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Testing and Investigations of Materials for Turbocompressor High-Temperature Components

Report for ISTC Project # 1313-2001

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ISTC

PROJECT # 1313

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Testing and Investigations of Materials for Turbocompressor High-Temperature Components

(from July 1, 2001 to June 30, 2002)

Project Manager – Romantsov Aleksey Alekseyevich

2002

1 Project Title - Testing and Investigations of Materials for Turbocompressor High-Temperature Components

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4 Project Start - July 1, 2001. Project Duration – 15 months.

5 Work Summary

5.1 The purpose of the Project is:

- to perform a complex of research and technological works with advanced structural materials for turbocompressor operating in helium fluid at temperature up to 850 ?C and at 60000 hours lifetime;
- to develop principal technological procedures of TC key components manufacture, including welding and heat treatment issues;
- to perform preliminary tests and investigations of materials and welded joints samples.

5.2 Expected results

Results of works under the Project will be:

5.2.1 Selection of materials and confirmation of their applicability for turbocompressor high-temperature components and other systems operating in similar conditions.

5.2.2 Proposals for principal technologies and manufacture methods of pilot lots of components.

5.2.3 Preliminary tests and investigations of materials and analysis of their results.

5.2.4 Demonstration of possible directions for modification of industrial and experimental alloys with the purpose of enhancing their properties for application in nuclear plants with specified parameters.

5.2.5 Determination of the concept of further works for turbocompressor materials and development of turbomachine design.

5.3 Scientific and Technical Approach

To achieve required purposes in compliance with adopted research methodology and world experience in performing materials testing, works were performed in the following main directions:

- development of requirements for materials;
- selection of materials for turbocompressor components with account of world experience in manufacturing such components and present-day development of manufacturing;
- development of principal technologies for blanks manufacture and their adjustment at models;
- development of principal technologies for welding and heat treatment of welded structures;
- determination of scope and methods of required testing;
- testing and investigations of materials and models samples;
- summarizing and analysis of results and preparation of a plan of further works for mastering of industrial manufacture of materials at the manufacturing enterprises including qualification tests as per RF GAN Regulations.

Manufacture of scaled models of turbocompressor high-temperature components, experimental tests at the special test facility will be carried out in further years following the completion of works under the present project in compliance with the technological development program.

Works under the project were performed stage by stage and involved 14 stages. Step-by-step performance of theoretical developments was envisaged for analysis of requirements for materials and subsequent samples testing according to the program developed. Results gained were programmed for discussions and analysis together with experts, who presented collaborators' interests.

6 Technical Progress over Period under Consideration

During first year over period from July 1, 2001 to June 30, 2002 works were performed according to stated purposes and main stages identified by the work plan. The following stages of the plan were completed during performance of works outlined by the annual work plan and attainment of stated purposes: ?-1, ?-2, ?-3, ?-4, ?-5, ?-6, ?-7. Summary of works under these stages is given below.

6.1 Stage ?-1. Development, output and concordance of input data for structural materials for manufacture of TC elements key units

Works under this stage resulted in issuance of research work report “Development of Input Data on Turbocompressor High Temperature Component Materials” (Product 02.03-35.1?, Inv.No.0206090).

The followings may be identified as key results of this stage:

6.1.1 The Product provides sketches for the following turbocompressor high-temperature components:

- working blade;
- nozzle diaphragm (apparatus);
- turbine disk for the assembly structure;
- turbine disk for the welded structure;
- turbine stator;
- volute.

All sketches of the turbocompressor components and arrangement of turbine components, including inlet volute, stator and blade system, are shown in Figures 1 – 7 and can be corrected during design.

The key factors that determine operability of TC components in terms of reactor are temperature, lifetime and mechanical loads during operation.

To specify reasonable requirements for turbocompressor materials, analysis of the turbine components temperature state and stress analysis in the most loaded components at operation temperature were performed.

To determine the temperature state of structural components, geometrical characteristics, heat exchange conditions along structure boundaries, thermal-physics characteristics of materials and boundary fluids /1, 2/ are established. The temperature state of turbine components under consideration within specified boundary conditions that correspond to the mode under consideration was calculated using a special computer code. Selection of boundary conditions represents a complicated ambiguous goal, which considerably influences results of calculations and can be corrected in the future.

Results of temperature state analyses for volute, stator casing, and turbine discs for first three stages of welded and assembled rotor options at 100 % and 15 % power operation are displayed in graphic form (Figures 8 – 22).

This work also provides the analysis of the stressed state using temperature calculation.

