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PROSPECTS FOR APPLICATION OF SHIP'S MULTI-MODULE GAS TURBINE ENGINES ON THE BASIS OF CERAMIC TUNNEL TURBOMACHINES

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ABSTRACT

Analysis of thermodynamic and thermal-engineering parameters of GTE for mercantile and naval marines was conducted. A conclusion was made that GTEs designed specially for application under sea conditions have the highest efficiency. This is the 36-37% efficiency for simple cycle GTEs. With application of the complex cycle, a notable increase in the engine efficiency could be attained, particularly, by use of structural ceramics (SCMs) on the basis of innovative materials and some novel technological and design concepts. It permits to raise the engine efficiency up to 50% even with the net power of 300-500 kW.

Results of numerical calculations for single unit and thirty two module GTEs demonstrated as follows. With the same baseline conditions, a multi-module unit has the volume which is more than twice less and the mass more than five times lower. Though when the number of GTE modules still further increases, decreasing of the turbomachine efficiency becomes a negative factor. To compensate it, it is required to increase the air heater regeneration ratio, to apply helical-channel turbomachines made of heat resistant SCMs, etc. Advantages of multi-module GTEs are evident. Thus, the mean efficiency of a machine during its lifetime increases. The handling independency increases, too. A need in outages to repair machines is eliminated. The control, governing and protection systems become simpler. The fire- and explosion safety increases. In fact, all the designing procedure now reduces to identification of the module number under conditions specified and within a space targeted.

As opposed to a conventional ship's GTE design with the engine having only a single electric net power generator, the multi-module design allows a fast implementation of the entire wide spectrum of operation duties required.

1. INTRODUCTION. POWER AND MINIATURIZATION

The concept of development of **multi-module GTEs** is based on a well known natural 3D space law: *«Should linear sizes **(D)** for an object vary by a factor of **(m)**, then its surface **(F)** varies by a factor of **(m^2)**, while the volume **(V)** and mass **(M)** vary by a factor of **(m^3)**». For power machines* (power **N~F**) it means: *«Should, **given the same conditions,** the power engine be scaled down **by a factor of (m)**, then its specific power (kW/kg, kW/l increases by a factor of **(m)**».*

Compare the specific mass power $\mathbf{N_{em}}$ for engines 1 and 2 at $D_1=mD_2$, $F_1=m^2F_2$; $V_1=m^3V_2$; $M_1=m^3M_2$:

$$N_{em1}=\frac{N_{e1}}{M_1}=\frac{m^2N_{e2}}{m^3M_2}=\frac{N_{em2}}{m}\text{; or}\qquad N_{em2}=mN_{em1}\qquad(1)$$

Thus, through the ten-fold increasing of the engine power we get the ten-fold increase in its specific power if the same baseline conditions are maintained (thermodynamic scheme, environment, fuel, TIT, $\pi_к$, efficiency for turbomachines, electric generator, combustor, air flow rate for cooling, regeneration ratio, pressure losses in combustor paths, air heater, intermediate air cooler, etc).

Certainly, **the baseline conditions** of the engines compared are not similar, since:

– with the linear reduction, the scale factor affects adversely the turbomachine characteristics, e.g. their **efficiency drops;**
– **friction losses and heat losses into environment increase** because of the "surface-volume" ratio increase;
– it becomes **impracticable** to use **cooling for the turbine blading** due to extremely thin airfoils of blades;
– challenges emerge with measuring parameters obtained for separate devices and the entire plant on the research and test rigs, these challenges not easily solved because to do it you need measuring devices based on the contact-free principles;
– a high accuracy is required for:
  - **sizes and geometry** of parts,
  - **gaps** between the rotor/stator elements,
  - surface roughness values,
  - out-of balance value at the rotor balancing;
– therefore **conceptually new structural materials and processes** of manufacture for engine parts and components are required.

At the same time, G.S. Skubachevsky [1] reported that the volume and mass law (**n=3**) is valid only for turbomachines, while the square law (**n=2**) is typically valid for other GTE turbounit devices manufactured of sheet materials (combustors, intake devices, plate heat exchangers, etc). Therefore, it is recommended in [1] to admit the scale degree exponent in the relations $V_1=m^nV_2$ and $M_1=m^nM_2$ as

$$n=2.6\ldots2.8, \tag{2}$$

i.e. at m=10 the engine specific power may increase, at least, , by a factor of six. This conclusion is confirmed by the Table 1 data where similar power engines are compared, namely Capstone C30 [2] and a multi-module engine made up of 15 gas turbine ceramic engines F/E-BC2 (Fig.1) with 2kW power each.

Table 1

Nos	**Parameter** \ **Company**		**Capstone**	**Multi-module GTE of 15 modules**
1	GTE		C30	15F/E-BC2
2	Power, kW		30	2×15=30
3	Electric efficiency, %		28±2	28±1
	NOx emissions, ppm (at 15% O_2)		<9.0	<5.0
5	Sizes (L×B×H), or ∅D×L, mm		1900×1344×714	(∅116×424)×15
6	Volume, m^3		1.823	0.0045×15=0.0675; 0.0672×1.5=0.1013*
7	Mass, kg		578	6×15=90
8	Specific power	mass, W/kg	51.9	333
9		volume, W/l	16.46	446/294*

