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Analysis and forecast on changes in the level of harmful substance emissions from aviation gas turbine engines

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Abstract

The projected levels of NO_x emissions for the standard LTO cycle were shown. The estimated range of applying the advanced schemes of fuel combustion in terms of engine OPR was reviewed based on of research results in world experience. Based on the Ivchenko-Progress SE experience in design of combustion chambers the forecasting of the NO_x level emitted from air engines was made. The estimated rates of NO_x emission level reduction were determined and shown for the period till 2050 engines depending on engine thrust class. The probability of achieving the aims of Flightpath 2050, Challenge 3, Goal 1, was shown for engines with different thrust range.

1. Introduction

One of the most important global problems of modern society is the strengthening of the negative anthropogenic impact on the environment. The existing and advanced technical aims of ACARE (Flightpath 2050, Challenge 3, “Protecting the environment and the energy supply”, Goal 1, “In 2050 technologies and procedures available allow a 90% reduction in NO_x emissions. These are relative to the capabilities of typical new aircraft in 2000”), [1]. Approximately 81% of the total energy produced in the world is the chemical energy of fossil fuels released as a result of a chemical reaction with atmospheric oxygen in the form of heat [2]. The main products of complete combustion of hydrocarbon fuels in air are carbon dioxide and water mixed with nitrogen [3,4]. At the same time, when hydrocarbon fuels are burned, substances that are dangerous to human health and the environment — harmful substances (HS) — are formed in insignificant amounts. In order to control HS emission in air transport, Committee on Aviation Environmental Protection (CAEP) and International Civil Aviation Organization (ICAO) introduced in 1986 the first International standards on emissions of NO_x (nitrogen oxides), CO, HC (unburned hydrocarbons) and smoke. The main goal is to reduce air pollution in the area of airports per landing and take-off (LTO)-cycle of engine operation.

Since 1986, there has been the practice of consistently tightening the ICAO International Standards to reduce NOx emitted from turbofan engines (CAEP/2 in 1996, CAEP/4 in 2004, CAEP/6 in 2008), while maintaining emissions of other HS at the same level [4]. ICAO regulatory restrictions on NO_x emissions are shown in Table 1.

The tendency to raise the net efficiency of the turbofan engine in order to improve its fuel efficiency leads to an essential increase in operation pressure and temperature at turbine inlet of modern turbofan engines and to a significant elevation of the reaction rate for NOx formation in the combustion chamber (CC) that complicate the problem of ensuring stringency of future environmental standards. CAEP/8 stringency was implemented since 2014. It specifies reduction of NO_x emission by 15 % compared to the stringency level of the year 2008 (or by 50% to the stringency level of the year 1986). Scheduled stringency of International Standards implies achievement by 2020 of the reduction in the target technological level of NO_x emission parameter by 45% related to the allowances of the year 2008. The target technological level of NO_x emission parameter should be lowered by 60% related to the stringency level allowances of the year 2008 [5] in the long-term outlook (by 2030). It’s possible to provide

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advanced stringency level for HS emission only on condition that new low-emission technologies of fuel combustion are applied. For example GE Aircraft Engine (USA) certified bypass turbofan engine GEnx with take-off thrust 255,3 kN for Boeing 787 in 2009. Ensure a NOx margin of 65.8% in relation to 2008 stringency level was achieved through the introduction of a TAPS fuel combustion scheme.

1.1 Method of research

ICAO regulatory standards limit the amount of pollutants emitted during a standard LTO cycle that takes into account information on emission levels, fuel consumption for take-off, climb, approach and taxiing power settings, take-off thrust level and OPR value. The total level of NO_x emissions for a standard LTO cycle is determined by the main factors: technological emission efficiency of the combustion chamber, specific fuel consumption of the engine and coefficient determining the characteristic level of emissions of the entire fleet of engines of this modification, k_Characteristic, which is a function of the number of engines tested during certification tests:

$$\frac{Dp\ NOx}{F_{00}} = \frac{60}{F_{oo} \cdot k\_\mathrm{Characteristic}} \cdot \sum \begin{cases} 26 \cdot EINOx_{taxi\,/\,iddle} \cdot G_{taxi\,/\,iddle} \\ 4.0 \cdot EINOx_{approach} \cdot G_{approach} \\ 2.2 \cdot EINOx_{\mathrm{climb}} \cdot G_{\mathrm{climb}} \\ 0.7 \cdot EINOx_{take-off} \cdot G_{take-off} \end{cases}$$

According to the ICAO standard, if the engine emissions level has been determined based on the results of a single engine during the tests, the corresponding characteristic level will be higher by 15.9%. If the emission level was estimated based on the measurements of three (five) engines, then the corresponding characteristic level would be higher only by 5.9% (4.5%). When performing a comparative analysis of the emission efficiency of certified engines, it was decided to use the corrected characteristic level of engines NO_x emissions - $(D_P\ NO_x/F_{00})_{3eng}$, which unifies the number of engines that were tested for certification k_Characteristic = 0.9441. Such correction allows reducing influence of the spread of the characteristic NO_x level for the LTO cycle, which arises from the use of k_Characteristic = 0.8627 – 0.9567 values, corresponding to the typical number of engines (1-5) used in the certification process

$$(D_P\ NO_x/F_{00})_{3eng} = (D_P\ NO_x/F_{00})\,/0.9441.$$

In order to determine the possibility of achieving the Flightpath 2050 target level, it is necessary to perform a comprehensive comparative assessment of target levels and technological NO_x emission efficiency achieved at the level of demonstrators and aircraft engines, divided into the following categories:

1) by engine type:
   - engines for small regional aircraft and business jets F_{00}<90 kN;
   - engines for large regional aircraft F_{00}=100…200 kN;
   - medium-size engines F_{00}=200…350 kN;
   - large engines F_{00}>350 kN.
2) by the year of engine certification:
   - engines of 1996-2005, characterizing the NO_x emission efficiency level of the year 2000
   - engines of 2006-2015, characterizing the NO_x emission efficiency level of the year 2010;
   - engines of 2016-2017, characterizing the NO_x emission efficiency level of the year 2020;
   - demonstrators of TRL4-6 level, characterizing the probable NO_x emission efficiency level of the year 2030 and after.
   - when forecasting the NO_x emission levels values $D_P\ NO_{x}\_ICAO/F_{00}$ presented in the ICAO database were used, version 24 dated 21.11.2017 [6].

