NO_x reduction strategies for high speed hydrogen fuelled vehicles

Antonella Ingenito [a,*], *Antonio Agresta* [a], *Roberto Andriani* [b], *Fausto Gamma* [a]

[a] *Department of Mechanical and Aerospace Engineering, University of Rome "La Sapienza", Rome, Italy*
[b] *Department of Energy, Polytechnic University of Milan, Italy*

A B S T R A C T

The growing need to drastically reduce aircrafts CO_2 emissions has led engineers and scientists in the last years to develop a clean, renewable and sustainable energy system Hydrogen as a green fuel in aviation is a good choice since does not emit any particulate, CO and CO_2.

However, its high combustion temperature is disadvantageous in terms of NO_x pro-duction. Further, the higher altitudes associated with hyper/supersonic flight make the emission of NO_x critical for the ozone layer. In fact, at current subsonic flight altitudes in the troposphere and lower stratosphere, NO_x emissions are associated with ozone pro-duction whereas, at altitude of 20,000–30,000 m, which corresponds closely to the maximum ozone density, NO_x can catalyze ozone destruction. Reduction of the NO_x Emission Index (grams of emission produced per kilogram of fuel consumed) remains therefore a primary concern. This paper has the goal to investigate possible strategies to reduce NO_x emissions from H2 combustion. Since these increase when burning fuel near stoichiometric air-to-fuel ratios, a strategy simulated in this study to reduce NO_x produc-tion consists in operating at lean or very lean equivalence ratios (thanks to the wider flammability limits of the hydrogen-air flames compared to kerosene-air flames), or in reducing the combustor length (thanks to the higher flame speed of hydrogen compared to other fuels. In this paper, the RQL (Rich-Quench-Lean) strategy for the NO_x abatement is proposed for a high speed hydrogen fuelled vehicle. This strategy has shown that the equivalence ratio in the rich strategy is a key parameter to reduce the nitrogen oxide emissions to ICAO acceptable values.

Introduction

The next generation of aircrafts might include long-distance high speed flights. In this context, the European LAPCAT II project had the goal to develop a commercial vehicle able to fly from Brussels to Sydney (~20,000 km) in less than 4–5 h [1]. Achieving this goal intrinsically required the investigation of hypersonic flight regime, a novel engine concept, and a high energy content fuel, such as liquid hydrogen [2]. Reaction Engines Ltd conceived SCIMITAR precooled engine [3–5], capable of sustained Mach 5 flight for the A2 LAPCAT vehicle (see Fig. 1) is such a novel engine. It has been derived from the Reaction Engines SABRE engine designed to power the SKY-LON SSTO spaceplane.

Liquid hydrogen is used for two main reasons. Firstly, it has a large calorific power value (120 MJ/kg) which reflects the LAPCAT project mission requirements. Secondly, although liquid hydrogen is a hard cryogen (having a low density of 68 kg/m^3 at a boiling point of only 21 K), it has a very high thermal capacity, almost 3.5 times that of water. If stored at low enough temperatures to maintain its state, it is used up to Mach 5 to precool the air entering the compressor, while maintaining an equivalence ratio close to that for

* *Corresponding author*. Tel.: +39 3346068243.
E-mail address: antonella.ingenito@uniroma1.it (A. Ingenito).

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Nomenclature

Acronyms

ICAO	International Civil Aviation Organization
RQL	rich quench lean
HSCT	high-speed civil transport
SST	supersonic transport
EPA	Environmental Protection Agency

Roman Symbols

A	Arrhenius constant
D	chamber diameter, [m]
G	standard-state Gibbs free energy, [kJ/mol]
P	pressure, [atm]
S	airflow split
T	temperature, [K]
V	velocity, [m/s]
E.R.	equivalence ratio
E.I.	emission index
T/O	take off
C/O	climb out
J	momentum flux ratio of the quench jets to the crossflow
WAQ	air entering the mixing region
FMR	air entering the rich reactor
υ	actual volumetric flow rate of the mainstream, [m^3/s]
n	number of orifices, [m]
d	secondary air orifice diameter, [m]
k	equilibrium constant
m, n	stoichiometric coefficients

Greek Symbols

Φ	fuel air ratio
ρ	density, [$kg\ m^{-3}$]
X	molar concentrations
Δ	change

Superscripts and subscripts

0	standard conditions
i	condition of i-th species
p	pressure

Fig. 1 – LAPCAT A2 vehicle with 4 SCIMITAR engines wing-mounted.

optimum performance. The critical issue concerning the hydrogen choice is the NO_x emission index (EI) [6,7]. The emission index of NO_x is of much concern regarding its effects on the ozone layer. The EI is defined as the grams of total NO_x emitted per kilogram of fuel burned. The conventional SCIMITAR engine produced an NO_x EI of 315 g/kg fuel, i.e., much higher than the ICAO EI constraint (40 g/kg fuel). By investigating the effect of temperature, pressure, equivalence ratio and residence time on the nitrogen oxide emissions, the rich-quench-lean approach has been proposed as a possible strategy for the conventional SCIMITAR engine NO_x abatement [8,9]. In order to suggest the most promising R.Q.L. key factors, i.e., the airflow split between the rich and the lean regions, a parametric analysis of the NO_x EI as a function of the rich stage equivalence ratio has been performed. This analysis has shown that, keeping the SCIMITAR overall E.R. < 0.8, it is possible to decrease the NO_x EI below the ICAO constraints.

Pollutants impact on environment and human health

Due to the growth of the aviation transport in the last decades, it is essential to consider the environmental impact of aviation to ensure in advance that such a rate of development is sustainable. The risk of climate change linked to the effects of greenhouse gases is a major concern: altered properties of the atmosphere affecting local areas include reduced visibility, resulting from the presence of carbon-based particulate matter, sulphates, nitrates, organic compounds, and nitrogen dioxide; increased fog formation and precipitation, reduced solar radiation, and altered temperature and wind distributions [10].

On a larger scale, greenhouse gases may alter global climates. Also, acid rain, produced from NO_x emissions (nitric oxide (NO) and nitrogen dioxide (NO_2) are the major constituents of NO_x) affects lakes and susceptible soils.

