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SUPERSONIC GAS-LIQUID CLEANING SYSTEM

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ABSTRACT

A system to perform cleaning and cleanliness verification is being developed to replace solvent flush methods using CFC 113 for fluid system components. The system is designed for two purposes, internal and external cleaning and verification. External cleaning is performed with the nozzle mounted at the end of a wand similar to a conventional pressure washer. Internal cleaning is performed with a variety of fixtures designed for specific applications. Internal cleaning includes tubes, pipes, flex hoses, and active fluid components such as valves and regulators. The system uses gas-liquid supersonic nozzles to generate high impingement velocities at the surface of the object to be cleaned. Compressed air or any inert gas may be used to provide the conveying medium for the liquid. The converging-diverging nozzles accelerate the gas-liquid mixture to supersonic velocities. The liquid being accelerated may be any solvent including water. This system may be used commercially to replace CFC and other solvent cleaning methods widely used to remove dust, dirt, flux, and lubricants. In addition, cleanliness verification can be performed without the solvents which are typically involved. This paper will present the technical details of the system, the results achieved during testing at Kennedy Space Center, and future applications for this system.

BACKGROUND

Cleaning and cleanliness verification are essential in the initial installation and maintenance of all fluid systems at Kennedy Space Center. The strict cleanliness requirements are derived from liquid oxygen (LOx) system compatibility. Hydrocarbon greases and oils can easily ignite in the presence of LOx. Any system connected to a LOx system must be as clean as the LOx system itself. Cleaning involves removing both particulate and non-volatile residue contaminants from LOx components. Cleanliness verification is essentially identical to cleaning except that a sample of the remaining contaminants, both volatile and non-volatile, must be collected and their levels measured. Freon 113 (CFC 113) has been used almost exclusively at Kennedy Space Center for cleanliness verification in LOx systems and in most other fluid systems where high levels of cleanliness are important. It is also used for some cleaning applications. CFC 113 is being phased out of production due to its detrimental effects on the Earth's ozone layer. This fact has prompted an effort within NASA to replace CFC 113 cleaning and cleanliness verification methods.

The current method for cleaning fluid systems at Kennedy Space Center is to flow large quantities of detergent and water at elevated temperatures through or across the components. The method for verifying cleanliness is to flush the component with CFC 113 which is then collected and evaluated. Evaluation of the collected CFC 113 consists of two parts, particulate and non-volatile residue (NVR). Particle counting is done by pouring the CFC 113 through filter paper and examining the paper under a microscope. NVR is measured by heating the sample until all volatile compounds evaporate then weighing the remaining material. Other cleaning and verification methods include solvent flushing and high-pressure water jets.

The new cleaning and cleanliness verification method uses impingement instead of a controlled solvent like CFC 113. This system uses supersonic two-phase flow nozzles to create high velocities at the surface of the component to be cleaned. The nozzle has a converging-diverging (de Laval) geometry. The compressibility of the gas accelerates the liquid droplets to velocities high enough to remove contaminants from impinged surfaces. The

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liquid can be collected for verification purposes. Currently, air or nitrogen is being used for the gas, and water is the liquid. The use of water has eliminated the environmental problems associated with CFC 113. The water is the cleaning and cleanliness verification agent. It can be collected so the particulate and the total organic carbon (TOC) content can be measured for cleanliness verification purposes.

This system has several advantages over high pressure water jets and solvent flushing methods. The pressures required to generate high velocities in a gas are considerably lower than in a liquid. The consumption of solvent in a gas-liquid spray is at least an order of magnitude lower than in a liquid only spray. The consumption advantage over solvent flush methods is even more dramatic. Also solvent flushing may leave behind insoluble particulate which impingement methods remove.

DESIGN APPROACH

The initial requirements which led to the development of this system were: (A) it must remove at least 80% of contaminants; (B) the 80% removal efficiency must be achieved using less than 100 ml of water per square foot of area to be cleaned; (C) it must be able to provide a stable water blank; and (D) water samples must be collectible for total organic carbon (TOC) analysis. The first requirement was based on the fact that a replacement system had to be able to clean at least as well as the CFC 113 cleaning method it replaced. Supersonic gas-liquid cleaning, water impingement, and alternate solvent flushing all could meet this requirement. The second requirement presented the greatest challenge, and ruled out systems using only water impingement or solvent flushing. This led to the idea of using high velocity gas-liquid flow to generate high impact velocities while simultaneously using less than 100 ml of water per square foot of cleaning area. A supersonic gas-liquid flow was the solution to the above constraints and considerations.

