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EXPERIMENTAL STUDY OF OVEREXPANDED AXISYMMETRIC JETS IMPINGING ON FLAT PLATE.

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ABSTRACT
This paper describes experimental results involving the measurement of acoustic pressure and sound pressure level (SPL) generated by the jet from an over-expanded convergent-divergent nozzle impinging on a flat plate. The goal of this work is to develop a better understanding of the acoustics of impinging jet flow field, which is of significant practical interest because of its presence in short take-off and vertical landing (STOVL) vehicles, multi-stage rocket separation, deep space docking, space module attitude control thruster operation, lunar and planetary landing and take-off, jet engine exhaust impingement, gas turbine blade failure, gun nozzle blast impingement, shock impingement heating, terrestrial rocket launch and other aerospace related and industrial applications. The jet was produced by a convergent-divergent nozzle connected to a settling pressure chamber. Acoustic measurements were made for five different overexpanded jets with chamber-to-ambient pressure ratios, Po /Pa = 5.26, 10.52, 15.78, 21 and 26.31 (which corresponds to fully expanded jet Mach number Mj = 1.74, 2.18, 2.44, 2.63 and 2.79 respectively). The present study is concerned with the measurement of Sound Pressure Level (SPL) produced by axisymmetric overexpanded convergent-divergent nozzle of exit diameter 10.3 mm designed for Mach 3.The plate upon which the jet impinges is large compared to the jet diameter (49d, where d is the nozzle exit diameter). Measurement of SPL between the frequencies 20Hz to 20KHz (audible range) have been made keeping an impingement plate perpendicular to the jet axis at a distance of 3d (d is the exit diameter of the nozzle). The measurements were conducted in an open atmosphere. The measurements were conducted upstream as well as downstream of the nozzle over an extensive envelop of jet operating conditions such as chamber stagnation pressure and mass flow rate through the nozzle. Near field acoustic measurements indicate that the presence of the plate increases the SPL by approximately 4 to 8 dB relative to a corresponding free jet.

Keywords: Impingement noise, Acoustic measurements, Sound Pressure Level.

1. INTRODUCTION
Supersonic jets are intense noise generators and means must be found to modify the noise generation process to reduce the noise level in the aircraft or in the launch vehicles to meet the community noise regulations. Supersonic jet noise is associated with noise due to mixing and shocks. The jet flow field is turbulent with both small and large scale structures capable of generating noise. Supersonic noise has three components (1) Turbulent mixing noise (2) Broad band shock associated noise (3) screech tones. Supersonic jets have shear layers (mixing layers) incorporated in their structures. It is known that instability waves are the dominant source of mixing noise radiating downstream [3, 4].

The methodology to predict the noise radiated to the far field is based on the determination of the axial growth of the instability wave in the jet shear layer. For high speed jets, the instability waves propagate downstream with local supersonic velocity. These fast moving waves generate intense Mach wave radiation. Under this circumstance the radiated noise characteristics strongly correlates with those of the instability waves. Pressure fluctuations in a turbulent field consisting of large scale structures are responsible for generation of turbulent mixing noise. Interaction of quasi periodic shock cells are large scale structures produce brand band shock associated noise (continuous frequency) and screech tones (discrete frequency)[2]. Instability waves occur due to the oscillations of large scale structures. Screech tone occurs as a result of acoustic feed back phenomenon.

The impingement flows are generally found to be extremely complex [5,6]. In some instances the flow field produced by the impingement of high speed jets produces adverse local flow conditions, which can potentially lead to the degradation of aircraft performance in a number of areas during hover. These adverse effects, collectively referred to as ground effects, are the result of the highly unsteady nature of the flow generated by the impingement of high speed jets, on the ground plane and the pressure field caused by the natural entrainment of the jets.

In spite of many previous studies describing these different noise sources, there is no analytical model available for predicting the characteristics of these environments. Therefore model and flight test data are required, and the only approach to the problem is small scale model tests. Hence the present work is concerned with the measurement of sound pressure level in the impingement field upstream of the nozzle.

2. EXPERIMENTAL SETUP

The experimental setup consists essentially of a pressure chamber and a nozzle exhausting on to a flat plate kept opposite to the direction of flow. Compressed air from compressed air receiver of 70 bar and 0.5 m^3 capacity, approximately at room temperature was supplied to the nozzle via a control valve and a settling pressure chamber. This chamber is a cylinder with a diameter of 0.421 m and length of 0.85 m, and is designed to withstand 50 bar pressure.

