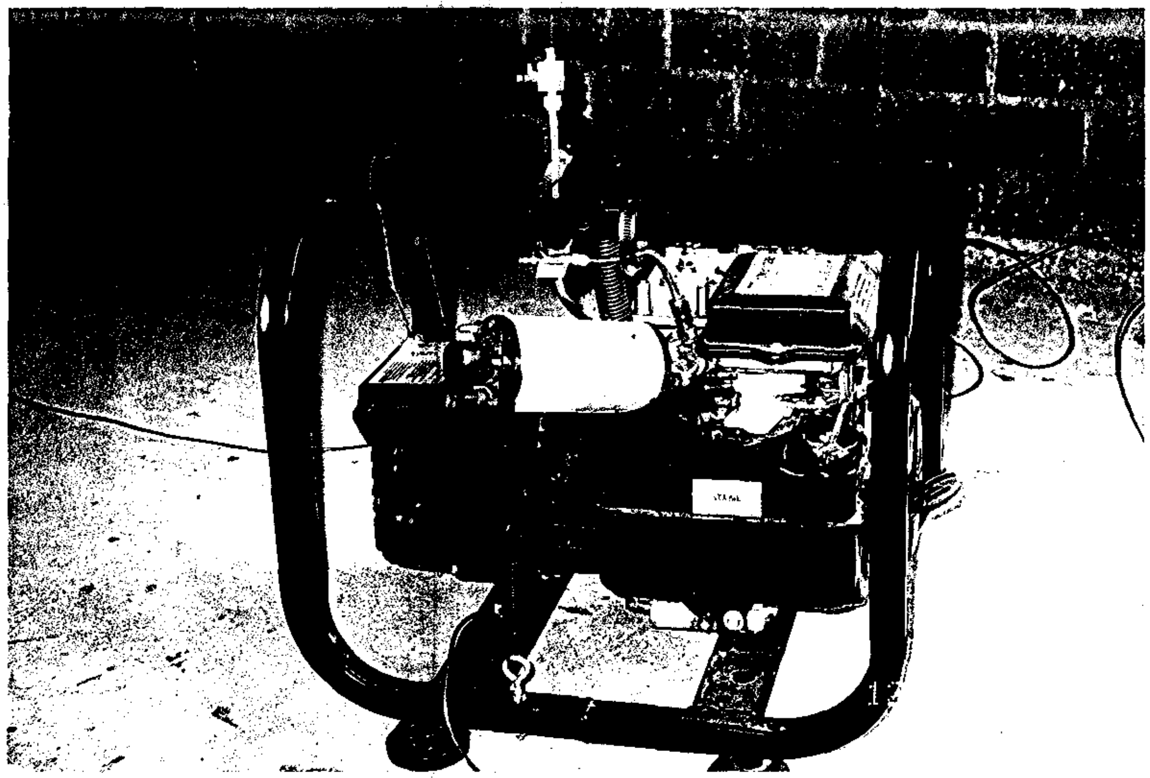


Figure 11. Photograph of preprototype converter design, operating on a 10-HP Briggs & Stratton engine on a portable generator platform

pressure pulses (affects dead volume), increased blower capacity combined with an air induction duct, a venturi induction port, and a rotary vane pump driven off the chain coupled with an air motion duct. The preliminary converter designs will be evaluated for efficiency, emissions, and performance using a simplified emissions test consisting of idle, half-throttle, and full-throttle tests using a Hamilton four-gas BAR 92 or equivalent automotive diagnostic test unit.

Load variation will be conducted using a direct-acting friction clutch electromagnetically driven to allow powerstat variation of the load applied. A laser tachometer will be used to measure rpm. Testing will be conducted at zero and 75% loadings simulating three of the recommended modes of the J1088 test procedures for small engines, and using three-mode (cold start, hot idle, and acceleration) testing for automotive converters. Testing will be conducted both before and after 100 hours of thermal exposure to evaluate thermal degradation performance. Furthermore, designs will be subjected to a 20-hour vibration durability evaluation to screen any thermomechanical durability problems. All prototypes will be instrumented with Honeywell microswitch pressure transducers (0-2 psi) and type K thermocouples with real-time monitoring using chart recorders and/or a PC-based data acquisition system. Fuel flow and torque will be recorded.

Iterative prototype development will include evaluation of dilution air injection modifications (volume, location, injector design), the effects of catalyst volume, thickness, cross-sectional area, and surface area on conversion efficiency, as well as muffler backpressure (measured in the exhaust pipe), and muffler surface and exhaust gas temperatures. Again the simplified THC, CO, CO_2, and O_2 diagnostic analysis will be used. Finally, complete reactor systems (up to four) will be fabricated in conjunction with the engine modifications discussed above, as standalone modifications, or with minor engine modifications. These engines will be subjected to complete emissions testing, as described below.

Converters will be packaged in 304 stainless cans for durability using welded construction. Borla Performance Industries will be responsible for providing exhaust systems for ULEV and high-performance automotive prototypes. Knisley Welding will provide exhaust systems for general aviation applications which will be fabricated from CRES 321. Two-stroke and ULGE engine exhaust systems and manifolds will be fabricated from 304 or Inconel sheet.

Emissions Test Procedures

Two levels of emissions testing will be conducted during the course of the program: a minimum cost screening method using an automotive smog tester with simulation, and complete two- or six-mode J1088 emissions testing and/or complete FTP testing with speciation.

Level one testing will utilize a standard automobile diagnostic service test machine (five-gas analyzer) to record HC, CO, CO_2, and O_2 emissions during exhaust reactor development and thermal aging studies. This is a low-cost test meant to gauge the percent conversion obtained under various throttle positions, and will be used to screen operating performance for iterative engine/reactor evaluation and development. This emissions test will consist of idle, half-throttle, and full-throttle tests using a five-gas automotive diagnostic test unit. Load variation will be conducted using a direct-acting friction clutch electromagnetically driven to allow powerstat variation of the load applied. A laser tachometer will be used to measure rpm. Testing will be conducted at zero and 75% loadings simulating three of the recommended modes of the J1088 test procedures. Fuel consumption will be estimated by engine weight change measurements, assuming that the change in weight is due to fuel/oil consumption. Alternately, the fuel consumption can be recorded through the insertion of a small (10-20 ml) graduated reservoir in the fuel line with a diaphragm marking the fuel level.

Level two emissions testing will be conducted on up to seven engine modification/ exhaust reactor combinations using the J1088 two-mode testing method and the fuel-flow method for converting emissions. The J1088 two-mode test consists of a weighted average of emissions/performance under two operating conditions, as shown in Table II. This emissions assessment from a fractional horsepower two-stroke engine will require a test facility with appropriate equipment to operate and control a chain saw engine under a variety of speed and load conditions. Instrumentation and equipment are also required to measure torque, speed, flow rates, pressures, temperatures, pollutant concentrations, and ambient conditions. This test equipment must be installed, debugged, and calibrated to assess emissions from two-stroke engines. Emissions measurements will be performed using a raw gas continuous emissions monitoring system including state-of-the-art gas analyzers, along with appropriate sampling conditions and management equipment. Emissions determination will be based on the fuel flow method. Particulate measurement will be conducted using constant volume sampling (CVS) system techniques.

The specific goals of the level two test program are as follows:

1. Quantify, through engine load, fuel use, and speed measurement, the exhaust emissions of reactive hydrocarbons (RHC), total hydrocarbons (THC), NO_x, CO, total effluent (total flow and nitrogen flow), PM, PM_{10}, $PM_{2.5}$, formaldehyde, acetaldehyde, benzene, 1,3-butadiene, styrene, CO_2, and O_2 for development engines and two durability test engines over four stages of engine life.

2. Identify emissions determined from the weighted multiple-mode test conditions of the existing J1088 protocol and/or the "California Exhaust Emissions Standards and Test Procedures for 1994 and Later Utility and Lawn and Garden Engines."

The level two test program will include facility preparation for adapting the current equipment and test stand design for 2-hp lawn mower engine testing to fractional horsepower two-stroke cycle engines. Facility preparation will consist of assembling the required equipment to operate and control two-stroke chain saw engines under a variety of load and speed conditions. A constant volume gas sampling system must be modified for particulate determination.

This test program will be performed in accordance with the project test plan and procedures demonstration, to be approved by ARB. Measurements will be performed to determine in-use mass rate and horsepower specific exhaust emissions of RHC, THC, NO_x, total effluent, PM, PM_{10}, $PM_{2.5}$, formaldehyde, acetaldehyde, benzene, 1,3-butadiene, styrene, CO, CO_2, H_2, and N_2. Emissions measurement will be conducted using a raw gas continuous emissions monitoring system (RGM) for CO_2,

Table II. J1088 Operating Modes and Weighting Factors

Operating Modes

J1088 Mode	1	2	3	4	5	6	7
Speed	Idle	Rated	85% of Rated	85% of Rated	85% of Rated	85% of Rated	85% of Rated
Load	0	Full	Full	75% of Full	50% of Full	25% of Full	Minimum

Weighting Factors

J1088 Mode	1	2	3	4	5	6	7
Hand held	10%	90%	—	—	—	—	—
Non-hand held	5%	—	9%	20%	29%	30%	7%

CO, RHC, THC, O_2, NO_x, and N_2 in conjunction with the continuous emissions measurement equipment system and a CVS technique for particulate sampling. The exhaust gas sampling system is designed to measure the true mass emissions of the engine exhaust. In the CVS concept, two conditions must be satisfied: the total volume of exhaust and dilution air must be measured, and a continuously proportioned volume of sample must be collected for analysis. Mass emissions are determined from the sample concentrations and total flow over the test period.

A positive displacement pump will be used to maintain proportional sampling in the sampling lines during the CVS procedure. The total volume of exhaust and dilution air is metered through the constant temperature and pressure conditions of the pump. The total volume is measured by counting the revolutions made by the calibrated constant displacement pump. Proportional sampling is achieved by maintaining a constant sample flow rate. The system consists of a dilution air filter and mixing assembly, a series of sample particulate filters, a positive displacement pump, assorted valves, pressure sensors, and temperature sensors.

