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Design and CFD Analysis of Supersonic Nozzle

Kishore M[1], Dr. Velliangiri M[2], Kirubakaran A[3], Kamesh Adithya S B[4], Naveen Kumar G[5]
[1, 3, 4, 5]Undergraduate students, [2] Assistant professor, Department of Mechanical Engineering, Coimbatore Institute of Technology, Coimbatore – 641014, Tamil Nadu, India

Abstract: Nozzle comprises the most significant component while designing high speed aircrafts. The method of characteristics is used for designing of supersonic nozzle. A MatLAB program is generated so as to arrive at the parameters of nozzle with respect to the input conditions. The nozzle was analyzed to find out the properties such as velocity, pressure, temperature and density of air flowing through it. The aim of the paper is designing of supersonic nozzle that would provide the required thrust that is needed at supersonic conditions for the aircraft to travel through and to predict the thrust values.
Keywords: Method of characteristics, MatLAB, thrust

I. INTRODUCTION

In the present scenario of rocket science, there is a need and urge for the development of more number of supersonic aircrafts. Supersonic aircrafts can travel much faster and can switch direction in flight and do not follow a predictable arc like conventional missiles, making them much harder to track and intercept. Brahmos I is a supersonic cruise missile developed by India's Defense. Nozzles are the devices designed to control the direction or characteristics of a fluid flow as it enters an enclosed chamber or pipe. A Nozzle is often a pipe or tube of varying cross sectional area and it can be used to direct or modify the flow of a fluid. Nozzles are frequently used to control the rate of flow, speed, direction, mass, shape and the pressure of the stream that emerges from them. In a nozzle, the velocity of fluid increases at the expense of its pressure energy.

II. METHODOLOGY

The sequence of works carried out is depicted in the following flowchart which clearly indicates the methodology that is been followed.

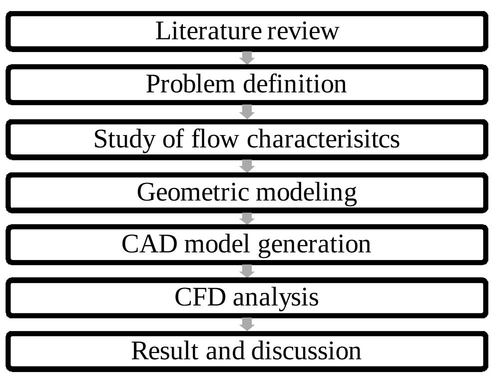

Fig. 1 Methodology

III.LITERATURE REVIEW

Zebbizhe et al. (2006) traced the profiles of the supersonic Plug Nozzle when this stagnation temperature is taken into account, lower than the threshold of dissociation of the molecules, by using the new formula of the Prandtl - Meyer function, and to have for each exit Mach number, several nozzles shapes by changing the value of this temperature. The authors concluded that the basic variable for our model is the temperature, and for the PG model is the Mach number. The design method and calculation in the nozzle is the same one between the two models except the equations of calculation changes in particular the Prandtl - Meyer function.

Al Ajlouni (2010) proposed that an advanced design method must be used when the conditions are critical and wave-free stream must be reached. The characteristic method is a general technique in which the design of a nozzle can be achieved. Unfortunately, this technique can be performed only through a lengthy graphical procedure. The characteristic method is a general technique in which the design of nozzles can be achieved. The design of the convergent part is less critical than the divergent part as it contains a subsonic flow. The author concluded that the characteristic method is the most appropriate method to be used with the design.

Khan et al. (2013) proposed a method based on the theory of characteristics for two dimensional, supersonic nozzle designs. Minimum length of the supersonic nozzle has been calculated for the optimum Mach number at the nozzle exit with uniform flow at the diverging section of the nozzle by developing a MATLAB program. Numerical solution is established for the two dimensional, steady, inviscid, irrotational and supersonic flow. The design considerations are concentrated at the diverging section. A characteristic is a curve along which the governing partial differential equations may be manipulated into ordinary differential equations. The authors concluded that the characteristic method is the most appropriate method to be used with the supersonic nozzle design.

