A PRELIMINARY STUDY OF SCRAM JET ENGINE USING STREAM THRUST ANALYSIS AND FIRST LAW AT DIFFERENT ALTITUDES

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Abstract

The SCRAM jet engine is a modification of the RAM jet engine and is capable of flying at speeds above Mach 5. In a SCRAM jet engine, the combustion takes place while the air is supersonic in nature. The purpose of the present work is to understand and model the components of a SCRAM jet engine and analyze them by the use of Thermodynamics. The First law of thermodynamics and Stream Thrust Analysis was used to determine pressure, temperature and thrust at different stations of the engine. Specific Thrust, Specific Impulse and Efficiencies were studied using both methods at altitudes 0(sea level), 15km and 25km. The assumptions, where necessary, were stated and followed. Independent parameters like cycle static temperature ratio and stream thrust were defined and studied. It was shown that the specific thrust and specific impulse increased with increase in altitude while the efficiencies decreased with altitude. A complex excel code was used to model the mathematics of the process.

Keywords: SCRAM Jet, Stream Thrust, Specific Impulse, Specific Thrust, Static Cyclic Temperature.

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1. INTRODUCTION

A SCRAM Jet engine is an evolution of a RAM jet engine which uses the 'ram' effect to accelerate at high speeds. The combustion in a RAM jet engine happens after the intake air is decelerated to sub-sonic speeds with the use of a normal shock wave, while a SCRAM jet engine employs the use of an oblique shock and the intake air is kept supersonic while entering the combustion chamber.

Ramjet engines are primarily used in supersonic flight at Mach speed of 3-6. SCRAM jet engines can go faster than Mach 5 due to supersonic combustion. Neither SCRAM jet or Ramjet engines need to be axisymmetric due to the absence of rotating parts[7][10].

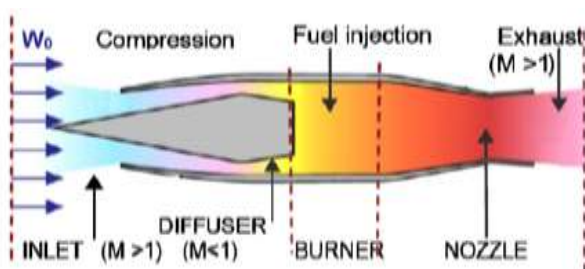### 1.1 Schematics of a SCRAM Jet Engine

Figure 1: RAM Jet configuration [8]

The Ram jet engine can go up to Mach 6. It makes use of the 'ram' effect (compressed air) to achieve this speed. At such speeds, combustion becomes a problem. A normal shock at the end of the diffuser slows the air to below sonic speed for combustion. At speeds lower than Mach 6, this would be fine but as the speed increases, the dissociation effect increases in the combustion chamber decreasing the efficiency of combustion. In order to reduce dissociation, a SCRAM jet configuration (Supersonic Combustion RAM

Jet) is employed, here the air entering the combustion chamber is supersonic, slowed by an oblique shock at the end of the diffuser.
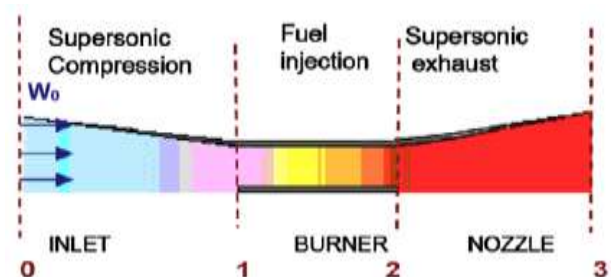

Figure-2: SCRAM Jet configuration [8]

The usual configuration of a jet engine consists of a diffuser to compressor the air, a combustion chamber to add and burn fuel and a nozzle to expand the air. This holds true for a SCRAM jet engine.

