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Development of High-Temperature Acoustic Liners

Floyd Roberts
Mabels Prototyping, St. Petersburg, FL 33706
Bruce Vu
NASA Kennedy Space Center, KSC, FL 32899
Walter Eversman
University of Missouri Rolla
Gerry Arner
Mabels Prototyping St Petersburg Fl 33706
David Burd
University of Missouri Rolla

Abstract

The launch of space vehicles generates extreme conditions, such as vibrations and acoustics that can affect the launch pad, space vehicles, and their payloads. These acoustic loads are the results of intense acoustic environment generated by the interaction of the rocket-engine exhaust stream mixing with the ambient atmosphere. The primary source of structural vibrations and internal loads during launch is due to these acoustic loads. Therefore, being able to manage and suppress these undesirable conditions is critical to proper functioning of vehicle components, payloads, and nearby ground support equipments. Passive methods of sound mitigation such as acoustic liners are especially attractive as they are economical and efficient. An acoustic liner coating for use in the ducted exhaust system, capable of withstanding high exhaust temperature up to 3500 degrees Farenheit, has been designed. Experimental testing has investigated the coating for high temperature survival (plasma jet)and acoustical impedance (acoustical wave tube).

Introduction:

Background

Acoustical noise is an unwanted product of rocket propulsion. Acoustical stress is a primary design consideration in much of launch facility ground support equipment. The acoustic power emitted by the Saturn V vehicle at launch was about 2 x 108 W [1]. The acoustic energy associated with launch vehicle exhaust is mainly a function of exhaust gas velocity, exhaust gas density, and the velocity of sound in disturbed medium. The acoustic energy is highest at the nozzle exit, and decreases as a function of the square of the distance from the source.

Traditional models of rocket exhaust divide the plume into two parts, downstream of the shock wave and upstream of the shock wave. A principal difference of the two parts is that high frequency noise typically is associated upstream of the shock wave and low frequency noise is associated with a downstream position. The shock wave itself is a significant generator of sound as is the highly turbulent mixing of the hot gas exhaust and the ambient gas.

There exists a large body of information on the design of acoustic treatment for inletand fan exhaust ducts of turbofan engines. In the case of both inlet and exhaust the flow is at relatively high speed but it is near ambient temperature in the inlet duct and it is only at slightly higher temperature in the fan exhaust duct. The conventional approach to treatment results in a design which uses a porous face sheet backed by honeycomb cavities. Acoustic liners of this type are referred to as locally reacting because they do not permit propagation axially within the lining. These locally reacting liners are generally tuned to frequencies characteristic of the acoustic source, although some attempt may be made to obtain broad-band attenuation. The environment which this conventional technology addresses is benign when compared to the expected hot gas environment this proposal addresses. Two principal complications are addressed in the present study; first the presence of extremely high temperature gas flow with or without high particulate content renders the conventional technology of acoustic treatment design developed in aircraft engine applications largely inappropriate. The second complication arises due to the broadband (substantial low frequency content) characteristic of rocket engine noise.

Significance of the current work

This work demonstrated experimentally a high temperature, (tested to 3500 degrees MSFC Plasma Jet Facility) acoustical absorption, (25% in normal incidence acoustical wave tube testing) coating for ducted acoustics. The combination of a material which applies like a traditional coating, can survive 3500 degree exhaust temperatures and provide a measure of acoustical absorption to dampen the resultant acoustical stresses which are therefore incident on the vehicle is a most promising step for the design of lower weight higher ISP lower cost propulsion.

We have demonstrated that production of a sound absorption coating is possible in the extreme environment of rocket exhaust gas impingement {exhaust ducting}. Based on the combination of screening through acoustical wave tube and plasma jet (3000 deg+) torch work a coating formula was developed with provided both survival at extraordinarily high heat flux AND acoustical damping of approximately 25%.

Main text

Coating design approach:
Although it is appropriate to consider processes of application, adhesion, and application environment within the design approach this paper will confine itself to the aspects of acoustical damping and thermal survival. Acoustical absorbers are applied either as liners or as discrete cavities both act as a series of Helmholtz resonators that remove energy from the vibratory system[1]. The typical treatment is to consider one resonator element as the mass of gas in the orifice using the volume of gas behind it to form a traditional oscillatory system.

Conceptually we address three absorption mechanisms which we have attempted to integrate into the current coating. First is as discussed above the use of cavities as traditional Helmholtz resonators, Second is the use of "stub tuners" as passive secondary resonators in the cavities, and Third is the use of traditional elastomeric material response.

Working backward, traditional elastomeric material response damps the incident acoustics through a time dependent viscoelastic response to normally applied force. This mechanism is applied two ways in the current system. The first use is as an undercoating material system formulated for elastomeric response at room temperatures (relevant to wall temperatures – based on current organic duct coatings). The second use is through hot surface use of material which will provide elastomeric response at operating temperatures. This second use we hope will provide a synergistic response at actual use temperatures between cavity based Helmholtz resonators and elastic material absorption.