∗ coefficient accounting for inter-module volume

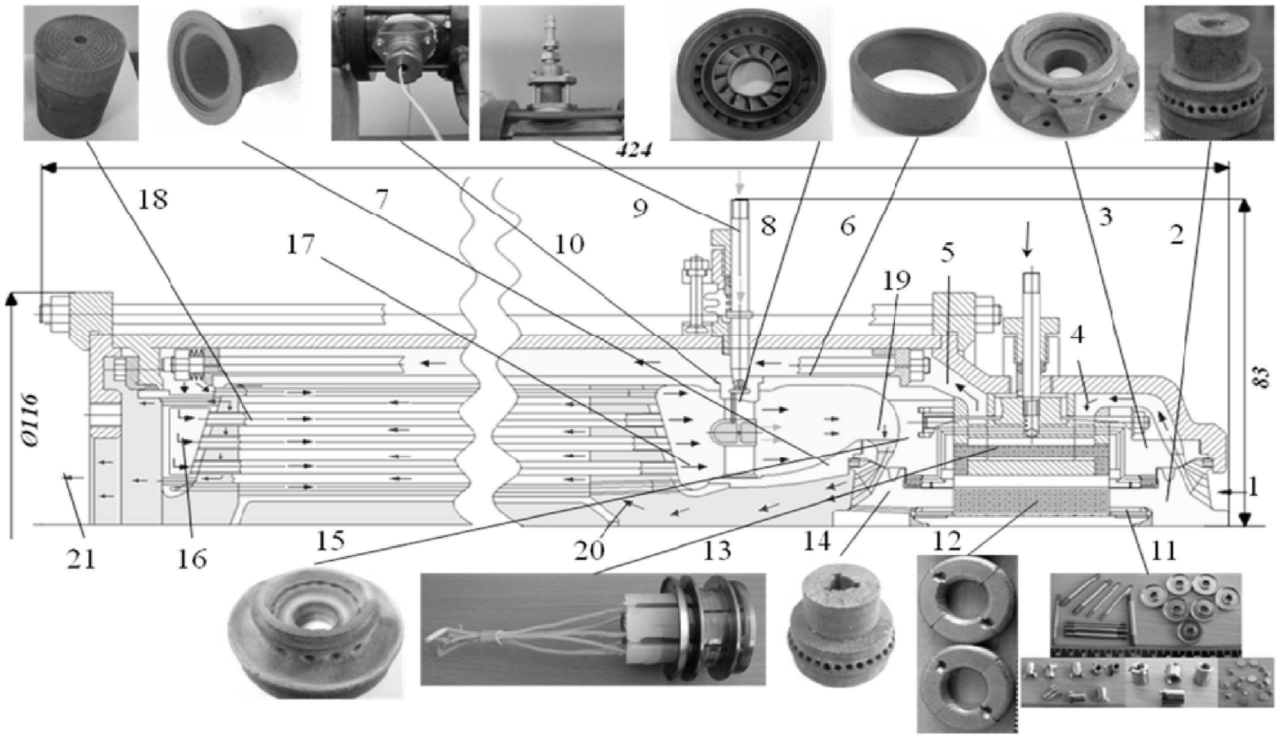


Figure 1. Ceramic engine F/E-BC2.

Designations: 1 – air inlet (**16.7 g/s**); 2 – compressor impeller (**К**) (**230,000 rpm**); 3 – diffuser **К** (**π_k=2.5; 133°C**); 4,5 – air inlet/outlet from electric generator (EG); 6,7 – outer and inner liners of combustor (**CC**); 8,9,10 – **CC** devices: 8 – dome, 9 – fuel supply, 10 – igniter ; 11,12 – metal parts and permanent magnets of **EG** rotor; 13 –**EG** stator; 14 – turbine (T) wheel; 15 – T nozzle vanes; 16,17 – air inlet/outlet from recuperator (**R**); 18 – heat exchange elements **P**, (**1003°C, E_r=86%, ΔP_Σ=6%**); 19 – gas to **T** (**1350°C**); 20,21 – gas inlet/outlet (**1144°C**) from **P** (**299°C**)

2. POWER AND GIANTISM

An international survey [3] shows (Fig.2) that for the decade period (2006 through 2015) 12,100 GTEs of the total power of 344,080 MW must be manufactured. The total cost of these machines will be not lower $143 bln in the 2006 prices (Fig.2), i.e. each kilowatt of power at a manufacturer, on the average, will cost $416.

Expenses connected with transportation to a site, site arrangements (buildings, power carrier supply, load lifting devices, noise silencing, etc.), personal training, and protection of the environment included, the cost of the installed power at a Customer will amount to $1,800-2,000 per kW.

At the same time, the market contribution of GTEs of power less 3 MW is only **1.4%** (Fig. 3) of the total cost of GTEs, while that of GTEs of power ranging 20 MW to 180 MW and higher is 87%.

Powers of single gas turbine engines, those that are being designed and manufactured, are rather high, and actually all leading power machine manufacturers worldwide follow the trend of gigantism in what concerns the production of the power generation plants**,** including not only standard designing, manufacture, test, adjustment and refinement procedures, but, also, introduction of conceptually novel high techs into spheres of materials, designing, development of hardware and technologies.

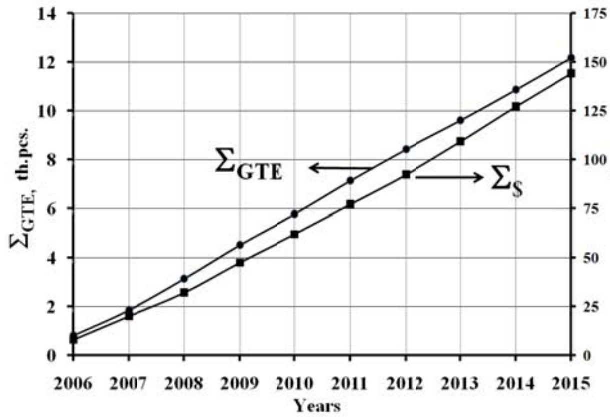


Figure 2. Production of gas turbine engines for the 2006 through 2015 period, and their cost [3].

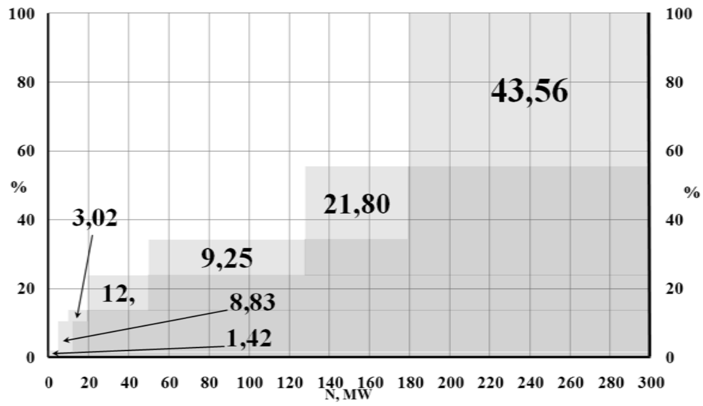


Figure 3. Contribution of power range into cost of manufacture of gas turbine engines for the 2006 through 2015 period.

3. CURRENT SHIP'S GTEs. THE PRESENT STATE.

Main gas turbine manufacturers design, manufacture, test, and sell **GTEs for general industrial usage.** In most cases, when a manufacturer is ordered to fabricate a special application gas turbine drive, some minor **updates** are made or a supply of an additional equipment is arranged; both measures aimed to adjust a serial production GTE for **operation under conditions of** a gas pipeline compressor station, emergency electric station, or a **ship's machine room**. Typically, a ship's power engine is a single or twin unit of the power ranging 5 to 25 MW. It may be intended either for a special application (Saturn, Zorya-Mashptoject), or for a general industrial usage (General Electric, Solar Turbines, Rolls-Royce, etc) [3].