Theoretical Development

The design of the supersonic gas-liquid flow nozzles was based on equations for the one-dimensional, irrotational, frictionless expansion of a gas containing a dispersion of small liquid droplets. The flow was assumed to be homogeneous and adiabatic with uniform velocity. In addition, thermal equilibrium was assumed to exist between the gas and the liquid.

Denoting the air temperature by T, and using subscript a for all air properties. The usual equation of state is

$$P_a v_a = R_a T \tag{1}$$

If the liquid droplet density is very large compared to the air density and if the mixture contains mass, m_l of liquid droplets and mass m_a of air. The mass ratio $m = m_l/m_a$. The apparent density (or specific volume) will be related to the air density (or specific volume) by

$$\frac{\rho}{\rho_a} = \frac{v_a}{v} = 1 + m \tag{2}$$

where

$$m << 1$$

From equation (2),

$$v_a = v(1 + m) \tag{3}$$

also,

$$P_a = P \tag{4}$$

Substituting equations (2), (3), and (4) into equation (1) gives

$$Pv = \frac{R_a}{1+m} T$$

This is the equation of state for the mixture.

If the gas and liquid droplets are in thermal equilibrium, the total entropy of both together remains constant. Thus, if the droplets have a specific heat of c, their entropy increase accompanying a heat transfer dQ to the air is

$$ds_d = \frac{dQ}{T} = cm\frac{dT}{T}$$

The entropy increase for the air is

$$ds_a = \frac{dQ}{T} = c_{pa}\frac{dT}{T} - R_a\frac{dP}{P}$$

Since

$$ds_d + ds_a = 0$$

then

$$\frac{dT}{T}(c_{pa} + mc) - R_a\frac{dP}{P} = 0$$

or

$$\frac{dT}{T} = \frac{R_a}{c_{pa} + mc}\frac{dP}{P}$$

or

$$\ln T = \frac{R_a}{c_{pa} + mc}\ln P + \ln C_1$$

where

$$C_1 = \text{constant}$$

Therefore,

$$TP^{-\Psi} = \text{constant}$$

where

$$\Psi = \frac{R_a}{c_{pa} + mc}$$

or

$$\frac{P^{(\gamma-1)/\gamma}}{T} = \text{constant} \tag{5}$$

where

$$\frac{\gamma-1}{\gamma} = \frac{R_a}{c_{pa} + mc} \tag{6}$$

Equation (5) is the expansion law of the gas-liquid mix, hereinafter called the pseudo gas. Since

$$R_a = c_{pa} - c_{va}$$

Equation (6) gives

$$\gamma = \frac{c_{pa} + mc}{c_{va} + mc} \tag{7}$$

The effect of mutual heat transfer (thermal equilibrium) is therefore to modify the isentropic exponent to the value given by equation (7).

Therefore, the pseudo gas behaves as if it possessed a specific gas constant given by

$$R = \frac{R_a}{1 + m}$$

and a value of the specific heat ratio, γ, given by equation (7), but in other ways obeys all of the well-known one dimensional flow relations of gas dynamics that can be taken from a standard text.

Technical Development

The supersonic nozzle design parameters were chosen based on the 100 ml per square foot of cleaning area requirement, and the need to achieve high velocity at impact. The first requirement led to the choice of a flowrate of 30 ml/min based on a cleaning rate of one square foot in three minutes. The gas flowrate of 30 scfm (standard cubic feet per minute) was chosen based on existing gas supply capacity. This set an m value of ~.03 with a corresponding pseudo gas γ of 1.34. These values were used to generate an isentropic flow table for the pseudo gas.

The Mach number versus area ratio (exit area/throat area) values from the isentropic flow table were plotted in order to decide which area ratio to use (refer to Figure 1). The area ratio was chosen at a point where the rate of change in Mach number with area ratio began to decrease significantly. The rationale was that before this point a small change in area ratio produced a large change in Mach number, and after that point the converse was true. Thus high exit velocities could be achieved without making an inordinately large exit cone.