The demonstrators parameters that allow us to estimate the probable emission level of 2030 were taken from [7, 8].

1.2 Results and discussion

Existing long-term technology goals of ACARE (SRIA1, SRIA2, Flighpath 2050), NASA (HSCT, AST and UEET), as well as target levels of programs (NEWAC, LEMCOTECH) encourage the aircraft engine industry to develop research-and-engineering solutions for the subsequent introduction of technologies that will ensure the reduction of NO_x emissions by 50-70 % and 80-90 % over the long term against the regulatory requirements CAEP2 without

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deteriorating other characteristics of combustion chambers (requirements for starting, margins for lean and rich blowout limits, combustion efficiency, harmful emissions of CO and smoke number, profile factor and pattern factor at the combustor chamber exit).

Table 2 shows technology levels of NO_x emissions of CAEP, NASA, SRIA and Flightpath 2050.

As the experience of Ivchenko-Progress SE and other enterprises shows, after obtaining ultra-low NO_x emissions at one or several design conditions during tests of innovative combustion technology at a combustor rig (corresponding to TRL 3-4 level), at least 10-15 years are required to develop a new technology up to the level of TRL 9.

Fig. 1 shows the predicted data of a characteristic NO_x emission level for the following fuel combustion technologies: PERM EV (pre-evaporated rapid mixing), MSFI (multistage fuel injection), LDI (lean direct injection), used for estimating the level of NO_x emission efficiency of the year 2030.

During the first year of research activities of Ivchenko-Progress SE according on the PARE’s contract, the task was to perform an analysis of the NO_x emission efficiency level of the engines certified in the period of 2000-2018, as well as to forecast the trends of environmental performance improving by 2020-2050.

The performed trend analysis of the NO_x emissions characteristic level of the GE, P&W, Rolls-Royce Ltd, CFM engines certified within the period of 1995-2017, depending on the year of certification does not allow identifying obvious trends that will ensure a high degree of reliability of NO_x emissions forecasting in 2025-2050. The main reason for the large spread of NO_x emission values is a wide range of engine parameter variation, summary data on the ranges of OPR, BR, F_{oo}, specific fuel consumption variation for the engines of each company, given in Table 3.

Based on the performed analysis, the engines listed in Tables 4-6 were selected, as engines which characterize the level of NO_x emission efficiency of the year 2000, 2010 and 2020, respectively.

As reference points characterizing the level of NO_x emission efficiency of the engines created after 2025 for Ivchenko-Progress SE’ forecasting, there was selected the estimated time to achieve the TRL 8 level of technology by aircraft engine companies that as of 2015-2018 had a technology advance for reducing emissions, corresponding to the level of TRL 4-6. It should be noted that the term of introducing advanced technologies of TRL 4-6 level will be directly determined by the rates of further stiffening of regulatory requirements limiting the NO_x emission level, as well as the amount of funding allocated for the study of advanced concepts formulated by representatives of the leading scientific institutes in the industry.

The list of demonstrators characterizing the level of NO_x emission efficiency after 2025 and their main parameters are given in Table 7.

The forecasted rates of NO_x emission reduction in different periods and for different engine thrust ranges are shown in Fig. 2-5.

In Fig. 2-5 the numbers from 1 to 70 show each position of the engine, which is listed in Tables 4-7 (Ident).

Table 8 presents the forecasted rates of NO_x emission reduction with regard to CAEP2 for each engine type.

Note that the forecast was based on the NO_x emission efficiency level of demonstrators corresponding to the TRL=5-6. Below, we use the probability estimates of the ability to provide ACARE target levels.

Several concepts of low-emission combustion of liquid fuels [*14*] were elaborated to reduce emission of one of the main pollutant components (nitrogen oxides). These include:

- method of fuel nonstoichiometric combustion;
- concept of rich-quench-lean (RQL) combustion;
- advanced approach to combustion of lean homogenized fuel-air mixtures (LPP);
- fuel lean direct injection (LDI);
- techniques on affecting the flame by water vapor [*15, 16*] and electric fields;
- preparation of combustion components at micro- and macro- levels;
- combustion of biofuels [*17*] and other.

Combustion of lean homogenized fuel-air mixtures is seen as the most advanced concept for multiple-mode combustion chambers of air engines.

The estimated range of applying the advanced schemes of fuel combustion is shown in Fig. 6 versus engine OPR.

The results on review of the total scope of elaborations in reduction of harmful substance emission enables us to mark out the following typical technologies of fuel burning in combustion chambers of bypass turbofan engines meeting the existing ecological requirements:

- RQL pattern, burning of rich mixture with further rapid air admixture and afterburning of lean mixture (Reach Quench Lean);
- LPP pattern, burning of lean premixed and prevaporized mixture (Lean Premixed Prevaporized);
- LDI pattern, burning with lean injection directly into the burning area (Lean Direct Injection);
- pattern of burning in the combustion chamber with variable geometry;
- pattern of combustion in catalytic burner.