Benson (2020) proposed that the Method of Characteristics (MOC) is a classic technique for designing supersonic nozzles. An interactive computer program using MOC has been developed to design and analyze supersonic nozzle flow fields. The program calculates the internal flow for many classic designs, such as a supersonic wind tunnel nozzle, an ideal 2D or axisymmetric nozzle, or a variety of plug nozzles. The author concluded that the program can also calculate non-ideal nozzles, such as simple cone flows, to determine flow divergence and non uniformities at the exit, and its effect on the plume shape.

Zhang et al. (2017) proposed an aero spike nozzle designed for 20 bar pressure ratio. In order to improve the performance of the aero spike nozzle for various conditions, optimization of the nozzle was carried out for some important design parameters and their performances were studied for cold flow conditions. An aero spike nozzle is often referred to as an altitude compensating nozzle, because of its specific design capability of maintaining aerodynamic efficiency as altitude increases and thus throughout the entire trajectory. The authors concluded that the expansion ratio for a full length spike at design altitude is equivalent to the chamber exit lip area divided by throat area.

IV. METHOD AND ASSUMPTIONS CONSIDERED

The sequence of works carried out is depicted in the following flowchart which clearly indicates the methodology that is been followed.

A. Methods for Nozzle Parameters calculation (Method of Characteristics)

First order partial differential equations in chemical engineering arise in models of processes that are dominated by convection rather than by dissipative processes. For example, consider a process that can be described by the 1-D convective diffusion equation with chemical reaction.

$$\frac{\partial c}{\partial t} + V\frac{\partial c}{\partial x} = D\frac{\partial^2 c}{\partial x^2} + f(c,k)$$

This process involves multiple time scales as follows:

1) Diffusive time scale : $\tau_D = L^2/D$
2) Convective time scale : $\tau_C = L/V$
3) Reaction time scale : $\tau_R = 1/k$
4) When diffusion and convection are important, the ratio of the respective time scales gives the Peclet number $Pe = V\,L/D$.
5) When reaction and diffusion are important, the corresponding dimensionless group is the Thiele modulus $\varphi^2 = kL^2/D$
6) When convection and reaction are important, the ratio of time scales gives the Damkler number $Da = Lk/D$.

Thus in the limit of large Peclet numbers with finite Damkler numbers, the system is described by a first order PDE, which when expressed in suitable dimensionless variables takes the form,

$$\frac{\partial c}{\partial t} + Pe\frac{\partial c}{\partial x} = f(c)$$

In particular, we use the above equation to motivate the basic solution method we will used, called the method of characteristics.

B. Assumptions Considered

The assumptions are explained clearly as follows,

1) *Flow:* The flow is considered as Isentropic - Reversible and Adiabatic process. This process means that there are no frictional losses and there is no heat loss through the walls. The flow is also considered to be Laminar.
2) *Nozzle type:* The shape of the nozzle is Divergent section alone. This means that the sonic flow is accelerated to the desired supersonic velocity.
3) *Chamber Pressure:* The chamber pressure decides the Mach number of the subsonic flow at the entry condition. The chamber pressure is assumed to be 1.671* e6 Pa.

4) *Chamber Temperature:* The chamber Temperature decides the sound velocity at the particular point. The Chamber Temperature is assumed to be 3500 K.
5) *Flow Medium:* The Medium of flow is Air.
6) *Specific Heat Ratio:* The Specific Heat Ratio is the ratio of the Specific Heat at constant pressure to the Specific Heat at constant Volume. It is assumed as 1.4.
7) *Area inlet of the Nozzle:* The Area Inlet of the Nozzle is assumed and calculated based on the inlet pressure of the system.

V. DESIGN METHODOLOGY

The design of supersonic nozzle has dealt with by following certain sequence of works which is depicted in the following flowchart.

Nozzle type is chosen
↓
Fixed the assumptions
↓
Analytical calculation of design parameters
↓
Implying Method of Characterisitics, MatLAB code is generated
↓
Computerised calculation of co-ordinates of the curve
↓
CAD model generation
↓
The orthographic and isometric views are generated
↓
2D surface is created for analysing
↓
Switching over to Analysis phase

Fig. 2 Design methodology

VI. GEOMETRICAL MODELLING

The nozzle profile chosen for designing and analysis in supersonic conditions is Minimum length nozzle. In order to expand an internal steady flow through a duct from subsonic to supersonic speed the duct has to be divergent in shape. If the nozzle contour is not proper, shock waves may occur inside the duct. The method of characteristics provides a technique for properly designing the contour of a supersonic nozzle. Rocket nozzles are short in since in cases where rapid expansions are desirable such as the non-equilibrium flow in modern gas dynamic lasers.