The catalytic destruction of stratospheric ozone by NO was also investigated [11,12]. In fact, the reaction mechanism shows that NO catalyzes the destruction of ozone molecules in the stratosphere [13]:

$NO + O_3 \rightarrow NO_2 + O_2$

$NO_2 + O \rightarrow NO + O_2$

Net reaction:

$O + O_3 \rightarrow 2O_2$

Removal of O_3 from the stratosphere allows harmful ultraviolet solar radiation to penetrate to the Earth's surface.

That's why, the European Union and the U.S. Environmental Protection Agency (EPA) are applying pressure on the International Civil Aviation Organization. ICAO promotes the safe and orderly development of international civil aviation throughout the world. It sets standards and regulations necessary for aviation safety, security, efficiency and regularity, as well as for aviation environmental protection and regulates aircraft emissions, in particular additional nitrogen oxide reductions [7].

In Table 1 [3], emissions from various aircraft are summarized. The Concorde values were measured in flight. The supersonic transport (SST) column represents estimates to atmospheric chemistry models and reflects the relative lack of sophistication of models at the time [14]. The High-Speed Civil Transport (HSCT) column refers to work in the United States in the 1990s and illustrates advances in emissions characterization and chemical modeling at that time [10,15]. The SCIMITAR engine emissions were obtained from finite rate chemical kinetics calculations.

Compared with other high speed vehicles, SCIMITAR-powered aircraft would have no SO_x, soot, CO or CO_2; however its NO_x emissions are excessive.

NO_x mechanism

Nitric oxide is an important minor species in HC combustion because of its contribution to air pollution. A comprehensive review of the NO_x reaction process is provided by Ref. [16].

Table 1 – Emissions from selected high speed aircraft (EI in units of grams emission per kilogram of fuel burned)[3].

	Concorde	SST	HSCT	SCIMITAR
Mach number	2	2.4	2.4	5
Cruise altitude (km)	18.3	20	20	24–28
EI CO_2	3155	*	3155	0
EI CO	3.5	*	2.9	0
EI H_2O	1237	1250	1237	8810
EI NO_x	18	40	3–15	315
EI hydrocarbons	0.2	*	0.3	0
EI soot	0.03	*	0–0.02	0

*Not considered.

Nitric oxide is formed by chemical mechanisms that involve nitrogen from the air, such as: the thermal or Zel'dovich mechanism [17,18], the Fennimore or prompt mechanism [19] and the fuel mechanism [20]. The thermal mechanism dominates in high-temperature combustion over a fairly wide range of equivalence ratios, while the prompt mechanism is particularly important in rich hydrocarbons combustion. It appears that the fuel mechanism plays an important role in the production of NO in very lean, low-temperature combustion processes.

In the SCIMITAR engine, the Zel'dovich mechanism is the most important mechanism for NO_x formation, due to the high flame temperature when burning hydrogen. This mechanism consists of the two chain reactions:

$O + N_2 \leftrightarrow NO + N$

$N + O_2 \leftrightarrow NO + O$

The extended Zel'dovich mechanism includes the additional reaction:

$N + OH \leftrightarrow NO + H$

which becomes important in fuel-rich mixtures when O and O_2 concentrations are low.

In the extended Zel'dovich mechanism, the first reaction is the rate-limiting step. In this step, high activation energy is required to break the triple bond in the N_2 molecule. The rate of formation of NO via the Zel'dovich mechanism can be obtained using chemical kinetics, combined with steady state assumptions for the N-atom concentration and partial equilibrium assumption for the O-atom concentration [17,18]:

$$\frac{d[NO]}{dt} = \frac{A}{\sqrt{T}}[N_2][O_2]^{\frac{1}{2}} \exp\left[\frac{-38370}{T}\right]$$

The rate shows an exponential dependence on the combustion gas temperature and O_2 concentration.

Therefore, in the next section a parametric analysis of the pollutants production as function of temperature, pressure, E.R. and residence time in order to define key issues for a NO_x reduction strategy has been performed.

NO_x emissions analysis: Results and discussion

The goal of this section is to perform a parametric analysis of the pollutants production as function of inlet temperature, pressure, E.R. and residence time in order to define key issues for a NO_x reduction strategy.

Simulations have been performed by means of the CHEMKIN PRO software [21].

Fig. 2 shows the simplified combustor concept. In particular, there are two sources of inlet gas (Air and H2), one perfectly stirred reactor (air and hydrogen are supposed to be perfectly mixed) and an outlet flow.

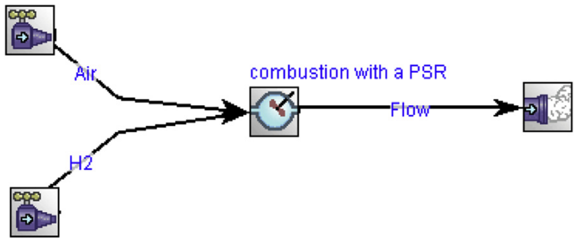

Fig. 2 – Simplified combustor concept.

Konnov's H2/air kinetic scheme [22] consisting of 1016 reactions and 127 species has been implemented.

Figs. 3–5 show that the NO increases with the residence time until equilibrium is reached and keeps constant thereafter. In particular, assuming as initial temperature Ti = 1000 K, at p = 10 atm and E.R. = 0.5, the NO_x keeps increasing with time (from 0 at t = 0 s to 0.02 at t = 0.05 s) since the equilibrium for NO_x production is not reached, whereas, assuming Ti = 1400 K, NO increases from 0 to 0.0138 at t = 0.04 s and then remains constant. Therefore, reducing the residence time, i.e., the combustor length, in principle it is possible to reduce nitrogen oxide production.

Increasing the initial temperature, the NO_x production increases whatever the equivalence ratio and pressure.

After a residence time of 10 ms, highest NO_x concentration is in proximity of the stoichiometric equivalence ratio, and decreases going to leaner or richer mixtures.

In fact, assuming a residence time of 0.01 s, increasing the equivalence ratio from E.R. = 0.5 to E.R. = 1 (at a fixed temperature Ti = 1000 K) raises X[NO] from 0.0008 to 0.006 (compare Figs. 3 and 4).

Still increasing the equivalence ratio from stoichiometric to rich, the nitrogen oxide molar fraction starts decreasing down to 0.002 at E.R. = 0.4 (see Figs. 4 and 5).

The same behavior is found at higher temperature Ti = 1400 K: the nitrogen molar fraction initially increases from 0.008 to 0.009 and then decreases to 0.004 at the E.R. respectively of 0.5, 1 and 1.4 (compare Figs. 3–5).