Nomenclature

P_i	Pressure at reference station 'i'(mPa)
T_i	Temperature at reference station 'i' (K)
V_i	Velocity at reference station 'i' (m/s)
F	Thrust(N)
m_0	Inlet mass flow rate(kg/s)
m_f	Fuel flow rate(kg/s)
g_0	Acceleration due to gravity(m/s^2)
I_{sp}	Specific Impulse(s)
h_{pr}	Heating value of fuel(kJ/kg)
T_{sp}	Specific Thrust(m/s)

η_0	Overall efficiency
η_p	Propulsive efficiency
η_i	Efficiency of the 'i' component
M_i	Mach number at 'i' station
ψ	Cycle static temperature ratio
s_i	Entropy at 'i' station
C_P	Heat Capacity(kJ/K)
R	Gas constant(kJ/kgK)
f	Stoichiometric fuel/air ratio
S_a	Stream Thrust Function

2. Component Modelling of SCRAM Jet
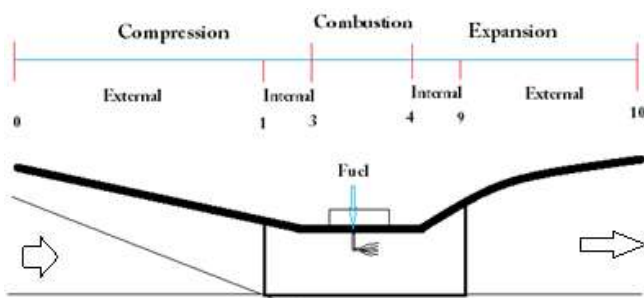
Figure 3: SCRAM Jet Engine Components

Table-1: Components of SCRAM Jet engine

Reference station	Engine Location
0	Free stream Conditions External compression begins
1	External compression ends Internal compression begins Inlet or diffuser entry
3	Inlet or diffuser exit Internal compression ends Burner or combustor exit
4	Burner or combustor exit Internal expansion begins Nozzle entry
9	Internal expansion ends Nozzle exit External expansion begins
10	External expansion ends

The numbers mentioned in table 2 are standard for a SCRAM jet engine and have been widely used. The missing numbers in between account to additional components such as injectors, mixers etc when in use [7].
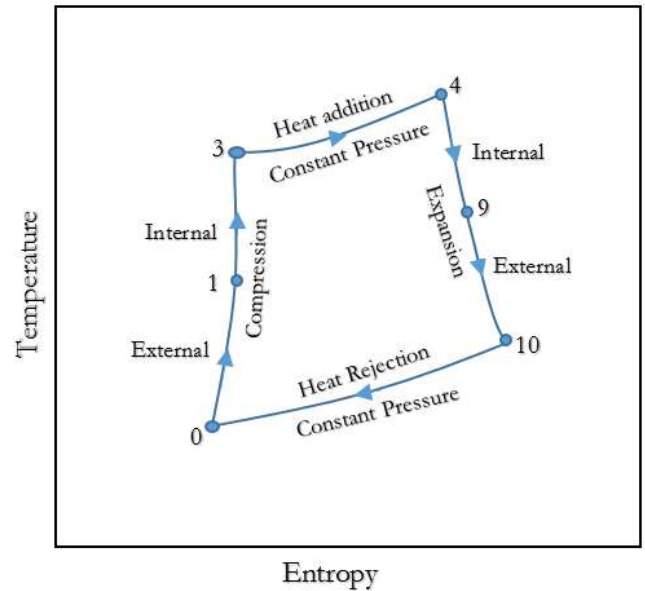
2.1 Ideal Brayton Cycle

Figure-4: Ideal Brayton Cycle[7]

Figure.4 shows an ideal Brayton cycle. The engine is treated as a cycle and all its parameters are studied under its assumptions.

Point 0-3 represents the compression in the engine. In this work, cyclic static temperature which is the ratio of the burner entry static temperature to the freestream temperature was prioritized. The compression was taken to be adiabatic and isentropic.

Point 3-4 represents the process of heat addition. This process involved adding heat without the addition of mass and heat addition at constant pressure was studied.

Point 4-10 represents the process of expansion. This process was also considered as adiabatic and isentropic.

Point 10-0 represents the process of heat rejection. This fictional process was taken into account to maintain the equilibrium of the process. [1][5][7][8][9].

2.2 Assumptions

The calculations within this work were done with some assumptions, they are stated below.
(a) The working fluid was a pure substance and it was always in an equilibrium state.[7][8]
(b) The working fluid returns to its original state after the process.(Heat rejection process)[7]
(c) The whole system was treated as a control volume without any interactions with the surfaces. The system was treated as one-dimensional problem.[8]
(d) Combustion takes place only at constant pressure and dissociation effects were neglected.[8]

2.3 General Methodology

The present work consists of thermodynamically analyzing a SCRAM jet engine by using the mathematical formulation of the First law of thermodynamics [7] and a concept of thrust-work potential called Stream Thrust [3].