A convergent-divergent (over-expanded) nozzle of throat diameters 5 mm and exit diameter of 10.3 mm designed for a Mach number of 3 was used in this experimental work. This nozzle was made of brass material. An impingement plate of diameter 0.5 m and thickness of 0.05 m made of mild steel was used for jet impingement experiment. The measuring and recording equipment consisted of a ½” Bruel & Kjaer Pre-polarised microphones type 4189, which is used in conjunction with a B & K Pre-amplifiers type 2669 and a 4 channel conditioning amplifier B & K type 2690. Measurements were made simultaneously with the microphones and a Mediator B & K type 2238 which measures SPL at a point in order to check the accuracy of the microphones. The microphones are mounted at various positions along the jet axis (both downstream and upstream) using a stand constructed of mild steel framework. Microphone holders are positioned at 90^0 to the jet axis at 0.3 m interval. Fig.1 shows the schematic layout of an experimental setup.

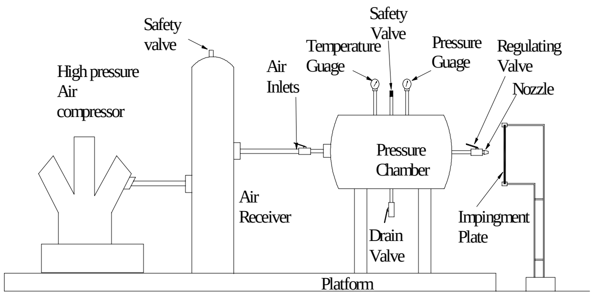

Fig.1 Schematic diagram of an experimental set-up.

3. MEASUREMENT DETAILS

Measurements of sound pressure level between frequencies of 20 Hz to 20 kHz (audible range) have been made keeping an impingement plate perpendicular to the jet axis at a distance of 3d (d is the exit diameter of the nozzle). Measurements were recorded simultaneously with all the microphones and a mediator axially as well as radially up to 145d(1.5 m) at an interval of 29d(0.3 m) each downstream and upstream of the nozzle. For free jet experiment measurements were obtained at the same locations by removing impingement plate. For all the microphone locations the pressure ratio was varied in about 5 steps from 4.9 bar to 24.5 bar. These measurements were obtained both upstream and downstream of the nozzle. The noise signal was processed through a 32 channel Data Acquisition system (Daqboard 2000 Iotech USA). Time average of the square of acoustic pressure and SPL were calculated using theoretical relations and software developed for this purpose which was also checked with DASY Lab software. For these experiments the stagnation temperature in the settling pressure chamber was observed to be equal to room temperature. In addition frequent checks were made on the microphone calibration using a B & K Piston phone type 4220.

4. RESULTS AND DISCUSSIONS

The data obtained experimentally can be represented in the form of graphs by non-dimensionalising the variables, so that it can be used for predicting the noise in similar applications. Noise measurements were carried out with impingement, choosing five axial as well as five radial locations in the upstream and downstream of the nozzle each of 29d (0.3m). An impingement plate was kept in front of the nozzle at a distance 3d from the nozzle exit. Experiments were carried out in an open field. Measurements were also carried out without impingement for all the locations in order to compare the noise levels with impingement but results are not reported here due to space constraint. The spectral and other analysis were carried out at all points. But in this article, the analyses is confined to a point located at 29d axially and radially both upstream and downstream of the nozzle. Similar variations were observed at all the locations.

Fig. 2. represent the variation of Sound Pressure Level (SPL) with the ratio of mass flow rate through the nozzle to the maximum mass flow rate. SPL increases with increase in flow rate through the nozzle since a turbulent jet flow involves inertial forces associated with the fluctuations of momentum flux and these forces are responsible for generating the sound. As mass flow rate through the nozzle increases, the corresponding momentum flux will also be increased which in turn increases the acoustic pressure. It is also evident from the figure that the intensity of sound was more in the upstream region compared to downstream because of changes in the acoustical properties of the flow after it impinges on a plate.