As for the effect of pressure, Fig. 6 shows that for lean mixtures (i.e. E.R. = 0.5), the increase of pressure increases NO at the combustor exit; for stoichiometric or rich mixtures instead, the NO_x production increases with pressure until 2 atm and then stays approximately constant (see Fig. 7).

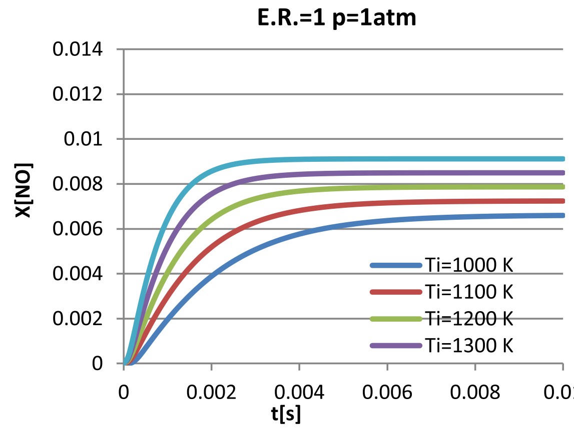

Fig. 4 – X[NO] history vs T at p = 1 atm and E.R. = 1.

The 'greenest' equivalence ratio, i.e. the equivalence ratio that allows the lower NO_x production depends on the residence time within the reactor (see Fig. 6): in fact, for the initial temperature Ti = 1400 K p = 2 and assuming a residence time of 0.01 s, $X_{NO} = 0.002$ at E.R. = 0.5, $X_{NO} = 0.004$ at E.R. = 1.4 and $X_{NO} = 0.009$ at E.R. = 1; increasing the residence time to 0.01 s increases the NO_x concentration, and in particular, $X_{NO} = 0.004$ at E.R. = 1.4, $X_{NO} = 0.01$ at E.R. = 1 and $X_{NO} = 0.012$ at E.R. = 0.5. Therefore in order to control the NO_x emissions, an appropriate choice of the equivalence ratio, pressure and temperature is critical.

The combustor initial temperature and pressure also affects the ignition delay time, calculated as the time spent to reach a temperature of 400 K above the ignition one; as known the increase of temperature always has the effect to decrease the ignition delay time. As for the pressure, a "knee shape" ignition delay behavior is found (see Fig. 7). In particular, going from 1 atm to 2 atm, no variation are predicted while, increasing the pressure from 2 atm to 7 atm, the ignition delay increases from 0.2 ms to 7.4 ms, and start decreasing when the pressure increases beyond 7 atm.

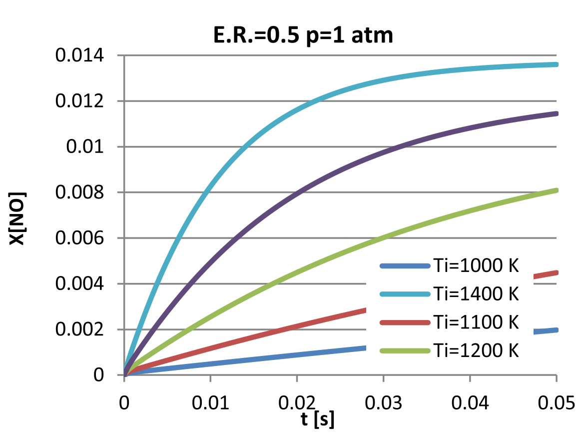

Fig. 3 – X[NO] history vs T at p = 1 atm and E.R. = 0.5.

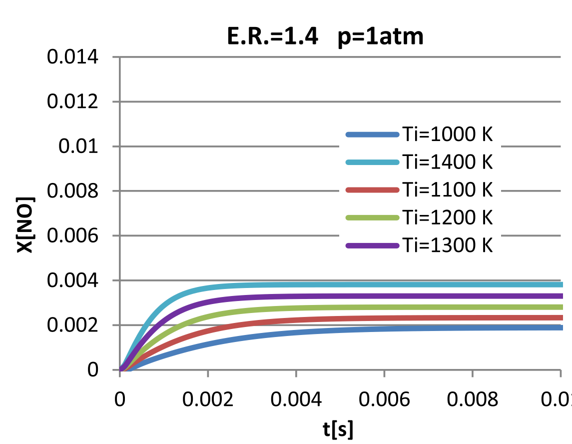

Fig. 5 – X[NO] history vs T at p = 1 atm and E.R. = 1.5.

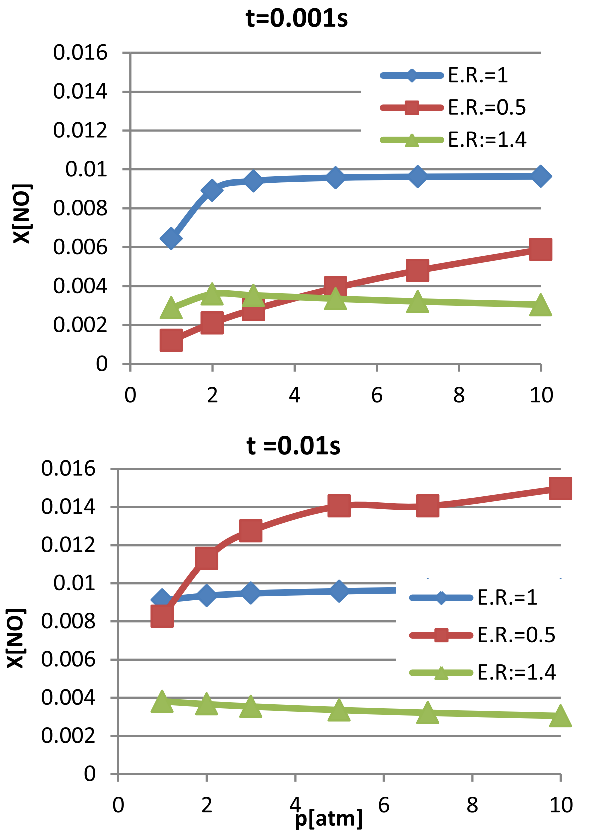

Fig. 6 – X[NO] vs p and E.R. at Ti = 1400 K at t = 0.001 s (top) and t = 0.01 s (bottom).