The engine can simply be taken as an ideal Brayton cycle and performance parameters such as overall efficiency and propulsive efficiency along with other variables were studied [9]. The whole system was divided into individual components or sub-systems to analyze and optimize piecewise performance. More advanced methods such as treating the whole vehicle in terms of explicit second-law characteristics, considering the whole system as a stream tube have been studied [1]. The performance of the system in terms of thrust and propulsive losses in terms of entropy have also been studied [2].

In this work, only the First Law and Stream Thrust analysis was done using codes similar to those presented in [7] for different altitudes.

Table-2: Altitude Parameters

Altitude (m)	Temperature (K)	Pressure (mPa)	Density (kg/m^3)
0(Sea Level)	288	101.3	1.225
15000	216.55	12.11	0.195
25000	222	2.55	0.04

A complex and rigorous Excel code was developed based on the formulation and ideas presented in [7] [9].

3. Analysis

Some of the definitions that are employed in understanding the performance of a SCRAM jet engine are stated [7][8],

Specific Thrust - It is the ratio between uninstalled thrust and the entry mass flow rate

$$.T_{sp} = F/m_0 \qquad (1)$$

Specific Impulse - Ratio of uninstalled thrust and fuel weight flow.

$$I_{sp} = F/g m_f \qquad (2)$$

Overall Efficiency -Ratio of thrust power to chemical energy release rate of fuel.

$$\eta_0 = FV_0/m_f h_{pr} \qquad (3)$$

Propulsive Efficiency - Ratio of the thrust power to the engine mechanical power.

$$\eta_p = 2/((V_{10}/V_0) + 1) \qquad (4)$$

3.1 First Law

The first law of thermodynamics was used to determine the values of parameters at different stations of the engine. The parameters that were in the study are temperature, pressure and entropy. The mathematical formulation of these relations is clearly presented in [7]. An independent variable called the *cyclic static temperature* represents the maximum allowable compression temperature.

$$\psi = \frac{T_3}{T_0} \geq 1 \qquad (5)$$

The value for this limiting temperature was taken as 1580 K [7]. Another parameter that is co-dependent on the cyclic static temperature is the *burner entry Mach number* and its relation is as follows

$$M_3 = \sqrt{\frac{2}{\gamma_c-1}\{\frac{T_0}{T_3}\left(1 + \frac{\gamma_c-1}{2}M_0{}^2\right) - 1\}} \qquad (6)$$

These relations were set because of practical limitations [7].

Table-3: Input for Altitude 25 km (First Law)

Input for Altitude 25 km		
M_0	6	
Gamma	1.4	
Speed of Sound	298.663	m/s
V_0	1791.978	m/s
T_0	222	K
T_3	1580	K
ψ	7.117117	
$n_b.fh_{Pr}/Cp_0.T_0$	16.78487	
n_c	0.9	
n_b	0.9	
$\dot{m}_0$	300	kg/s
n_e	0.9	
C_{p0}	1000	J/kg K
C_{pc}	1090	J/kg K
C_{pb}	1510	J/kg K
$C_{pc}.R_e/R_c.C_{pe}$	0.722	
C_{pe}	1510	J/kg K
$R_c(air)$	287	J/kg K
$R_e(air)$	287	J/kg K
fh_{Pr}	4140268	J/kg
$R_0(air)$	287	J/kg K

3.2 Stream Thrust

The first law cannot account for the mass, energy fluxes within the engine, this was accounted (with assumptions) by using momentum relations and the parameter *stream thrust function* [7].The assumptions are as stated before.

In its mathematical approach, the analysis averages the values of parameters such as static pressure etc. Such a case is the pressure at station 10, where the static pressure should match free stream pressure which would otherwise result in the flow being *under-expanded* or *over-expanded*.