Next is the use of stub tuners as passive secondary resonators. Simply put this mechanism is intended to provide diving board like structures within the cavities which may sympathetically absorb acoustic energy. Currently we have no mechanism other than statistical probability to place or orient these structures.

Finally there is the use of cavities as traditional Helmholtz resonators. The outer coating was formulated to provide tight porosity, but porosity that proceeded continuously through to the coating back plane surface. Considering a traditional liner using the mass of gas in the orifice as a spring and the entrapped mass behind it as a damper we essentially throw a lot of junk into the mass end of the system, (at temperatures relevant material has softened and the presence of high porosity high tortuousness cavities create a much more complex / chaotic damping environment. The intent is to create a gas/elastomeric chamber hybrid damping medium.

Even thought the Helmholtz theory is well understood a problem exists in applying the theory to conditions of high pressure , high temperature and sound energy levels. This is where our work is leading us. See discussions at the end regarding viscoelastic behavior of gaseous medium.

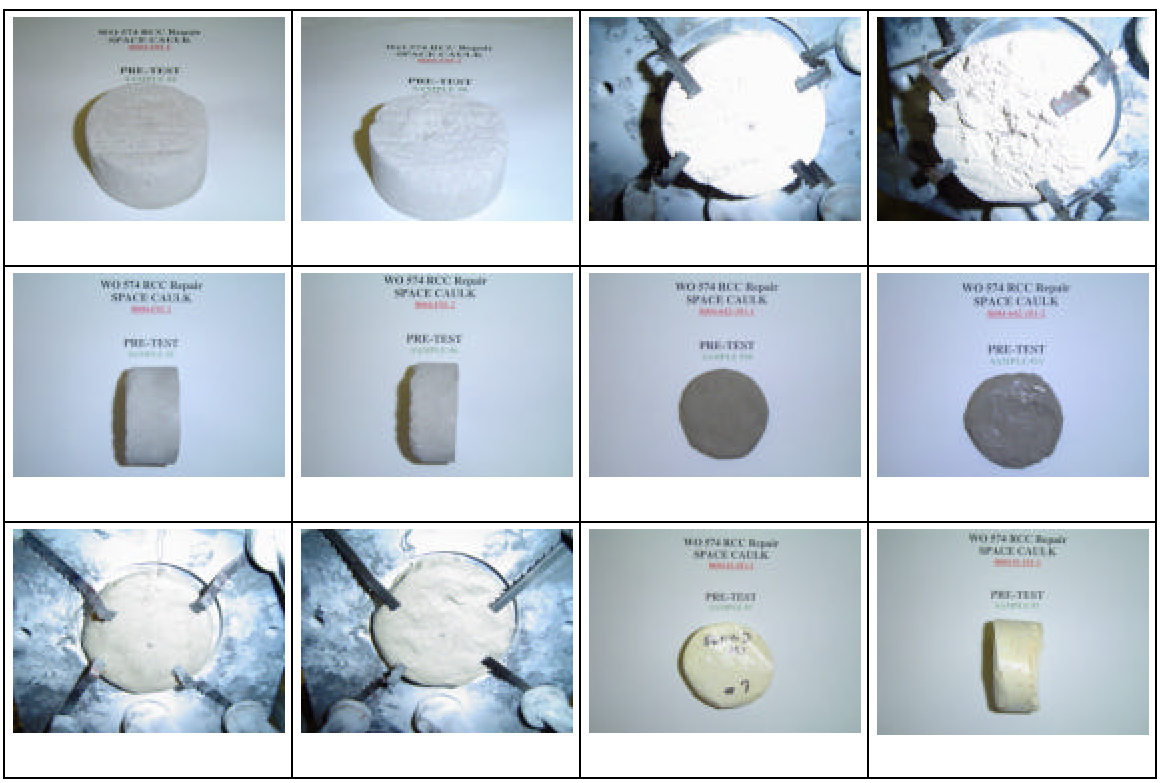
A fourth mechanism was investigated which was to provide a composite material with extremely weak inter-facial bonding such that acoustical energy is absorbed by relative motion between matrix and particle. We attempted several families which we hoped would exhibit absorption based on this behavior however we were never able to produce a viable coating which had appropriate mechanical properties yet would also provide some relative motion at the temperatures and intensities of the normal incidence testing. All of these coatings either fell apart prior to testing or at best failed to thrive.

Formulation

To arrive at a successful coating in the ares of acoustical performance, High temperature survival, and coating stability formulation families were developed for each arena or requirement and the successful aspects were carried forward for integration. Details on coating formulations are appropriately covered in other material focused venues, however it is appropriate here to provide background relevant to the coating which is providing successful test results.