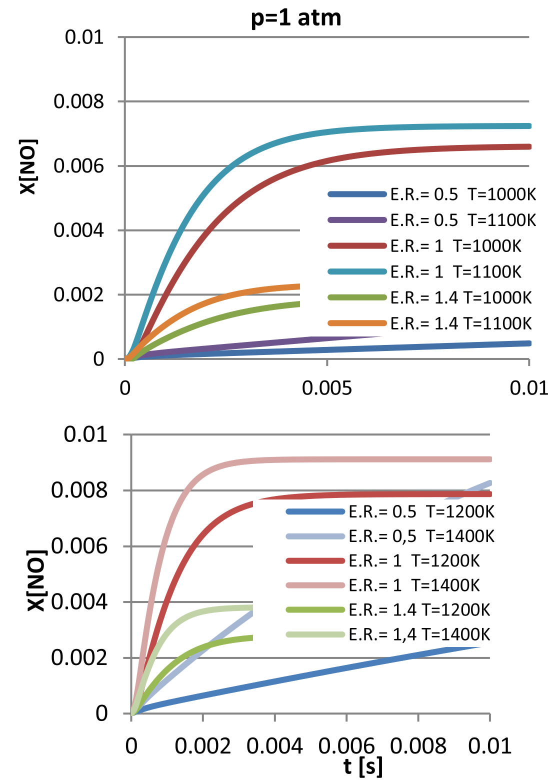

Fig. 8 – X[NO] history vs E.R. and combustor inlet T = 1000–1100 K (top) and T = 1200–1400 K (bottom), at p = 1 atm.

Analyzing NO_x vs time, Fig. 8 and 10 show that the choice of the equivalence ratio is highly affected by the exhausts residence time.

In fact, assuming a nominal combustor pressure of 1 atm and a initial temperature of T = 1400 K, the three curves of the X[NO] production against the residence time cross each other at t = 0.0035 s and at t = 0.009 s.

Therefore, before t = 0.0035 s, an equivalence ratio of 0.5 results in the greenest value, whilst it is the worst after 0.009 s.

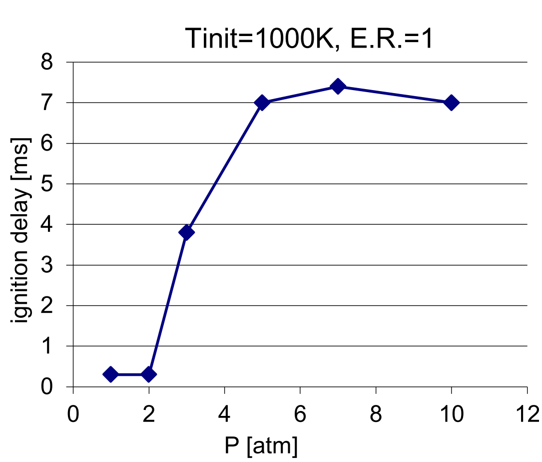

Fig. 7 – Ignition delay time vs pressure.

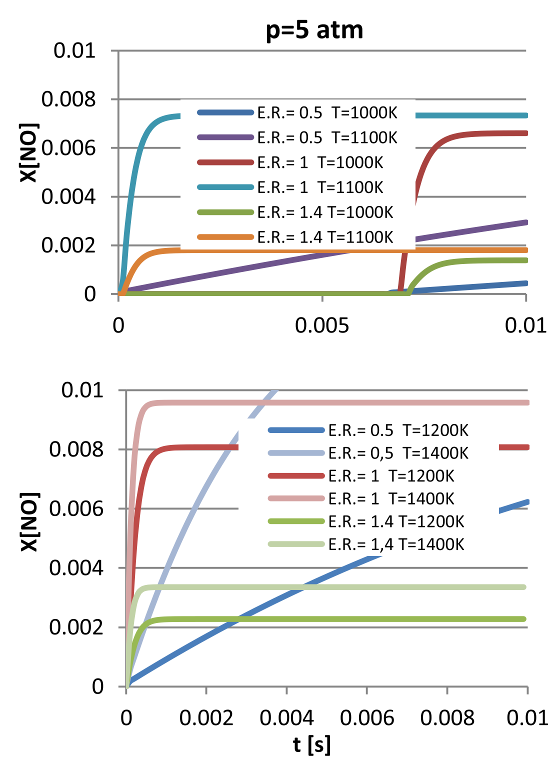

Fig. 9 – X[NO] history vs E.R. and combustor inlet T = 1000–1100 K (top) and T = 1200–1400 K (bottom), at p = 5 atm.

Hence, the NO_x reduction strategy is sensitive to the combustor operative conditions and the exhausts residence time.

Assuming instead a lower temperature, i.e. Ti = 1100 K, the three curves (at p = 1 atm) for the three different equivalence ratios, don't cross in time. This suggests that the strategy to limit NO seems simple: burn leaning, E.R. = 0.5 in this case is the best choice.

At combustor pressures higher than 1.5 atm (e.g. p = 5, 10 atm) the three E.R. curves always cross (see Figs. 9 and 10).

By zooming on Fig. 10 (Fig. 11), the history of NO_x emissions as a function of E.R. shows that, in order to reduce the NO_x emission, it is convenient previously burn a rich mixture and then a lean mixture. This suggests the implementation of the RQL strategy to reduce NO_x emissions [23,24]. This strategy, in fact, consists of burning with a rich equivalence ratio, mix instantaneously the burned mixture and then burn with a lean equivalence ratio.

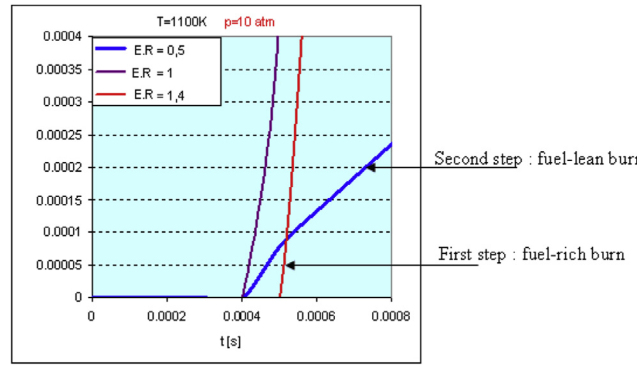

Fig. 11 – Zoom on NO emissions vs time: Burn via RQL.