Analysis of thermodynamic and thermal-engineering parameters of GTEs installed on mercantile and naval marines allows making a conclusion that **GTEs designed intentionally for application under sea conditions** have intrinsically the highest efficiency (Table 2).

Table 2

Main thermal-engineering and mass-size[1] parameters of the best ship's GTEs

Parameter[2]	601-KF9[3]	601-KF11[3]	M70FRU[4]	UGT 10000[5]	Spey[3]	UGT 15000+[5]	M90FR[6]	WR-21[3]
$N_{ен}$, MW	6.468	7.829	8.8	10.5	19.5	20	20.2	21.6
$G_в$, kg/c	23.3	29.4	33.3	36.7	66.7	71.1	74.6	73
$b_{ен}$, g/kW·h	228	227	234	241	230	226	228	**190**
η_e, %	36.7	36.9	36.6	36.0	36.4	36.5	36.0	**44.4**
TIT,°C	-	-	1220	1200	-	1160	1160	1100
E_r, %	-	-	-	-	-	-	-	~75
π_k,	15.0	19.8	18.5	19.3	21.9	19.4	19.4	17.11
n,th.rpm	11.5	11.5	6.5	3	5.5	3	3.45	3.6
M^2, t	38.1	39.9	2.4	5	25.7	9	8.9	46
V^2, m^3	90	90	9.05	13.8	58.1	35.4	35.4	102

1Electric generator**,** electric engine not considered, 2Rated duty parameters: Nен – power, $G_в$ – air flow, $b_{ен}$ – specific fuel consumption, η_e – efficiency, TIT – gas temperature at turbine inlet, π_k – pressure rise ratio, E_r – regeneration ratio, n – speed, M and V – mass and volume, [3]Rolls-Royce [4-11], [4]OAO «NPO «Saturn» [12-14], [5] GP NPKT «Zorya-Mashproject» [15,16], [6] ZAO «Turborus» [17].

Actually, all these engines have simple cycle with the efficiency of **36-37%** at the rated conditions; they should be installed on ships and vessels of all classes as cruising and high speed engines with actually similar determining parameters for **TIT, π_k,** and with regularity of variations of the relative specific fuel flow — as function of the relative power — (Fig. 4).

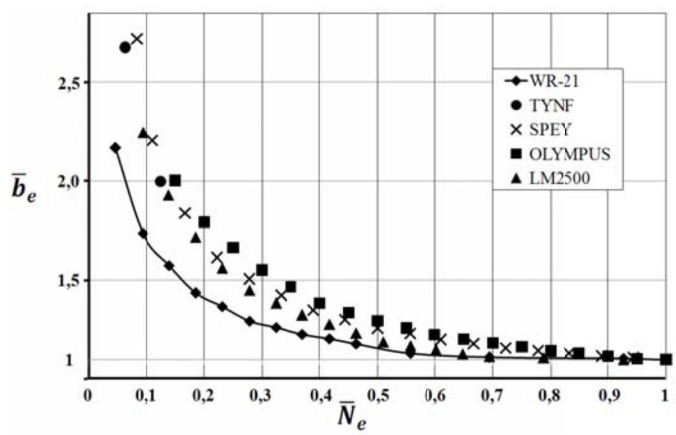


Figure 4. Relative fuel flow rate vs relative power for single-module ship's GTEs [11]. ($N_{ен}$ and $b_{ен}$ – rated duty parameters).

At the same time, mass-size values differ notably from unit to unit since **they depend primarily on a design approach applied, with various materials and technological aspects of production involved.** E.g. the mass and volume of Rolls-Royce GTEs are nearly one order over those of the "Saturn" and "Zorya-Mashptoject" GTEs of the same power. It can be seen now that the **ship's GTEs M70FRU and M90FR, which total lifetime amounts to 40,000 hours [5,12], are the most acceptable candidates for making comparison with the complex cycle ship's GTEs.**

Application of complex cycle GTEs ensures a considerable increase in the engine efficiency, especially, by use of heat resistant and high thermal stability materials, effective structures for cooling of turbine blading, combustor liners, and heat exchange surfaces of air heaters. These gains were achieved in the **ship's GTE WR-21 of Rolls-Royce and Westinghouse production (Table 2).** Here, TIT is 1,100°C, the cycle is **regenerative with intermediate cooling.** The latter makes this engine a most efficient. Therefore, **WR-21** is admitted to be the most adequate illustration of a ship's GTE to make comparison with the ship's ceramic engines (CGTE), given these CGTEs are developed on the basis of a similar complex cycle for a civic ship's application.

Application of uncooled ceramic components (combustor liners, nozzle vanes, and turbine wheel, heat exchange surface P, gas duct lining) allows a considerable increasing of the GTE efficiency. At tests of the ceramic GTE CGTE302 of 300kW power of Kawasaki production at TIT=1350^{0}C, the design efficiency η_e=42% [18] was obtained.

4. SHIP'S CERAMIC GTEs

4.1 Ceramic GTEs under development

A numerical optimization study was carried out. Its purpose was to explore the rated operation duties for ship's CGTEs projects under baseline conditions in accordance with ISO and at the same initial technical parameters. The calculation results for optimum pressure rise ratios in each CGTE are summed up in the Table 3 and shown in Fig.5.

Table 3

Main thermal-engineering and mass-size[1] parameters of CGTEs under development

Parameter[2]	CGTE					
	Single-unit					Multi-module
	8-17.5	8-19	16-38	16-35	F/E-BC500	**32F/E-BC500**
Neн, MW	8	8.7	16.5	16.5	0.5	16.3
$G_в$, kg/s	17.5	19.0	38.0	35.0	1.17	37.4
$b_{eн}$, g/kW·h	162		163	162	173.8	161.7
η_e, %	51.5		51.1	51.5	48	51.6
TIT, °C	1400					
Regeneration ratio, Er, %[2]	85					
Pressure rise ratio, π_k,	10	12	10	12	10	
Speed, n, Krpm	12.7	13.55	9.58	9	67/38	
Mass, M, t	14.8	16.3	35.5	31.2	0.625	20.0
Volume, V, m^3	150	164	358	315	6.30	202

[1] Electric generators, service space included, [2]ref. note 2 (Table 2).