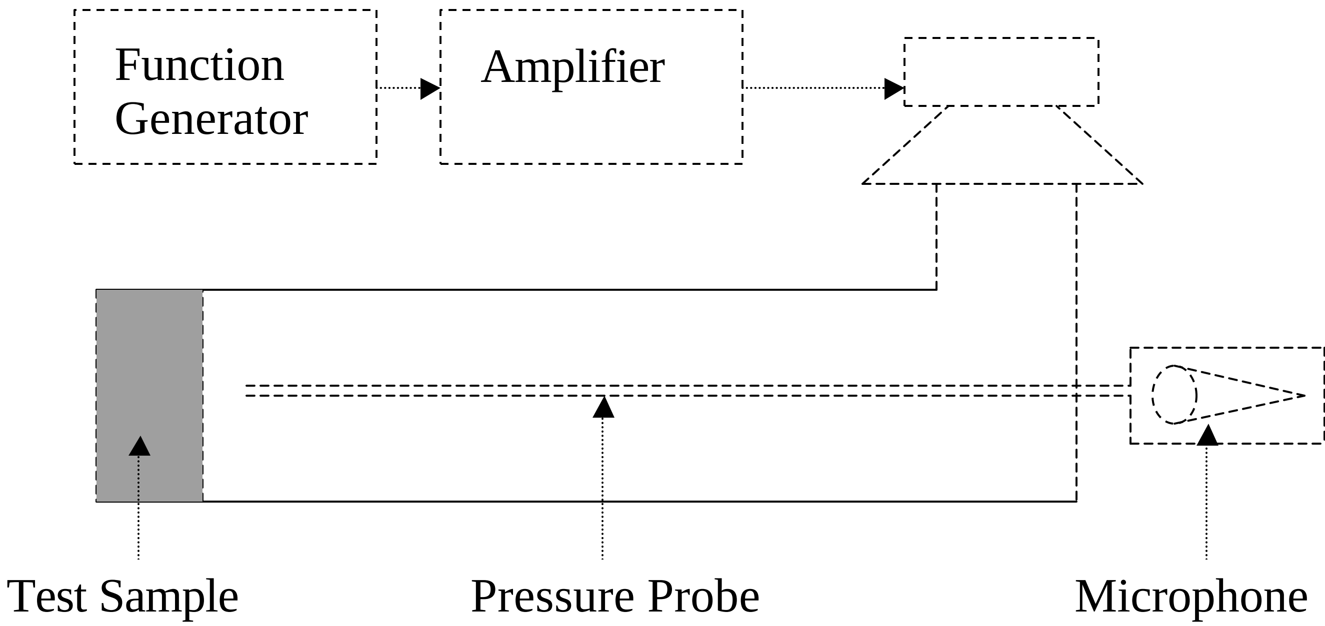
Sodium silicate binder

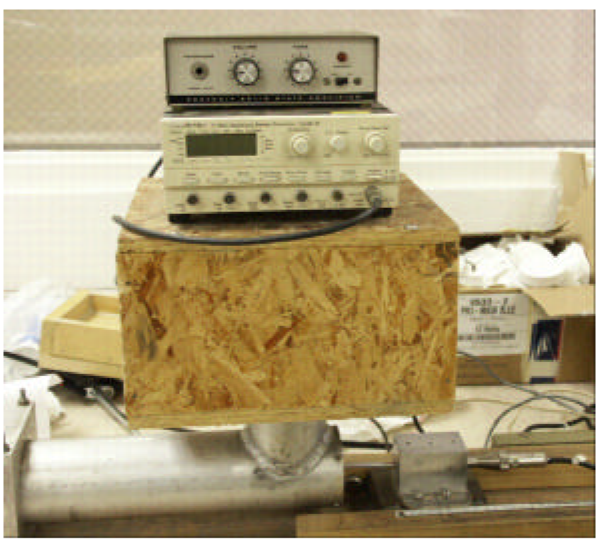
The sodium silicate binder system this was not expected to survive the experimental heat flux, however because sodium silicate systems are also industrially developed we felt that the relative ease of formulation would allow us to look at the high temperature properties of some of the other materials which we intended on using as filler and acoustical absorption material. This group of filler and absorption materials would include many of the ceramic spheres, the platelet materials and the whisker materials. In plodding through screening tests for the particulate we were quite surprised to have a sample which survived. Hindsight has lead us to the presumption that the thermal mass provided by the entrained particulate coupled with the thermal conductivity of the sodium silicate matrix produces a system which is able to buffer the heat flux capacitively. It accepts the heat flux based on the ratio of particulate to matrix and survives as long as the particulate is able to absorb the heat based on the heat transfer rate to greater depths of material (depth based on the thermal conductivity of the sodium silicate matrix at temperature) or back surface cooling rates.