Stress analysis is performed for the following most loaded turbine components:

- working blades;
- rotor discs;
- nozzle diaphragm (apparatus) blades;
- turbine stator;

Layout of turbine components, sketches for turbocompressor components and results of thermal calculations

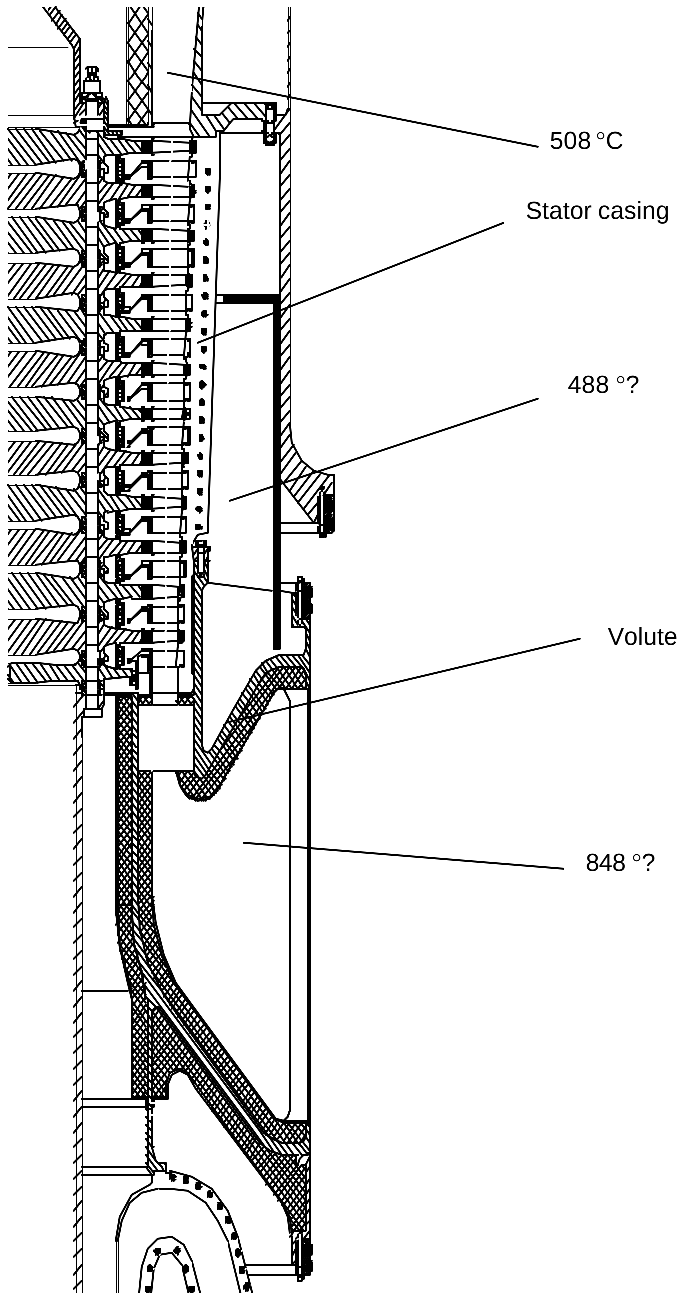
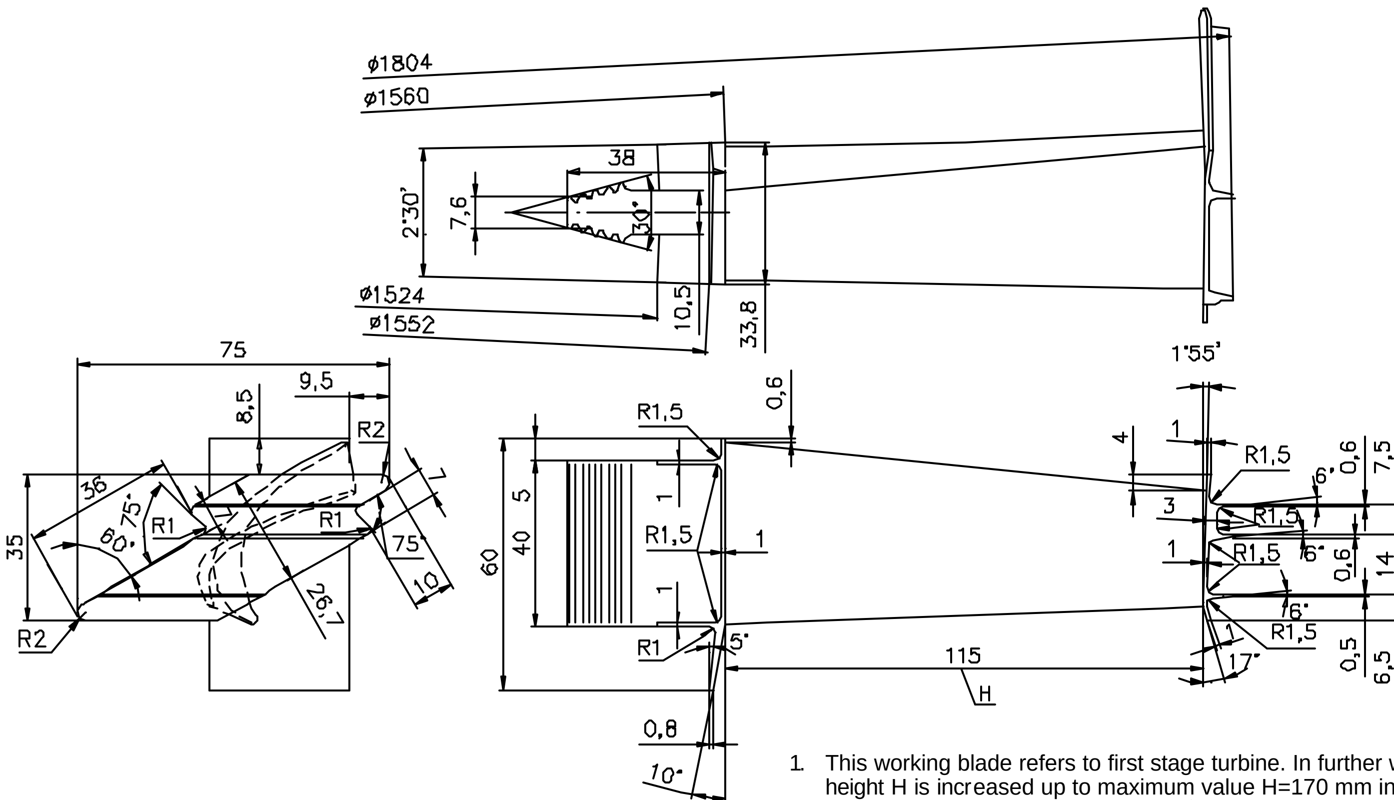
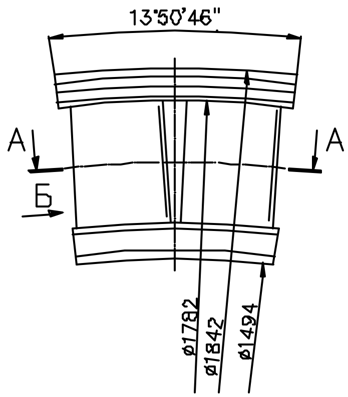