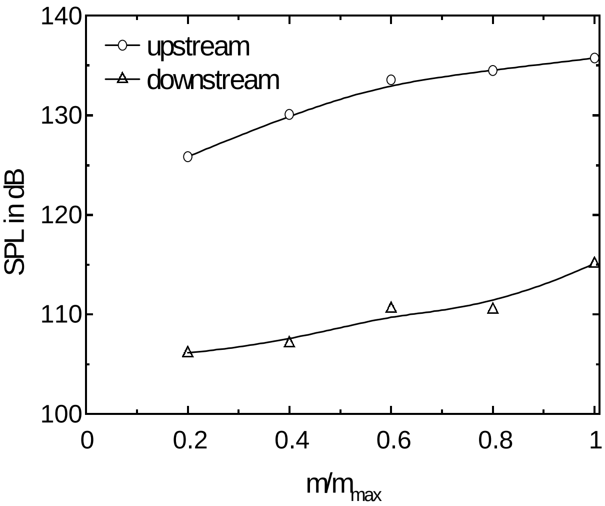

Fig.2. Variation of SPL with the ratio of mass flow rate to maximum mass flow rate

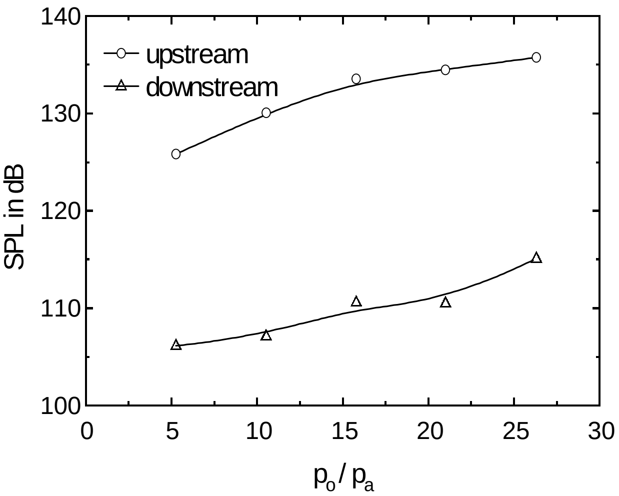

Fig.3. Variation of SPL with the chamber stagnation pressure to atmospheric pressure

Fig 3. represent variation of SPL with the ratio of chamber stagnation pressure to the atmospheric pressure. SPL increases with increase in stagnation pressure. As the pressure increases there is increase in mass flow rate through the nozzle. SPL will also increase with increase in jet exit parameters. Since the nozzle is overexpanded and the generation of jet mixing noise is associated with highly fluctuating mass flux which is proportional to jet exit parameters. Similar variations were observed without impingement; the only difference was that the magnitude of SPL is more downstream as compared to impingement results.

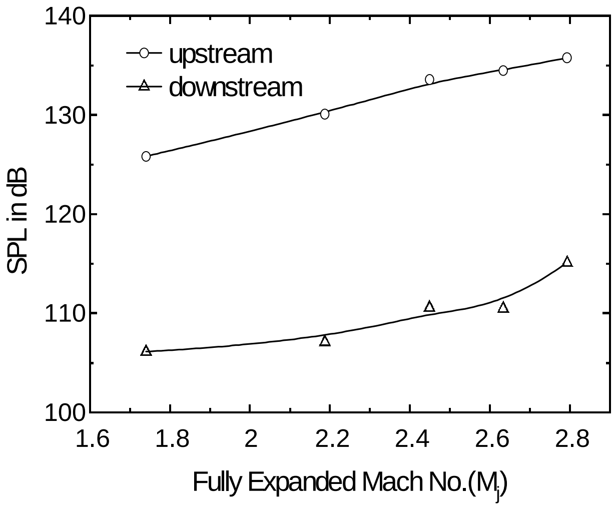

Fig.4. Variation of SPL with fully expanded Mach number

Fig. 4 represent variation of SPL with fully expanded jet Mach number. SPL increases with increase in fully expanded jet Mach number. Since noise radiated from a turbulent jet is directly proportional to the fully expanded jet velocity. The magnitude of Sound Pressure Level is more for upstream conditions due to the reasons explained earlier. Fig 5 (a) to Fig 5 (e) represents a constant Sound Pressure Level (SPL) contour plot for the nozzle both downstream and upstream with different chamber stagnation pressures shown therein. It may be observed from the figure that the maximum sound is radiating in the direction making an acute angle with a jet axis (< 15^0 - 20^0). Maximum noise sources are located near the impingement plate in the upstream side of the nozzle nearer to the nozzle exit.