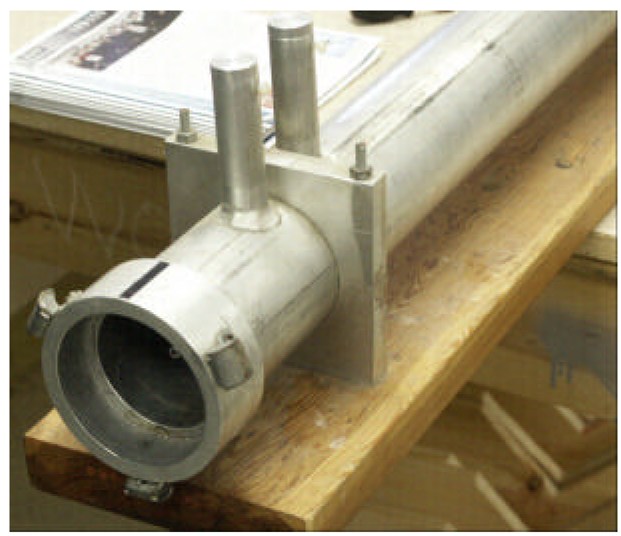


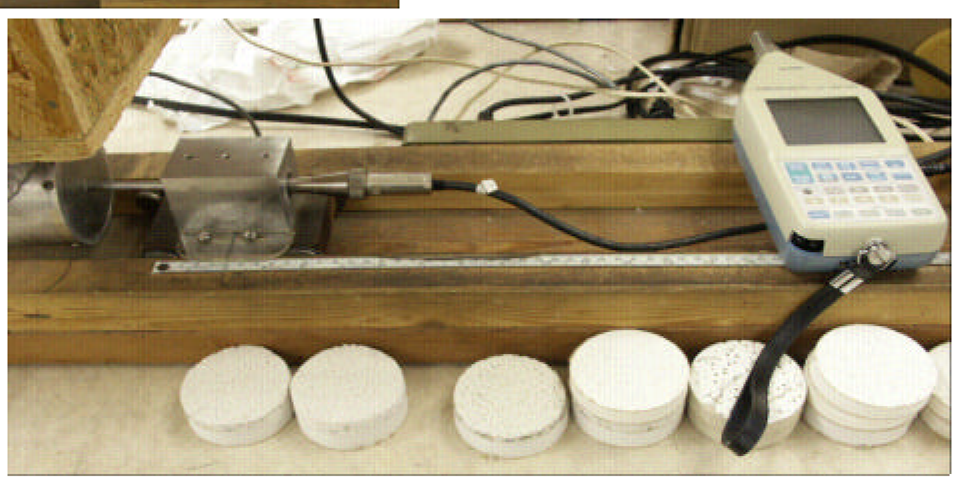
Acoustical Results

Acoustical testing was performed in the University of Missouri Rolla standing wave tube to determine the absorptive characteristics of each material at 63, 125, 250, 500 and 1000 Hertz. A relatively standard acoustical wave tube set up was used as diagramed below.