RQL combustion principles

General description

The Rich-Burn, Quench, Lean-Burn (RQL) combustor concept is introduced as strategy to reduce nitrogen oxides emissions [25,26]. Rich-burn, Quick-quench, Lean-burn combustor zones are characterized by the presence of two separate reaction zones, operating respectively in rich and lean conditions. The idea is to take advantage of the good stability and low NO_x emissions associated with the rich combustion zone and, subsequently, to complete the combustion of the unburned H_2 in a lean stage where additional NO_x production is also low.

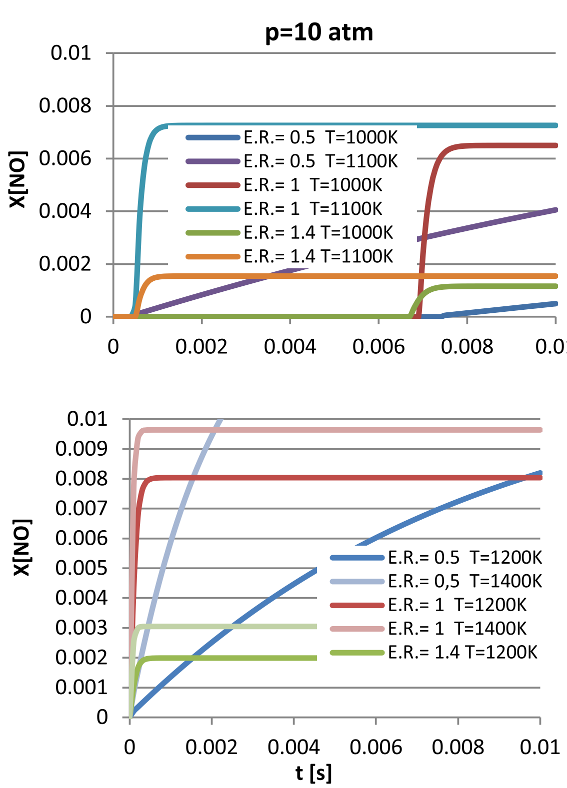

Fig. 10 – X[NO] history vs E.R. and combustor inlet T = 1000–1100 K (top) and T = 1200–1400 K (bottom), at p = 10 atm.

The RQL concept is predicated on the premise that the primary zone of a gas turbine combustor operates most effectively with rich mixture ratios.

For staging to be effective, the mixing of rich products and air must be very rapid. Fig. 12 gives conceptual illustration of this combustion mode.

The ideal concept is illustrated in Fig. 12 for a rich-lean sequence. Consider the ideal staged-combustion process in Fig. 12 represented by the path 0–1–2–3 where the bell-shaped curve represents the NO_x yield for a fixed residence time, ($\Delta t = \Delta t_{rich}$). In the rich stage, the amount of NO_x formed in the time Δt_{rich} is represented by the segment 0–1. Secondary air is then instantaneously mixed ($\Delta t_{mix} = 0$) with the rich (segment 1–2) with no additional NO_x formed. In the lean stage, the H_2 is oxidized and an additional amount of NO_x is formed (segment 2–3) in the time associated with the lean stage (Δt_{lean}).

The burned fuel from the rich primary zone will be high in the concentration of partially oxidized hydrogen; therefore, the addition of a secondary air is needed to oxidize the high concentrations of hydrogen, and intermediates. This is accomplished by injecting a substantial amount of air through wall jets to mix with the primary zone effluent and create a " lean-burn" condition prior to the exit plane of the combustor.

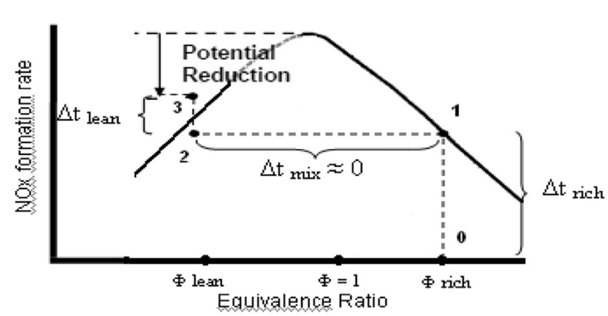

Fig. 12 – Schematic representation of staged combustion on NO_x [26].

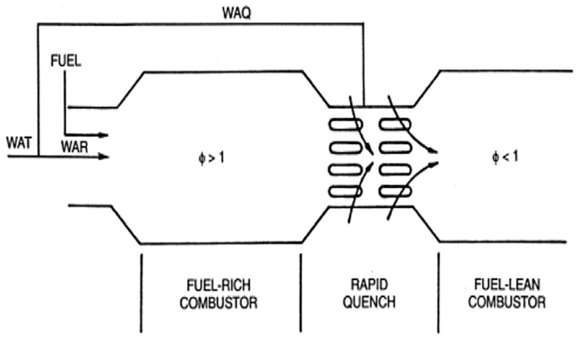

Fig. 13 – Airflow distribution into RQL.

Determination of mixing characteristics

In the RQL combustor, jet mixing plays an important role in minimizing all pollutant emissions and maximizing combustion efficiency. The rich and lean combustion zones of an RQL combustor are established by dividing the total combustor airflow.

Since all of the fuel is injected into the first combustion zone, the rich and lean zone equivalence ratios (Φ_{rich} and Φ_{lean}, respectively) are related by the airflow split (S) defined to be the ratio of the rich zone airflow (WAR) to the total combustor airflow (WAT) (Fig. 13):

$$S = \frac{WAR}{WAT} = \frac{\Phi_{lean}}{\Phi_{rich}} \tag{1}$$

At high power, with a nominal value of $\Phi_{lean} = 0.4$, 23% of the total combustor airflow is admitted to the rich zone to achieve $\Phi_{rich} = 1.8$. The airflow not admitted into the rich combustor is termed the quench airflow, and is rapidly mixed into the rich combustor effluent to achieve the overall lean combustor equivalence ratio. Since values for S are typically 20–30%, the quench airflow (WAQ) represents the majority of the combustor airflow, between 70 and 80%. If a rapid transition from the rich to lean conditions is not achieved, near-stoichiometric mixtures will exist for unacceptably long times and high temperatures and high NO_x formation rates will be experienced.

The quench mixer configurations being considered for the RQL combustor are generally fixed geometry devices. As shown in Fig. 13, jets are typically injected in crossflow.

One parameter of importance to the mixer performance is the momentum flux ratio (J) of the quench jets to the crossflow. Generally, an optimal value of J exists which maximizes the mixing.

Fig. 14 – Sketch of RQL combustion in a cylindrical duct [26].