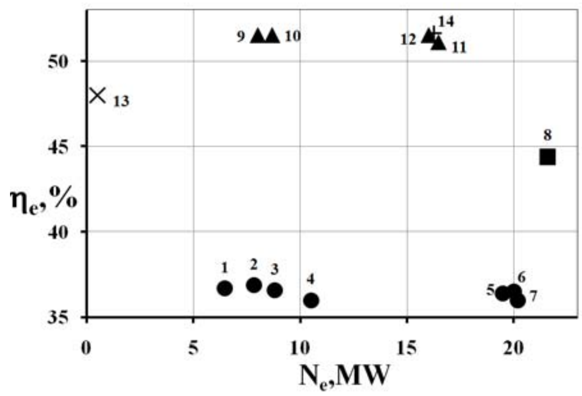


Figure 5. Comparison between efficiencies η_e of ship's GTEs:
- simple cycle: 1 - 601-KF9;2 - 601-KF11; 3 - M70FRU; 4 - UGT 10000; 5 – Spey; 6 - UGT 15000+; 7 - M90FR; **- complex cycle:** 8 - WR-21; 9 – CGTE 8-17,5; 10 – CGTE 8-19; 11 – CGTE 16-38; 12 – CGTE 16-35; 13 – CGTE 0,5-1,17; 14 – multi-module 32F/E-BC500.

It could be seen from the comparison data (Table 1) that the high efficiency, achieved by development of a ceramic micro engine F/E-BC2, is a result of not only a notable increase in TIT (up to 1623K/1350°C) at the uncoooled ceramic micro turbine inlet, but, first and foremost, thanks to **implementation of high tech concepts** within the overall complex of the process of development of **innovative materials, technological and design approaches.**

4.2 Specific features of developed ceramics and technologies

Innovative material sciences concepts include primary non-shrinkage corundum-carbide-silicon-boron-nitride **ceramics (К3BNК)**, which can be machined with no use of diamond tools. These ceramics are also adaptable to welding and their heat resistance and thermal stability values do not depend on the temperature up to 1400°C. All the main gas turbine engine devices were manufacture using these novel materials through development and introduction of the LLS (Laser-layer Sintering) technology for structural ceramics, due to which the challenge of the **powder distribution and packing** prior to sintering was successfully solved. Among other techniques applied are: implementation of the **sintering** process (synthesis sintering, laser spot size, synthesis atmosphere, scanning rate); SCM powder **levitation** due to the optic pressure; a**ssessment** of stresses and means of their elimination; s**trength** of the final product; f**inishing treatment** of the surface and inner channels.

4.3 Tunnel turbomachines

Blade-free tunnel turbomachines, where functions of the annular grates, axial or radial blades of the nozzle vanes are fulfilled by the circular **conic channel-tunnel system** (Fig. 6a). A detailed description of the tunnel turbomachine design is presented in [19,20].

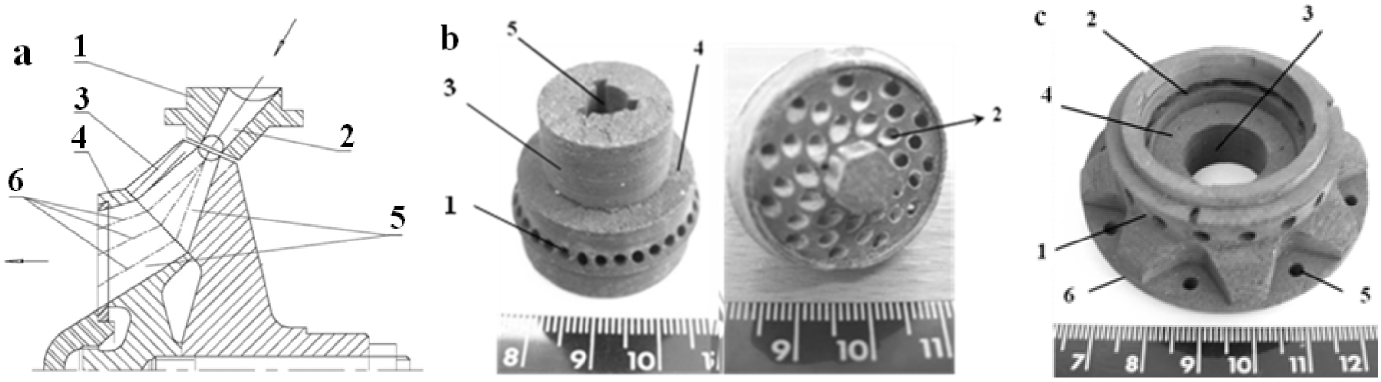
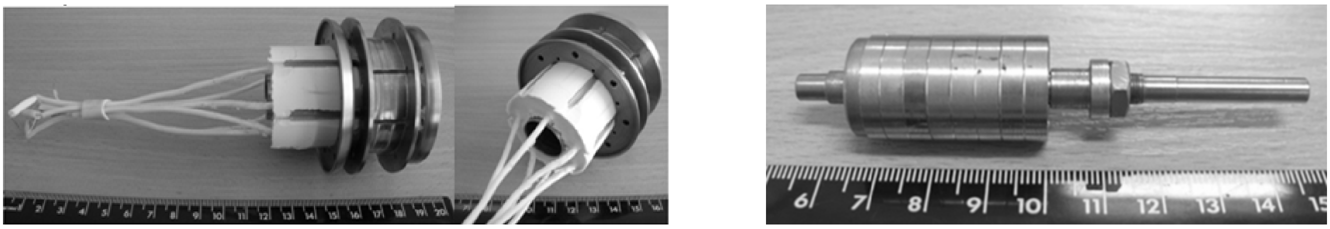


Figure 6. Ceramic tunnel (blade-free) turbine CGTE F/E-BC2.
a) Design scheme: 1 – annular nozzle vanes, 2 – nozzle tunnel channel, 3 – peripheral disc of turbine wheel, 4 – near-axial disc of turbine wheel, 5 – working tunnel channels, 6 – projections of axial lines of various groups of tunnel channels with alternating geometry.
b) Rotor: 1,2 – inlet and outlet of working media from tunnel channels, 3 – rotor portion of journal bearing, 4 – rotor portion of thrust bearing, 5 – bypass connection with electric generator rotor.
c) Nozzle vanes: 1,2 – inlet and outlet of working media into tunnel channels, 3 – stator portion of journal bearing, 4 – stator portion of thrust bearing, 5 – holes to admit ties, 6 – flange of connecting with EG stators.