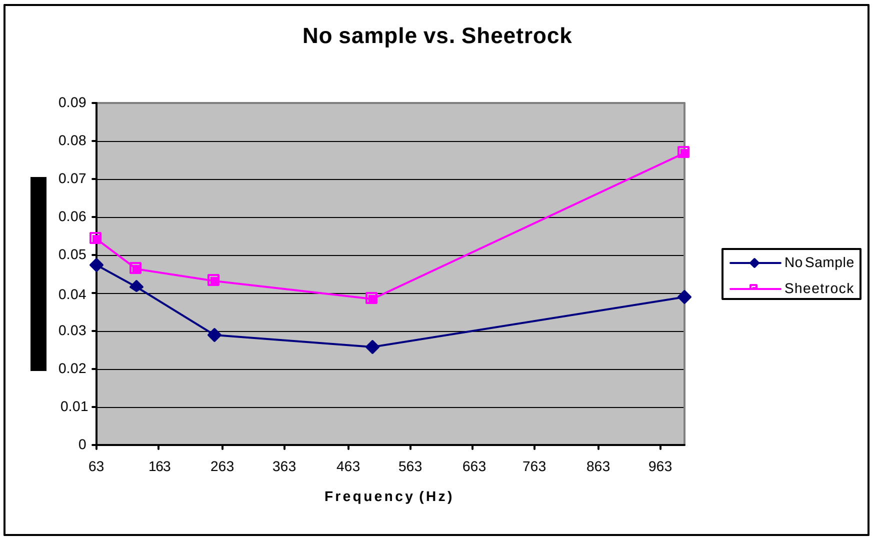






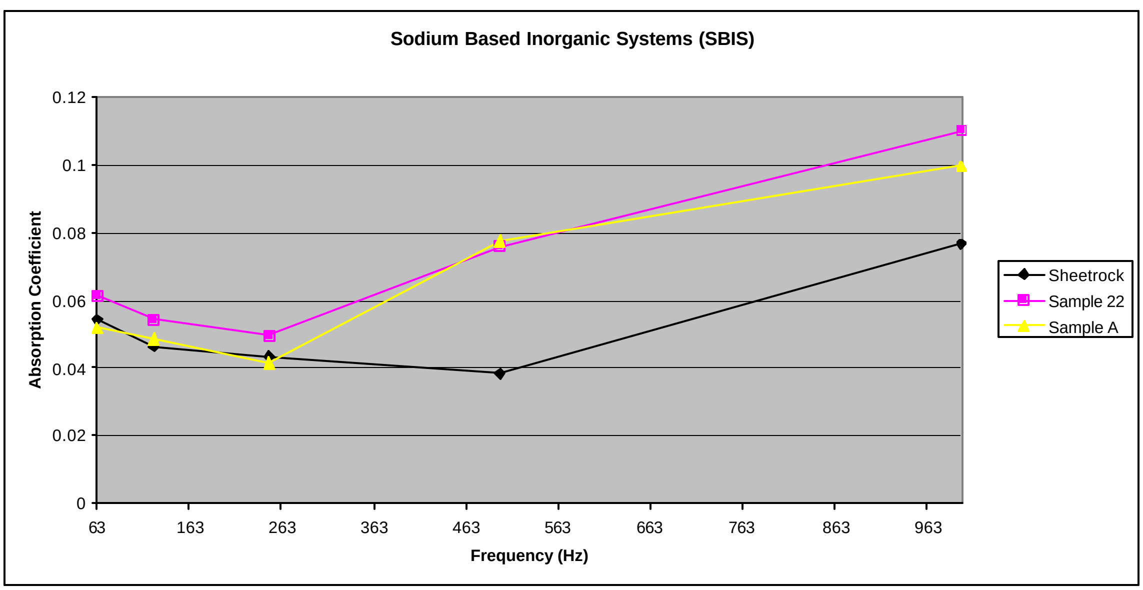


Samples was mounted on Sheetrock substrate and the test results were plotted with the absorptive properties of the Sheetrock substrate for comparison. The absorptive properties of the Sheetrock sample vs. no sample can be seen in the figure below.