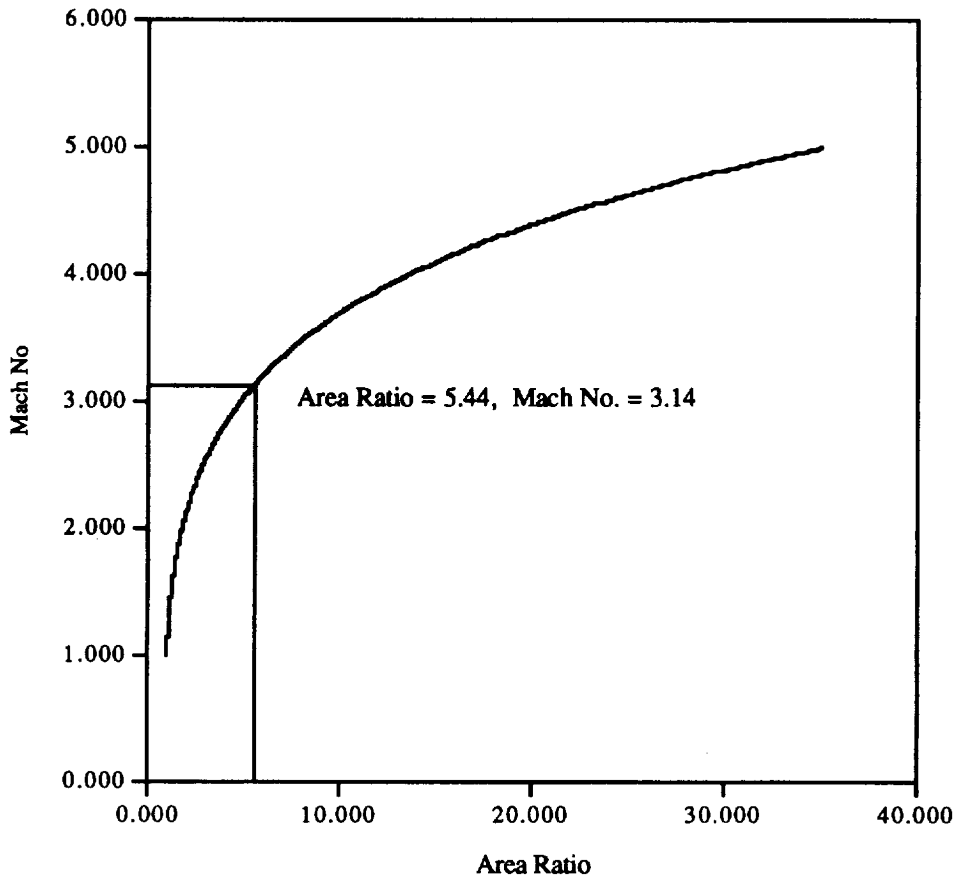

Figure 1. Mach Number Versus Area Ratio Plot

The liquid injection and mixing was the next problem which had to be tackled to make the 5.44 area ratio nozzle (hereinafter referred to as the nozzle) work as intended. The liquid which was to be used was distilled water, and the chosen gas was initially nitrogen and later breathing air. The water needed to be injected so that it would atomize and mix with the gas flow. Several ideas were considered; these included pre-mixing, injection in the center of the gas flow both towards and against the flow, and side injection into the gas tube through a small orifice. The last idea was implemented for the sake of design simplicity and ease of manufacturability and maintenance. The injection location was initially chosen just upstream of the nozzle. It was deemed that this location would not give the water sufficient time to form large droplets and subsequent stratified flow. A hand-held prototype system with this configuration was successfully tested.

The prototype system used three nozzles with axes arranged at the vertices of an equilateral triangle. The water was injected at the center of one of the sides of the triangle. This configuration provided excellent mixing and water distribution to all three nozzles. The water injection location also made the system insensitive to nozzle/injector orientation, so the nozzles could be pointed in any direction allowing access to all sides of a part being cleaned. Figure 2 is a diagram of the prototype system.