Table 2 – Combustor inlet conditions.

Scimitar combustor	
Air	
Total pressure	10 bar
Total temperature	920 K
Mass flow rate	173.6592 kg/s
H_2	
Total pressure	10 bar
Total temperature	989 K
Mass flow rate	4.048 kg/s
Combustion chamber	
Total pressure	7.6 bar

For a fixed geometry jet mixer, J depends primarily on the density and velocity of the air entering the mixing region (WAQ) and the rich exhaust mixture already burned in the first reactor (FMR):

$$J = \frac{\rho_{WAQ} \cdot V_{WAQ}^2}{\rho_{FRM} \cdot V_{FRM}^2} \tag{2}$$

The velocities V_{WAQ} and V_{FRM} are not given in practical cases, but knowing the volumetric flow rates under standard conditions of pressure and given temperature, these velocities can be calculated using:

$$\begin{aligned} \nu_{WAQ} &= n \cdot \left(\frac{\pi d^2}{4}\right) \cdot V_{WAQ} \\ \nu_{FRM} &= \left(\frac{\pi D^2}{4}\right) \cdot V_{FRM} \end{aligned} \tag{3}$$

where ν_{FRM} is the actual volumetric flow rate of the mainstream, D is the combustor diameter, ν_{WAQ} is the actual volumetric flow rate for all orifices (n), and d is secondary air orifice diameter. This actual density and the volumetric flow rate were replaced by standard conditions values (with T, the mixing temperature), using the following equation:

$$\begin{aligned} \rho &= \rho_0 \left(\frac{T_0}{T}\right) \\ \nu &= \nu_0 \left(\frac{T}{T_0}\right) \end{aligned} \tag{4}$$

Thus, the new momentums ratio expression:

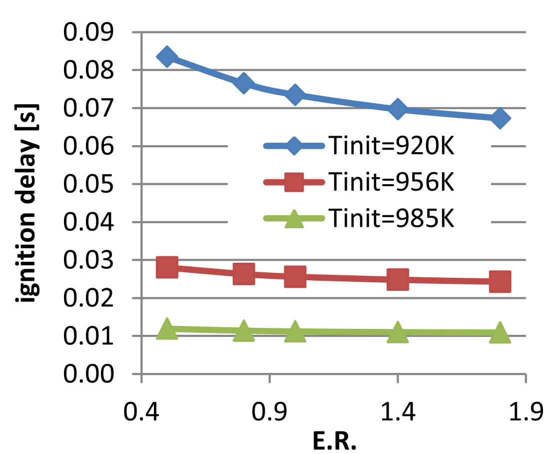

Fig. 15 – Ignition delay time vs E.R. (p = 7.6 atm).

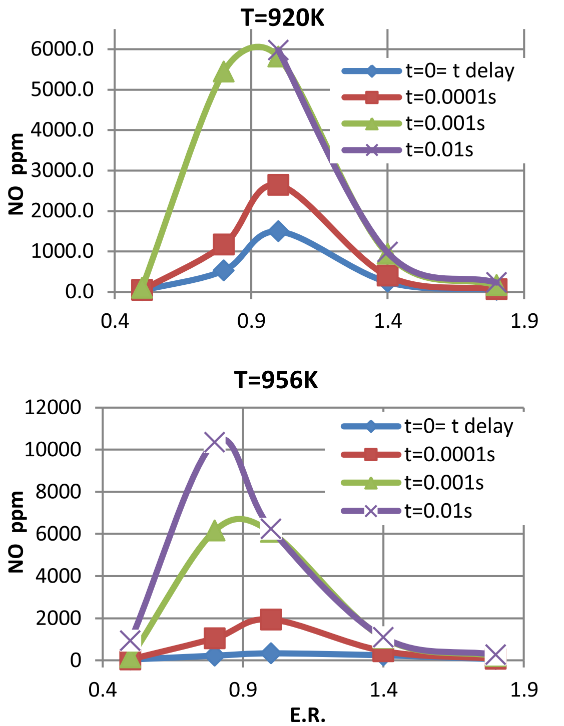

Fig. 16 – NO_x (ppm) vs E.R. at different residence times.

$$J = \left(\frac{T_{FRM}}{T_{WAQ}}\right)\left(\frac{\rho_{WAQ_0}}{\rho_{FRM_0}}\right)\left(\frac{\nu_{WAQ_0}}{\nu_{FRM_0}}\right)^2\left(\frac{nd^2}{D^2}\right)^2 \quad (5)$$

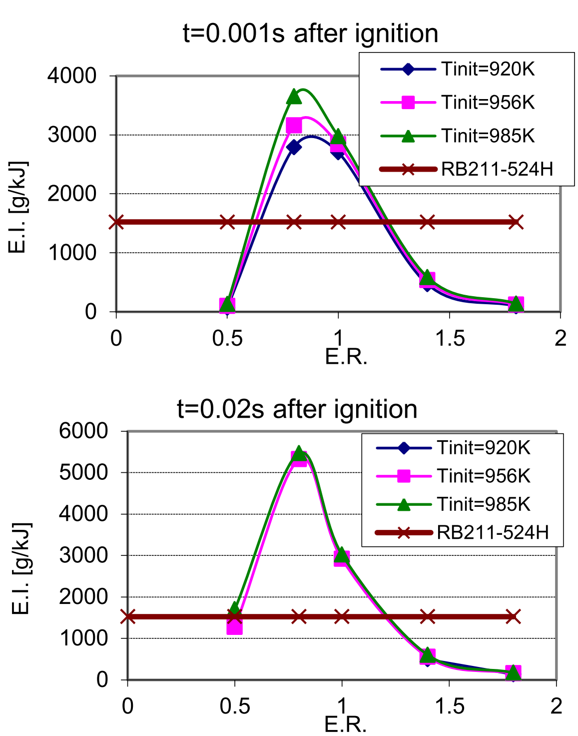

Fig. 17 – E.I. [g/kJ] compared with RB211engine (t = 0.001 s, t = 0.02 s).

Table 3 – RB211 engine from ICAO data bank.

Engine	Eng type	B/P ratio	Rated output	EI NO_x		
				T/O	C/O	App
			(kN)	g/kg		
RB211-524H	MTF	4.2	264.4	65.84	46.31	10.26
			(kN)	g/kJ		
RB211-524H	MTF	4.2	264.4	1524	1072	238

The momentum flux ratio can now be calculated from Eq. (5) based on the conditions and geometric configurations used in the chemical processing industries.