The exhaust gas analytical system for HC, CO, and CO_2 consists of a flame ionization detector (FID) for the determination of hydrocarbons, non-dispersive infrared analysis (NDIR) for the determination of CO and CO_2, and chemiluminescence for the determination of NO_x. Samples will be passed through a catalyst to reduce any NO_2 to NO in addition to passing through filters and a cold trap prior to NO_x analysis. For the CO, CO_2, and O_2 analysis, all emissions will pass through a water knockout trap, cold trap, and filters before reaching the analyzers. During the testing sequence, all analyzers will be calibrated at least monthly using a ±1% accuracy primary standard, NIST traceable gases, and a 10-point gas splitter. All analyzers will be zeroed and spanned before and after all emissions measurements. The applicable quality assurance measures given in the ARB document for both the RGM and CVS test methods will be followed.

Specific hydrocarbon emissions will be measured using extractive sampling techniques. A gas sample for measurement of methane, benzene, 1,3-butadiene, and styrene will be collected in a nominal 5-liter tedlar bag from a port following the filters. Benzene, 1,3-butadiene, and styrene will be determined using EPA method TO-14. This is a gas chromatography/mass spectroscopy (GCMS) method utilizing a cryogenic trapping technique. The limits of detection are 1.6 ppb for benzene, 1.2 ppb for styrene, and 2.0 ppb for 1,3-butadiene.

Formaldehyde and acetaldehyde will be determined through EPA method 0011. Samples collected in tedlar bags will be drawn through a chromatographic grade Sep-Pak C-18 cartridge. The cartridge is coated with acidified 2,4 dinitrophenylhydrazine (DPNH). The derivatives are eluted from the sampling cartridge using acetylnitrile and are quantified using reverse-phase HPLC. The sampling limits of detection are 0.02 μg/5 ml.

CVS methods will be used for particulate measurement using a microdilution tunnel. All conditions for collecting and measuring particulates given in the ARB document using the CVS testing methods will be followed. Collection flow and sampling time will be adjusted to give a ≈5-mg particulate sample. The particulate mass will be determined by gravimetric techniques from sample filters installed in the CVS unit. After drying and weighing, methyl chloride extraction of the soluble organic fraction will be conducted. The residue will then be reweighed and subjected to metallographic analysis by optical and SEM microscopy at Ultramet to determine the makeup of the particulates.

The total exhaust of water will be collected by passing a known quantity of the dilute exhaust through impingers containing anhydrous isopropyl alcohol (IPA). The water concentration in the impingers will be measured using the Karl Fischer analysis method. It is understood that olefins dissolved in the IPA can interfere with Karl Fischer analysis; however, it is assumed that the much higher concentration of water will make this effect insignificant. The amount of combustion water will be determined by subtracting the ambient air water from the total water measured.

Small Engine Durability Testing

Engine durability exposure will be conducted using a test stand including a direct-acting friction clutch as described above. A test procedure utilizing McCulloch-recommended on/off, multipositional, and load/throttle/speed variations will be conducted. The durability cycle will include, as a minimum, 400 hours of J1088 test modes according to the J1088 weighing factors, 200 on/off cycles, with at least 100 cycles allowing for complete engine cooldown, 50 hours of throttle variation, and 100 hours of additional running time. Complete J1088 two-mode emissions testing with speciation will be conducted at 0-1, 95-105, 295-305, and 535-545 hours of run time. J1088 test procedures and speciation will be as described above. At 50-hour intervals, level one emissions/performance testing will be conducted to directly compare level one and level two emissions and performance test results, and to more accurately track any degradation in emissions or performance. At the conclusion of durability testing (after 550 hours), the engine will be disassembled and all components inspected for weight loss, dimensional change, and deposit composition, characteristics, and thickness. This post-test evaluation will enable the sources and causes of any deterioration to be determined and potential improvements or solutions identified.

WORK PLAN

ICAT funds will be used to develop improved catalyst formulations and low-cost methods for their application to SiC foam substrates; characterize catalyst samples; and construct, test, debug, and begin qualification of catalytic aftertreatment devices for high-performance auto and off-highway vehicles, as well as utility lawn and garden engines. Matching funds will be provided in the form of a portion of an SBIR Phase II program being performed for NASA Lewis Research Center, which will allow design, testing, and beginning of FAA STC procedures for noise- and pollution-reducing exhaust systems for general aviation aircraft. Matching funds will also be provided through waiver of all G&A expenses involved in the performance of the project, and waiver of fee.

Task 1: Bench Testing

Subtask 1.1: Support Fabrication

Approximately 1400 in^3 of $Ultrafoam_{SiC}$ supports will be manufactured from foam stock of appropriate pore size.

Subtask 1.2: Catalyst Optimization

While a baseline catalyst system has been developed, converter performance is closely tied to the catalyst formulation. To this end, a series of alternate catalyst formulations will be applied to the $Ultrafoam_{SiC}$ supports using organic and aqueous chemistries. A matrix of up to 80 catalyst formulation variations, including catalyst loading, catalyst composition, support surface treatments, and activation procedures, will be fabricated on test coupons for characterization and rig performance testing.

Subtask 1.3: Catalyst Characterization

Catalyst formulations will be characterized using appropriate techniques, which may include BET, hydrogen chemisorption, and optical and SEM microscopy. Tested formulations will include the baseline platinum catalyst, three off-the-shelf vendor-supplied two and three-way formulations, and those applied in subtask 1.2.

Subtask 1.4: Catalyst Performance Testing

Catalyst samples will be characterized for conversion efficiency and reaction kinetics using an instrumented laboratory test rig consisting of a preheater, gas mixing board, and chemical analysis (FID and/or FTIR). Reaction kinetics will be characterized for CO, HC (propylene), and NO_x conversion as a function of gas temperature, composition, and flow rate.

Task 2: Small Engine Prototype Development

Subtask 2.1: Small Engine Prototype Design and Fabrication

Prototype converters will be designed and fabricated for an appropriate 5- to 10-HP side-valve engine, an appropriate 20- to 50-cc two-stroke engine, and (if time and funding permit) a 400- to 500-cc marine (jet ski) or recreational (off-highway vehicle) engine. Both through-flow and radial-flow designs will be developed and fabricated.

Subtask 2.2: Small Engine Prototype Testing and Debugging
Initial screening of small engine converter designs will be conducted using an in-house emissions test cell. Debugging will consist of modifying thermal conditions, secondary air injection rate modifications, mixture ratio modifications, and general size and shape variations necessary to eliminate flame generation and other identified defects in the initial prototype(s).

Subtask 2.3: Small Engine Prototype Converter Qualification
J1088 test procedures, including speciation, will be conducted on the top prototype design(s) for each engine family.

Task 3: Automotive Converter Prototype Development

Subtask 3.1: Automotive Converter Prototype Design and Fabrication
Up to 15 prototype converter designs will be developed for a high-performance aftermarket exhaust system for application to high-performance automobiles.

Subtask 3.2: Automotive Converter Prototype Testing
Six-mode emissions and cold-start emissions will be measured on each of the prototype automotive converters using FTP procedures and speciation. Performance characteristics (horsepower and backpressure) will be compared to conventional honeycomb support designs.

Task 4: General Aviation Emissions Survey and Prototype Development

Subtask 4.1: General Aviation Emissions Survey
HC, NO_x, and CO emissions generated by six classes of general aviation engines, including O-200, O-320, O-360, and O-420 engines (Lycoming and Continental), will be measured under full-, idle-, and partial-throttle conditions.

Subtask 4.2: General Aviation Exhaust System Prototype Design and Testing
A minimum-backpressure converter design will be developed for the O-200 or O-360 class of general aviation engines. This exhaust system will be installed and emissions reductions measured on either a Cessna 150 or Piper Archer aircraft.

Task 5: Reporting

Progress reports will be submitted at the end of each task. At the conclusion of the program, a final report will be prepared documenting the results of Tasks 1-4.

RELATED RESEARCH

Substantial work is currently being conducted in order to meet ULEV automotive standards, including electrically heated catalysts, close coupled catalysts, and higher surface area, lower heat capacity supports. ARB has funded a program relating to small ULGE engine converters, currently being conducted by a team of Emissions & Fuels Research and AlliedSignal, and has previously funded similar efforts at Southwest Research Institute. No research has been reported on emissions control for personal watercraft or general aviation aircraft, although engine research is underway in these areas.

Ultramet has extensive experience in the fabrication of cellular materials, having infiltrated reticulated carbon foams with refractory metals and ceramics by CVD/CVI for a wide variety of applications. Numerous government- and industry-sponsored programs have developed lightweight foams for low-frequency acoustic damping; fusion reactor firstwall shielding; laser, nuclear, and other directed energy hardening; lightweight mirror structures for solar concentrators; solid rocket hot gas valves; high temperature thermal insulation; hydrogen collection and/or storage via metal hydride formation; thermal management (heat pipes and active cooling); and gas turbine engine hot section components. Much IR&D and non-SBIR work has also been done on CVI foams, and several papers have been presented and published. Under internal funding, Ultramet has successfully licensed tantalum foams for medical bone implants, and has performed preliminary studies of metallic foams for hot gas filters, diesel particulate traps, and catalyst supports. These projects have demonstrated the commercial feasibility of CVD/CVI foam, and provided the infrastructure to successfully carry out the proposed program.

Since late 1992, Ultramet has been developing SiC foam for small engine converter applications under IR&D funding. This development work has resulted in packing, canning, and insulation technology capable of supporting and sealing the foam catalyst support in the 170-dB, 900°C environment found in two-stroke engine exhaust reactors. This development program has relied on the application of platinum from platinum acetylacetonate by CVD which, while effective, is more expensive and less tailorable (codeposition is difficult) than the proposed aqueous solution plating. The proposed process will also be adapted for the small engine and motorcycle converter projects currently being funded internally at Ultramet, while the packing, flow, and insulation materials and procedures developed under the IR&D program will be supplied to the proposed effort.

Also under IR&D funding, Ultramet has supplied material for evaluation as a particulate trapping medium to most diesel engine manufacturers (Cummins, Detroit Diesel Allison, and Caterpillar), although none have yet adopted its use, instead focusing their resources on the wall-flow cordierite materials. During this development effort, considerable testing was conducted on Ultramet-supplied material at SwRI, including testing of a particulate trap design on a light-duty vehicle. Ultramet has formed a strategic partnership with an aftermarket performance exhaust system manufacturer, Borla Performance Industries, to further pursue this effort into commercialization.

Ultramet has also completed an SBIR Phase I program for NASA, now well into Phase II, to develop foam modifications and catalyst formulations for the catalytic ignition of oxygen/hydrogen and decomposition of monomethyl hydrazine for liquid rocket engine applications. In this work, Ultramet has developed fabrication processes to produce foams in pore sizes up to 1000 ppi (comparable to 1,000,000 cells in a honeycomb monolith) and has optimized CVD application techniques for an iridium catalyst. Current work is focused on application of a dendritic surface coating to further increase surface area without affecting pressure drop or catalyst life, and on testing of catalytically ignited rocket engines.