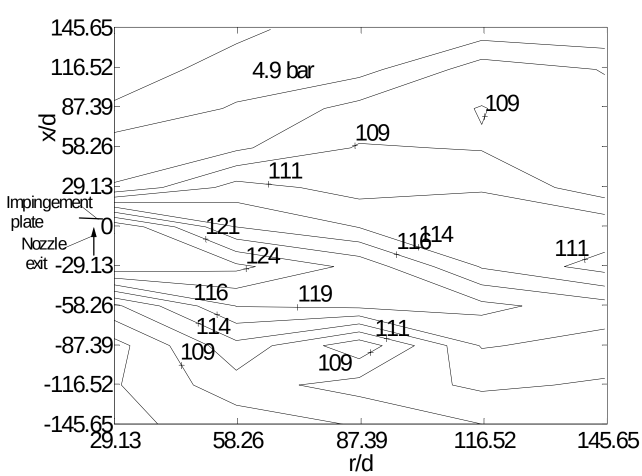

Fig 5(a)

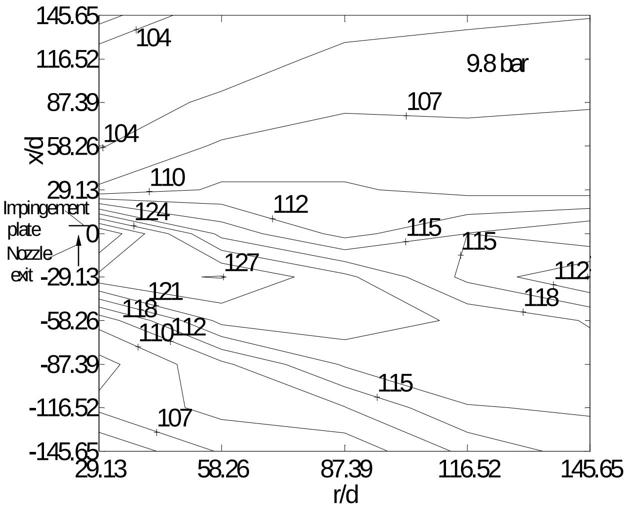

Fig 5(b)

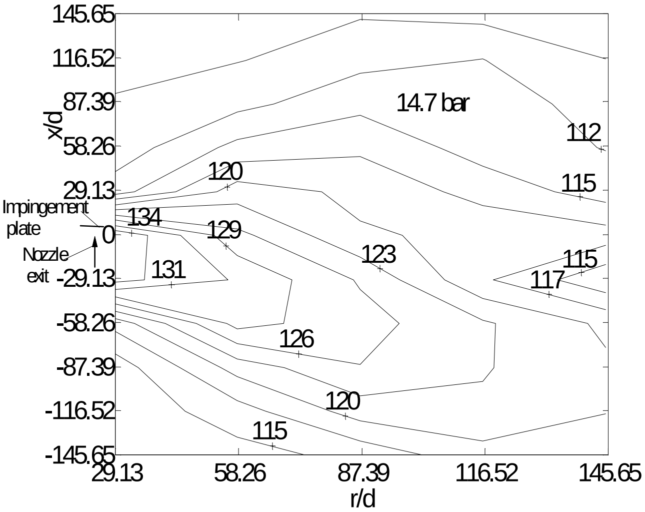

Fig 5(c)

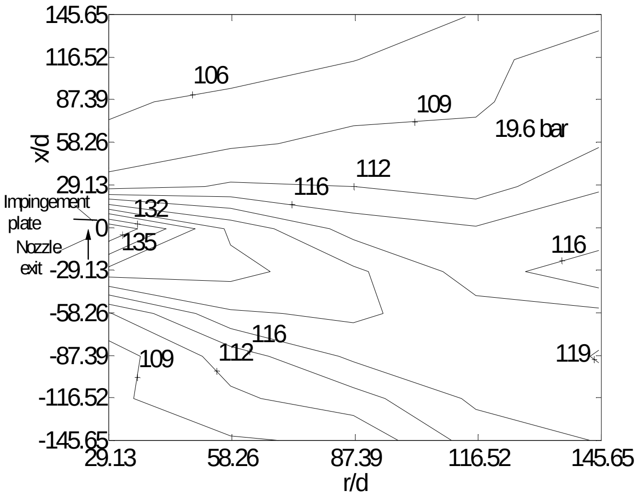

Fig 5(d)