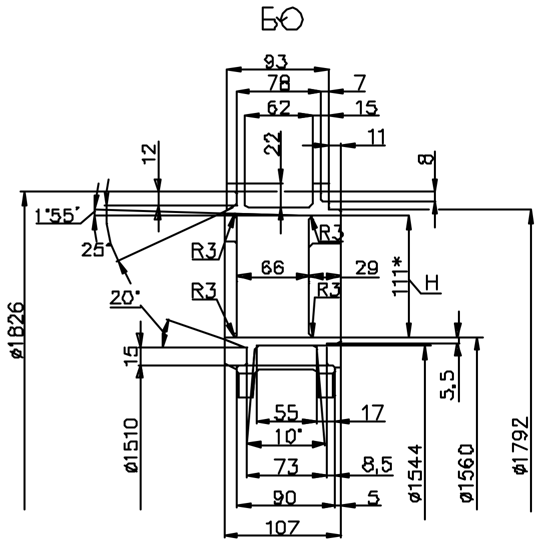
Figure 1 – General view of the turbine components



1. This working blade refers to first stage turbine. In further working blades height H is increased up to maximum value H=170 mm in the last stage.
2. Material density is taken as 8.4 g/cm^3.
3. Requirements for material mechanical properties are specified in technical requirements for materials for turbocompressor main elements.

Figure 2- Sketch of the blade of the first stage turbine





1. This nozzle diaphragm refers to the turbine first stage. In further nozzle devices height H increases up to maximum size H=165 mm in the last stage.
2. Material density is taken as 8.4 g/cm^3.
3. Reference dimensions.
4. Requirements for mechanical properties of the material are specified in technical requirements for materials for main turbocompressor elements.