Table III summarizes the extensive amount of previous and ongoing research at Ultramet related to the development and manufacture of the Ultrafoam and/or UltraCat products.

Table III. Ultramet Relevant Prior Work

Project Title	Funding ($1000)	Funding Type	Period of Performance	Description
Integral Metal-Loaded Carbon HEL Protection Material	50	SBIR Phase I (Air Force)	10/85 - 3/86	WC foam
TiC-Infiltrated Graphite Structures for Fusion Reactors	50	SBIR Phase I (DOE)	7/86 - 1/87	TiC foam
Special Density Materials for HEL Hardening	50	SBIR Phase I (DNA)	2/87 - 8/87	TiC-coated W foam
Special-Z Materials for Protection Against HEL and Nuclear Threats	50	SBIR Phase I (DNA)	2/87 - 8/87	TiC-coated W/Nb foam
HEL and Projectile Protection	50	SBIR Phase I (DNA)	11/86 - 6/87	TiC-coated B_4C foam
Lightweight Mirror Structures	50	SBIR Phase I (NASA)	3/87 - 8/87	B_4C foam with various reflective faceplates
Ultralightweight High Temperature Materials	50	SBIR Phase I (SDIO/AF)	9/87 - 2/88	(HfB_2/TiC)-coated Re foam
High Performance High Temperature Heat Pipes	50	SBIR Phase I (NASA)	2/88 - 8/88	W foam
Advanced Thermal Protection Materials	50	SBIR Phase I (NASA)	2/88 - 8/88	(HfC/SiC)-coated Re foam
Lightweight Mirror Structures, Phase II	494	SBIR Phase II (NASA)	10/88 - 4/91	HfC/SiC foam with various reflective faceplates
Hydrogen Collectors for Space Flight Applications	50	SBIR Phase I (NASA)	1/89 - 7/89	Mg_2Ni, $LaNi_5$ foams
Novel Acoustic Damping Materials	50	SBIR Phase I (Navy)	9/89 - 2/90	Al-filled B_4C, SiC, TiB_2 foams
Hydrogen Storage in Metal Hydrides	50	SBIR Phase I (Air Force)	9/89 - 3/90	Mg foam
Rhenium Foam Development, Phase II	493	SBIR Phase II (SDIO/AF)	3/90 - 12/92	Re foam
Lightweight Thermal Protection System...	50	SBIR Phase I (Air Force)	6/90 - 12/90	HfC/SiC foam with HfC/SiC facesheets
Improved Heat Shield for Long Boost-Glide Trajectories	49	SBIR Phase I (Air Force)	5/91 - 1/92	Aerogel-filled HfC/SiC foam with HfC/SiC facesheets
Fabrication of a Prototype Solar-Powered Hydrogen Rocket Engine	49	SBIR Phase I (Air Force)	8/91 - 2/92	Re-coated HfC, NbC, TaC, TiC foams; Re foam
Monolithic Noble Metal Catalysts for O_2/H_2 Thrusters	49	SBIR Phase I (NASA)	1/92 - 6/92	Ir-coated C, SiC, Si_3N_4 foams
Lightweight SiC/Ceramic Foam Mirror Structures	48	SBIR Phase I (NASA)	2/92 - 8/92	SiC foam with SiC reflective faceplate
Enabling Materials Technology for Nuclear-Thermal Propulsion	50	SBIR Phase I (DOE)	7/92 - 2/93	NbC foam
Tantalum Foams for Cancellous Bone Implants	50	SBIR Phase I (NIH)	6/92 - 12/92	Ta foam

Table III. Ultramet Relevant Prior Work (continued)

Lightweight Thermal Protection System, Phase II	326	SBIR Phase II (Air Force)	6/92 - 12/94	Ceramic foam/facesheet sandwich panels
Advanced Refractory Materials for Nuclear-Thermal Propulsion	50	SBIR Phase I (SDIO/AF)	7/92 - 1/93	NbC-, HfC-, TaC-, ZrC-coated PG foams; NbC foam
Thermal Protection System for MaRV, Phase II	469	SBIR Phase II (Air Force)	9/92 - 3/95	C foam/ceramic facesheet sandwich panels
Design and Fabrication of Solar-Thermal Thruster, Phase II	493	SBIR Phase II (Air Force)	11/92 - 4/95	Re foam
Cooled Ceramic Composite Stator Vane for Turbine Engines	50	SBIR Phase I (NASA)	12/92 - 6/93	SiC foam with various facesheets
Lightweight SiC Reflectors for Space Optics, Phase II	500	SBIR Phase II (NASA)	5/93 - 5/95	SiC foam with SiC reflective faceplate
Monolithic Catalytic Igniters for Propulsion Applications, Phase II	498	SBIR Phase II (NASA)	8/93 - 8/95	Ir foam
Noise Reduction System for General Aviation Aircraft	70	SBIR Phase I (NASA)	1/94 - 6/94	SiC foam
3-D Continuously Reinforced Metal Matrix Composites	65	SBIR Phase I (NSF)	4/94 - 9/94	Al-filled B_4C, SiC, TiB_2 foams
Cooled Ceramic Composite Vane Assembly, Phase II	500	SBIR Phase II (NASA)	2/94 - 2/96	SiC foam with various facesheets
Advanced Materials for Automobile Airbag Systems	74	SBIR Phase I (DOT)	9/94 - 5/95	Nb, SiC foams
Refractory Foam Filters for Molten Metal Filtration	65	SBIR Phase I (NSF)	3/95 - 9/95	SiC foam
Noise Reduction System for General Aviation Aircraft, Phase II	496	SBIR Phase II (NASA)	2/95 - 2/97	SiC foam
Solid Rocket Motor Throat Inserts	73	CR&D (Thiokol)	1987-88	Re foam
Laser-Hard Materials	54	CR&D (Lockheed)	1987-88	TiC-coated W, Nb foams
Brilliant Pebbles Lifejecket	251	CR&D (MRC)	1990-93	C foam with various facesheets
Brilliant Pebbles Lifejacket	69	CR&D (LLNL)	1991-92	C foam with various facesheets
Piston for Regenerative Engine	85 to date	CR&D (Rejen)	1994-present	SiC foam
Foam Development	>600 to date	IR&D	1991-present	C, SiC, Ta foam
Hot Gas Filter for Automobile Airbags	>100 to date	CR&D, IR&D (various)	1991-present	Proprietary foams
Catalytic Converter for Two-Stroke Engines	240 to date	IR&D	1992-present	Pt-coated SiC foam
Reconstructive Bone Implants	>1,000 to date	Joint venture (Implex)	1992-present	Ta foam

PROJECTED PRODUCTS AND RESULTS

The proposed program will provide prototype designs for catalytic exhaust systems for small and medium class ULGE engines and high-performance ULEV automotive engines. Specifically, the program will produce the following results:

- Detailed sizing information will be developed to allow exhaust system performance and size to be determined for reasonable extensions of the prototype units (such as 1-3 HP, 5-10 HP, and 100-150 HP).

- Optimal catalyst loading and geometric surface area will be determined for ULGE and automotive applications, allowing a standardized product to be manufactured.

- Low performance and cost impact catalytic converters and exhaust systems for two-stroke engines in the 1-3 HP class will be developed and qualified to 1999 ARB standards on unmodified or slightly modified engines meeting 1995 ARB standards. This will lead to OEM and aftermarket exhaust products for two-stroke ULGE equipment.

- Low performance and cost impact catalytic converters and exhaust systems for side-valve four-stroke ULGE engines in the 3-10 HP class will be developed and qualified to 1999 ARB standards, leading to OEM and aftermarket exhaust products for side-valve four-stroke ULGE equipment.

- Low performance impact environmental exhaust systems for the performance and racing industry will be evaluated, resulting in a minimum performance impact design allowing reduced emissions from performance and racing cars.

- Small size and low cost converters for ULEV automobile OEM and aftermarkets will be developed, allowing marketing, sales, and licensing of fast-lightoff and close-coupled converter supports to the automotive industry.

ANTICIPATED BENEFITS

The successful completion of the proposed program will speed up the development and qualification of improved, faster lightoff, lower cost, and lower backpressure pollution control aftertreatment devices for utility lawn and garden equipment, automotive engines, off-highway and marine recreational vehicles, and general aviation aircraft. The targeted applications support ARB goals and both the federal and state implementation plans.

Economically, the successful development and commercialization of the proposed technology will produce both jobs and tax revenues for California, as well as significant cost savings to the consumer. For example, approximately 925,000 ULGE systems are sold annually in California, and will be subject to ARB regulations requiring aftertreatment devices beginning in 1999. Production of converter units in California will result in the creation of a \$5-15 million/yr business requiring the creation of 50-100 new jobs which would otherwise go to other states. At a projected market share for Ultramet of 30%, this will result in the creation of 15-30 new jobs and the generation of \$1.5-4.5 million/yr in gross revenues. As ARB regulations are adopted nationwide, this market will expand to approximately 14 million units per year, for which Ultramet projects the ability to obtain a 25% market share representing the creation of 200-400 jobs and revenues of \$20-50 million/yr.

A projected 10% market share for ULEV vehicles represents a market of 3 million converter units per year, involving the creation of 400-600 jobs and revenues of \$60 million/year. General aviation, off-highway and marine recreational vehicle engines represent additional revenues of \$7-10 million/year (at a projected 45% market share) and the creation of 100 jobs.

The proposed program will augment current projects and investment at Ultramet, and will develop the detailed performance and design data needed to justify the installation of a manufacturing facility to increase production of Ultrafoam$_{SiC}$. The proposed program addresses both near-term (automotive high performance aftermarket) and intermediate-term markets (ULGE), and provides a position for further product development in an expanding \$1.4 billion industry with global markets.

Key marketing benefits of the proposed technology compared to honeycomb monolithic supported catalytic converters include the following:

- Reduced size (2-3x)
- Reduced cost (30-50%)
- Insensitivity to misfiring and overheating
- Faster lightoff and lower cold start emissions
- No flame generation when used on small engines
- Applicability to ULGE engines
- Low backpressure
- Lower performance impact
- Simultaneous noise and emissions reductions
- Eliminates requirement for large engine-converter setbacks

Industrial benefits include the development of a market which enables the scaleup of CVD SiC processes to a commercial scale. This will provide a low-cost, needed source for high-quality advanced ceramics, which will potentially impact almost all sectors of the chemical process, power generation, propulsion, paper and pulp, and metals heat treatment industries. The proposed project will act as a catalyst to generate the funding necessary for scaleup.