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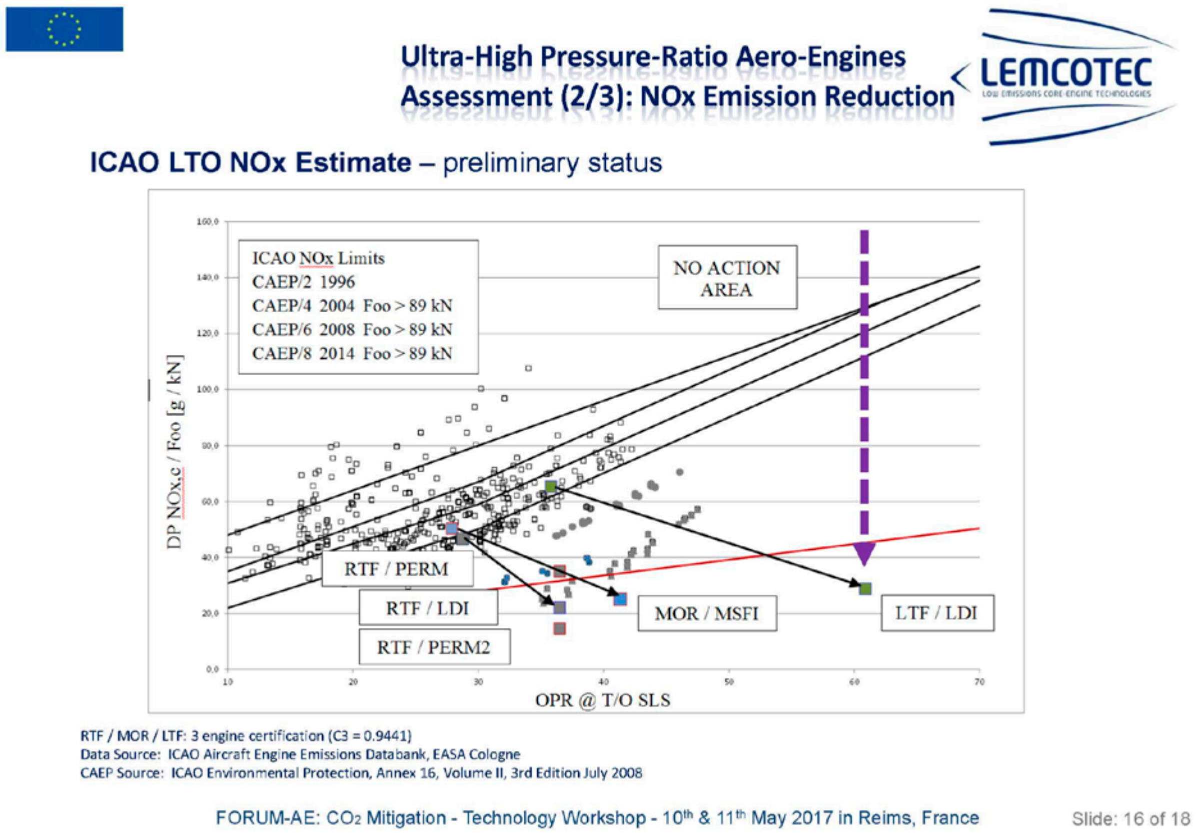

Ultra-High Pressure-Ratio Aero-Engines
Assessment (2/3): NOx Emission Reduction

ICAO LTO NOx Estimate – preliminary status

RTF / MOR / LTF: 3 engine certification (C3 = 0.9441)
Data Source: ICAO Aircraft Engine Emissions Databank, EASA Cologne
CAEP Source: ICAO Environmental Protection, Annex 16, Volume II, 3rd Edition July 2008

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Figure 1: Estimated level of NO_x emission efficiency of the year 2030 [7]

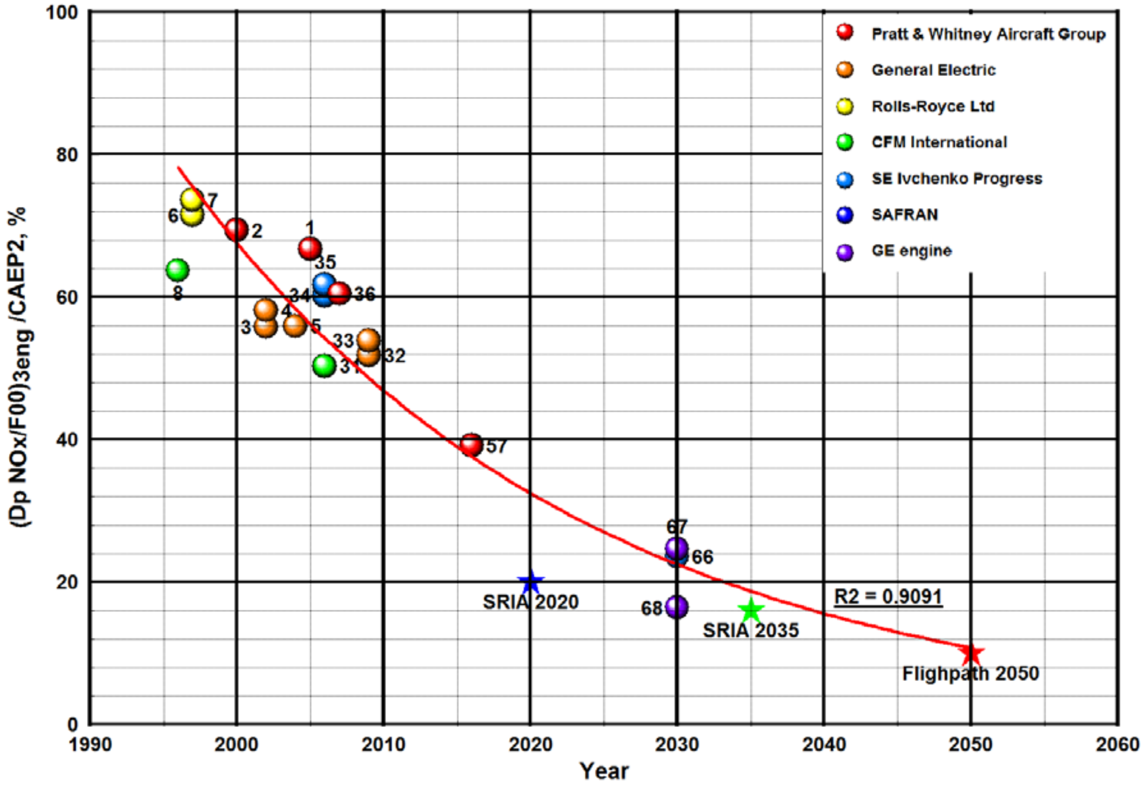

Figure 2: The estimated rates of NO_x emission reduction within the period of 2000-2050 for the engines F_{00} <90 kN