4.4 Integration of turbocompressor and electric generator

Ceramic micro electro turbocompressor **(μETC), as a solid integrated structure** designed and manufactured in the process of the plant development, with the rotor and the stator components and parts of EG fitting the rotor and the stator components and parts of TC (Fig. 7). With this design execution, a reliable cooling of the EG stator and rotor is achieved using the compressed air that leaves the compressor, with an appropriate increase in the engine efficiency. It occurs because the heat removed by the EG returns into the cycle heating at the same time the air that enters the air heater.



a b

Figure 7. Integrated EG on permanent magnets.
Designations: **a – EG** stator complete; **b – EG** rotor complete.

4.5 Low toxic emissions combustor

A «green» ceramic combustor with the "cold" flame on the basis of complete fuel combustion arranged within the separation zone behind the annular flame holder flowed around with twisted counter-displaced jets (Fig. 8, Fig. 9).

The like burning technique was studied in depth at the Nevsky Works (Russia) and applied to the serial production 25 MW GTN-25 plants [21]. As applied to the ceramic combustor, the design, based on the above technique, was essentially updated and survived successfully a cycle of rig tests.

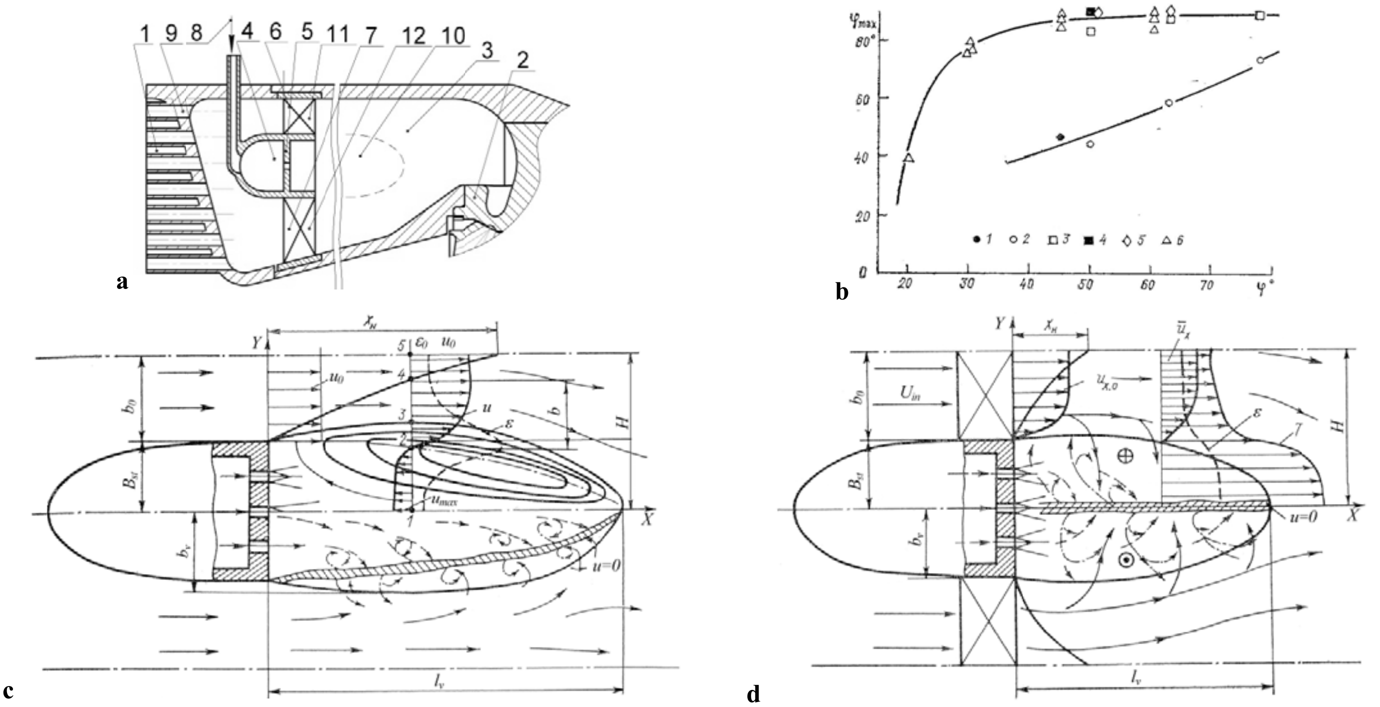


Figure 8. Design and schematic diagram of flame stabilization at CC burner flowed around by counter-twisted jets system.
a) Design scheme of ceramic CC: 1 –AH, 2- nozzle vanes in T, 3- CC, 4- dome, 5- flame holder, 6- external swirler, 7- internal swirler, 8- fuel gas supply, 9- air from AH, 10- separation zone, 11,12 – directions of air twisting for external and internal dome swirlers.
b) Angle φ_{max} between tangential jets on separation zone boundary within initial section (x=0) vs baseline angle of stream twisting φ_0 in swirlers and sleeve ratio for swirlers $\beta=(d_{вв}/d_н)^2$.
c and d) Flame stabilization within separation zone downstream of body flowed around with turbulent untwisted (c) and opposite sign twisted (d) streams: I-III – direction of stream motion: I – air, II – fuel, III – combustion products; u – axial velocity; ε - turbulence extent; l_v – separation zone length; T – temperature; H, $B_{ст}$, δ_0, δ, $\chi_н$ – characteristic sizes; 1…5 – characteristic points of flow structure.