Environmental benefits arise directly from the reduction of HC and CO from currently unregulated sources for which pending and planned legislation is in the works. Table IV summarizes ULGE equipment currently in use in California. If the goals of the program are met, with an average life expectancy of six years, engines starting in the 1998 model year would be replaced with engines emitting 75-90% less HC and CO. Table V summarizes the total statewide emissions from ULGE engines. Assuming a 17%/year replacement rate beginning in 1998, the development and implementation of converters for ULGE engines will result in a reduction of approximately 70 tons/day of CO and 10 tons/day of hydrocarbons in 1998 and each subsequent year through 2003, when a peak reduction of 60 tons/day of HC and 400 tons/day of CO will be reached compared to 1989 emissions levels.

The proposed program will also provide the first realistic environmental impact assessment of light piston-powered aircraft in California, as well as an impact assessment of regulating/controlling emissions from this source.

Benefits will be evaluated analytically based on the measured exhaust compositions compared to 1994 standards. Milestones, including completion of a business plan, fabrication of prototypes, reaching emissions goals, securing of outside financing, formation of joint ventures and business alliances, and job generation will be monitored for the duration of the program and a period of four years following the program. Since the proposed ICAT program is designed to be the catalyst for securing product development and scaleup financing leading to obtaining market share, these parameters may be tracked for the period following prototype demonstration. Emissions performance will be certified by an independent testing vendor.

The environmental impact of the proposed program will be negligible. The byproducts of the production process are silica and water vapor, both of which are inert and non-toxic substances. Commercialization would result in a minor impact with regard to landfill material, less than 50 m^3/yr.

Table IV. ULGE Equipment Currently in Use in California

PRODUCT CATEGORY	TOTAL UNITS IN-USE IN CALIFORNIA	% HOME	% COMM	UNITS HOME	UNITS COMM
WALK BEHIND MOWERS	2,148,526	95%	5%	2,039,026	109,500
RIDING MOWER (FRT ENG)	73,052	97%	3%	70,740	2,312
RIDING MOWER (REAR ENG)	24,377	97%	3%	23,693	684
GARDEN TRACTOR	39,202	97%	3%	38,175	1,027
TILLERS	119,385	68%	32%	81,598	37,786
SNOWTHROWERS	42,202	90%	10%	37,982	4,220
GENERAL UTILITY	303,100	44%	56%	134,308	168,792
SHREDDERS/GRINDERS	20,809	64%	36%	13,219	7,590
SPECIALIZED TURF CARE	11,869	0%	100%	0	11,869
4-CYC BLOWERS/VACUUMS	3,638	75%	25%	2,744	895
4-CYC EDGERS/TRIMMERS	52,979	79%	21%	41,737	11,242
2-CYC EDGERS/TRIMMERS	941,157	90%	10%	843,225	97,932
2-CYC BLOWERS/VACUUMS	345,564	90%	10%	312,374	33,190
CHAIN SAWS	518,048	92%	8%	476,169	41,879
TOTAL UNITS	4,643,907			4,114,990	528,918

Table V. Total Statewide Emissions from ULGE Engines

Effluent	Four Stroke Engines	Two Stroke Engines	TOTAL	Consumer Applications	Commercial Applications	TOTAL
HC	17	53	70	16	55	70
CO	331	164	495	133	363	495
NOX	1.77	.22	1.99	.59	1.40	1.99
PM	.28	1.14	1.41	.30	1.12	1.41

(Percent)

Effluent	Four Stroke Engines	Two Stroke Engines	TOTAL	Consumer Applications	Commercial Applications	TOTAL
HC	24.3	75.7	100	22.8	77.2	100
CO	66.9	33.1	100	26.9	73.1	100
NOX	88.9	11.1	100	29.6	70.4	100
PM	19.8	80.2	100	21.3	78.7	100

COMMERCIALIZATION PLAN

TARGET MARKETS

One primary and three niche markets are targeted for prototype development and testing in the proposed program. The primary market is 1-10 HP two-stroke and side-valve four-stroke ULGE engines. This market consists of some 14 million units annually in the United States, and close to 30 million units per year worldwide. Of these, approximately 925,000 are sold annually in California.

Equipment in the "lawn and garden" category includes:

walk-behind mowers	blowers/vacuums
riding mowers	string trimmers
lawn tractors	snow blowers
fixed-blade edgers	chainsaws
roto-tillers	hedge trimmers
shredders/grinders	other implements

Equipment in the "utility" category includes:

pumps	compressors
generators	grinders
sprayers	vibrators/finishers
special-purpose saws	refrigeration equipment

The vast majority of this equipment is powered by internal combustion engines less than 25 HP, and two-stroke engines dominate the lightweight high-power powerplants. Most of the equipment falls under SIC code 3524, "Lawn and Garden Equipment." According to the U.S. Department of Commerce/Bureau of the Census data, the total volume of shipments for code 3524 is as summarized in Table VI.

The industry is represented by three associations:

OPEI:	Outdoor Power Equipment Institute
PPEMA:	Portable Power Equipment Manufacturers Association
EMA:	Engine Manufacturers Association

According to OPEI's profile of the outdoor power equipment industry, a total of $4.47 billion in shipments was produced in 1989, including $3.27 billion in finished goods, $1.07 billion in engines, and $130 million in components. Of all the components purchased for the manufacture of finished goods, engines account for the single largest value item, as shown in Figure 12. Unit sales are dominated by walk-behind mowers followed by hand-held two-stroke equipment, as illustrated in Figure 13. Sales of most equipment types have remained flat over the last several years, and California represents approximately 6% of the nationwide sales in each category. The addition of a catalytic converter system to these engines will account for a 5-10% increase in the unit cost of a small engine.

Based on discussions with small engine manufacturers, the desired unit cost for the converter support/catalyst combination is approximately $5/unit, with the total cost for the converter system being in the $5-10 range for <10-HP equipment and in the $10-20 range for 10-25 HP engines. Converter requirements to meet 1999 standards are a 75-80% reduction in THC and CO emissions, no effect on BSFC

Table VI. U.S. Sales of Gasoline-Powered Engines Less Than 25 HP

PRODUCT CATEGORY	AVG SALES PREVIOUS 8 YEARS	1981	1982	1983	1984	1985	1986	1987	1988	1989	% OF TOTAL 1989
WALK BEHIND MOWERS (1)	5,700,000	4,600,000	4,600,000	4,400,000	4,950,000	5,193,000	5,400,000	5,900,000	5,600,000	5,300,000	40.1%
RIDING MOWER:FRT ENG (1)	494,000	370,000	393,000	415,000	502,000	548,000	623,000	800,000	812,000	793,000	6.0%
RIDING MOWER:REAR ENG (1)	314,000	250,000	261,000	276,000	354,000	355,000	322,000	376,000	375,000	260,000	2.0%
GARDEN TRACTOR (1)	220,000	151,000	146,000	129,000	152,000	147,000	149,000	150,000	170,000	139,000	1.1%
TILLERS (1)	667,000	501,000	497,000	408,000	394,000	362,000	311,000	272,000	285,000	305,000	2.3%
SNOWTHROWERS (1)	1,577,000	345,000	95,000	284,000	348,000	421,000	482,000	526,000	532,000	543,000	4.1%
GENERAL UTILITY (2)	915618	640083	621696	618184	689820	727678	754836	827070	806910	765,074	5.8%
SHREDDERS/GRINDERS (3)	21,772	19,443	16,330	23,239	34,229	55,770	67,211	59,454	72,330	77,405	0.6%
SPECIALIZED TURF CARE (3)	11,643	10,620	14,168	12,688	14,277	24,952	49,015	24,359	38,046	31,108	0.2%
4-CYC BLOWERS/VACUUMS (3)	9,531	9,776	10,103	3,996	8,598	5,742	9,630	10,285	14,323	16,342	0.1%
4-CYC EDGERS/TRIMMERS (3,4)	141,236	143,906	184,363	169,916	141,100	164,313	136,500	153,600	170,400	185,888	1.4%
2-CYC EDGERS/TRIMMERS (5)	?	308,595	568,131	717,279	828,000	1,713,000	1,847,000	2,102,000	2,314,000	2,542,000	19.3%
2-CYC BLOWERS/VACUUMS (3,4)	?	285,682	525,948	664,022	766,522	1,125,679	951,472	991,854	1,393,710	950,868	7.2%
CHAIN SAWS (6)	1,564,000	1,323,800	1,560,249	1,261,545	1,121,000	1,252,000	1,152,000	1,193,000	1,155,000	1,294,000	9.8%
TOTAL UNITS	11,635,800	8,958,964	9,492,988	9,354,869	10,303,546	12,095,034	12,254,764	13,384,822	13,738,719	13,202,685	100%

SOURCES OF DATA:

(1) SHIPMENTS BY U.S. AND FORIEGN MANUFACTURERS AS REPORTED BY THE OUTDOOR POWER EQUIPMENT INSTITUTE

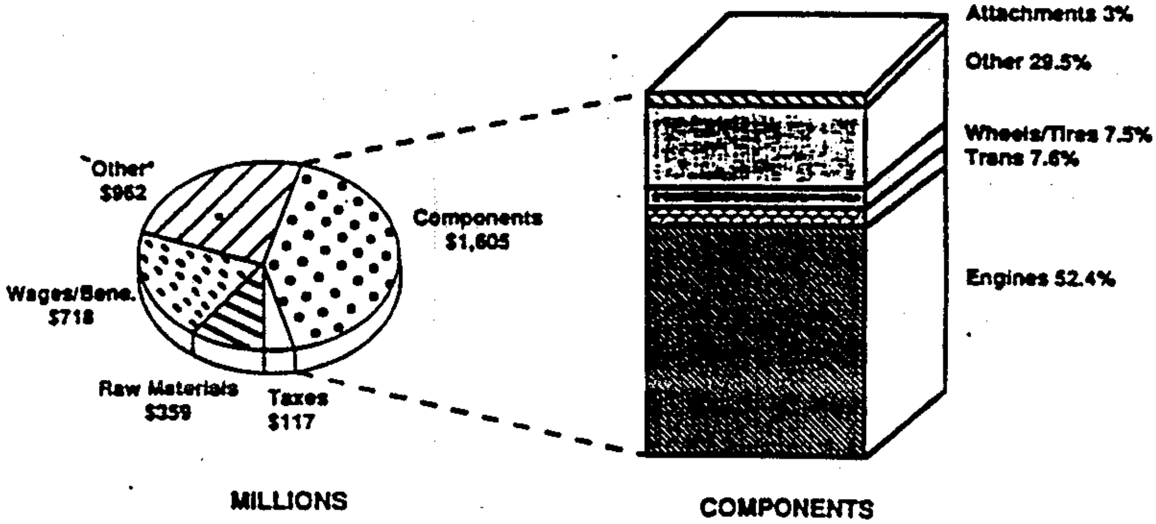
(2) DERIVED FROM INTERVIEWS WITH U.S.ENGINE MANUFACTURERES AND ASSUMES THAT GENERAL UTILITY ENGINE SALES AVERAGE APPROXIMATELY 6% TO 8% OF LAWN AND GARDEN SALES

(3) U.S. DEPARTMENT OF COMMERCE, BUREAU OF THE CENSUS, "CURRENT INDUSTRIAL REPORTS-FARM MACHINERY AND LAWN & GARDEN EQUIPMENT",1980-1988: 1989 DATA WAS ESTIMATED USING SIMPLE REGRESSION.