This correlation shows that mixing is much more efficient as the air mass flow rate in the mixing region is high. This means that mixing is favoured by imposing very rich conditions in the first reactor, in order to ensure a high J in the mixing region. The quantitative effect of this choice on the NO_x emission index should therefore be investigated.

In particular, writing J as function of the rich and total equivalence ratio, it can be noted that J increases by increasing the rich equivalence ratio, and by decreasing the total equivalence ratio.

$$J = \frac{\phi_R - \phi_T}{\phi_T}\frac{V_{WAQ}}{V_{FRM}}\frac{D^2}{nd^2} = \left(\frac{1}{S} - 1\right)\frac{V_{WAQ}}{V_{FRM}}\frac{D^2}{nd^2} \quad (6)$$

Eq. (6) shows the geometric and thermodynamic parameters that should be accounted to maximize mixing. A fast (ideally instantaneous) mixing separates rich and lean combustion, as shown in Fig. 14.

Applying the RQL strategy to the scimitar combustor

The previous section has shown that, looking at the impact of E.R., temperature, pressure and residence time on NO mole fraction, it is possible to derive a strategy to reduce NO_x emissions. In particular, at combustor pressures higher than 1.5–2 atm, the three E.R. curves (lean, stoichiometric and rich) always cross in time elapsing.

Since the SCIMITAR combustor pressure is 7.6 atm, the RQL strategy seems workable and is investigated in the following.

In particular, assuming as SCIMITAR Engine reference conditions those at the combustor inlet summarized in Table 2 [5], the NO_x production has been estimated.

In order to find the effect of the initial temperature on the SCIMITAR engine NO_x EI and on the ignition delay, and assuming the nominal pressure of 7.6 atm, three different temperatures (920 K, 956 K and 985 K) have been simulated.

Fig. 15 shows that depending on the mixture initial temperature, the equivalence ratio affects significantly the ignition delay. In particular, at T = 920 K, increasing the equivalence ratio from 0.5 to 1.75, the ignition delay decreases by about 19%. Assuming an initial mixture temperature higher than 920 K, i.e., $T_{init} = 956$ K, for the same equivalence ratio range, the ignition delay decreases by about 8%.

Increasing the exhaust residence, the NO_x (in ppm) peak shifts from E.R. = 1 to E.R. = 0.8 (see Fig. 16).

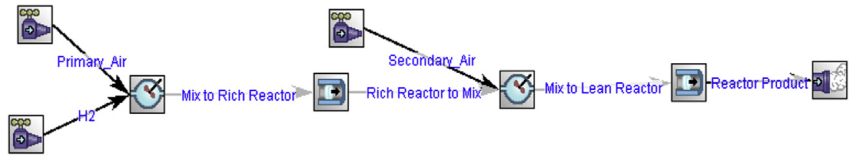

Fig. 18 – RQL combustor model.

These figures confirm that by reducing the residence time the pollutant emissions significantly decrease: this means that the combustor length has a significant impact on the NO.

As for the NO_x EI, since hydrogen and kerosene have different reaction heat of combustion, i.e.

$$\Delta Hr_{ker} \approx 43.2 \text{ MJ/kg}$$

$$\Delta Hr_{hyd} \approx 119.7 \text{ MJ/kg}$$

and the ICAO normative are generally referred to hydrocarbons, the SCIMITAR EI has been calculated both in terms of g/kJ and of g/kg. The EI expressed in g/kJ gives an idea of the NO_x produced with respect to the combustion heat released.

Fig. 17 shows that assuming a residence time of 0.001 s after ignition, the NO_x EI peak decreases from about 3800 g/kJ to about 3000 g/kJ, by decreasing the initial temperature from 985 K to 920 K. Increasing the residence time to 0.02 s, the NO_x EI peak increases to roughly 5400 g/kJ for both temperatures.

In order to estimate the acceptable level of NO_x EI, these values have been compared with those the RB211 engine that is among those engines with the highest NO_x emissions in the ICAO data bank [7]: this engine has been chosen as the worst reference limit.

The RB211 EI has been calculated both in terms of both g/kJ and of g/kg: E.I (see Table 3).

Using the E.I. (in g/kJ) of the RB211 as the maximum acceptable value, Fig. 17 shows that the SCIMITAR engine emissions become acceptable only for E.R. < 0.6 and E.R > 1.2.

Actually, since the SCIMITAR nominal equivalence ratio is 0.8, the NO_x EI is maximum, confirming the necessity to implement a NO_x reduction strategy. Note also that increasing the residence time, from t = 0.001 s to t = 0.02 s, the lean mixture always overcomes the E.I. limits and therefore the only possible strategy became to burn rich.

Table 4 – RQL SCIMITAR conditions.

RQL SCIMITAR condition analyzed			
Air mass flow rate in the rich reactor	Equivalence ratio in the rich reactor	Air mass flow rate in the lean reactor	Overall E.R.
7.2	19.4	166.6	0.8
17.2	8.1	156.6	
37.2	3.7	136.6	
47.2	2.9	126.6	
77.2	1.8	96.6	
107.2	1.3	66.6	

In the next section the RQL strategy for the SCIMITAR conditions is reported.

Modeling approach of the RQL strategy and results

In this Section, the effect of the equivalence ratio in the rich stage on the SCIMITAR combustor NO_x emissions has been analyzed. In order to verify a geometry strategy, also the effect of the residence time in the rich combustor has been examined.

Simulations have been performed by means of the CHEMKIN-PRO SW.

In the RQL combustor in Fig. 18, there are three sources for inlet flow (Primary Air, H2, and Secondary Air), two perfectly stirred reactors (Mix reactors), two plug-flow reactors (Rich Reactor and Lean Reactor) and an outlet flow (reactor products).

In the first reactor, (mix to rich reactor), air and H2 are perfectly mixed; once mixed, the fresh mixture stays within the rich reactor for 0.005 s The equivalence ratio in the rich reactor has been varied from 1.29 to 19.36, corresponding to the hydrogen and air mass flow rate reported in Table 4. The residence times in the rich reactors are respectively 0.001 s, 0.02 s, 0.05 s, 0.08 s and 0.125 s. Downstream of the rich stage, the flow is instantaneously mixed with the secondary air and entered in the lean reactor for 0.05 s: therefore, the initial time in the lean reactor corresponds to the exit time in the rich reactor.