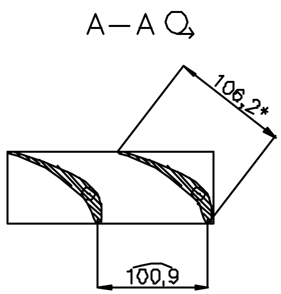
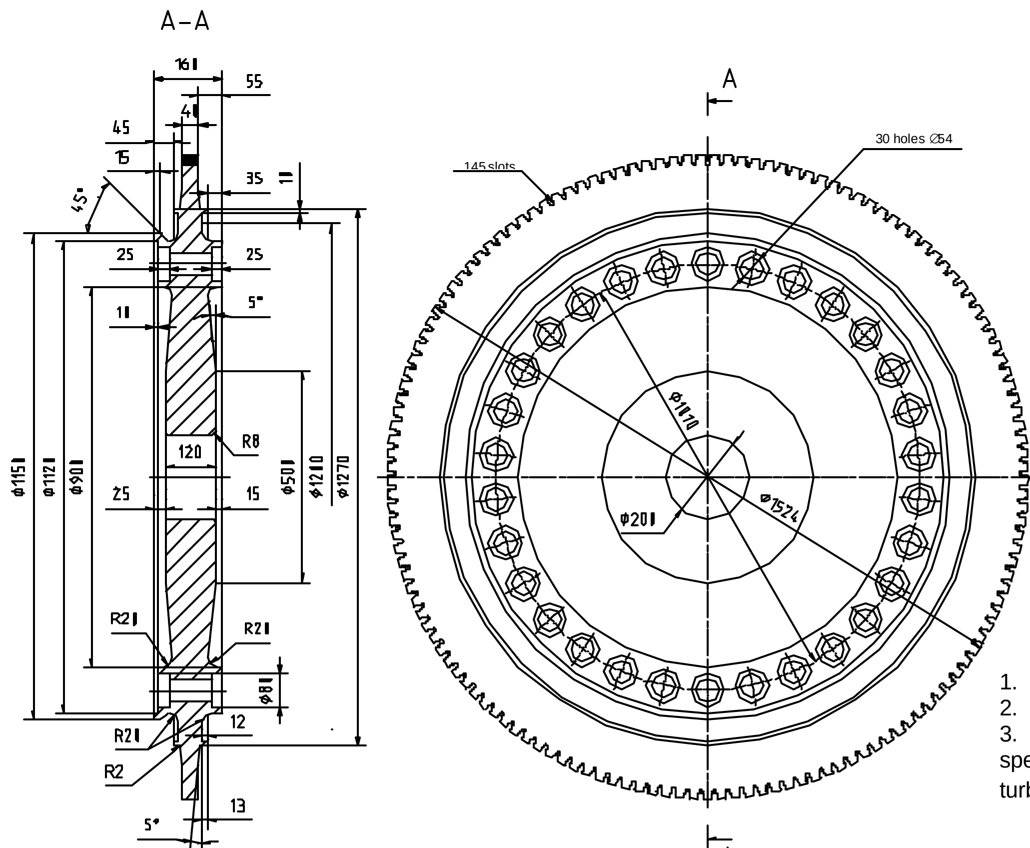
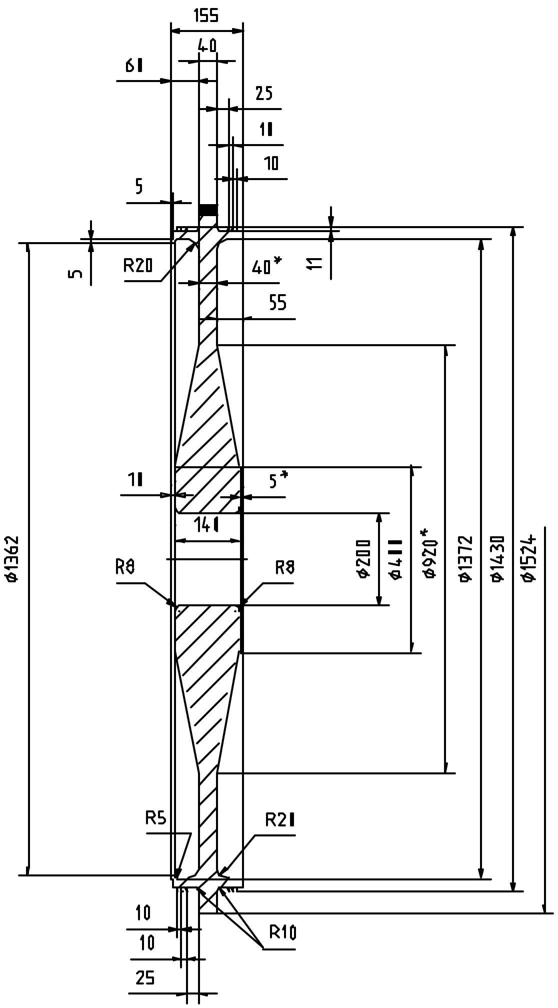