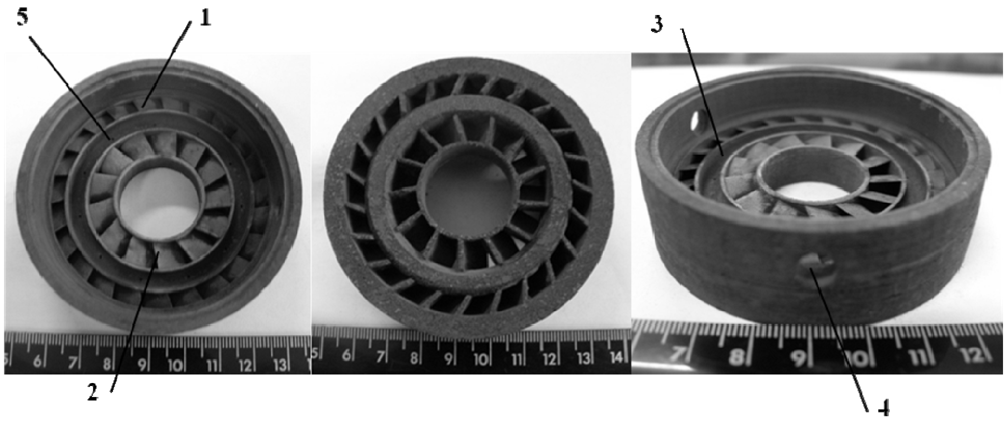
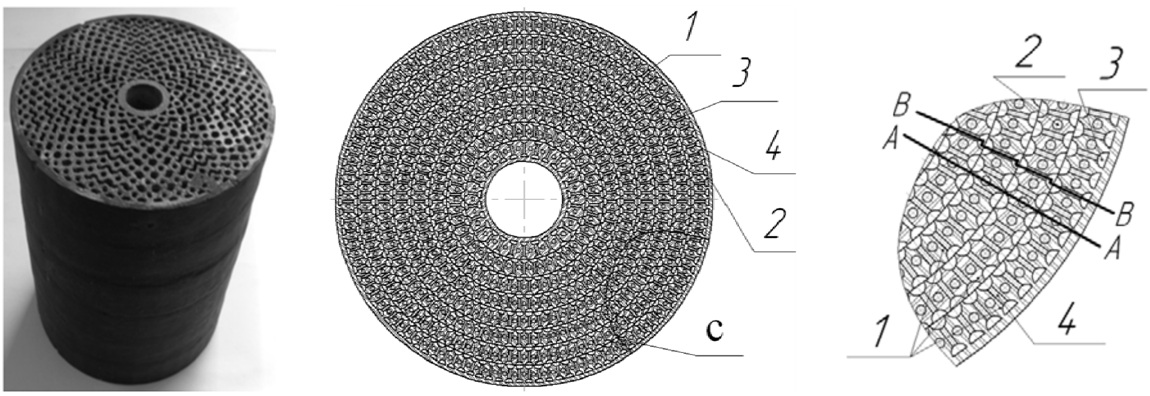


Figure 9. Photo of CC dome.
Designations: 1 – external air swirler, 2 – internal air swirler, 3 – flame holder, 4 – holes to admit igniter, 5 – fuel holes.

4.6 Matrix recuperative air heater

A distinguishing feature of the developed heat exchanger is the matrix-annular structure of the μR matrix; it enables a free variation of determining geometries for the heat exchange surface (Fig. 10), due to which an optimum heat exchange geometry could be realized at any value of the air velocity at the recuperator inlet.



a **b** **c**

Figure 10. Ceramic R (a) and cross section (b, c) of its cylindrical matrices.
Designations:1 – annular section of matrices, 2 – air channels, 3 – gas channels, 4 – connecting cylindrical gas channels.

4.7 Multi-module ceramic GTE

Implementation of the innovations developed allowed to solve a complex task encountered during development of micro engines of the 2kW electric power, namely **a high efficiency (28%)** that exceeds a mean efficiency level (24%) for GTE of 1.5 to 4.3 MW power that have been widely applied to the gas industry (Fig. 11).

So, along with ship's ceramic engines of single-module execution of 16 MW power, it would be much to the point to perform analysis of a **multi-module** power engine including, e.g., 32 ceramic ship's CGTEs of 500 kW power (Fig. 12).

A characteristic feature of the like engine (Fig. 13) is that the effective power is produced by integrated electric generators and in HPTC and LPTC.

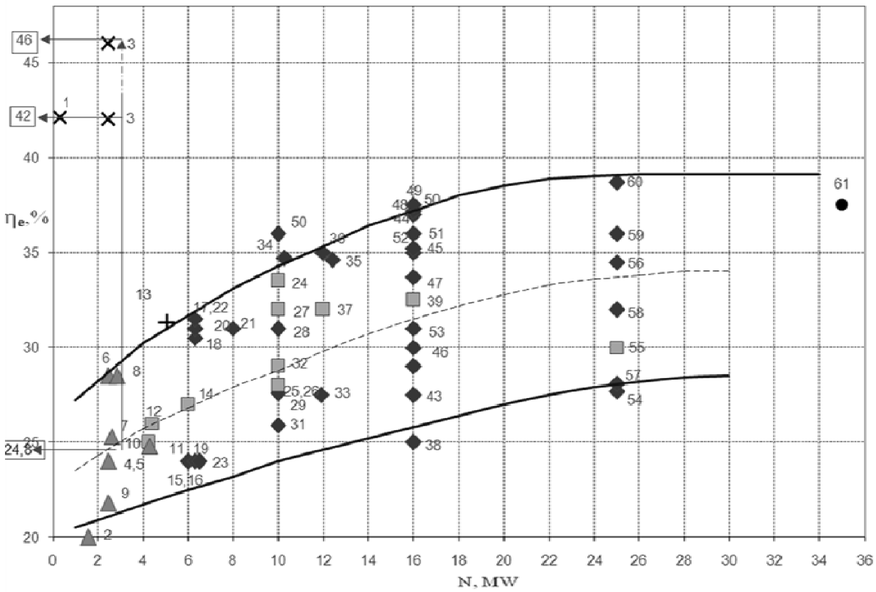


Figure 11 Efficiency of GTE of a unique gas supply system (UGS) of Russia.

Metal GTE: ▲♦ - simple cycle(12,14,24,25,27,32,37,39,55), ■ - regenerative cycle (2,4-11,15-23,26,28-31,33-36,38,40-54,54-60), ● - gas-steam cycle (61);

Ceramic GTE: + - simple cycle (**13 - Centaur 50S**, Solar Turbine, USA), × - regenerative cycle (**1 – CGT-302**, Kawasaki, Japan; **3 – CGTE-2.5**, Boyko Center, Russia); ♦×■ - gas compressor drive, ●▲ - electric generator drive.