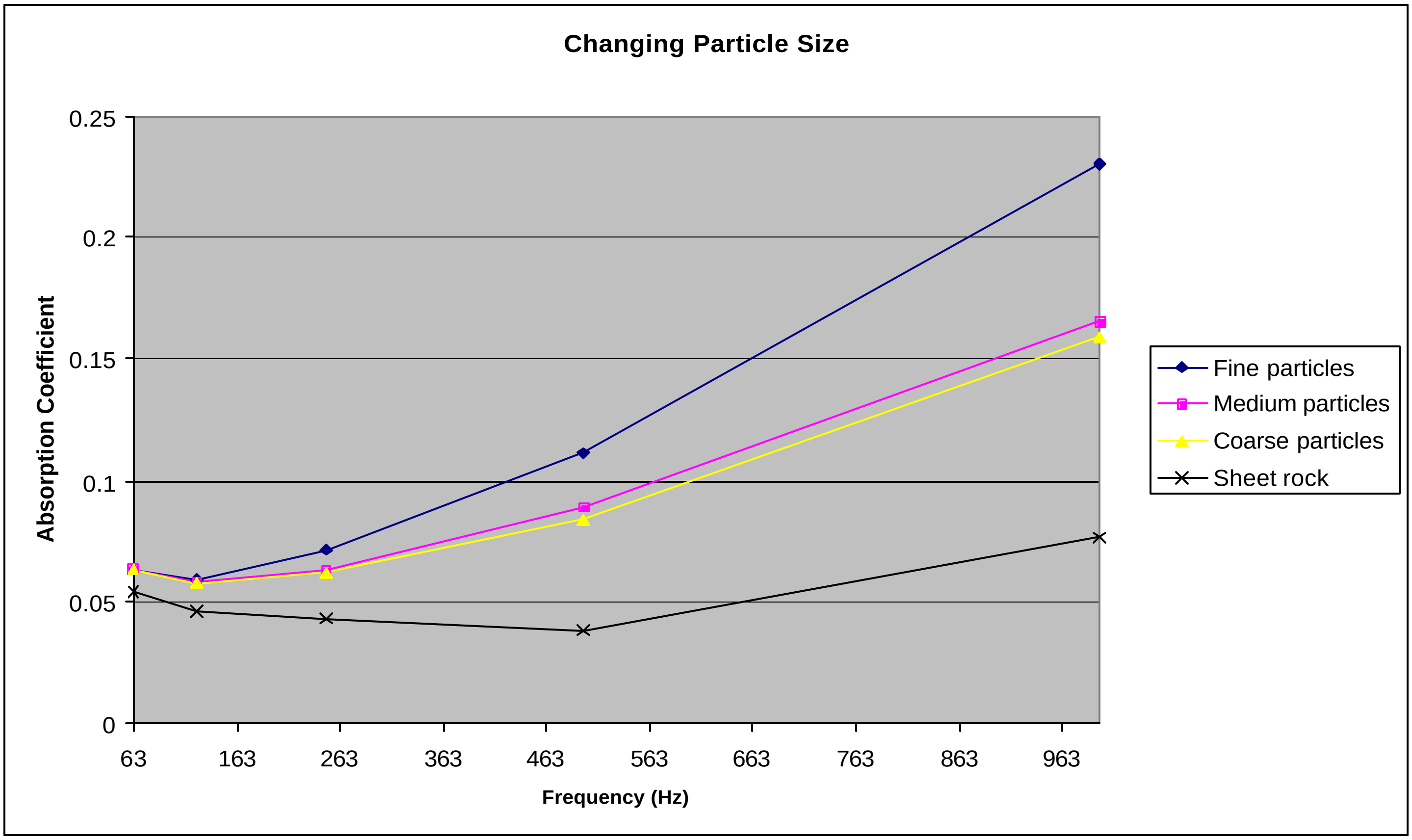


As expected, the sheetrock had minimal absorption in the frequency range of concern. This validated its use as a substrate.

There were six families of coatings, each with a myriad of formulated variations which were investigated and those results are detailed elsewhere [2]. This paper will limit itself to discussions on the elasomeric system and the sodium based system. Shown below is one of the first sodium based samples to demonstrate any successful impedance.

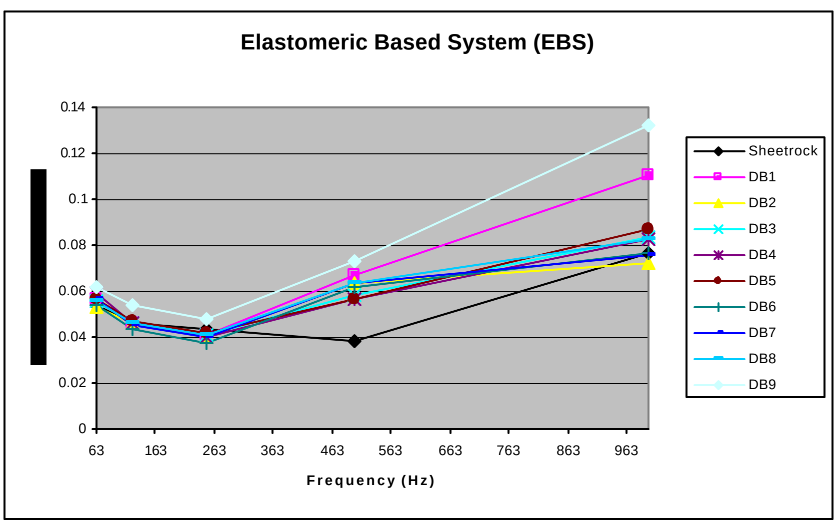


Later changes in porosity in the sodium based system produced acoustic absorption near 25%.



The other more traditionally formulated acoustical absorption coating was an elastomeric based system. These architectural grade material samples had holes drilled in the sheetrock substrate of the system samples. This significantly increased the absorption as frequency increased. Shown below is a composite of families where direct material absorption based on elastic response of the material is expected to be the primary absorption mechanism.