The geometric modelling of supersonic nozzle has been done as follows:

Take z = 6500 m; P_2 = 0.44 bar; M = 3; γ = 1.4; d_2 = 0.6 m, A_2 = 0.282 m^2

A. Pressure

$$\frac{P}{P_t} = \left[1 + \frac{\gamma - 1}{2} M^2\right]^{\frac{-\gamma}{\gamma - 1}}$$

Upon substituting, we get, P_t = 16.1 bar

B. Area

$$\frac{A}{A^*} = \left[\frac{\gamma + 1}{2}\right]^{\frac{-\gamma+1}{2(\gamma-1)}} . \frac{\left[1 + \frac{\gamma - 1}{2} M^2\right]^{\frac{\gamma+1}{2(\gamma-1)}}}{M}$$

Upon substituting, we get, A^* = 0.0665 m^2

Therefore, inlet diameter = 0.29 m

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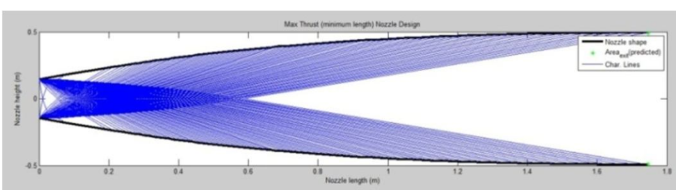
The input and output parameters are depicted in the table mentioned below.

TABLE I
Input and Output Parameters for Nozzle Profile Generation

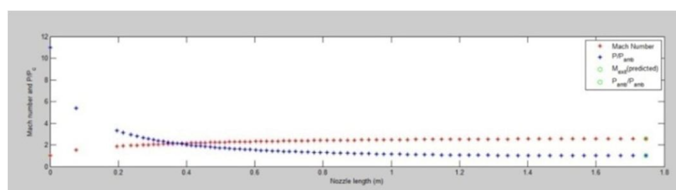
Geometrical modelling			
S. No	Inputs		Output Parameters
	Parameters	Values	
1.	Chamber Temperature	3000 K	Thrust
2.	Chamber Pressure	1600000 Pa	Exit velocity
3.	Specific Heat Ratio	1.4	Exit Mach number
4.	Ambient Pressure	101325 Pa	Exit Area
5.	Ambient Temperature	300 K	Throat Area
6.	Height of flight	0 to 10000 m	-
7.	Inlet Mach number	1	
8.	Diameter of Inlet	0.29 m	
Curve generation			
S. No	Inputs		Output Parameters
	Parameters	Values	
1.	Number of Characteristics Line	75	Contour of the Nozzle
2.	Maximum iterations	10000	Area mach Relation curve
3.	Plotter	1	Mach error curve
4.	Initial step	0.03	Area error curve

The geometrical modelling is done after certain conditions (like inlet diameter, inlet pressure of nozzle) are assumed. While designing the Convergent-Divergent nozzle, the length of the nozzle plays a vital role in decreasing the pressure of the flow in diverging section.

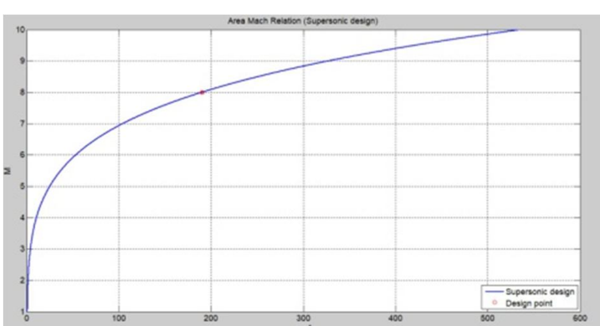
The length should be in the ratio for length to throat diameter (L/D) does not exceed 10 for the optimum nozzle. The MatLAB code finally generates the nozzle profile required and the co-ordinates are stored in the form of a table which is later imported into CAD model platform for further processes. The MOC results as follows.