Figure 3– Sketch of the nozzle diaphragm of the first stage turbine



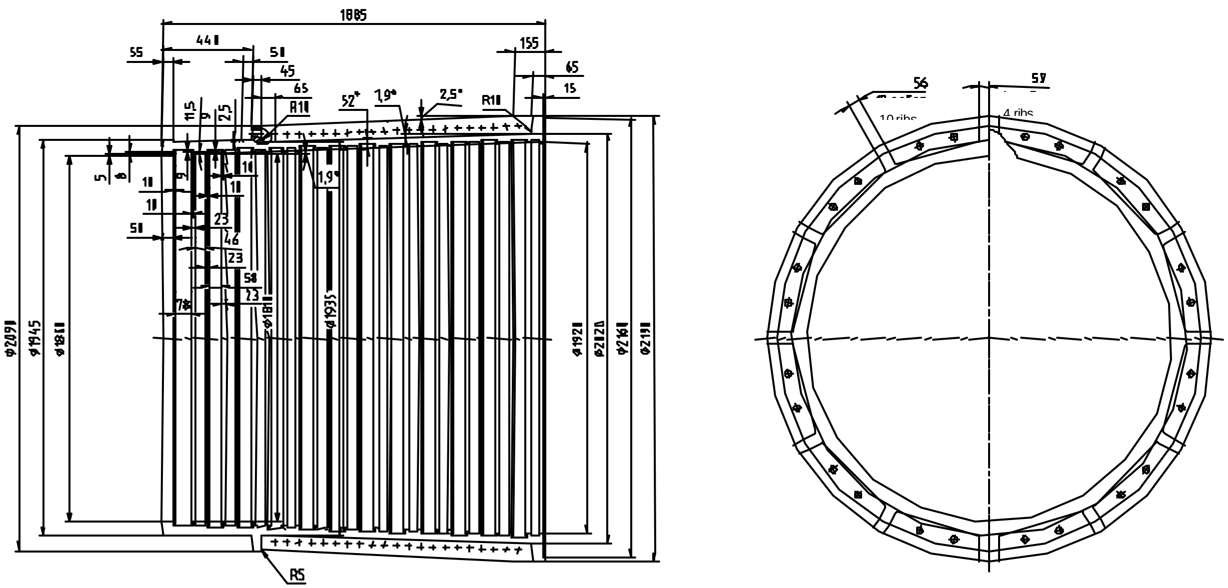
1. This disk is intended for turbine rotor assembly.
2. Material density is taken as 8.32 g/cm^3.
3. Requirements for mechanical properties of the material are specified in technical requirements for materials for main turbocompressor elements.

Figure 4 – Sketch of assembled turbine rotor disk



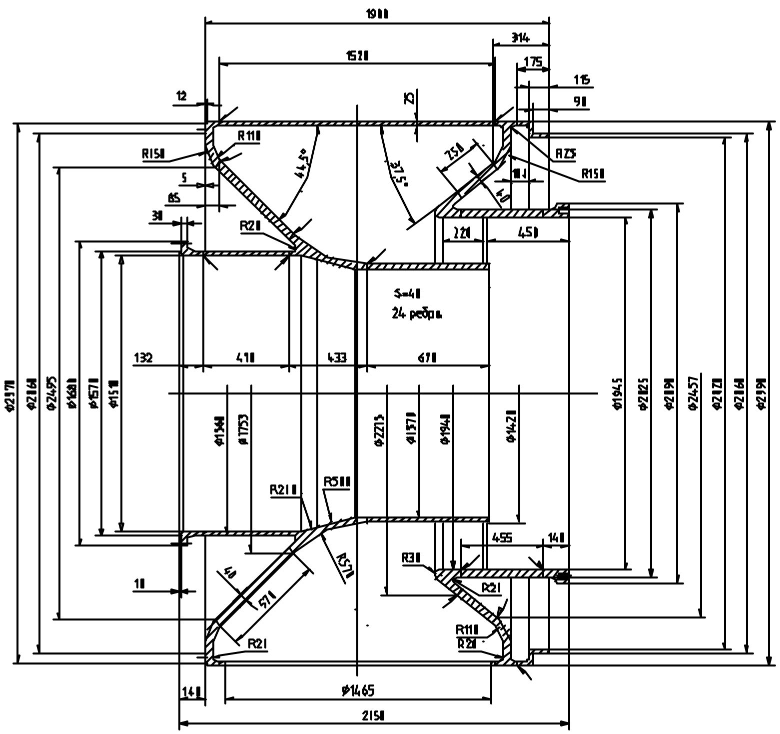
1. This disk is intended for welded turbine rotor.
2. Material density is taken as 8.32 g/cm^3.
3. Reference dimensions.
4. Requirements for mechanical properties of the material are specified in technical requirements for materials for main turbocompressor elements.