These successful samples where the acoustic



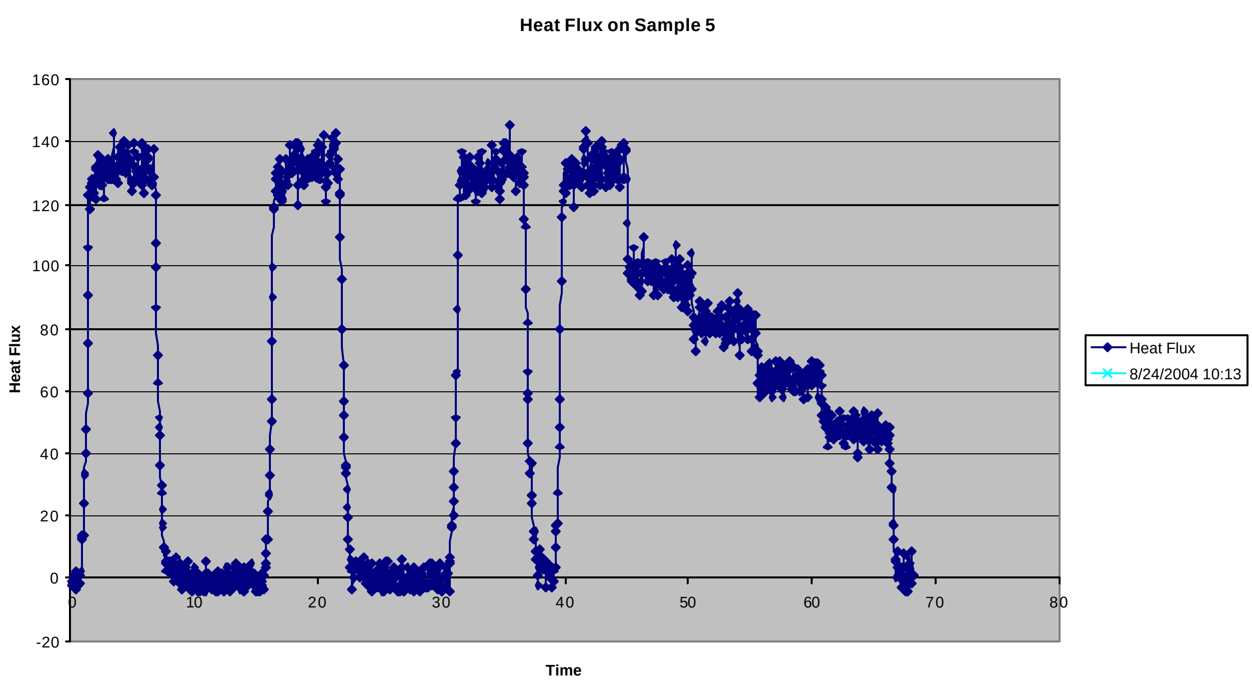
behavior was based upon matrix elasticity utilized a material with a Young's modulus of approximately 5000psi with included particles with moduli in the range of 10000 to 1000 psi.

High Temperature Exposure
(MSFC Plasma Jet)

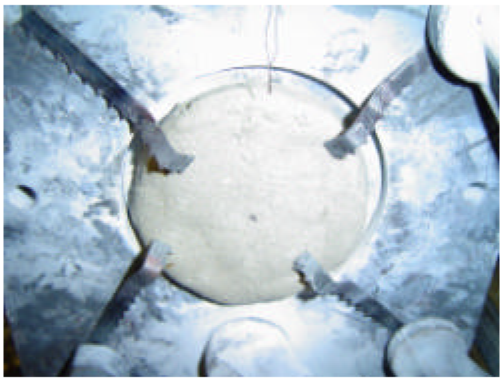
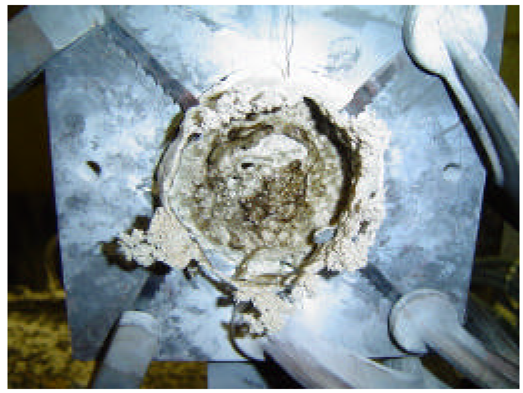
We have been very fortunate to have the cooperation of Marshall Space Flight Center and their plasma jet facility. The plasma jet provides 130 BTU / SqFt/Sec with 500 m/sec hot gas flow of argon/nitrogen. This has enabled us to provide a level of experimental and in servic e proof of concept which is not practical through other means.

Plasma Jet Torch Testing

The MSFC Plasma Jet Testing has provided an excellent initial screening process for the high temperature ducting applications. MSFC was able to run samples in a reentry test matrix. The heat profile is much more aggressive both from a time and a heat flux standpoint than that which is expected on launch hardware. Fortunately for this work the plasma jet does not chemically simulate reentry but in fact provides an appropriate heat flux and a high velocity hot gas stream. The plasma torch feedback controls provide a defined heat flux rather than a predetermined temperature. This is actually the most practical way of obtaining reliable data around the expected use conditions as the kinetics of material emissivity and combustion both are sufficiently complex to make instantaneous temperature measurement unlikely. Approximate front surface temperature measurements are made using an optical pyrometer. Because of the ongoing change in surface emissivity due to temperature change and to ongoing material phase changes it is not currently possible to gather an exact surface temperature. The estimates provided for the samples based on the pyrolaser measurements are surface temperatures in the range of 2750 –3600 F. Shown below is a representative heat flux profile for the sodium based samples.