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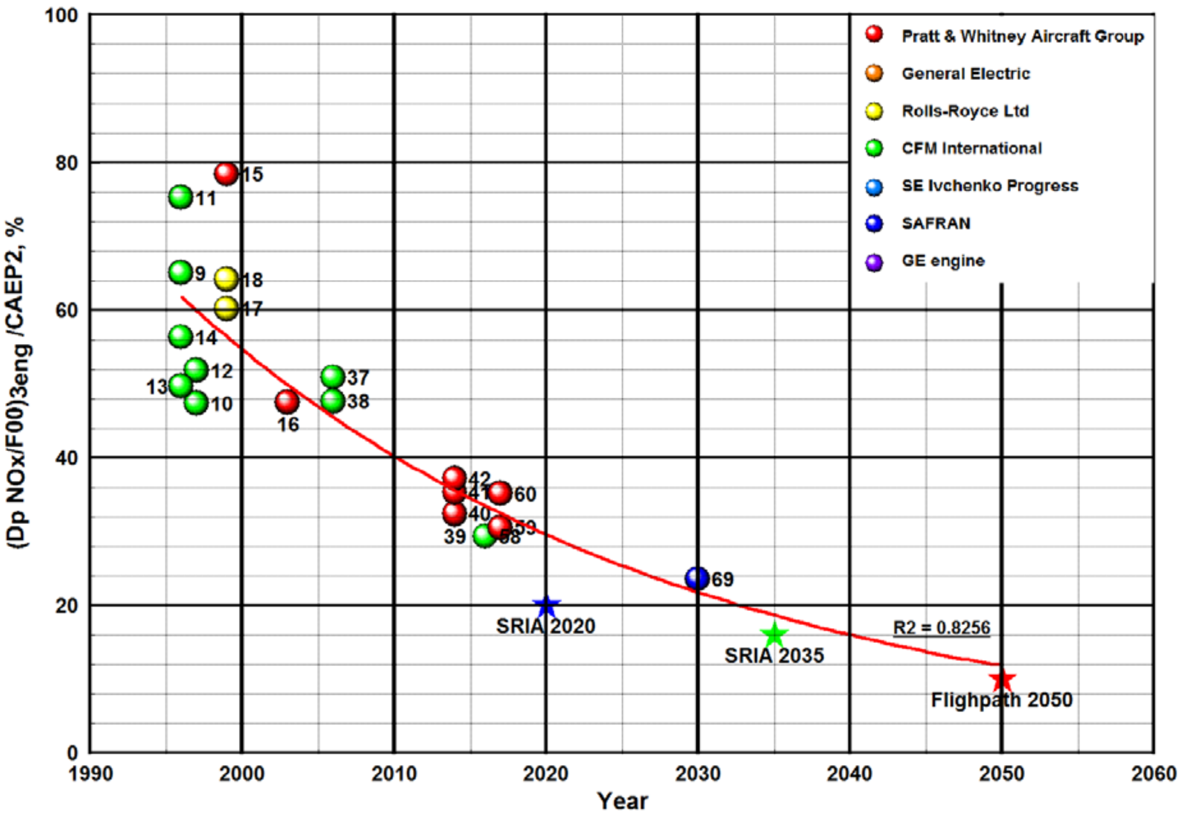

Figure 3: The estimated rates of NO_x emission reduction within the period of 2000-2050 for the engines F_{00} = 90…200 kN

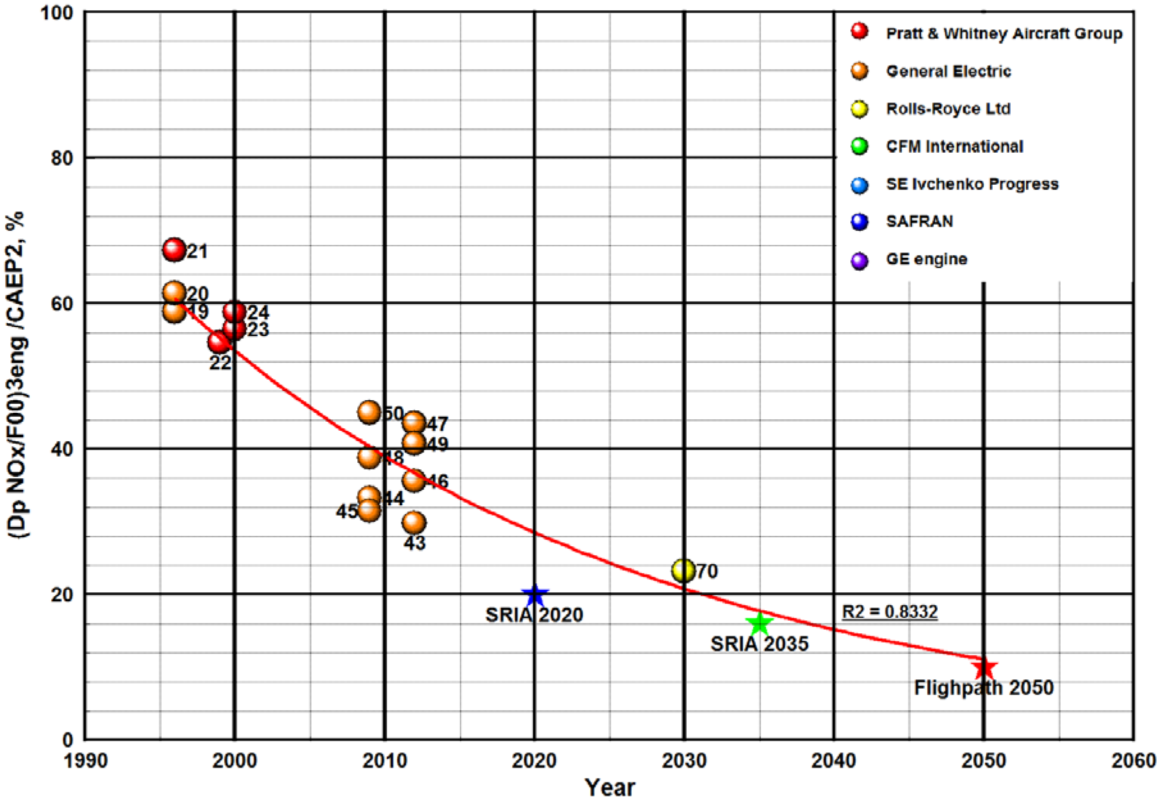

Figure 4: The estimated rates of NO_x emission reduction within the period of 2000-2050 for the engines F_{00} = 200…350 kN