The EI and Temperature history within the lean reactor (second stage) assuming different rich reactor residence times is shown in Fig. 19 (respectively cases from 1 to 5 refer to rich reactor residence time of 0.001 s, 0.02 s, 0.05 s, 0.08 s and

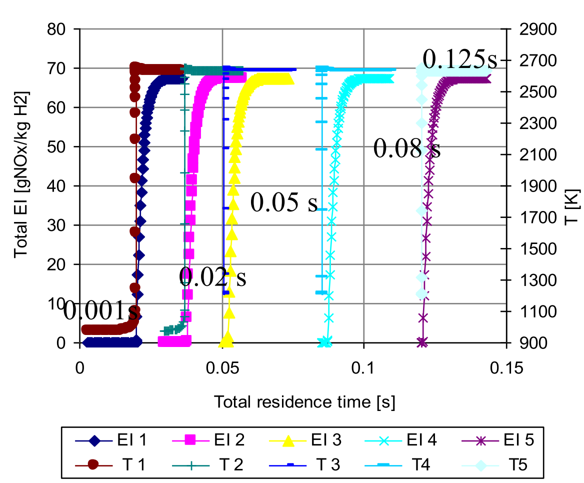

Fig. 19 – T and EI as function of the RQL geometry strategy for E.R. = 8.1 in the rich stage.

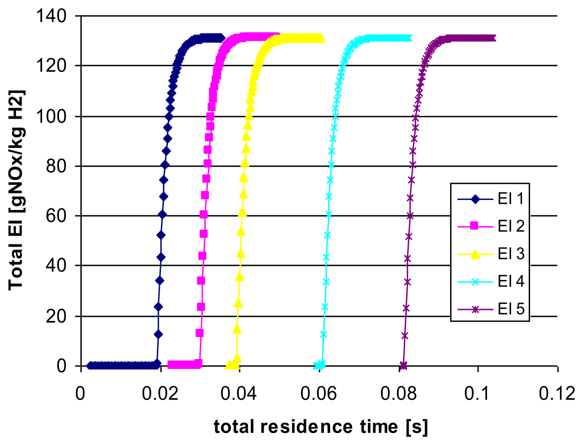

Fig. 20 – EI as function of the RQL geometry strategy for E.R. = 3.73 in the rich stage.

0.125 s).It can be noted that different initial temperatures within the lean reactor correspond to the different residence time.

Notwithstanding the different initial temperatures at the rich reactor entrance, the equilibrium flame temperatures are approximately the same.

The same behavior is observed for the final nitrogen oxide mass fraction. This suggests that the NO_x EI is almost indifferent to the secondary air injection schedule.

This behavior is confirmed also for the other equivalence ratios in the rich region (see Figs. 20 and 21).

Figs. 20 and 21 also show that nitrogen oxide emissions decrease with the E.R. increase in the rich stage from about 130 at E.R. = 3.73 to 35 at E.R. = 19.36.

This preliminary analysis therefore indicates that the RQL strategy makes the engine E.I. independent on overall residence time and that he E.R. in the rich stage is a key parameter in the NO_x reduction strategy using RQL.

In fact, keeping the nominal SCIMITAR E.R. = 0.8, and increasing the E.R. in the rich stage from 1.3 to 19.36, the NO_x EI decreases from 360 gNO_x/kg fuel to 35 gNO_x/kg fuel (see Fig. 22). A fit between the EI and the E.R. in the rich stage is:

$$EI = 426.73\,ER^{-0.8563} \tag{7}$$

Assuming for example an E.I. of 20 an equivalence ratio in the rich stage higher than 35.65 should be assumed to make

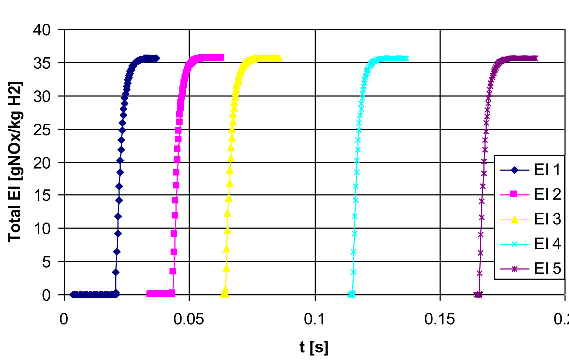

Fig. 21 – EI as function of the RQL geometry strategy assuming E.R. = 19.36 in the rich stage.

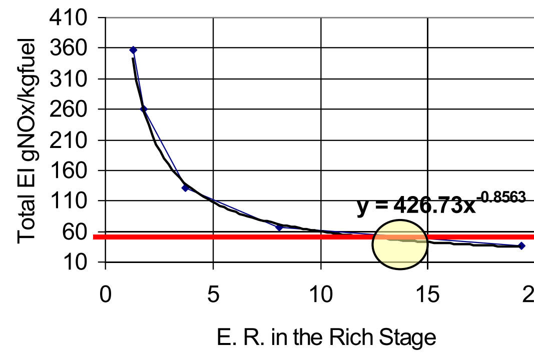

Fig. 22 – EI vs E.R. in the rich stage.

the SCIMITAR engine emissions acceptable at its nominal pressure, temperature and E.R. conditions. The high equivalence ratio in the rich stage has also the advantage to improve mixing efficiency.

Conclusion

The goal of this paper was to identify key parameters for the NO_x reduction in order to define a technology for these pollutants abatement, keeping the engine performance.

The strategy proposed is the Rich-Quick-Lean engine, whose characteristics, based on the NO_x behavior at the different equivalence ratios, permit to reduce the nitrogen oxides formation.

This combustor is namely divided into two stages, a rich and lean stage.

The analysis of the effect of the residence time within each stage of the combustor has shown that the RQL strategy makes the combustor NO_x production independent on the overall residence time.

The equivalence ratio in the rich stage has been shown to be a key parameter, affecting the quality of the mixing between the first stage exhausts and the secondary air and also producing a dramatic reduction of the NO_x formation.

In fact, for the nominal SCIMITAR E.R. = 0.8 it is possible to lower the NO_x EI from 576 gNO_x/kg fuel to 60 NO_x/kg fuel by assuming an E.R. higher than 10 in the rich stage.

A fit of NO_xEI vs the "rich stage" E.R. has located at 35.65 the equivalence ratio in the rich stage that will ensure an acceptable E.I. of 20.

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