The stream thrust function was defined as

$$Sa_0 = V_0 \left(1 + \frac{RT_0}{V_0{}^2}\right) \qquad (7)$$

In this case, the specific thrust was defined as

$$\frac{F}{\dot{m}_0} = (1 + f)Sa_{10} - Sa_0 - \frac{R_0 T_0}{V_0}\left(\frac{A_{10}}{A_0} - 1\right) \qquad (8)$$

Table-4: Input for Altitude of 25 km (Stream Thrust)

Input for Altitude 25 km		
M	6	
ψ	7.117	
V_0	1799.144	m/s
n_c	0.9	
n_b	0.9	
n_e	0.9	
fh_{Pr}	4140268	J/kg
T_0	222	K
R	289.3	J/kg K
C_{pc}	1090	J/kg K
C_{pb}	1510	J/kg K
C_{pe}	1510	J/kg K
γ_C	1.362	
γ_B	1.238	
γ_E	1.238	
P_{10}/P_0	1	
f	0.0291	
hf	0	
V_{fx}/V_3	0	
V_f/V_3	0	
$C_f A_w/A_3$	0	
T^0	222	K

4. RESULTS AND DISCUSSIONS

The study of parameters such as propulsive efficiency, Specific Impulse and Specific Thrust are given in the graphs.
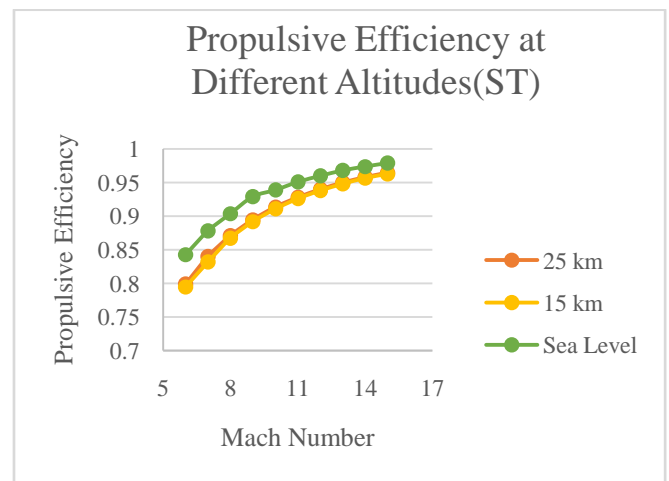
4.1 Propulsive Efficiency

The First Law shows the efficiency to be the same for altitudes 15km and 25km while sea level efficiency is high (this is due to the availability of oxygen in the air for combustion) in graph-1
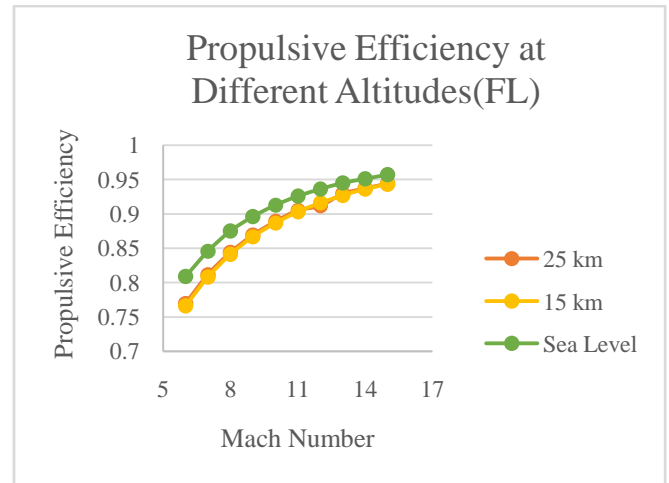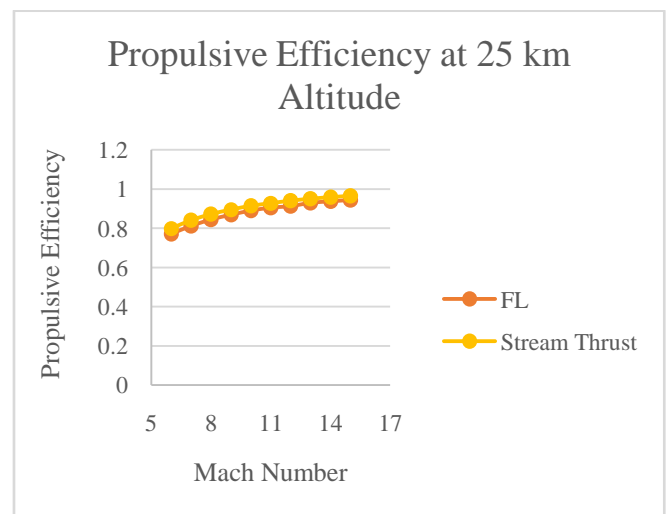