(4) DATA IN THE SOURCE DOCUMENT FOR 1984,86,87 & 88 INCLUDE ELEC TRIC EQUIPMENT. FOR THESE YEARS THE GAS ENGINE VALUES WERE OBTAINED USING SIMPLE REGRESSION OF PROPORTIONS DERIVED FROM MORE DESCRIPT DATA FOR OTHER YEARS.

(5) 1984 THRU 1989 DATA OBTAINED FROM THE OUTDOOR POWER EQUIPMENT INSTITUTE'S 1990 UTILITY EQUIPMENT MARKET SURVEY. DATA FOR EARLIER YEARS IS ESTIMATED BASED ON THE SALES TREND OF 2 CYCLE BLOWERS AND VACUUMS.

(6) 1984 THRU 1989 DATA OBTAINED FROM THE OUTDOOR POWER EQUIPMENT INSTITUTE'S 1990 UTILITY EQUIPMENT MARKET SURVEY. DATA FOR EARLIER YEARS IS BASED ON U.S. DEPT OF COMMERCE, BUREAU OF CENSUS DATA.



*Includes profits of approximately $390 milloion as well as fixed costs such as depreciation, utilities, etc.

Figure 12. ULGE equipment industry expenditures for components

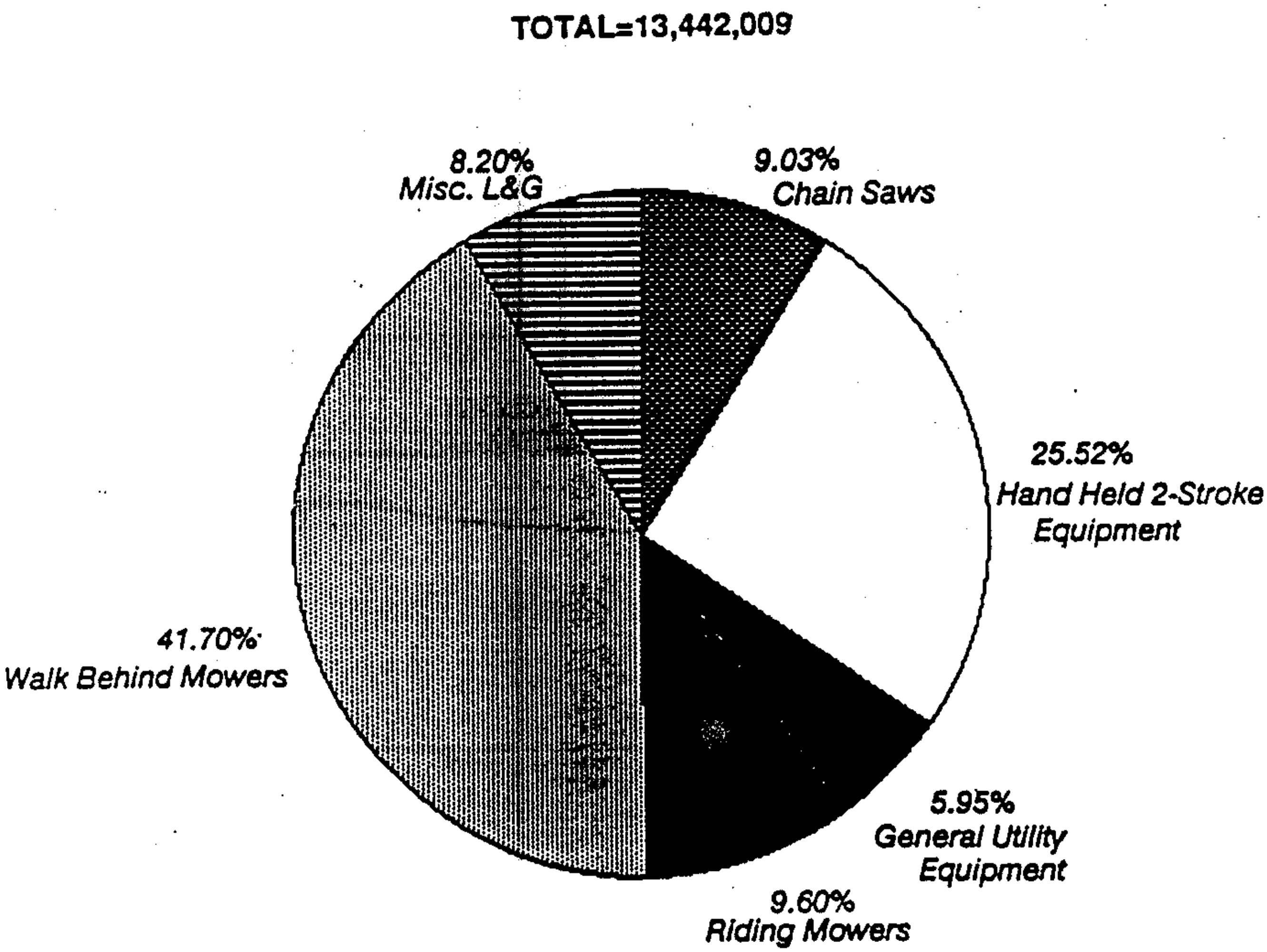


Figure 13. Average annual U.S. unit sales for ULGE equipment for 1987-89

and power, multipositional (for two-stroke) operational capability, and conformance with all federal and state regulations.

Performance automotive applications represent a niche market targeted for the performance and racing industry. This market is not currently employing converters, being dominated instead by stainless steel exhaust systems. This market represents a market which will pay a premium for performance (backpressure), and is currently served through performance automotive distribution channels such as NAPA, Trak Auto, etc. This is an aftermarket product specifically targeted at young, wealthy sport enthusiasts and amateur and professional stock and street car racers.

The general aviation market is currently unregulated in emissions, although the FIP and SIP call for increased fees based on emissions levels. The largest impact and the target market will be to fixed base operators, which own and maintain fleets of aircraft for such uses as agricultural service, sightseeing, shipping, pilot training, etc.

POTENTIAL SPINOFFS

The Ultrafoam$_{SiC}$ material was originally developed for hupersonic vehicle structural reentry thermal protection systems and has direct application in the fields of turbine engine noise reduction systems (for such applications as the High Speed Civil Transport), flameholders for ramjet engines, catathermal combustion systems for gas turbine engines, regenerators and heat transfer media for regenerated turbine and diesel engines, and regenerated heat treatment furnaces. Further, Ultrafoam$_{SiC}$ is an ideal structure for mass transfer media to replace raschig rings, etc. for the chemical process industry. Additionally, Ultrafoam$_{SiC}$ is under development for hot gas and liquid metal filters, including the filtration of aluminum, titanium, and ferrous alloys for investment casting, and hot gas filters for automotive airbags.

UltraCat spinoff markets representing some $400 million have been identified, including off-highway vehicles, catalyzed combustion systems (such as low-NO_x burners and water heaters for residential applications), diesel engines, flue gas cleanup, turbine engine pollution control, restaurant equipment pollution control, VOC pollution control, radiant burners for low-NO_x burner systems, and coal-fired boiler pollution control. The proposed technology is generic in application to all of these markets and pollution control applications.

The catalytic converter market is a key market enabling scaleup to cost-effective production of the Ultrafoam and UltraCat materials. With the production scale required to meet projected converter demand, material costs will be reduced by over one order of magnitude, making the material and systems cost-effective for the spinoff applications which by themselves are not large enough to support large-scale commercial production.

COMPETITION

Currently, the converter market can be subdivided into catalyst support manufacturers (NGK, Corning), new support developers (Emitec, Texas Instruments, Precision Combustion), and catalyst application companies (Hereaus, Engelhard, Johnson-Matthey, and AlliedSignal). Additionally, there are system development houses, although OEMs do the majority of exhaust system development, which is then duplicated or licensed to manufacturers for the OEM and aftermarket markets.

Because of the potential market size, the catalytic converter market is extremely competitive. For the proposed applications, competition exists in the form of alternate substrates ranging from conventional automotive cordierite honeycombs (Celcor from Corning) to metallic honeycombs (Emitec, Grolsch, Texas Instruments). More direct competition comes from ceramic foams (Selee and HiTech Ceramics) and the newly developed Microlith technology developed by Precision Combustion.

Typical automotive catalysts consist of a three-way catalyst (composed of a gamma-alumina washcoat impregnated with a platinum-rhodium-palladium catalyst) supported on a through-flow cordierite honeycomb substrate. This cordierite support is not adaptable to the small utility engine due to temperature and reaction kinetic concerns. An adaptable substrate material has been demonstrated in the form of a wire mesh, screen, or expanded metal; however, these systems (currently produced by Grolsch in Austria) are too expensive for adaptation to small utility engines, with a complete converter system costing approximately \$70-150. Ultramet has demonstrated that a silicon carbide foam support meets the requirements for a small utility engine catalytic converter by providing the high conversion efficiency, high temperature capability, and thermal properties required. Furthermore, this SiC support can be manufactured at lower cost (approximately \$2-3/unit) than either extruded honeycomb material or the metallic supports (\$6-10/unit). Other potential competing supports include densified ceramic fiber products (\$8-15/unit).