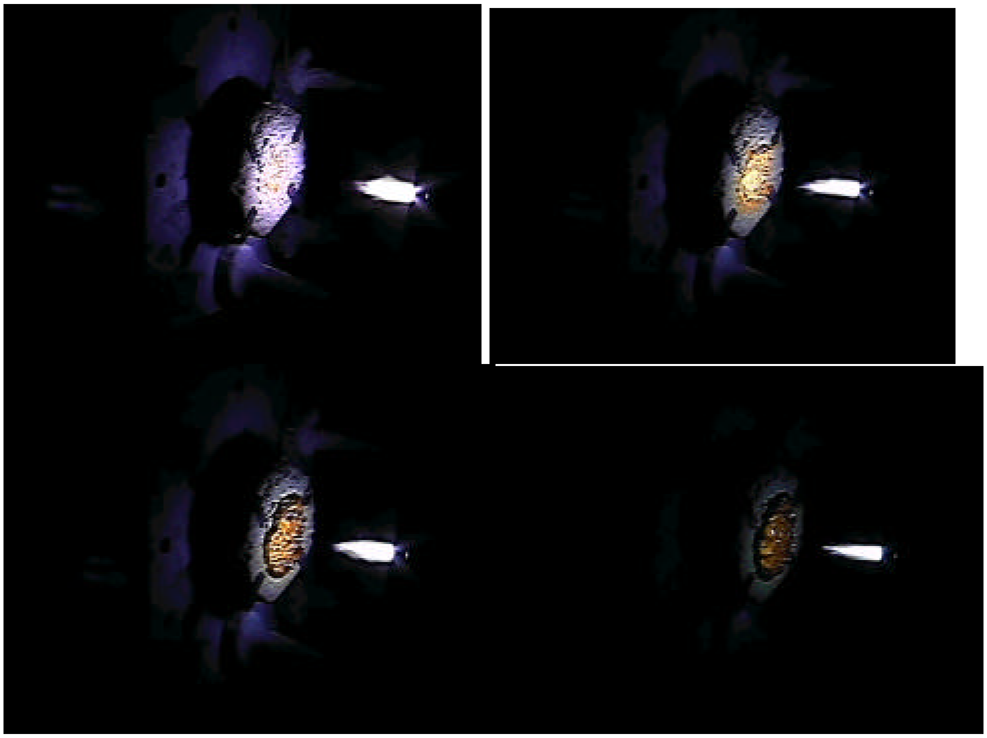
A large number of varied formulations were tested in this portion of the work, often the purpose was to investigate the effects of various filler materials which we felt would aid in acoustic absorption. Shown below are samples using a specialty magnesia silicate filler in an alumina base. The alumina samples despite several variations in formulation parameters continued to provide anomalous thermal behavior. The best description of this appears to be generation of internal porosity with an exterior skinning of the samples. Upon exposure to the plasma torch these samples were consistent in demonstrating muffin like behavior. Representative post test photos are shown below.

Attempts were made to vary binder levels and filler materials, but none of the formulations were able to avoid this behavior. Currently the presumption is that this effect is due to the formation of a higher temperature phase of alumina spinel which fills the surface porosity during the firing process.

The Sodium Silicate samples were initially formulated with a variety of clays which were were interested in getting thermal properties of. There was no expectation that these samples would be able to survive the heat flux. It was quite a surprise then that these samples provided the results that they did. The positive sodium results in both cases led us to a cooperative formulation which is shown on the following page these samples provided an acoustic absorption in the wave tube of approximately 25%

Samples were weighed before and after to determine total weight loss. Samples as currently formulated have a definable weight loss which is centered at the torch application region. Fairly easy to see in the photographs below. This localization appears to indicate that a duct coating recoating will be effective (i.e. not a leaching phenomena).



5-10-15-20 Minutes

Successful Test Finish at 23 minutes

As a closure we investigated a composite of the elastomeric and the inorganic silicate mechanisms which
have provided the highest acoustical damping. The reasoning behind investigation of the composite is twofold. For the ducts in which the material would be placed the inorganic portion of the composite would form the outer layer at thickness providing adequate thermal protection and the , the organic portion of the material would provide adhesion to the substrate and additional pass through acoustical damping.

<u>Problems with the current work, Future Challenges.</u>

- The high temperature environment of the plasma jet only provides proof testing with regard to heat flux, we hope to incorporate proof testing at SSC where appropriate chemical species are present as well as this may introduce significant additional erosion.
- All of the acoustical testing to date has been done at room temperature, obviously material changes at high temperature will affect the absorptive behavior.
- Great pressures yield chaotic changes in viscosity all of the testing to date has been performed at relatively low sound intensity levels.

Reference

[1] Rocket Propulsion Elements 1992 -6th edition George P Sutton
[2] KSC STTR Phase One Final report

Acknowledgements

- We have been very fortunate to have the cooperation of Marshall Space Flight Center and their plasma jet facility. This has enabled us to provide a level of experimental and in service proof of concept which is not practical through other means.
- We are looking forward to guidance from KSC for future development of this material so that we may eventually provide a coating which is put into use in a service environment.