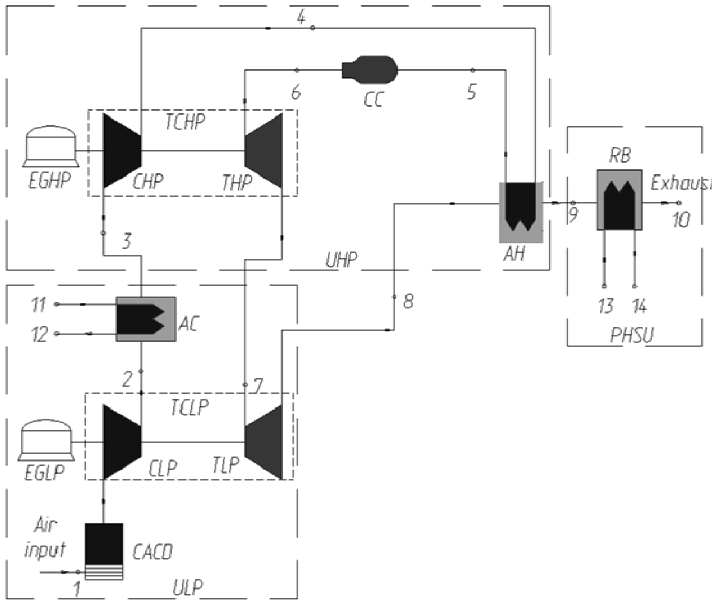


Figure 12. Thermo-dynamic scheme of ship's CGTE E/F-BC500 of 500 kW power.
Designations : CACD – complex air-cleaning device; AH – air heater; RB – recovery boiler; AC – air cooler; PHSU – power-and-heat supply unit; U – unit; C – compressor; T – turbine; EG – electric generator; CC – combustor chamber; HP and LP – high and low pressure.

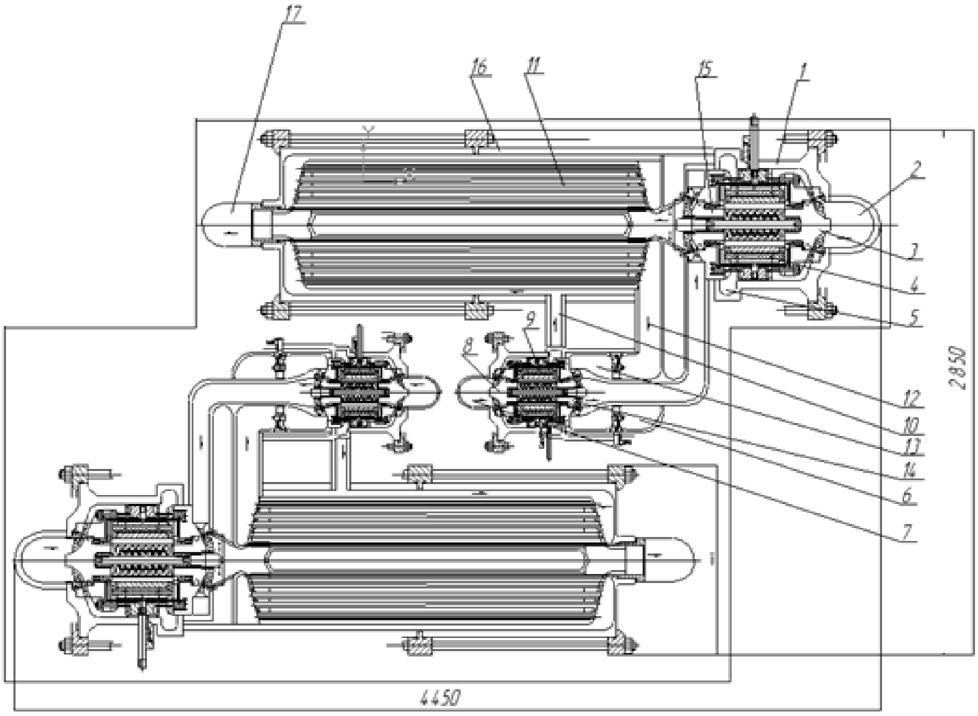


Figure 13. Unit of two modules for ship's CGTE 32E/F-BC500 (unit power – 1 MW, engine power – 32 MW).
***Designations*: **1-LPU, 2-suction in LPC, 3-LPC, 4-LPEG, 5-air supply into AC, 6-HPSU, 7-air supply from HPC, 8-HPC, 9-HPEG, 10-air discharge from HPC to AH, 11-AH, 12-air supply from AH to CC, 13-CC, 14-HPT, 15-LPT, 16-solid casing for CGTE, 17-exhaust gases discharge to RB.

The modules are united, for a space economy, in pairs into units of twin CGTEs. The internal location of each module is made in a manner that minimizes the volume of hot gas and air ducts with reducing hydraulics and heat losses into the environment.

The mass of the multi-module complex cycle ceramic GTE of 16 MW is not in excess of 20 t. (Table 3), including air heaters, electric generators, etc. In the above comparison of single-unit and multi- module versions of CGTE of 16 MW power, the number of modules can be increased, which will entail reduction of power (e.g.: 64×250 kW, 132×125 kW, etc.), and, accordingly, reduction of the cost and mass-size parameters of the entire engine, with increasing, at the same time, the ship's operating maneuverability.

Advantages of the multi-module version for GTE are clear:

– **Independency of the sea transport will increase** due to increasing the efficiency, reducing the mass and overall siz**es** of GTE;

– **a need in** outages for repair will be eliminated since any module could be replaced with a spare one;

– **average efficiency will rise dramatically** over the period of the engine running (Fig.14), since the power regulation is put into effect by modules switching on – switching off, these modules operating always at the most efficient duty (Fig.14).

– control, governing and protection systems **will be simplified essentially;**

– **fire and explosion safety of engines will increase since modules operate with gas lubrication**;

– in most cases, an engine **designing** will include no more than identification of a number of modules, their arrangement and connection to working media supply-discharge, power carriers, control, etc systems under conditions specified and within a space targeted;

– **and the first consideration** is that, as a result of all these measures, **expenses on manufacture** (materials, hardware, labor force, premises, transportation, tools, rigs, etc) **and running** (repair, service, diagnostics, spare parts, etc) will be substantially reduced.