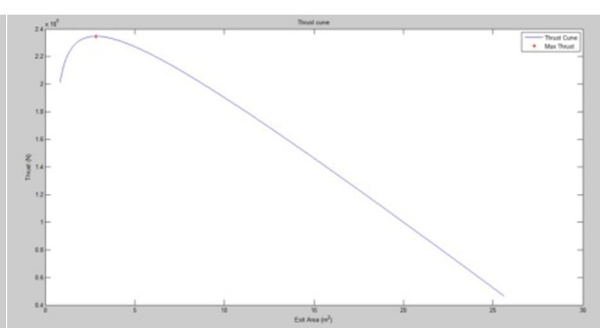
(A) Nozzle profile



(B) Length vs Mach



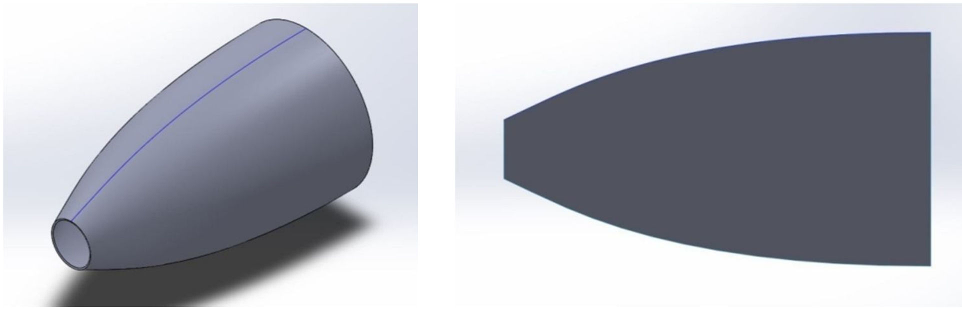
(C) Area Mach relation



(D) Area thrust graph

Fig. 3 Supersonic nozzle - MOC results

The nozzle profile that is to be imported is stored in .txt format. It is then imported into CAD platform and the 2D surface is generated for carrying out analysis.



(A) Isometric view of nozzle (B) Surface of nozzle for analysis

Fig. 4 Supersonic nozzle - Isometric view and 2D surface

VII. GRID GENERATION

After importing the CAD model, meshing or grid generation is carried out. The type of mesh is triangular mesh. After face meshing and body sizing at the mesh part coordinate name was selected along the boundary named: Inlet, outlet and walls. The number of elements and nodes formed for nozzle are 18527 elements and 18794 nodes respectively.

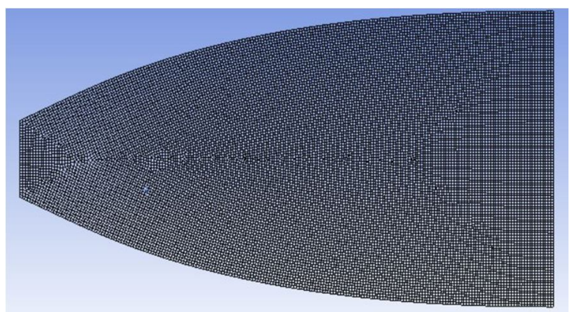


Fig. 5 Mesh pattern

VIII. PRE PROCESSING

The pre processing procedure of supersonic nozzle is depicted in the following flowchart.