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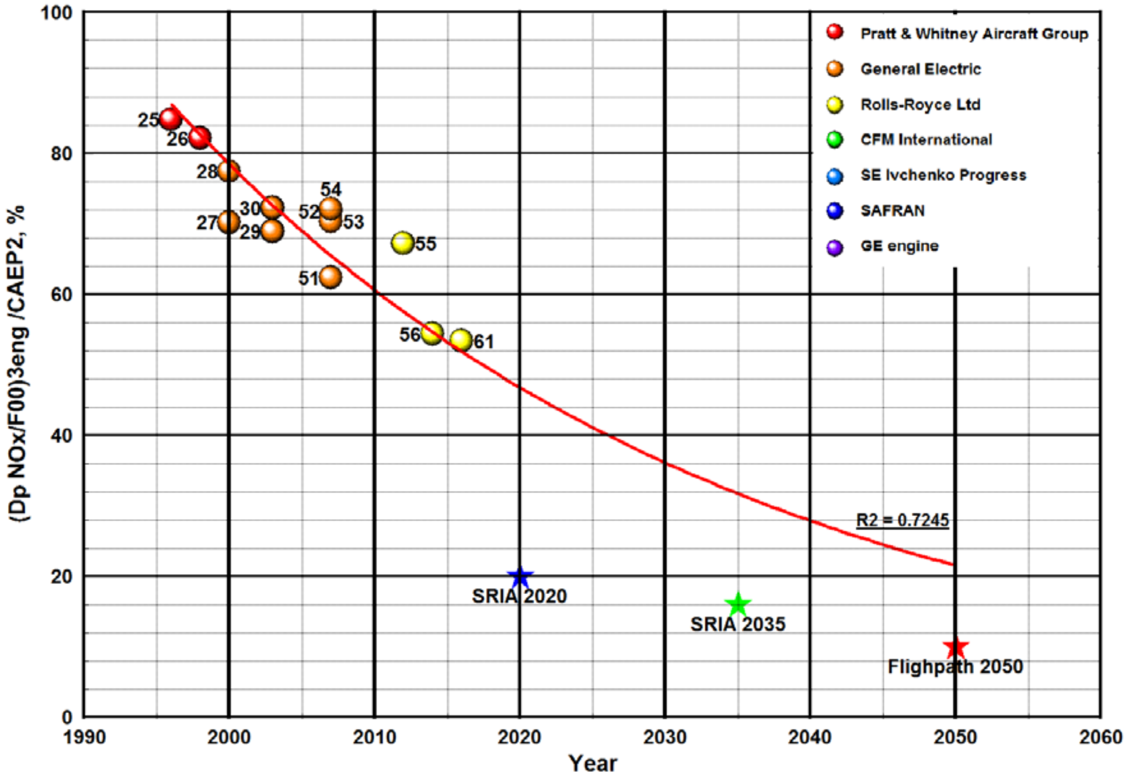

Figure 5: The estimated rates of NO_x emission reduction within the period of 2000-2050 for the engines $F_{00} > 350$ kN

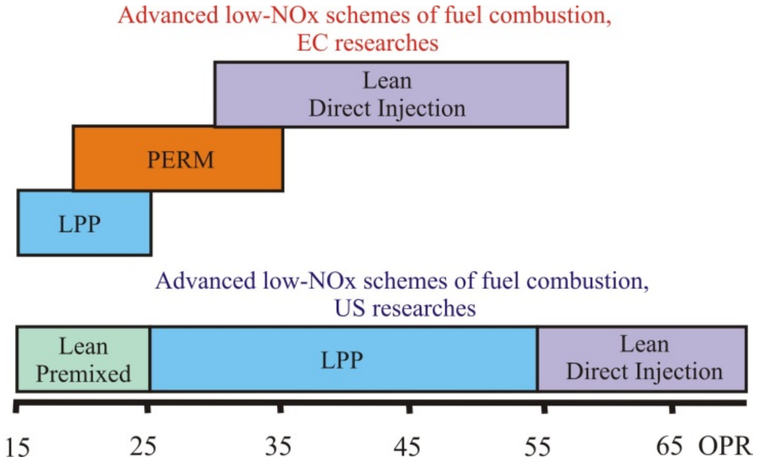

Figure 6: Estimated scope of applying the advanced schemes of fuel combustion versus engine OPR.

Table 1: Regulatory level of NO_x emissions according to ICAO requirements

Source	Regulatory restrictions LTO NO_x	F_{00}, kN	OPR	Application
CAEP/2	$32 + 1.6 \cdot OPR$	>26.7 kN	–	since 01.01.1996
CAEP/4	$37.572 + 1.6 \cdot \mathrm{OPR} - 0.2087 \cdot \mathrm{F}_{00}$	$26.7\ \mathrm{kN} < \mathrm{F}_{00} \le 89\ kN$	≤ 30	since 01.01.2004 new and
	$19 + 1.6 \cdot \mathrm{OPR}$	$> 89\ kN$	≤ 30	