Figure 5 – Sketch of welded turbine rotor disk



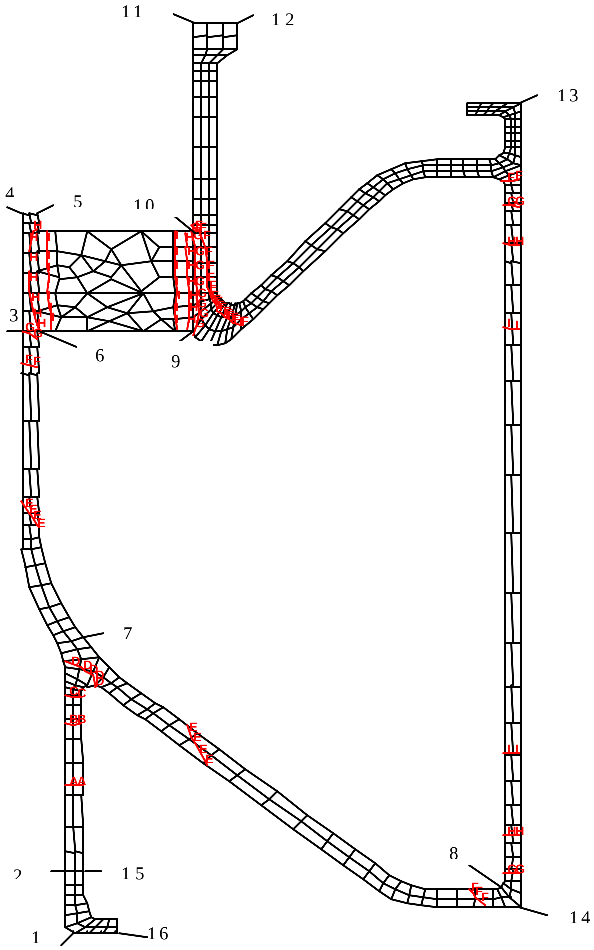
1. Material density is taken as 8.2 g/cm³.
2. Reference dimensions.
3. Requirements for mechanical properties of the material are specified in technical requirements for materials for main turbocompressor elements.

Figure 6 – Sketch of the turbine stator



1. The sketch shows planned location of welds. The number and arrangement of welds is to be determined when selecting the technological procedure of article manufacture.
2. Material density is taken as 8.2 g/cm^3.
3. Requirements for mechanical properties of the material are specified in technical requirements for materials for main turbocompressor elements.

Figure 7 –Volute sketch



? = 148.2
? = 230.5
C = 312.3
D = 395.2
E = 477.5
F = 559.8
G = 642.2
H = 724.4
I = 806.8

Figure 8 – Results of the calculation of the volute temperature state (^{0}?)