The potential weakness of the product is market unfamiliarity and the risks involved in production scaleup (costs). Key strengths are small size, high temperature capability, low backpressure, and enhanced durability.

COMMERCIALIZATION

The planned program will specifically develop aftertreatment systems for the high-performance automotive aftermarket, utility lawn and garden equipment, and (under matching funds) the general aviation industries. ULGE and general aviation represent currently unregulated emissions sources which are rapidly coming under legislation in California, nationwide, and in Europe, and represent (for the converters) $200 million and $4 million markets respectively. No current pollution control products are available for either of these markets, providing a prime opportunity for new materials and systems to be implemented with minimum barriers to market. Similarly, the high-performance automotive aftermarket represents an approximately $38 million market which is a steppingstone to the >$1 billion automotive converter market. Additional spinoff markets representing some $400 million include off-highway vehicles, diesel engines, flue gas cleanup, turbine engine pollution control, and commercial broiler pollution control, among others. The proposed technology is generic in application to all of these markets and pollution control applications.

The commercialization strategy to be pursued is to use the program funds to leverage ongoing IR&D and federal funding to create and qualify prototypes. Market share will be realized by targeting untapped markets with commercial partners already servicing these industries, and through qualification through OEMs with major market shares in each target market. Borla Performance Industries has been selected for the performance automotive aftermarket, while Briggs & Stratton and McCulloch have been targeted for ULGE, representing 25%, 35%, and 25% market shares in their respective markets. For general aviation, the O-200 and O-360 engines have been targeted, which power >80% of all general aviation aircraft now flying. Knisley Welding, representing a 65% market share in general aviation aftermarket exhaust systems, has been selected as the commercialization partner for this application.

The high-performance automotive aftermarket is estimated to be the first commercial opportunity, with the first system to be put into production within one year of program completion, with additional systems being qualified and marketed at a rate of approximately 2 per year after introduction of the first system. The ULGE market does not materialize in the domestic mass market until 1998 production (1999 model year), which may be pushed back depending on political pressure placed on ARB. By targeting the major producers of two-stroke and side-valve engines, a 5-10% overall market share (1.3% of all California engines) is expected beginning in 1999, increasing to a 20-35% market share as ARB regulations are adopted nationwide (expected by 2005).

The general aviation market will be approached through design of an improved exhaust system which reduces both noise and emissions reductions. The key selling point is cabin comfort, with the economic incentive to be provided by the proposed increased user fees based on emissions, which would be eliminated through use of a qualified emission control system.

A six-stage commercialization plan will be followed:

1. Feasibility Demonstration (completed 11/94)
   The feasibility of the UltraCat converter system has been demonstrated in terms of no horsepower reduction and meeting 1999 emissions standards for

CO and THC. Approximate sizing and costing has been prepared indicating not only performance feasibility, but economic feasibility.

2. Prototype Development and Demonstration (ongoing; includes ICAT)
Prototype converters for target markets will be developed, with input from OEMs to ensure acceptability. Detailed sizing information and catalyst loading and geometric optimization will be conducted to allow detailed designs and costs to be determined.

3. Converter Productization (after ICAT, through 1998)
Exhaust systems will be developed and qualified/certified for specific engines and OEM products.

4. Manufacturing Scaleup (1997-1999)
The UltraCat converter manufacturing process will be scaled up to reach cost-effective production, with the emphasis on repeatable, reliable manufacture at high yields and minimum cost.

5. Commercial Sales (1997-?)
Working through OEMs and distribution and marketing partners, aftermarket, distributor, and OEM sales will be made. Goals are to reach a 30% market share in the target markets by 2000. Market and product development will be conducted for spinoff markets.

6. Ongoing Cost Reduction (1999-?)
Process improvements will be made to reduce costs and increase the quantity and quality of the UltraCat product line.

Ultramet internally financed stage 1, at a cost of ≈$70,000 in direct labor and material costs (≈$250,000 fully loaded with overhead and G&A expenses), in addition to patent, attorney, marketing, and travel costs on the order of $60,000. Ultramet is currently seeking government programs, venture capital, and partners to finance stages 2-4. Total financing required for stages 2-4 is expected to be $8-12 million. The proposed ICAT program is a necessary catalyst to complete stage 2 and allow stages 3 and 4 to be financed.

The critical path to commercialization involves stages 1-5, with the commercialization period commencing in 1997 and ending in 2000. The minimum commercial sales milestone for 2000 is considered to be 450,000 units/year, necessary to provide continuing breakeven operation of the UltraCat plant.

A key element of the commercialization plan is obtaining the required financing and marketing partners for commercialization of the ULGE products. Ultramet has identified potential partners which are described in the financing section of this proposal. Key elements desired in a partner include the following:

- Knowledge of the ULGE and automotive marketplaces
- Distribution channels
- Financial capability to support the project for up to three years
- Understanding of ceramic materials and the CVD manufacturing process
- Knowledge of catalyst application technology and catalyst formulations

Ultramet has secured partners for the commercialization of general aviation and high-performance automotive products. In the general aviation market, Ultramet will license the technology and Supplemental Type Certificates to Knisley Welding, which will obtain the PMA necessary to manufacture, market, and distribute aviation products. For the high-performance automotive market, Ultramet intends to license the UltraCat technology to Borla Performance Industries for the PRI market, and backlicense Borla designs for the OEM ULEV market.

To date, combined federal, commercial, and internal investment in the development of the Ultrafoam and UltraCat products is nearly $8 million, all of which is being leveraged in the proposed program. Table III summarized the extensive amount of previous and ongoing research at Ultramet related to the development and manufacture of the Ultrafoam and/or UltraCat products.

Prior and current federal investment is $5.6 million, consisting of 25 SBIR Phase I and 9 SBIR Phase II projects beginning in late 1985 and continuing at least through early 1997; an additional $1.6 million exists in the form of four pending Phase II proposals that would extend into 1998 if awarded.

Commercial and Ultramet internal expenditures on Ultrafoam and UltraCat development exceed $2 million to date since 1987, with the majority coming since 1991. This investment consists of foam manufacturing development costs (including capital expenditures), tantalum foam production and product development for medical implants, UltraCat converter development, patent and attorney costs, and related travel and marketing expenses:

- Foam manufacturing development and equipment expenditures (Ultramet IR&D)
- Licensee investment in Ultramet for process scaleup and production of tantalum foam medical implants (Ultramet and licensee financing)
- UltraCat feasibility demonstration (Ultramet IR&D)
- Planned continuing investment in UltraCat product development (Ultramet financing)
- Investment in corporate infrastructure necessary to support projects (Ultramet financing)
- Patent and attorney expenses (Ultramet financing)

Ultramet currently holds three patents on various foam technologies and potential products, with two more pending, including one for the SiC foam catalyst support (UltraCat).

FINANCIAL

Table VII details the projected income from UltraCat converter sales for the next five years. This income statement is based on the following assumptions:

- Income in 1996 is solely through development and prototype sales.
- Beginning in 1997, sales are the result of aftermarket automotive products and introduction on one model of small engines for field trials.
- Starting in 1998, penetration into a single model of ULEV vehicles is achieved, along with 1-2 models from the leading manufacturer in each of the ULGE engine categories.
- Full-scale introduction is achieved into the ULGE market in 1999 with two manufacturers representing 35 models of ULGE engines. ULEV and high-performance automotive sales increase in market share as the technology is proven.
- Desired market share of the ULGE market is achieved in 2000.

The key assumptions are the implementation of ARB ULGE standards for 1999 and future engines, which may slip by several years, and their planned adoption by EPA. For the ULEV market, regulatory impact is the enforcement of ULEV standards beginning in 1998.

Total anticipated investment required to complete commercialization stages 2-4 (described previously), not including basic research expenses previously incurred, is estimated at $8-12 million. Of this amount, approximately $600,000 is required for stage 2, prototype development and demonstration, which is to be financed through the ICAT program and matching funds from Ultramet.

Stage 3, product development and certification, is expected to cost approximately $1.2 million. Ultramet is currently searching for business alliances, joint venture partners, and venture capital (small business investment corporations and investment groups) to finance commercialization stages 3 and 4.

Stage 4, manufacturing scaleup, is expected to require $5-9 million. Anticipated sources of financing include joint venture partners, venture capitalists, the Small Business Administration and the Technology Reinvestment Project (federal funds), private investors, and investment bankers.

Candidate joint venture partners contacted to date include BFGoodrich, BP-Hitco, Kaiser, Corning, Dow Chemical, 3M, Selee, Dupont Lanxide, and Arthur D. Little. Ultramet is in contact with the Project for a New Los Angeles and the Economic Development Corporation in an effort to arrange financing, and is presenting a business plan in April 1995 at the North Coast Capital Showcase in Cleveland. Ultramet has prepared a tentative business plan for presentation to these sources of venture capital.

In January 1995, Ultramet submitted a preproposal to ARPA under the Technology Reinvestment Project (TRP), requesting $3.5 million for Ultrafoam/UltraCat development in a teaming arrangement with BP-Hitco, SAIC, and Oak Ridge National

Table VII. UltraCat™ Sales Projections
(all units in thousands)

Year	Funding	Units	Sales	NIBT*
1995	500			
1996	1,300	1	92	
1997	2,700	10	1,020	255
1998	3,000	100	4,360	916
1999	5,500	1,000	12,300	1,968
2000	13,000	10,000	51,660	6,716

* net income before taxes

Laboratory. The preproposal was subsequently selected for a full proposal submission. Due to Congressional spending cuts, the 1995 TRP program has been delayed, and is currently expected to be funded at a substantially reduced rate when the House and Senate reach a compromise on the deficit reduction package (the House had reduced TRP funding from $500 million to zero, which the Senate then restored to $200 million). Since the UltraCat technology is derived from reentry thermal protection materials, the proposed project represents a close fit with the TRP goals and requirements.

It is anticipated that the successful completion of prototype development and demonstration will be a critical and enabling factor in securing stage 3 and 4 financing. As such, the proposed ICAT program is extremely timely; the target markets are time-sensitive, since regulations come into effect in the 1998-2000 time frame, and the product must be ready for production by that time. The requested ICAT funding represents a critical mass of financing and resources necessary to commercialize the UltraCat converter technology.

The key risks involved in securing financing are the ability to price the product at the projected rate, which requires an 80% yield in the manufacturing process, as well as enforcement of planned regulations.