	$42.71+1.4286\cdot \mathrm{OPR}-$ $-0.4013\cdot \mathrm{F}_{00}+0.00642\cdot \mathrm{OPR}\cdot \mathrm{F}_{00}$	$26.7\ \mathrm{kN}<\mathrm{F}_{00}\leq 89\ kN$	$30<OPR<62.5$	modernized engines
	$7+2.0\cdot \mathrm{OPR}$	$>89\ kN$	$30<OPR<62.5$	
	$32+1.6\cdot OPR$	–	≥ 62.5	
CAEP/6	$38.5486+1.6823\cdot \mathrm{OPR}-$ $-0.2453\cdot \mathrm{F}_{00}-0.00308\cdot \mathrm{OPR}\cdot \mathrm{F}_{00}$	$26.7\ \mathrm{kN}<\mathrm{F}_{00}\leq 89\ kN$	≤ 30	since 01.01.2008 new and modernized engines
	$16.72+1.4080\cdot \mathrm{OPR}$	$>89\ kN$	≤ 30	
	$46.16+1.4286\cdot \mathrm{OPR}-$ $-0.5303\cdot \mathrm{F}_{00}+0.00642\cdot \mathrm{OPR}\cdot \mathrm{F}_{00}$	$26.7\ \mathrm{kN}<\mathrm{F}_{00}\leq 89\ kN$	$30<OPR<82.6$	
	$-1.04+2.0\cdot \mathrm{OPR}$	$>89\ kN$	$30<OPR<82.6$	
	$32+1.6\cdot OPR$	–	≥ 82.6	
CAEP/8	$40.052+1.5681\cdot \mathrm{OPR}-$ $-0.3615\cdot \mathrm{F}_{00}-0.0018\cdot \mathrm{OPR}\cdot \mathrm{F}_{00}$	$26.7\ \mathrm{kN}<\mathrm{F}_{00}\leq 89\ kN$	≤ 30	since 01.01.2014 new and modernized engines
	$7.88+1.4080\cdot OPR$	$>89\ kN$	≤ 30	
	$41.9435+1.505\cdot \mathrm{OPR}-$ $-0.5823\cdot \mathrm{F}_{00}+0.005562\cdot \mathrm{OPR}\cdot \mathrm{F}_{00}$	$26.7\ \mathrm{kN}<\mathrm{F}_{00}\leq 89\ kN$	$30<PR<104.7$	
	$-9.88+2.0\cdot OPR$	$>89\ kN$	$30<OPR<104.7$	
	$32+1.6\cdot OPR$	–	≥ 104.7	

Table 2: Long-term technology levels of $\mathrm{NO_x}$ emissions for the standard LTO cycle

Organization	Technology level name	Value	Year	Source
CAEP	CAEP MT (medium-term technology goals)	–45% CAEP/6; 7.9+0.79·OPR	2020	[9]
	CAEP LT (long-term technology goals)	–60% CAEP/6; 5.8+0.58·OPR	2030	
ACARE	SRIA1	–80 % CAEP/2	2020	
	SRIA2	–84 % CAEP/2	2030	
	Flightpath 2050	–90% CAEP/2	2050	
CAEP potential future regulations, $F_{00}>89\ kN$ OPR > 30	CAEP /10	-17.401+2·OPR	–	[5]
	CAEP /12	-23.791+2·OPR	–	
	CAEP /14	-29.223+2·OPR	–	
	CAEP /16	-33.839+2·OPR	–	
	CAEP /18	-37.763+2·OPR	2024	
NASA, achieve TRL 6	N+1	40% CAEP6 LTO	2015	[10]
		–5% Cruise $\mathrm{NO_x}$ Emissions relative to 2005 best in class		

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	N+2	25 % CAEP6 LTO –0 % Cruise NO_x Emissions relative to 2005 best in class	2020-2025	
	N+3	20% CAEP6 LTO –80% Cruise NO_x Emissions relative to 2005 best in class	2030-2035	
Russia	Federal program "Development of Civil Aviation Equipment in Russia for the period of 2002-2010 and for the period up to 2015"	–30…–45% CAEP6	2015	[11]
Programs for the creation of new technologies in Europe	NEWAC, TRL 3-4	-60%...-70% CAEP/2	2010	
	Lemcotec, TRL 5-6	–65…-70% CAEP/2	2015	
USA programs	UEET	-70…-80 % CAEP2	2006	[12]
	ERA NASA Environmentally Responsible Aviation	-75% CAEP6 (NASA N+ 2 goal at TRL4-6)	2020	[10]

Table 3: Range of parameters variation of the engines certified within the period of 1995-2017

Characteristic	GE	P&W	Rolls-Royce Ltd	CFM
	F_{00} < 90 g/kN			
Bypass Ratio	5.09-5.7	4.1-11.64	3.0-3.3	5.5
OPR	21.7-27.3	20-35	15.75-16.4	21.4-21.59
F_{00}	55.19-83.7	26.87-87.96	61.6-68.5	86.7
Specific fuel consumption g/(kN·c)	9.95-11.17	7.05-11.88	11.87-12.8	9.71-9.85
	F_{00} = 100…200 g/kN			
Bypass Ratio	–	1.7-12.72	4.1	5-11.1
OPR	–	19.05-38.85	26-27.9	22.4-41.5
F_{00}	–	92.74-182.02	178.4-191.7	91.6-143.1
Specific fuel consumption g/(kN·c)	–	6.59-14.23	10.37-10.8	7.09-10.65
	F_{00} = 200…350 g/kN			
Bypass Ratio	5.1…9.4	4.6-6.7	5.03-9.74	–
OPR	31.37…47.5	28.41-33.8	34.48-44.1	–
F_{00}	255.3…349.2	258-344.5	251.9-345.9	–
Specific fuel consumption g/(kN·c)	7.35…9.76	8.83-9.88	7.12-9.8	–
	F_{00} > 350 g/kN			
Bypass Ratio	7.08…8.6	6-6.6	8.04-9.15	–
OPR	34.88…42.24	33.3-41.37	38.8-48.57	–
F_{00}	354.32…513.9	355.7-424.1	350.9-436.7	–
Specific fuel consumption g/(kN·c)	7.70…9.13	8.92-9.87	7.32-8.03	–

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Table 4: Parameters of certified engines that characterize the level of emission efficiency of the year 2000