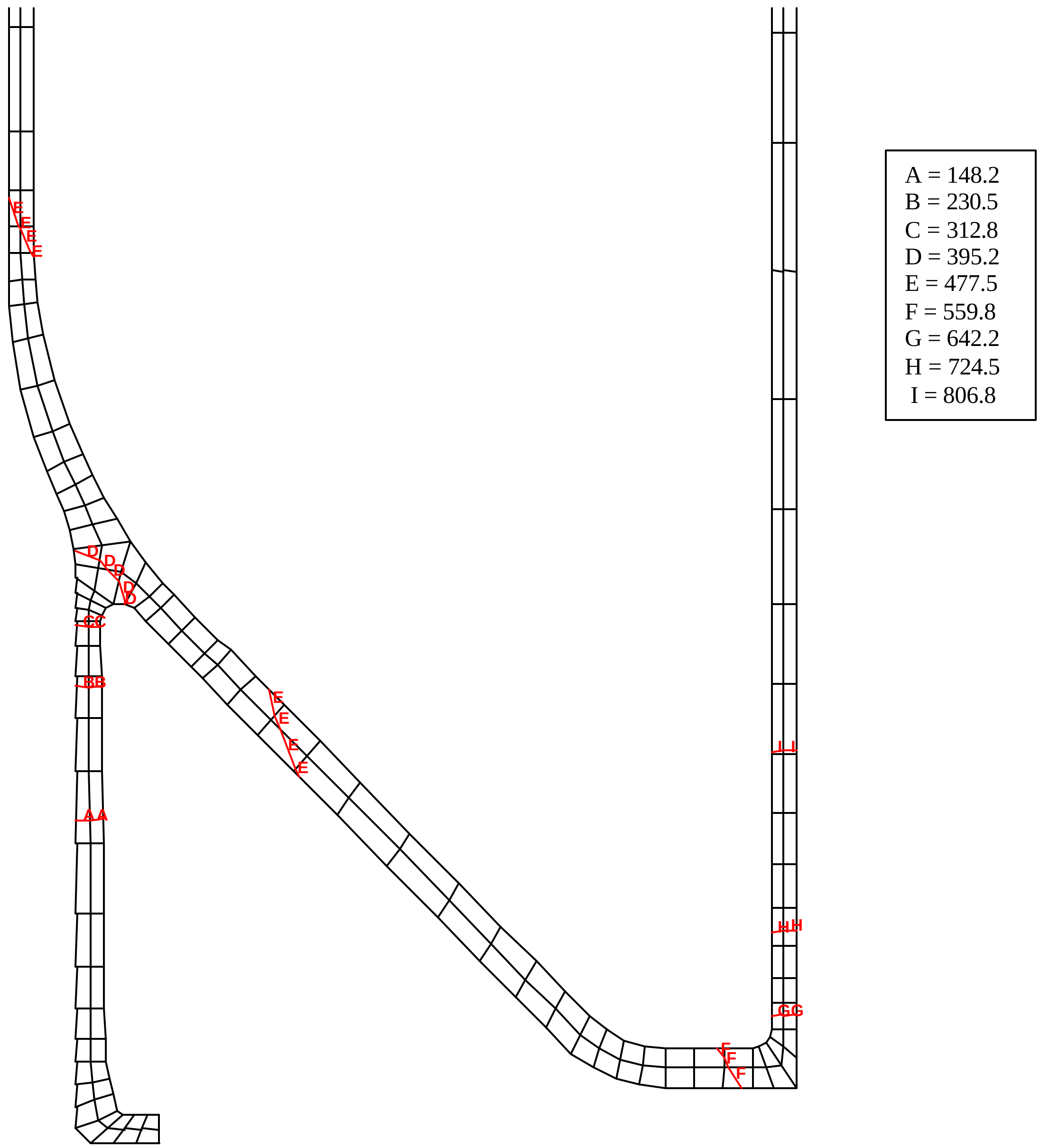


Figure 9 – Results of the calculation of the volute temperature state (^{0}?)