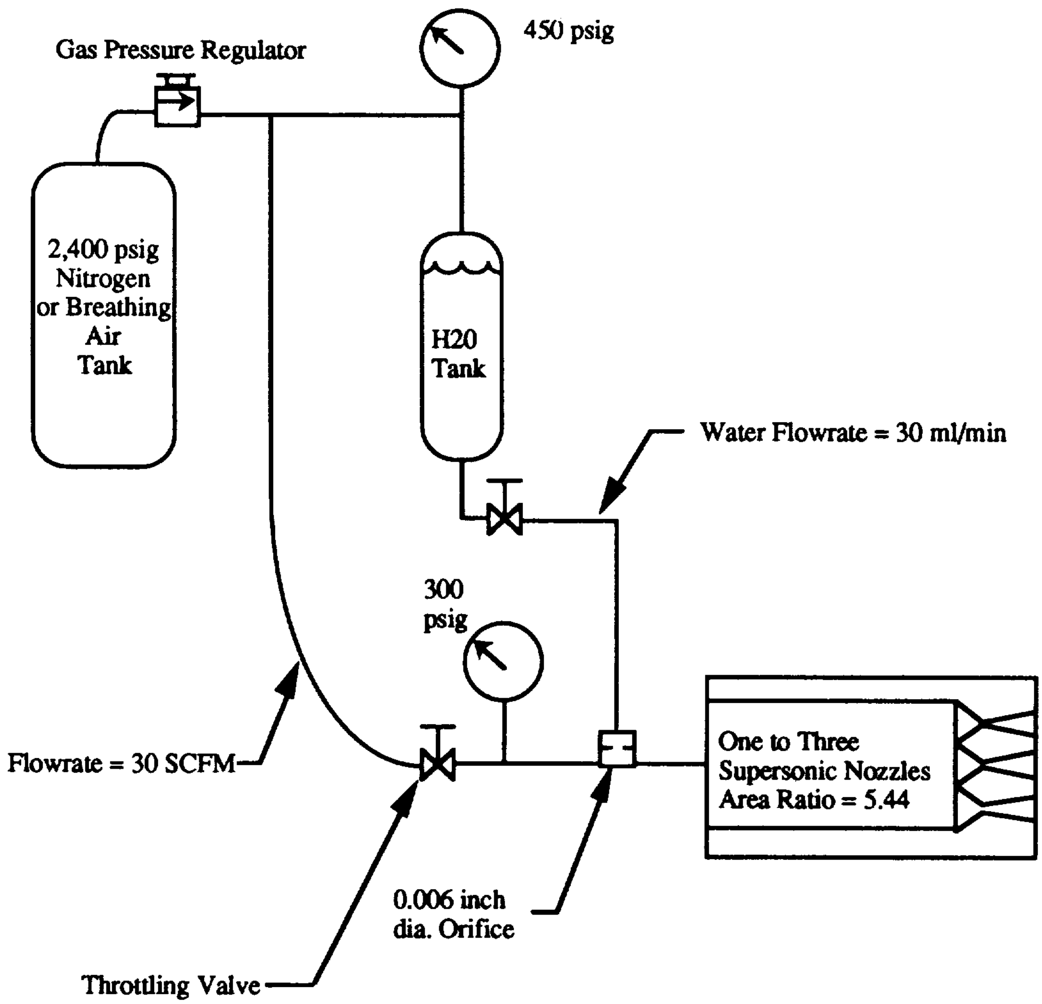

Figure 2. Gas-Liquid Supersonic Cleaning System Schematic

The system, as developed, required two hoses to extend to the nozzles, one for water and the other for air. Suggestions by the prototype system operators indicated that a single hose configuration would improve the ease of use of the spray nozzle. This prompted a modification of the injector location.

The injector was moved to the exit of the gas supply port prior to the twenty foot flexible hose to which the nozzles were attached. In order to keep the water and air mixed, the flow was made to go through a contraction upon exiting the flexible hose. This contraction served to increase the turbulence in the flow (Reynolds number > 5,000) which was sufficient to maintain mixing. This system configuration was also subjected to validation testing which is the subject of the next section.

SYSTEM VALIDATION

The existing specification for cleaning and cleanliness verification at Kennedy Space Center is based on using CFC 113. Before a new system can be accepted, it must be validated against the existing CFC 113 method. In the past, cleanliness was measured by weighing the non-volatile residue (NVR) and comparing it to the area of the surface in question. The rinse CFC 113 was collected, heated until the solvent and volatile reside evaporated, and weighed. The new verification method measures the total organic carbon (TOC) in the collected water sample. There needs to be a correlation between the NVR remaining on the surface and the TOC reading of the water sample.