Company	Ident	Engine	Combustor	OPR	F_{00}	Year	LTO NO_x, average	$(D_P NO_x/F_{00})_{3eng}$, g/kN	$(D_P NO_x/F_{00})_{3eng}$ /CAEP2, %
F_{00} < 90 kN									
P&W Aircraft Group	1	PW307A	TALON II	20.21	28.49	2005	40.50	42.90	66.68
	2	PW308A	Annular	20.4	30.71	2000	42.33	44.84	69.36
General Electric	3	CF34-8E2	LEC	21.71	55.19	2002	35.14	37.22	55.77
	4	CF34-8E5A1	LEC	24.12	62.49	2002	38.71	41.00	58.08
	5	CF34-10E6A1	SAC	27.3	83.7	2004	39.91	42.27	55.86
Rolls-Royce Ltd	6	TAY 650	Pedhead	15.9	67.2	1997	38.75	41.04	71.46
	7	TAY 651	Pedhead	16.4	68.5	1997	40.45	42.85	73.57
CFM Int	8	CFM56-7B18		21.59	86.74	1996	39.99	42.36	63.65
F_{00} = 90…200 kN									
CFM International	9	CFM56-7B20		22.61	91.63	1996	41.83	44.31	64.99
	10	CFM56-7B20/2		22.77	91.63	1997	30.58	32.39	47.33
	11	CFM56-7B27		28.63	121.44	1996	55.27	58.54	75.24
	12	CFM56-7B27/2		28.84	121.44	1997	38.23	40.49	51.82
	13	CFM56-5B1/2P	DAC-II	30.5	133.5	1996	37.90	40.14	49.68
	14	CFM56-5B3/2P	DAC-II	32.8	142.4	1996	44.93	47.59	56.33
Pratt & Whitney Aircraft Group	15	JT8D-219	Environmental Kit (E_Kit)	20.27	96.52	1999	47.70	50.52	78.41
	16	PW6122A	Talon II	25.7	98.31	2003	32.80	34.74	47.51
Rolls-Royce Ltd	17	RB211-535E4	Phase 5	26	178.4	1999	41.80	44.27	60.16
	18	RB211-535E4B	Phase 5	27.9	191.7	1999	46.40	49.15	64.13
F_{00} = 200…350 kN									
General Electric	19	CF6-80C2B8F	1862M39	31.37	267	1996	45.65	48.35	58.83
	20	CF6-80E1A4	Low emissions	34.5	297.44	1996	50.52	53.51	61.37
Pratt & Whitney Aircraft Group	21	PW4074D		31.76	333.2	1996	59.93	63.48	67.24
	22	PW4X58	Talon II	28.41	258	1999	39.9	42.26	54.56
	23	PW4164	Talon II	30.1	284.68	2000	42.7	45.23	56.42
	24	PW4168	Talon II	31.84	302.5	2000	46	48.72	58.74
F_{00} > 350 kN									
Pratt & Whitney Aircraft Group	25	PW4084D		36.36	369.6	1996	72.14	76.41	84.74
	26	PW4098		41.37	424.1	1998	76.10	80.61	82.09
General Electric	27	GE90-85B	DAC II	37.7	395.3	2000	61.15	64.77	70.16
	28	GE90-94B	DAC II	40.53	432.8	2000	70.76	74.95	77.39
	29	GE90-110B1	DAC	39.73	492.6	2003	62.15	65.83	68.88
	30	GE90-115B	DAC	42.24	513.9	2003	67.89	71.91	72.21

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Table 5: Parameters of certified engines that characterize the level of emission efficiency of the year 2010

Company	Ident	Engine	Combustor	OPR	F_{00}	Year	LTO NO_x, average	$(D_P\ NO_x/F_{00})_{3eng}$, g/kN	$(D_P\ NO_x/F_{00})_{3eng}$/ CAEP2, %
F_{00} < 90 kN									
CFM International	31	CFM56-7B18/3	Tech Insertion	21.4	86.7	2006	31.46	33.32	50.31
General Electric	32	CF34-10E6	2253M21-PFN	25.5	77.4	2009	35.60	37.71	51.80
	33	CF34-10E5A1	2253M21-PFN	27.2	83.7	2009	38.40	40.67	53.86
IVCHENKO-PROGRESS	34	D-436-148 F1	-	19.8	64.43	2006	36.18	38.32	60.18
	35	D-436-148 F2	-	20.73	68.72	2006	37.96	40.21	61.70
Pratt & Whitney Aircraft Group	36	PW307A	TALON II	20.21	28.49	2007	36.70	38.87	60.42
F_{00} = 90…200 kN									
CFM International	37	CFM56-7B20E	Tech Insertion	22.4	91.6	2006	32.59	34.52	50.88
	38	CFM56-5B8/3	Tech Insertion	22.7	96.1	2006	30.71	32.53	47.61
Pratt & Whitney Aircraft Group	39	PW1122G-JM	TALON X	28.78	107.82	2014	23.80	25.21	32.30
	40	PW1127G1-JM	TALON X	31.66	120.43	2014	25.30	26.80	32.42
	41	PW1130G-JM	TALON X	35.52	134	2014	29.60	31.35	35.29
	42	PW1133G1-JM	TALON X	38.85	147.28	2014	33.00	34.95	37.12
F_{00} = 200…350kN									
General Electric	43	GEnx-1B54/P2	TAPS	35.5	255.3	2012	24.97	26.45	29.78
	44	GEnx-1B64/P1	TAPS	40.5	298	2009	30.36	32.16	33.22
	45	GEnx-1B64	TAPS	40.6	298	2009	28.77	30.47	31.43
	46	GEnx-1B64/P2	TAPS	40.9	298	2012	32.71	34.65	35.56
	47	GEnx-2B67/P	TAPS	43.55	299.81	2012	41.72	44.19	43.46
	48	GEnx-1B70/75/P1	TAPS	43.5	321.6	2009	37.17	39.37	38.75
	49	GEnx-1B70/72/P2	TAPS	43.9	321.6	2012	39.27	41.60	40.68
	50	GEnx-1B74/75/P1	TAPS	46	341.2	2009	44.75	47.40	44.89