Fig 6(a) to Fig6 (e) represent power spectral density plots for upstream and downstream conditions corresponding to the chamber stagnation pressure shown therein. Power spectral density is the amount of power per unit (density) of frequency (spectral) as function of the frequency. The power spectral density, describes how the power (or variance) of a time series is distributed with frequency. Mathematically, it is defined as the Fourier Transform of the autocorrelation sequence of the time series. From these plots one can find the maximum energy (in SPL) contained by the noise signal and corresponding peak frequencies, which are responsible for generating maximum sound pressure, and also its location can be identified in the nozzle operating region.

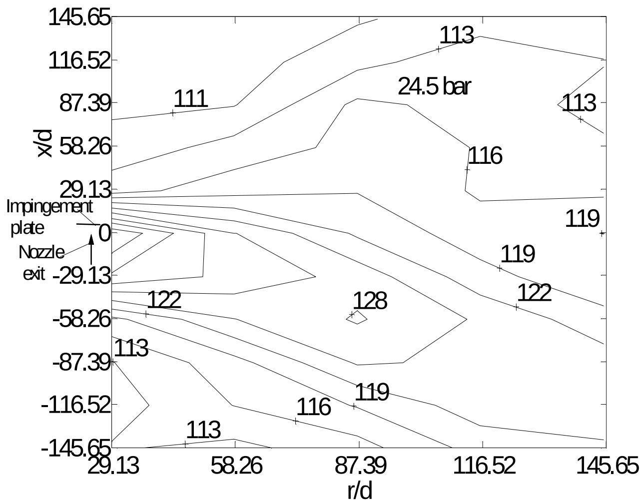

Fig 5(e)

In the present article the noise signal was analysed at all chamber stagnation pressures. With the information obtained, a systematic approach can be established to control the noise. In this work the analysis was used to find the magnitude of noise and the location of dominant noise sources. It is evident from these graphs that the maximum energy contained by the signal corresponds to very high frequency (above 10Khz) for all the chamber stagnation pressures. Hence the maximum noise sources (screech tones) are located near the impingement plate in the upstream side of the nozzle nearer to the nozzle exit. It is clear from FFT plots, the maximum frequency of a signal remains same both for upstream and downstream but magnitude of SPL is low downstream.

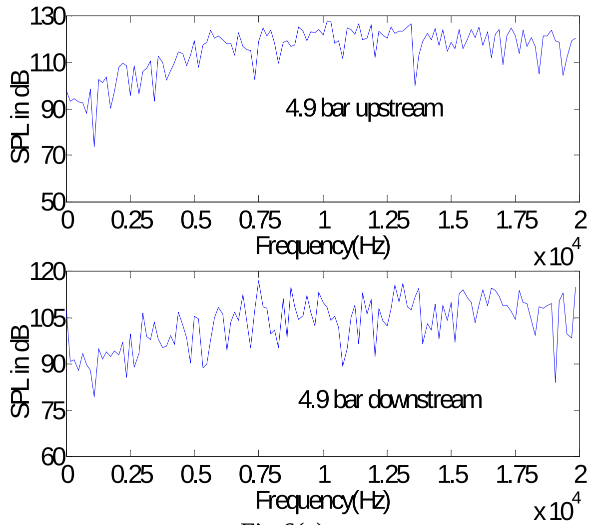

Fig 6(a)

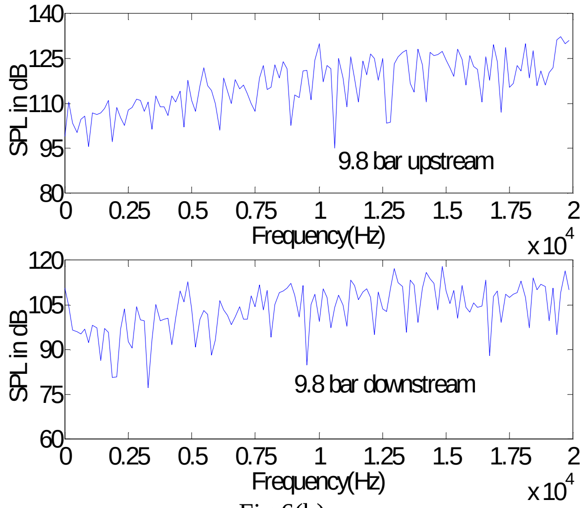

Fig 6(b)