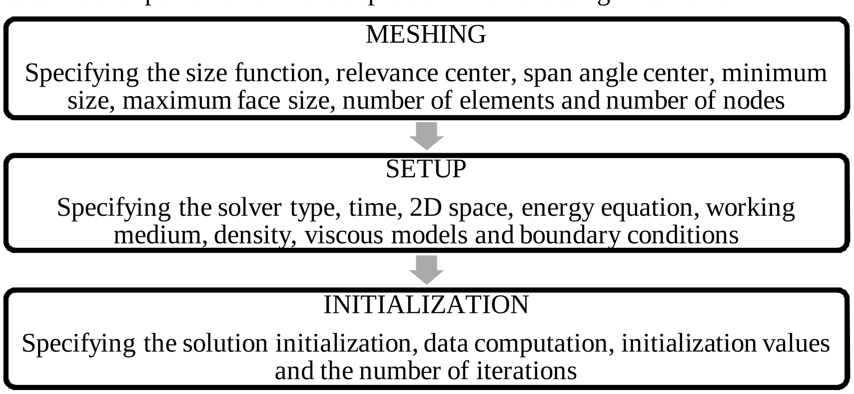


Fig. 6 Pre processing procedure

At the setup portion Solver type was selected as density based, time was steady and 2D space was selected as Planar. Then in model section energy equation was on and laminar viscous model was chosen. Air is taken as a working medium and density was selected as an ideal gas. At boundary condition section, pressure far - field (inlet) is chosen. The initial gauge pressure at the inlet was given as 1600000 Pa; the total temperature at the inlet was given as 3000 K; the Mach number at inlet is given as 1. The pressure outlet is chosen; the gauge pressure at the outlet was given as 0 Pa, the backflow total temperature was given as 300 K.

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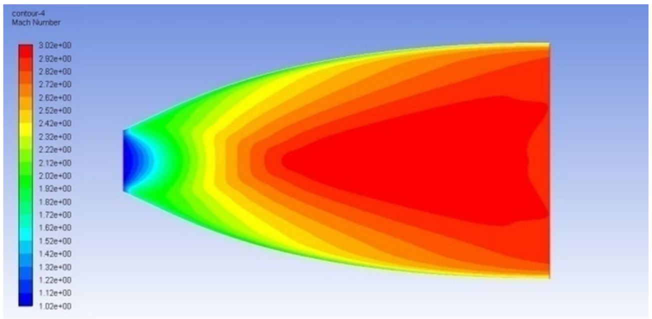
Fluent defines the total pressure as gauge pressure with respect to operating pressure. It also defines the total temperature as a gauge temperature with respect to operating temperature. Standard initialization was selected as solution initialization and the data was computed from the pressure inlet. The gauge pressure was given as 1600000 Pa; the temperature was given as 3000 K. The velocity in x - direction was given as 343 m/s. The velocities in y - direction was given as 0 m/s. The calculation is carried out for 1000 iterations for nozzle. The analysis setup and initialization values of nozzle are mentioned in the form of table mentioned below.

TABLE III
Analysis Setup and Initialization Values of Supersonic Nozzle

S. No	**MESHING**	
1.	Size function	Curvature
2.	Relevance center	Fine
3.	Span angle center	Fine
4.	Minimum size	1 millimetre
5.	Maximum face size	Default
6.	Number of elements	18527
7.	Number of nodes	18794
S. No	**SETUP**	
1.	Solver type	Density based
2.	Time	Steady
3.	2D space	Planar
4.	Energy equation	On
5.	Working medium	Air
6.	Density	As that of ideal gas
7.	Viscous models	Laminar
8.	Boundary conditions	Inlet conditions: ✓ Pressure far - field inlet is chosen ✓ Inlet gauge pressure: 1600000 Pa ✓ Inlet total temperature: 3000 K ✓ Mach number: 1 (343 m/s) Outlet conditions: ✓ Pressure outlet is chosen ✓ Outlet gauge pressure: 0 Pa ✓ Backflow total temperature: 300 K
S. No	**INITIALIZATION**	
1.	Solution initialization	Standard initialization
2.	Data computation	From Pressure far-field inlet
3.	Initialization values	✓ Gauge pressure: 1600000 Pa ✓ Gauge temperature: 3000 K ✓ Velocity (x - direction): Mach 1 ✓ Velocity (y - direction): 0 m/s
4.	Number of iterations	1000 iterations

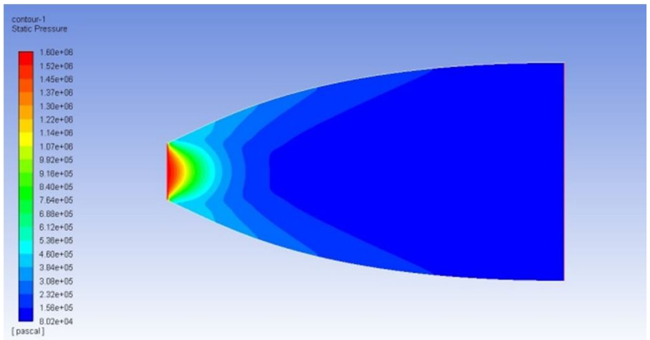
IX. RESULTS AND DISCUSSIONS

The results are extracted from CFD POST after the analysis from fluent flow solver. The Mach number, pressure, temperature and density contours of nozzle with respect to varying Mach regimes are displayed below.