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F_{00} > 350 kN									
General Electric	51	GE90-76B	PEC	35.5	363.22	2007	52.26	55.35	62.34
	52	GE90-77B	PEC	35.8	366.75	2007	60.47	64.05	71.74
	53	GE90-90B	PEC	39.85	419.25	2007	63.54	67.30	70.28
	54	GE90-94B	PEC	40.82	430.92	2007	66.23	70.15	72.09
Rolls-Royce Ltd	55	Trent 1000-K2	Phase5 Tiled	46.08	350.9	2012	67.06	71.03	67.18
	56	Trent XWB-79	Phase5 Tiled	38.81	355.2	2014	48.30	51.16	54.37

Table 6: Parameters of certified engines that characterize the level of emission efficiency of the year 2020

Company	Ident	Engine	Combustor	OPR	F_{00}	Year	LTO NO_x, average	$(D_P\ NO_x/F_{00})_{3eng}$, g/kN	$(D_P\ NO_x/F_{00})_{3eng}$/ CAEP2, %
F_{00}<90 kN									
Pratt&Whitney Aircraft Group	57	PW1519G	TALON X	32.28	87.96	2016	30.90	32.73	39.13
F_{00}=90…200 kN									
CFM International	58	LEAP-1A26/26E1	TAPS II	33.4	120.6	2016	23.64	25.04	29.31
Pratt & Whitney Aircraft Group	59	PW1129G-JM	TALON X	34.02	130.08	2017	27.20	28.81	30.52
	60	PW1130G-JM	TALON X	38.07	147.28	2017	31.30	33.15	35.12
F_{00}>350kN									
Rolls-Royce Ltd	61	Trent XWB-79	Phase5 Tiled	38.8	355.2	2016	47.40	50.21	53.37
	62	Trent XWB-84	Phase5 Tiled	41.1	379	2016	52.51	55.62	56.89
	63	Trent XWB-97	Phase5 Tiled	48.57	436.7	2016	65.16	69.02	62.91
General Electric [13]	64	GE9X 777-8x		60	392.4	2018	45.00	47.66	37.24
	65	GE9X 777-9x		60	431	2018	50.00	52.96	41.38

Table 7 – Parameters of demonstrators that characterize the level of emission efficiency after 2025 [7]

Company / Technology advance program	Ident	Engine	Combustor	TRL	Pressure	Rated	Year TRL8	$(D_P\ NO_x/F_{00})_{3eng}$, g/kN	$(D_P\ NO_x/F_{00})_{3eng}$ / CAEP2, %
F_{00}<90 kN									
IVCHENKO-PROGRESS	66	AI-28	TAPS	5	32.6	89.71	2030	19.84	23.57
GE Aircraft Engine [7]	67	RTF	LDI	5	36.4	81.9	2030	22.20	24.60
	68		PERM2	5	36.4	81.9	2030	14.80	16.40

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F_{00}=90…200 kN										
SAFRAN [7]	69	MOR	MSFI	5	46.3	140.8	2030	25.00	23.57
F_{00}=200…350 kN										
Rolls Royce (RR) [7]	70	LTF	LDI	6	60.9	348.4	2030	30	23.18

Table 8: Estimated rates of NO_x emission reduction relative to CAEP2 level for each engine type

	$(D_P\ NO_x/F_{00})_{3eng}$/CAEP2, %			
Engine	2020	2025	2035	2050
F00<90 kN	32.47	27.04	18.74	10.82
F00=90…200 kN	29.61	25.40	18.70	11.81
F00=200…350 kN	28.50	24.36	17.79	11.10
F00>350 kN	46.80	41.13	31.77	21.56
ACARE target level	20	–	16	10

Table 9: Estimated rates of NO_x emission reduction for each engine type

Engine type	The probability of meeting the target level		
	SRIA 2020	SRIA 2035	Flightpath 2050
F_{00}<90 kN	low	high	above average
F_{00}=90…200 kN	low	high	above average
F_{00}=200…350 kN	low	high	above average
F_{00}>350 kN	low	low	low

Conclusions

The analysis of Fig. 2-5 and Table 8 shows the following:
1. As of 2018, all companies under analysis showed no certified engines that meet the target level of SRIA 2020.
2. The results of reaching TRL=5-6 level within Lemcotec program allow achieving the target level of SRIA 2035 by the engines rated at F_{00} = 90-350 kN.
3. Availability of Ivchenko-Progress SE technology advance of TRL = 5 allows achieving the target level of SRIA 2035 by the engines rated at F_{00} <90 kN.
4. The lack of detailed information about the development of technology advance for reducing NO_x emissions of the engines rated at F_{00}> 350 kN does not enable us to reliably estimate the possibility of achieving the objectives of SRIA 2020, SRIA 2035, Flightpath 2050. Based on the historical NO_x emission reduction trend in this class of engines, we estimate the probability of achieving the goals of SRIA 2020, SRIA 2035, Flightpath 2050 as "low" (Table 9).
In carrying out further studies on PARE, we plan to improve the reliability of forecasting, using the results of NASA studies according to scenarios of the generations N + 2, N + 3.
5. The probability of achieving the goals of Flightpath 2050 by the engines rated at F_{00}=90–350 kN is estimated as "above average".

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In order to improve the accuracy of Ivchenko-Progress SE forecasting during the second and third years of work according to PARE’s contract, it is planned to additionally introduce a parameter into the forecasting that takes into account the contribution of research on NO_x reduction concepts, which are at the level of TRL 2-3.
Researches on program of Alternative Aviation Fuel Experiment (AAFEX) showed that one of the advanced approaches to reduce NOx emission is employment of alternative fuels [*18*].

Nomencalture

G – Fuel mass flow rate fuel, kg/s;
CAEP – Committee of Aviation Environmental Protection;
ICAO – International Civil Aviation Organization;
PARE – Perspectives for Aeronautical Research in Europe;
ACARE –Advisory Council for Aeronautics Research in Europe;
LTO – landing and take-off cycle;
OPR – overall pressure ratio;
TRL – Technology readiness level;
Ident – Identificator;
D_P NO_x/F_{00} – reference emission parameter;
F_{00} – engine maximum rated thrust, kN;
NO_x – nitrogen oxides;
Dp NO_x – mass of the gaseous pollutant NO_x emitted during the LTO cycle, g/kN.

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