Graph-1: Propulsive Efficiency at Different Altitudes(FL)

A similar trend is seen in the graph-2 for Stream Thrust analysis. It is also seen that the propulsive efficiencies are similar for both the first law and stream thrust analysis. With the study of efficiencies, it can be said that under certain assumptions, First Law and Stream Thrust analysis provide similar results, validating the procedure.Graph-3.


Graph-2: Propulsive Efficiency at Different Altitudes (ST)

Graph-3: Comparison of First Law and Stream Thrust
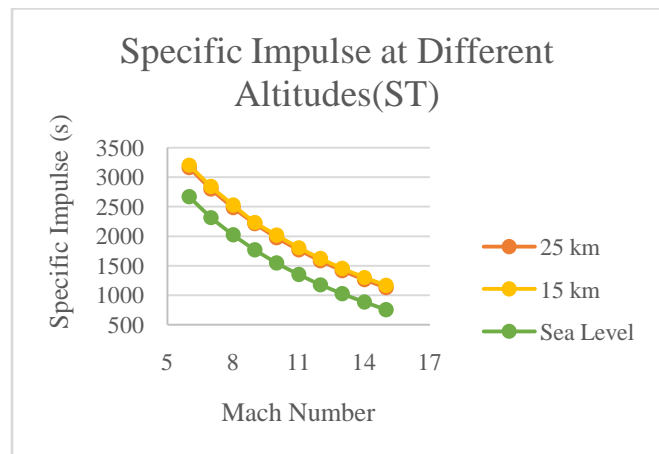
4.2 Specific Impulse

Although specific impulse is used to study the propulsion of rockets, it is used to here due to high speeds and the power of the engine. Graph-4 shows the specific impulse of the engine calculated using the First Law. It is seen the specific impulse is lower at sea level as opposed to propulsive efficiency. This is due to the difference in intake temperature T_0 and engine temperature at various stations. The specific impulse is similar for altitudes 15km and 25km.
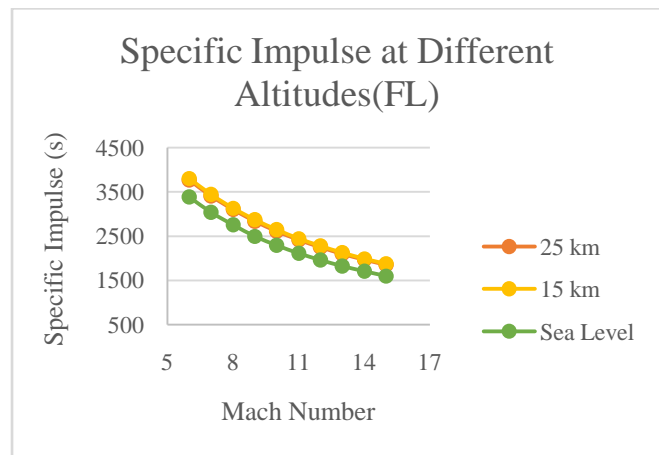
Graph-4: Specific Impulse at Different Altitudes(FL)

A similar trend is seen for specific impulse obtained through Stream Thrust Analysis show in graph-5.
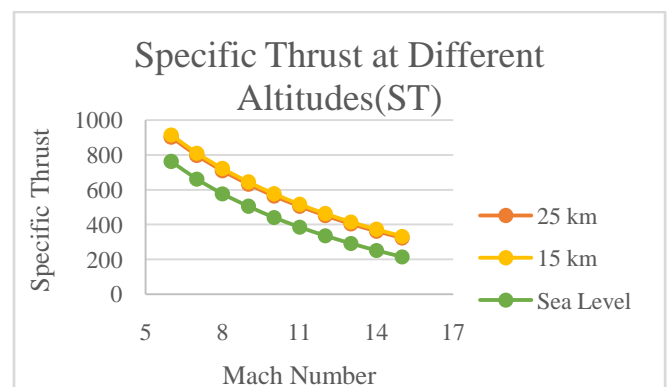