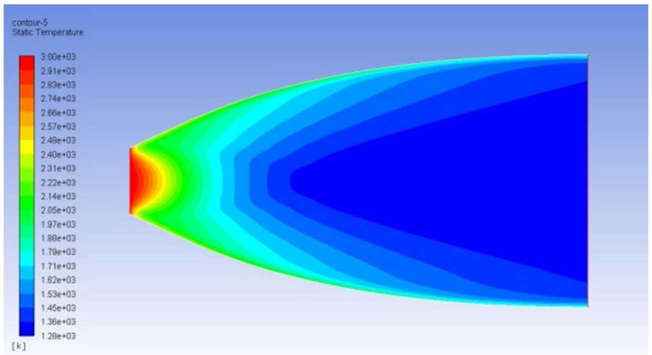
(A) Mach number Contour

By the results of the Mach number contour, in supersonic region it is observed that the Mach number at inlet is given as 1 and as it passes through the nozzle, the Mach number increases. The velocity increases as it passes through the nozzle and hence it is larger at the exit than the inlet. The outlet Mach number achieved is 3.02.



(B) Pressure Contour

By the results of the pressure contour, in supersonic region it is observed that the pressure decrease as it passes through the nozzle and hence it is larger at the inlet than the outlet. The outlet pressure is 95178.1 Pa. The pressure concentration is maximum at the inlet of the nozzle and it gradually decreases.



(C) Temperature Contour

By the results of the temperature contour, in supersonic region it is observed that the temperature decrease as it passes through the nozzle and hence it is larger at the inlet than the outlet. The outlet temperature is 1341.2 K. The temperature concentration is maximum at the inlet of the nozzle and it gradually decreases.

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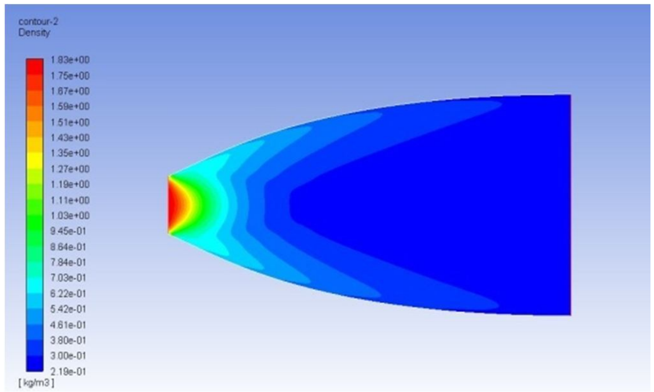

(D) Density Contour

Fig.7 Contours of Supersonic Nozzle

By the results of the contour, in supersonic region it is observed that the density at the inlet is higher as compared to that of the exit. This is in accordance with the analytical calculations made. The outlet density achieved is 0.247121 kg/m^3. The density concentration is maximum at the inlet of the nozzle and it gradually decreases.

X. CONCLUSIONS

The paper's ultimate aim is designing of supersonic nozzle with efficient flow characteristics. Based upon the results obtained as a result of the project work, it is found that Method of Characteristics can be implemented for designing of supersonic nozzles with respect to the assumptions made. It is also found that the Mach number, temperature, pressure, density variation are in accordance with the usual flow characteristics and analytically calculated results.

XI.NOMENCLATURE

TABLE IIIII
Symbols, Abbreviations and Nomenclature

SYMBOLS, ABBREVIATIONS AND NOMENCLATURE	CONTENT
ρ	Density (kg/m^3)
A	Area (m^2)
u, v	Velocity (m/s)
CFD	Computational Fluid Dynamics
3D	Three Dimension
2D	Two Dimension
γ	Specific heat ratio
CAD	Computer Aided Design
MOC	Method of Characteristics
M	Mach Number
P	Pressure (bar)
T	Temperature (K)
τ_D	Diffusive time scale (m)
τ_C	Convective time scale (m^{-1})
τ_R	Reaction time scale (m)

XII. ACKNOWLEDGMENT

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