PERSONNEL DESCRIPTION

PROJECT TEAM

The project team comprises Ultramet as the developer of UltraCat converter materials and technology, Borla Performance Industries as a manufacturer of high-performance automotive exhaust systems, and Valley Research Corporation as an expert in emissions testing and analysis. Ultramet will be the prime contractor, with Edwin P. Stankiewicz having lead responsibilities on the project.

Ultramet will be responsible for developing prototype designs for ULGE and ULEV converter designs and the fabrication and assembly of Ultrafoam and UltraCat materials and components. Ultramet will also conduct bench testing and prototype development testing during the prototype development stage of the effort.

Borla Performance Industries will be responsible for the design and fabrication of ULEV and high-performance exhaust systems. Borla will also provide consultation to ensure the manufacturability of these exhaust systems as designed by Ultramet.

Valley Research Corporation will be responsible for managing the qualification testing of ULEV and ULGE converter systems, performing exhaust speciation analysis, and performing data reduction and analysis of the tests. Valley Research will also conduct environmental impact assessments and provide consultation to ensure that the UltraCat exhaust systems conform to all federal, state, and local regulations and standards.

TECHNICAL QUALIFICATIONS

Ultramet, a small business incorporated in the State of California, is the established leader in the CVD and CVI of refractory metals and ceramics, fabricating more different materials by CVD than any other laboratory. Since its inception in 1970, Ultramet has developed or has been involved in the development of virtually every major area of this technology, and possesses a leading and proprietary position in the application of CVD/CVI to materials technology for government and commercial use. Ultramet has assembled one of the most competent, experienced CVD technical staffs anywhere, possessing an aggregate of several decades of CVD experience. Among these professionals are several internationally recognized leaders in the CVD field. Since 1980, Ultramet personnel have authored over 150 papers and reports on a wide variety of CVD applications. This multidisciplinary team provides the technical and managerial expertise necessary to ensure the successful completion of the proposed program.

Richard B. Kaplan (M.S.), president and technical director, founded Ultramet in 1970 after eight years of CVD R&D and managerial experience, and has managed the company through sustained growth while maintaining an active experimental role. Dr. Robert H. Tuffias, general manager and marketing director, joined Ultramet in 1982 after two decades of experience throughout the aerospace industry. Dr. Arthur J. Fortini, manager of R&D programs, joined the staff in 1991 following several years of academic and industrial CVD experience. Edwin P. Stankiewicz (M.B.A.), manager of new product development, joined Ultramet in 1991 with a combination of materials engineering and business administration experience. Andrew J. Sherman (M.S.) has become senior engineer and marketing manager since joining Ultramet in 1987. Research engineers Victor M. Arrieta (M.S., at Ultramet since 1984), Sangvavann Heng (M.S., at Ultramet since 1989), and Brian E. Williams (B.S., at Ultramet since 1988) comprise the remainder of Ultramet's technical staff. Operations manager Sam Gonnella and production manager Walter Abrams, co-founders of the company with Mr. Kaplan, each add over three decades of CVD experience to the Ultramet talent pool, as does R&D lab engineer Robert E. Benander.

The principal investigator for the proposed program will be Edwin P. Stankiewicz, supported by Andrew J. Sherman and other members of the Ultramet technical staff as needed.

Edwin P. Stankiewicz received a B.S. in materials engineering from Drexel University, and an M.B.A. from Pepperdine University. Following his B.S. he was a project engineer at BP America, working in molten metal filtration products and process metallurgy, and subsequently project manager of all aspects of a technical product line. After receiving his M.B.A., he worked as an independent business consultant, developing business plans including strategic planning, financial analysis, and marketing for emerging companies requiring startup or expansion capital. Mr. Stankiewicz joined Ultramet in 1991 as manager of new product development, initially working to successfully define and implement a process for in-house carbon foam production. He served as director of R&D programs from 1992 through 1994, managing the technical staff and company resources in the performance of all ongoing R&D work for government and industry. He recently returned full-time to new product development, with primary emphasis on the UltraCat converter product line.

Andrew J. Sherman received a B.S. in both ceramic engineering and chemical engineering from Ohio State University, and an M.S. in ceramic engineering from the same institution. While at Ohio State, he conducted research on corrosion, solid state electrical and transport properties, and thermodynamic modeling. Mr. Sherman joined Ultramet in 1987 as a research engineer; he has since become marketing manager in 1990, while continuing as senior engineer. His research interests include process development for CVD/CVI coatings, foams, fibers, fiber coatings, and composites, and characterization of their physical properties. He has been principal investigator or project engineer on numerous SBIR Phase I and Phase II programs, as well as on numerous programs for commercial customers. A key area of concentration in his work has been the development and characterization of the various Ultrafoam products, inlcuding the UltraCat converter technology.

Borla Performance Industries is a world-renowned manufacturer of automotive exhaust systems for the high-performance and racing industries, holding four patents in this area. Alex Borla is a respected fixture in the automotive exhaust system industry, and has successfully completed several previous ARB projects as well as development projects for most of the world's automotive companies. Mr. Borla has successfully built a multimillion-dollar business from scratch, providing high-performance exhaust systems to the PRI industry. In addition to the Flowmaster Plus product line, Mr. Borla holds numerous patents in the exhaust system area.

Dr. Yuji Horie will be principal scientist at Valley Research Corp., which will manage the testing, certification, and environmental impact assessment studies. Dr. Horie received his Ph.D. in chemical engineering from Kansas State University in 1972, and has 23 years of environmental sciences experience including tenure at Technology Service Corp. and Pacific Environmental Services prior to starting Valley Research Corp. in 1985. Dr. Horie has completed numerous studies for ARB and the EPA in the area of motor vehicle emissions and testing standards.

Following are Ultramet's relevant publications to date; not included are seven SBIR Phase II and two Phase I projects that are currently in progress. Those projects are, however, included in "Ultramet Relevant Prior Work" provided previously in "Related Research".

Relevant Publications by Ultramet Personnel

R.A. Holzl, R.H. Tuffias, and R.B. Kaplan, "Integral Metal-Loaded Carbon HEL Protection Material", Final Report (ULT/TR-86-4632), Contract F04704-85-C-0161, Air Force Ballistic Missile Office, Norton AFB, CA, March 1986.

J.G. Sheek and R.B. Kaplan, "TiC-Infiltrated Graphite Structures for Fusion Reactors", Final Report (ULT/TR-87-4832), Contract DEAC03-86-ER-80411, U.S. Department of Energy (DOE), Washington, DC, January 1987.

J.G. Sheek and R.H. Tuffias, "HEL and Projectile Protection", Final Report (ULT/TR-87-4916), Contract DNA001-87-C-0022, DNA, Washington, DC, June 1987.

J.G. Sheek, R.H. Tuffias, and R.B. Kaplan, "Special-Z Materials for Protection Against HEL and Nuclear Threats", Final Report (ULT/TR-87-4915), Contract DNA001-87-C-0049 DNA, Washington, DC, August 1987.

J.G. Sheek, R.H. Tuffias, and R.B. Kaplan, "Special Density Materials for HEL Hardening", Final Report (ULT/TR-87-4914), Contract DNA001-87-C-0050, DNA, Washington, DC, August 1987.

J.G. Sheek and R.B. Kaplan, "Lightweight Mirror Structures", Final Report (ULT/TR-87-6242), Contract NAS3-25145, NASA Lewis Research Center, Cleveland, OH, September 1987.

J.G. Sheek and R.H. Tuffias, "Ultralightweight High Temperature Structural Materials", AFAL-TR-88-078 (ULT/TR-88-6367), SDIO/Air Force Astronautics Laboratory, Edwards AFB, CA, March 1988.

J.G. Sheek and R.B. Kaplan, "Lightweight High Temperature Heat Pipes for Space Applications", AFWAL-TR-88-2134 (ULT/TR-88-6370), SDIO/Air Force Aeropropulsion Laboratory, Wright-Patterson AFB, OH, June 1988.

A.J. Sherman and R.B. Kaplan, "Advanced Thermal Protection Materials", Final Report (ULT/TR-88-6598), Contract NAS3-25411, NASA Lewis Research Center, Cleveland, OH, August 1988.

R.H. Tuffias and R.B. Kaplan, "Refractory Foam Composite Materials", <u>Research & Development</u> <u>31</u> (2), February 1989, 118-20.

M.J. DelaRosa and R.B. Kaplan, "Hydrogen Collectors for Space Flight Applications", Final Report (ULT/TR-89-6982), Contract NAS5-30485, NASA Goddard Space Flight Center, Greenbelt, MD, July 1989.

A.J. Sherman, "Novel Acoustic Damping Materials", Final Report (ULT/TR-90-7183), Contract N00014-89-C-0228, Office of Naval Research, Washington, DC, March 1990.

M.J. DelaRosa, "Hydrogen Storage in Metal Hydrides", AL-TR-90-031 (ULT/TR-90-7197), Air Force Astronautics Laboratory, Edwards AFB, CA, March 1990.

A.J. Sherman, R.H. Tuffias, and R.B. Kaplan, "Refractory Ceramic Foams for High Temperature Structures", presented at 1990 ACS Annual Meeting, Dallas, TX, 22-26 April 1990.

A.J. Sherman, B.E. Williams, M.J. DelaRosa, and R. La Ferla, "Characterization of Porous Cellular Materials Fabricated by CVD", presented at 1990 MRS Fall Meeting, Boston, MA, 26-30 November 1990; published in <u>MRS Symposium Proceedings, Vol. 207</u>: <u>Mechanical Properties of Porous and Cellular Materials</u>, K. Sieradzki, D.J. Green, and L.J. Gibson, eds. (Materials Research Society, Pittsburgh, PA, 1991), 141-49.

A.J. Sherman, Q. Jang, and R. La Ferla, "Lightweight Thermal Protection System for Hypersonic Vehicle Crew Escape", WL-TR-91-3051 (ULT/TR-90-7422), Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, OH, December 1990.

B.E. Williams and R.B. Kaplan, "Lightweight Mirror Structures, Phase II", Final Report (ULT/TR-91-6835), Contract NAS3-25418, NASA Lewis Research Center, Cleveland, OH, April 1991.

A.J. Sherman, R.H. Tuffias, and R.B. Kaplan, "Refractory Ceramic Foams: A Novel New High Temperature Structure", Ceramic Bulletin 70 (6), June 1991, 1025-29.

A.J. Sherman, A.J. Fortini, and R. La Ferla, "SiC Infiltration for Improved Ceramic Composites", Final Report (ULT/TR-91-7644), Grant ISI-9060236, National Science Foundation (NSF), Washington, DC, September 1991.