The first set of tests were performed on one square foot witness plates made of type 304 stainless steel. The majority of fluid components used at KSC are from the 300 series (austenitic) stainless steels so the data should be representative. The plates were contaminated with a known quantity of one of the following substances:

Hydrocarbon Grease
Hydraulic Fluid
Silicone and Fluorosilicone Greases
Fluorinated Grease

Fluorinated greases, such as Krytox 240AC or Tribolube 16, are used for assembling all fluid systems at KSC except hydraulic systems which are lubricated with hydraulic fluid. The other substances are common lubricants. The plates were contaminated with two to ten milligrams each with one of the contaminants then impinged for between two and eight minutes each. The results showed that two minutes is sufficient to sample one square foot of surface area. The data correlating the TOC to the removed and remaining NVR is shown in Figures 3 and 4. The supersonic nozzle tends to emulsify hydrocarbon contaminants, so the concentration is much higher than the contaminant solubility limit in water. To test the emulsification, the water samples were subjected to an ultrasonic agitation after collection, and then the resulting TOC readings were compared. The data from that test is shown in Figures 5 and 6. This test indicated that the nozzle emulsifies well enough such that another step was not necessary.

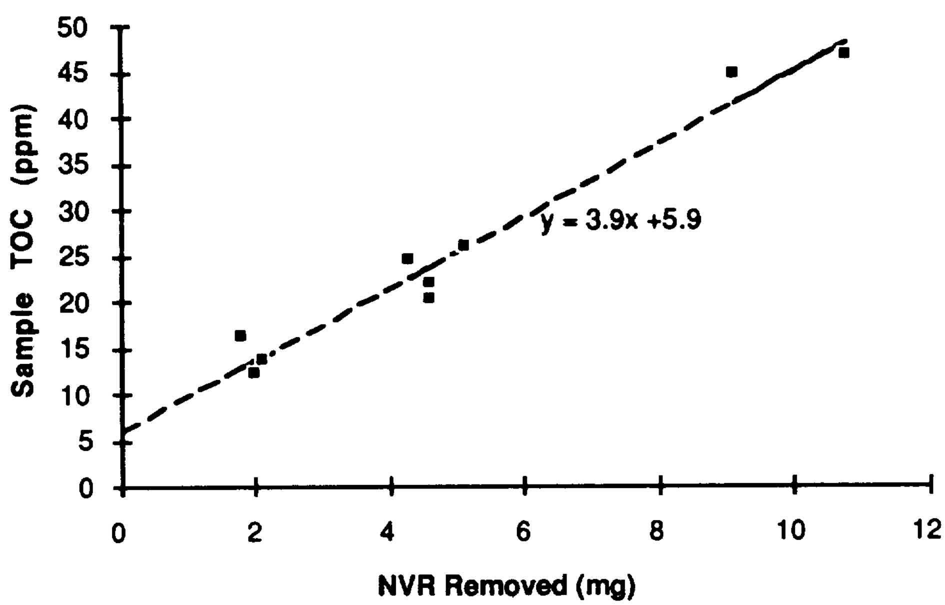

Figure 3. Correlation Between TOC Reading and NVR Removed

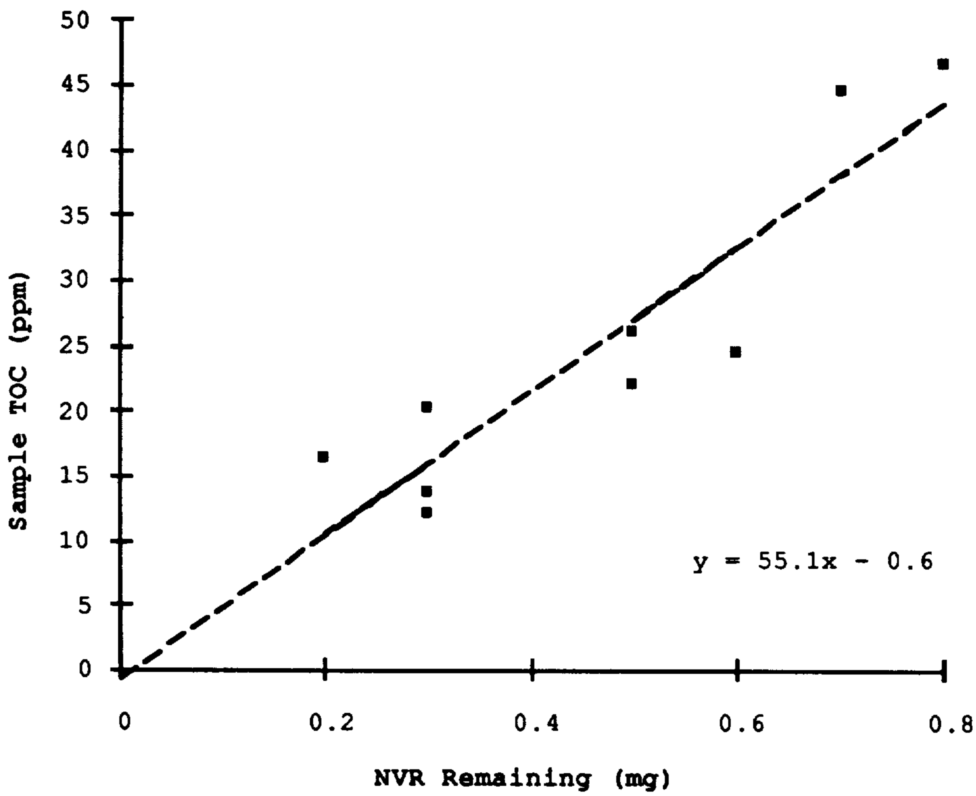

Figure 4. Correlation Between TOC and NVR Remaining After Cleaning

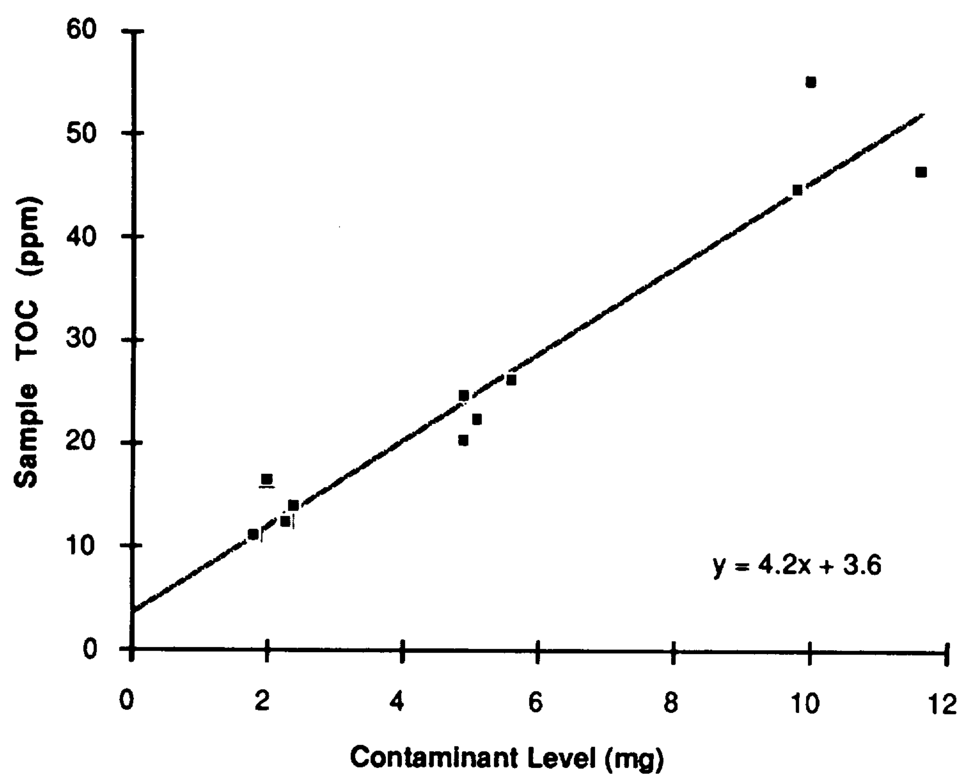

Figure 5. TOC vs. Initial Contaminant Level

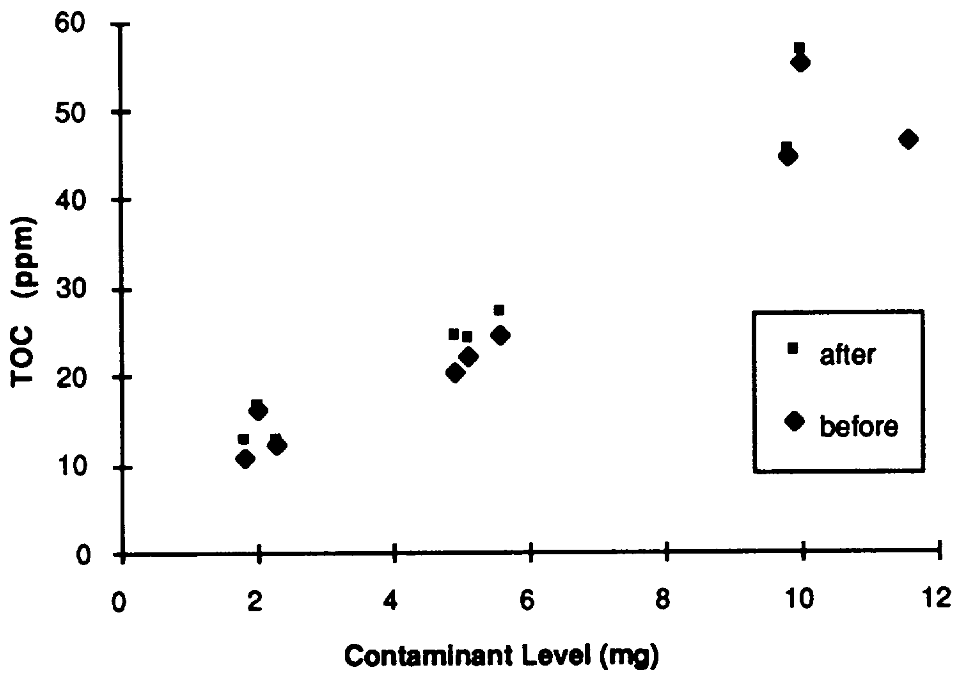

Figure 6 TOC Levels Before and After Ultrasonics

CURRENT AND FUTURE DEVELOPMENTS