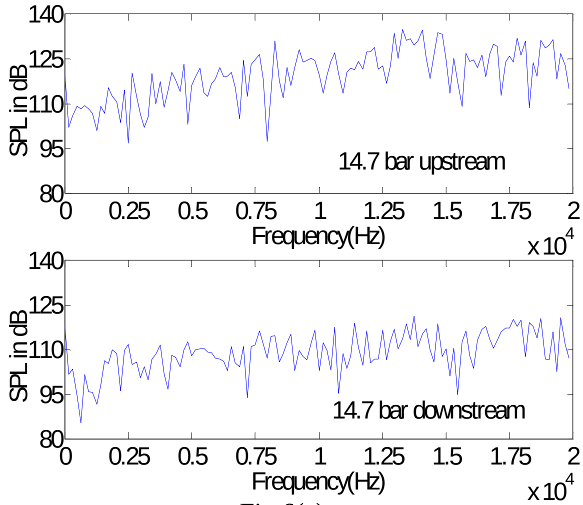

Fig 6(c)

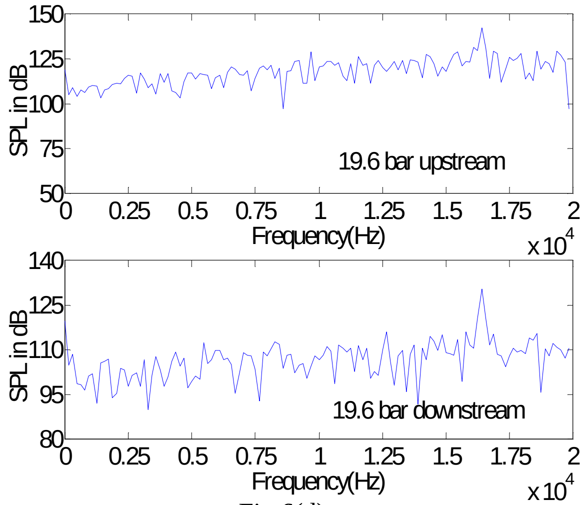

Fig 6(d)

5.CONCLUSIONS

The characteristics of the sound field of over expanded cold jet impingement have been studied experimentally in detail over an extensive envelope of jet operating conditions. It was observed from the graph that the maximum sound radiation occurs in the direction making an acute angle with jet axis (< 20^0 - 35^0). Maximum noise sources are located near the impingement plate in the upstream side of the nozzle nearer to the nozzle exit.

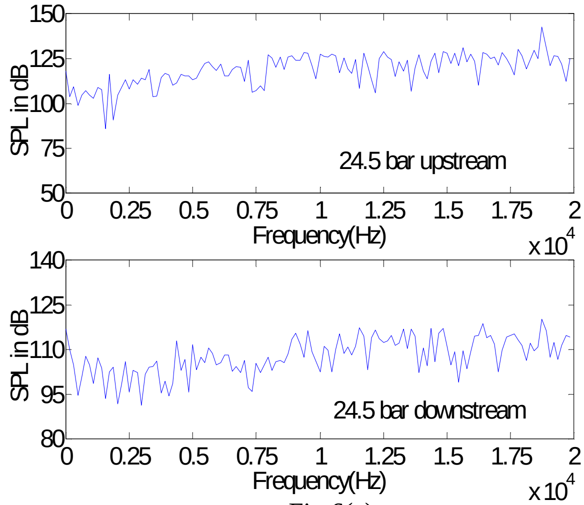

Fig 6(e)

Spectral and other analysis were done. The maximum SPL observed was about 139 dB and minimum of about 102 dB. Near field acoustic measurements indicate that the presence of the plate increases the SPL by approximately 4 to 8 dB relative to a corresponding free jet.

6. ACKNOWLEDGEMENT

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