Graph-5: Specific Impulse at Different Altitudes (ST)

4.3 Specific Thrust

Graph-6 shows the specific thrust analyzed by the First Law at different altitudes. A trend similar to specific impulse is seen in the graph. The specific thrust is lesser in case of sea level while higher for 15km and 25km. This is due to large differences in parameters pertaining to intake and component sections. The difference is high at higher altitudes.It can be said that drag is less at higher altitudes and the thrust depends upon drag. Graph-7 shows the specific thrust for Stream Thrust Analysis. The findings are similar to First Law.
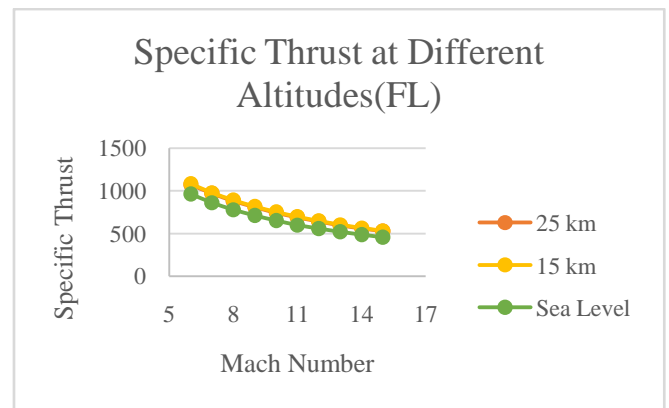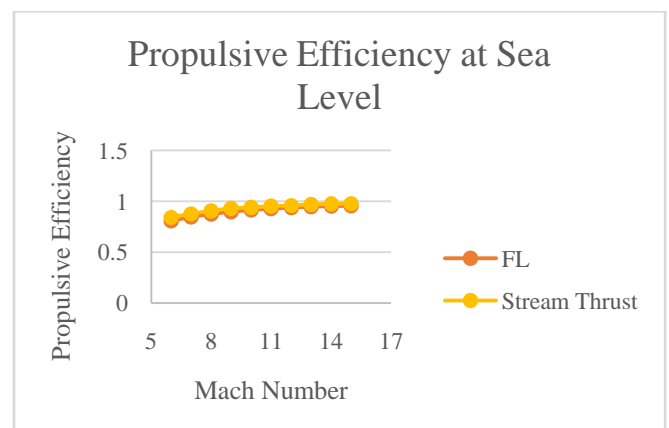

Graph-6: Specific Thrust at Different Altitudes(FL)

Graph-7: Specific Thrust at Different Altitudes(ST)
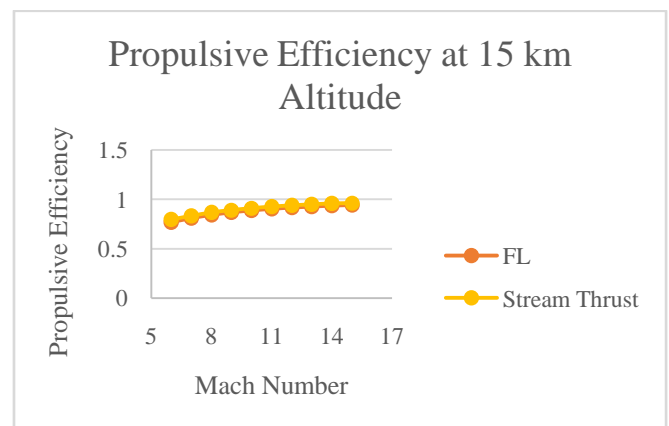
Graph-8: Propulsive Efficiency at 15 km Altitude

Graph-9: Propulsive Efficiency at Sea Level

5. CONCLUSIONS

This work shows the study of SCRAM Jet engines by using the First Law of thermodynamics and Stream Thrust Analysis. It is seen that at altitudes higher that 15km, specific thrust and specific impulse are high while the opposite is true in case of propulsive efficiency. Although only propulsive efficiency was compared here, other parameters can be compared to validate both methods. But this would require an in-depth understanding of many variables that influence the process. The assumptions also play an important role. This presentation provides only a preliminary analysis, but can be developed into greater detail in future works.

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BIOGRAPHIES

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