The system was developed to clean and verify fluid components for the Space Shuttle program, but there are several other direct applications. Compressed gas bottles are required to be cleaned to the same levels as the LOx system components. These bottles are difficult to clean without an effective solvent due to the limited access to the inner surface. The widely used 2400 psig compressed gas bottles (k-bottles) are approximately eight inches in inside diameter. The only opening in a k-bottle is the single one-half inch pipe thread fill and drain connection. The current method for cleanliness verification is to flush the k-bottle with CFC 113. The gas-liquid nozzle would be a good candidate for verification except that the nozzles as designed would not fit through the opening. Several designs to use the existing nozzle on a rotating spray head were studied and abandoned. Finally a new nozzle was designed which has no converging section. With only a diverging section the nozzle is much smaller than a full converging-diverging nozzle. In theory a nozzle with no converging section is a diffuser which can achieve sonic velocity at the throat and lower velocity at the exit. This design controls the geometry of the approach to the throat of the diverging-only nozzle. This diverging-only nozzle design is supersonic with approximately a 20% loss in fluid momentum compared with a converging-diverging nozzle of the same dimensions and area ratio. The k-bottle spray head contains three diverging-only nozzles, one aimed straight down the bottle, one at 30° from the bottle axis, and one at 210°. The two angled nozzles are collinear so there is no side load on the spray head. The only net load on the spray head is the axial force created by the thrust of the straight through nozzle. The 210° nozzle covers the entrance region of the bottle and contributes to cleaning the side wall. The straight through and 30° nozzles combine to clean the flat bottom while the 30° nozzle also helps clean the side walls. This spray head design may be used to clean short, straight pipes and other small diameter pressure vessels.

Another application of the nozzle is the cleaning of large diameter pipes and pressure vessels. This design uses a rotating spray head like the k-bottle cleaner. In large pipes there is room for the full converging-diverging nozzle so the cleaning is more efficient. The nozzles in the large pipe spray heads are offset to produce a torque around its axis to cause rotation. The k-bottle cleaner requires an external force to spin the spray head. There will be a different spray head for different size ranges of pipe. Current development work is being done on cleaning large pipelines with this device. A pipe crawler is used to carry the rotating nozzle through the pipe while pulling a gas-liquid supply hose. Verification of cleanliness can be accomplished by collecting the liquid either at the crawler or at the entrance to the pipe and examining it by any of a number of methods.

SUMMARY

The system was developed to eliminate CFC 113 for cleanliness verification of large fluid system components at Kennedy Space Center. The supersonic nozzle arrangement was tested extensively against the CFC standard. Once the system was verified, work began on development of this technology for other applications. These include: the compressed gas cylinder spray head using the diverging only supersonic nozzles; and a nozzle configuration with the rotating spray head for large pipes and pressure vessels. Other potential applications include flux removal from printed circuit boards, degreasing operations, and cleaning operations which require minimization of the quantity of solvent used.