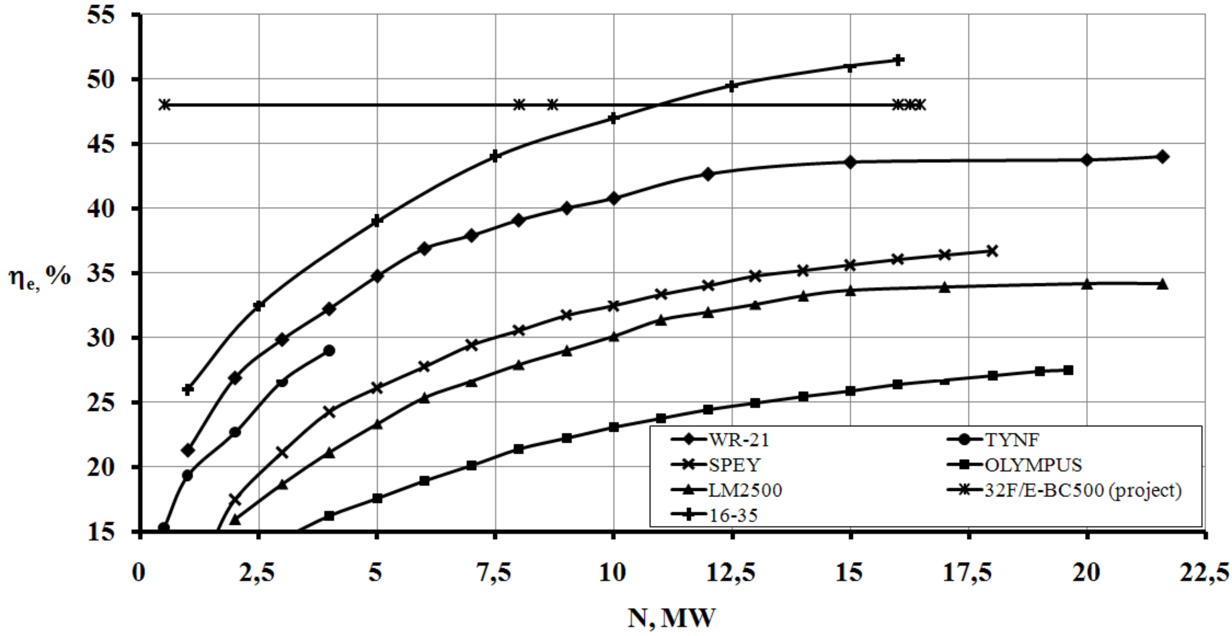


Figure 14. Efficiency vs operation duty for single-unit [11] (WR-21, TYNF, SPEY, OLYMPUS, LM2500) and multi-module GTEs.

5. SUMMARY

Application of multi-module plants instead of single –unit ones of the same power reduces the cost of the power produced. This is achieved not only by substantially lower mass-sizes and, accordingly, lesser expenses for production and running, but, first and foremost, at the expense of operation at any power required under rated, most efficient, eco-friendly, and reliable conditions as well as thanks to elimination of outages to carry out repairs.

All the above could **make generation** of the electric, heat, and mechanical **power much cheaper** and lead to a more **reliable** and less costly **running of GTEs** [22].

REFERENCES

1. G.S. Skubachevsky, Aviation gas turbine engines. Design and calculation of parts, M: «Mashinostroyenie», 1974., 520 p.

2. www.capstoneturbine.com

3. Franus D.J., “Gas turbine sales begin rising again”, International Turbomachinery HANDBOOK 2007, 10/2006 (Vol. 47 No.6) pp. 12-16.

4. Catalogue of gas turbine equipment «Gas turbine technologies » - 2007, 296 p.

5. Allison Industrial and Marine Engines. Harnessing the Power Technology. Ad materials of the Rolls-Royce company.

6. Advanced power systems. For efficient power generation Ad materials of the Rolls-Royce company. Rolls-Royce Aerospace Group (Allison).

7. Industrial/Marine Gas Turbines. Model 501-KB58. Ad materials of the company Rolls-Royce Aerospace Group (Allison).

8. Spey marine gas turbine for navy application. www.rolls-royce.com.

9. Sawyer’s Gas Turbine Catalogue 1969, ed. by R. Tom Sawyer, 413 p.

10. Rolls-Royce WR-21, The free encyclopedia Wikipedia. http://en.wikipedia.org/wiki/WR-21.

11. Colin R, The WR-21 Intercooled Recuperated Gas Turbine Engine – Integration Into Future Warships, Proceedings of the International Gas Turbine Congress 2003 Tokyo, November 2-7, 2003, IGTC2003Tokyo OS-203, 6 p.

12. Sea ship’s engines «M70FRU» NPO «Saturn»,Ltd www.npo-saturn.ru/!new/index.php?pid=92.

13. War engines. Sea ship’s engines NPO «Saturn»,Ltd www.npo-saturn.ru/!new/index.php?pid=83.

14. Military-Industrial Survey «Arsenal», №1, 2008, p. 138.

15. Catalogue of power equipment, 2009, Gas turbine technologies, p.135-142.

16. Gas turbine engine UGT10000 with electric generators, gas blowers and ship’s propellers driving www.zmturbines.com/Rus/Products/Engines/UGT_10000.htm.

17. Sea ship’s engines «M90FR» NPO «Saturn», Ltd www.npo-saturn.ru/!new/index.php?pid=94.

18. Tatsumi T., Development of the 300 kW ceramic gas turbine CGT302. Ceramic Gas Turbine Design and Test Experience. Progress in ceramic Gas Turbine Development, ASME PRESS, edited by Mark van Roode, Mattison K., Ferber, David W.Richerson, Vol.1, 2002, chapter 15, pp.331-360.

19. A.Soudarev, A.Souryaninov, V.Tikhoplav, A.Molchanov, P.Avran, L.Lelait, Novel blade-free turbomachine concept for microgasturbine engine applications. (Part 1. Design. Design characteristics. Metal model realization), International Gas

Turbine Congress 2003, November 2-7, 2003 Japan, Tokyo, Paper TS-041, 8 p.

20. A.Soudarev, A. Souryaninov, V. Tikhoplav, A. Molchanov, P.Avran, L.Lelait, Pioneer concept of blade-free turbomachines for micro gas turbine engines. (Part II. Tests of metal model of micro turbine), Proceedings of the International Gas Turbine Congress 2007 Tokyo, December 3-7, 2007, Paper TS-019, 4 p.

21. Soudarev A.V.,Tikhoplav V.Yu., "Research-Engineering Center "Ceramic Heat Engines (NIZ KTD) at the Research-technological Institute for Power Engineering (NITI EM)". Ceramic Gas Turbine Design and Test Experience. Progress in ceramic Gas Turbine Development, ASME PRESS, edited by Mark van Roode, Mattison K., Ferber, David W.Richerson, Vol.1, 2002, chapter 32, pp.683-707.

22. Micro turbine electric stations Capstone C1000 were launched into industrial operation in Yakutia, Gas Industry, №7, July 2010, p.7.