A.J. Sherman and B.E. Williams, "Improved Heat Shield for Long Boost-Glide Trajectories", Final Report (ULT/TR-91-7770), Contract F04704-91-C-0030, Air Force Ballistic Missile Office, Norton AFB, CA, January 1992.

M.J. DelaRosa and R.H. Tuffias, "Fabrication of a Prototype Solar-Powered Hydrogen Rocket Engine", Final Report (ULT/TR-92-7828), Contract F29601-91-C-0094, Air Force Phillips Laboratory, Edwards AFB, CA, February 1992.

A.J. Sherman and R.H. Tuffias, "Room and Elevated Temperature Properties of Ceramic Foams", presented at 1992 Advanced Aerospace Materials/Processes Conference (AeroMat), Anaheim, CA, 18-21 May 1992.

R. La Ferla, Q. Jang, and R.H. Tuffias, "Monolithic Noble Metal Catalysts for H_2/O_2 Thrusters", Final Report (ULT/TR-92-7966), Contract NAS9-18698, NASA Johnson Space Center, Houston, TX, July 1992.

B.E. Williams, "Lightweight SiC/Ceramic Foam Mirror Structures", Final Report (ULT/TR-92-6033), Contract NAS1-19550, NASA Langley Research Center, Hampton, VA, August 1992.

M.J. DelaRosa and R.H. Tuffias, "Rhenium Foam Development, Phase II", Final Report (ULT/TR-92-7344), Contract F04611-90-C-0002, SDIO/Air Force Phillips Laboratory, Edwards AFB, CA, December 1992.

A.J. Fortini, C.N. Ward, and R.B. Kaplan, "Tantalum Foams for Cancellous Bone Implants", Final Report (ULT/TR-92-6140), Grant 1-R43-DE09781-01A1, NIH/National Institute of Dental Research, Washington, DC, December 1992.

B.E. Williams and R.H. Tuffias, "Advanced Refractory Materials for Nuclear-Thermal Propulsion", Final Report (ULT/TR-93-6197), Contract F29601-92-C-0096, SDIO/Air Force Phillips Laboratory, Kirtland AFB, NM, January 1993.

A.J. Fortini and R.H. Tuffias, "Enabling Materials Technology for Nuclear-Thermal Propulsion", Final Report (ULT/TR-93-6080), Grant DE-FG03-92ER81460, U.S. Department of Energy (DOE), Washington, DC, February 1993.

R. La Ferla, R.H. Tuffias, and Q. Jang, "Monolithic Catalytic Igniters", presented at the 29th Joint Propulsion Conference, Monterey, CA, 28-30 June 1993; published as AIAA 93-1905.

A.J. Fortini, R.H. Tuffias, and B.E. Williams, "Enabling Materials Technology for Nuclear-Thermal Propulsion", presented at the 29th Joint Propulsion Conference, Monterey, CA, 28-30 June 1993; published as AIAA 93-2260.

M.J. DelaRosa and R.H. Tuffias, "Design and Fabrication of a Solar-Powered Rocket Engine", presented at the 29th Joint Propulsion Conference, Monterey, CA, 28-30 June 1993.

S. Heng and A.J. Sherman, "Cooled Ceramic Composite Stator Vane for High Temperature Turbine Engines", Final Report (ULT/TR-93-6353), Contract NAS3-26841, NASA Lewis Research Center, Cleveland, OH, June 1993.

M.J. DelaRosa and R.H. Tuffias, "Materials Characterization and Design for Solar-Thermal Propulsion", presented at 1993 JANNAF Propulsion Meeting, Monterey, CA, 15-19 November 1993.

A.J. Sherman and S. Heng, "Noise Reduction System for General Aviation Aircraft", Final Report (ULT/TR-94-6664), Contract NAS3-27230, NASA Lewis Research Center, Cleveland, OH, July 1994.

A.J. Sherman, "Novel 3-D Continuously Reinforced Metal Matrix Composites", Final Report (ULT/TR-94-6678), Grant III-9361110, National Science Foundation (NSF), Washington, DC, October 1994.

MANAGERIAL CAPABILITIES

The principal investigator for the proposed program will be Edwin P. Stankiewicz, who will be the lead person having lead responsibilities and will be the main contact with ARB.

Edwin P. Stankiewicz received a B.S. in materials engineering from Drexel University, and an M.B.A. from Pepperdine University. Following his B.S. he was a project engineer at BP America, working in molten metal filtration products and process metallurgy, and subsequently project manager of all aspects of a technical product line. After receiving his M.B.A., he worked as an independent business consultant, developing business plans including strategic planning, financial analysis, and marketing for emerging companies requiring startup or expansion capital. Mr. Stankiewicz joined Ultramet in 1991 as manager of new product development, initially working to successfully define and implement a process for in-house carbon foam production. He served as director of R&D programs from 1992 through 1994, managing the technical staff and company resources in the performance of all ongoing R&D work for government and industry. Mr. Stankiewicz recently returned full-time to new product development, with primary emphasis on the UltraCat converter product line. His extensive experience in product development and commercialization at BP America, as an independent business consultant, and at Ultramet provides a key strength of the proposed effort.

Alex Borla of Borla Performance Industries will manage PRI product commercialization. Mr. Borla has successfully built a multimillion-dollar business from scratch, providing high-performance exhaust systems to the PRI industry. In addition to the Flowmaster Plus product line, Mr. Borla holds numerous patents in the exhaust system area.

Dr. Yuji Horie of Valley Research Corp. will manage the testing, certification, and environmental impact assessment studies. Dr. Horie has successfully completed numerous projects for ARB, and has an intimate knowledge of the California emissions regulatory environment.

COMMERCIALIZATION RECORD

Ultramet has been remarkably successful in transitioning SBIR Phase II programs into Phase III (commercialization), which offers the best example of its record in this area. The three most advanced programs in this regard are:

1. Chemical Rocket Combustion Chambers (material and application developed under NASA SBIR funding): Ultramet has been under contract to TRW since 1992, and Kaiser Marquardt since 1994, to fabricate a series of iridium/rhenium chambers for the 100-lb_f apogee kick motors on communications satellites. These have been used to date for demonstration/ validation and flight qualification testing. Ultramet anticipates signing multiyear production contracts with both TRW and Kaiser Marquardt in 1995 for flight units for use on Lockheed Martin and Hughes satellites, with first launch expected in early 1996.

2. Hot Gas Filters (material originally developed under SDIO SBIR funding; application developed by Ultramet marketing and IR&D funding): Ultramet is currently building qualification units for TRW, Morton International, and Thiokol driver and passenger side automotive air bags. Anticipated production is 100,000 units in 1996, potentially ramping up to 8,000,000 units by the end of the decade.

3. Bone Replacement Implants (material originally developed under SDIO SBIR funding; application developed under NIH SBIR funding and Ultramet marketing and IR&D funding): Ultramet has signed a licensing agreement with Implex Corp. (Allendale, NJ) to develop tantalum foams as implants for bone replacement/new bone growth. Successful implants in humans have been in progress in Europe since early 1994, and an agreement with a European partner for sales and distribution was recently concluded. FDA trials on humans are scheduled to begin in late 1995 for U.S. usage. Additionally, Ultramet is working with Osteonics, Zimmer, and other medical implant manufacturers, hospitals, and universities on hip replacements, jaw replacements, and other dental and musculoskeletal applications.

In summary, since 1986:

- Ultramet has received over $6.0 million in Phase III commercial sales, directly resulting from SBIR Phase II government-supported R&D work, from late 1986 through December 1994. This amount accounts for more than 18% of Ultramet's total sales over that period.

- Ultramet has invested over $2.0 million in IR&D funding support in the same areas.

- A total of more than $8.0 million has been received or invested by Ultramet in Phase III support.

Ir/Re combustion chamber development, mentioned above, offers an excellent example of the commercialization process at Ultramet as follows.

Under SBIR programs for the Air Force and NASA, Ultramet developed a process for the fabrication of iridium/rhenium liquid rocket combustion chambers having increased operating temperature capability over all previous materials, and thrusters of varying sizes and geometries were successfully produced and tested. The 600°C+ increase in operating temperature and output afforded by the Ultramet Ir/Re combustion chamber provides a 10- to 20-second increase in specific impulse, which results in a productivity increase of 5-10% that is estimated to provide a cost savings of nearly $2 million per vehicle. A Phase III contract was subsequently awarded by NASA Lewis for further optimization and production of these components, and Phase III activities with TRW, Aerojet, Kaiser Marquardt, and Atlantic Research commenced virtually with the conclusion of the original SBIR programs.

The clear market for these thrusters, in both government and commercial satellite launch systems, prompted Ultramet to invest substantial internal funding for optimization of the fabrication process, reproducibility, inspection, and scaleup. Specifically, two laboratories were constructed for separate, computer-monitored control of the iridium and rhenium deposition processes, and inspection is undergoing continued optimization.

Ir/Re chambers have passed demonstration/validation and are currently undergoing flight qualification by TRW, to be followed by flight units on Lockheed Martin and TRW satellites. As noted, Ultramet anticipates signing a multiyear production contract with TRW in 1995 to supply Ir/Re combustion chambers for Lockheed Martin and TRW satellites. Additionally, Ultramet is working with Kaiser Marquardt to develop Ir/Re chambers for Hughes satellites.

The Air Force and NASA SBIR Phase II programs for iridium/rhenium liquid rocket combustion chambers have resulted in $2.6 million in commercial sales from late 1986 to the present, including $568K in Phase III support from NASA Lewis as well as $2.033M in sales to commercial customers. Ultramet has also committed over $640K in IR&D funding to this effort over this period, including the construction of the dedicated, computer-controlled iridium and rhenium fabrication facilities, for a total of $3.24 million in overall Phase III support for this technology. As summarized above, this model is joined by several others, including the development of refractory metal foams for automotive airbag hot gas filters, and refractory metal foams for medical and dental bone implants.

Ultramet has thus demonstrated considerable success in bringing materials originally developed under government-funded R&D (SBIR) support to commercial fruition following the conclusion of that support. It should be noted, and expected, that the most substantial commercial success to date has been achieved in those programs that are the most mature. This is especially true in the field of advanced materials, where the time between the conception of an innovation and the initial demonstration of its feasibility, and its ultimate development into a viable commercial "product" -- the so-called product development cycle -- is substantially longer than in other more hardware- or software-oriented fields.