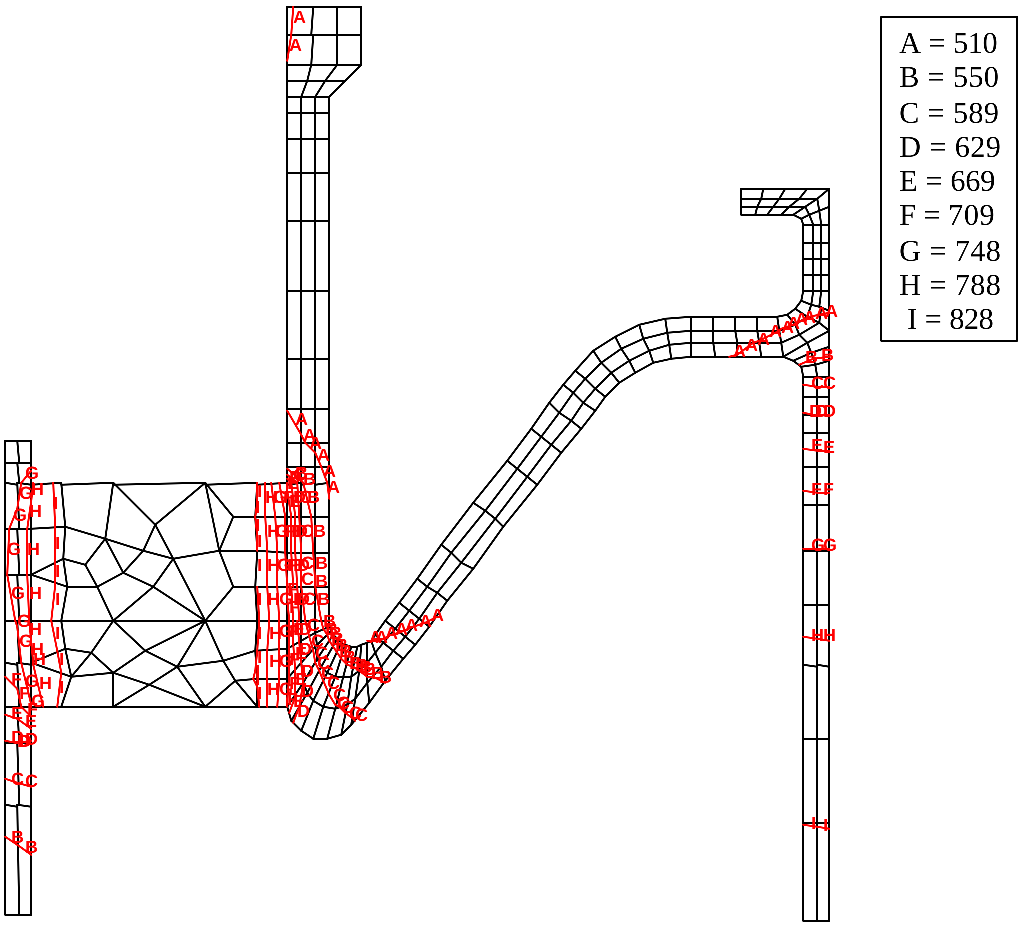


Figure 10 – Results of the calculation of the volute temperature state (^{0}?)

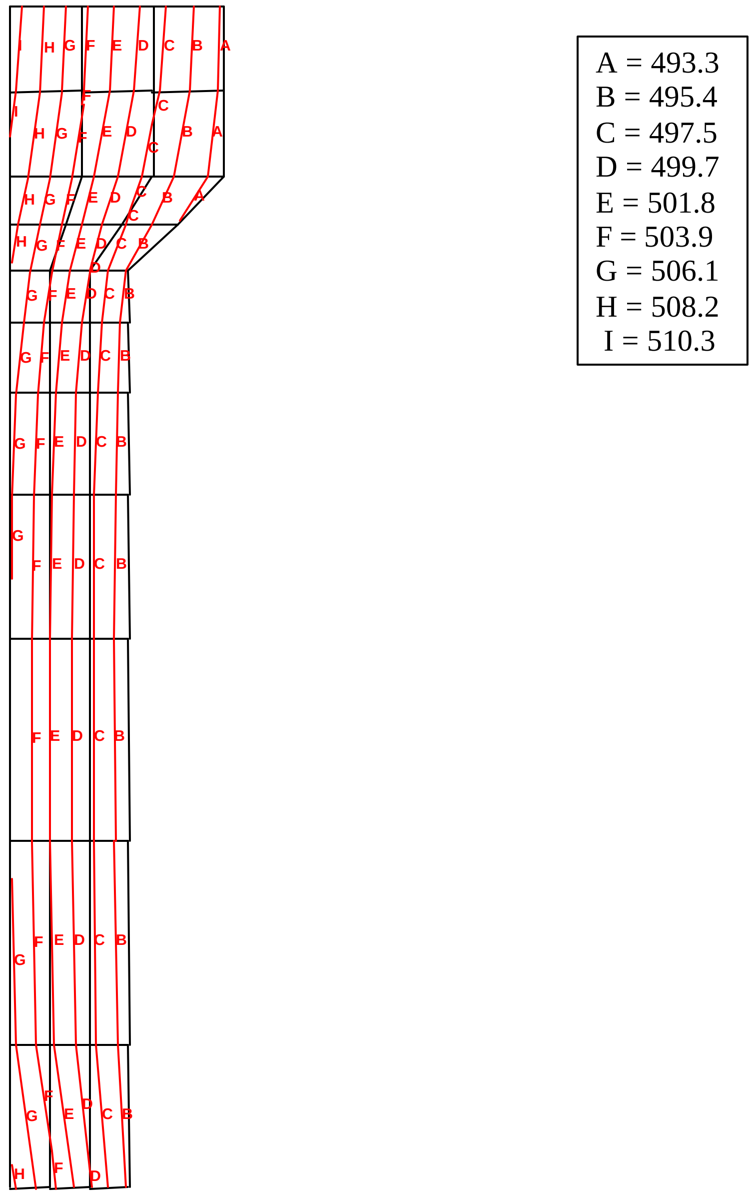


Figure 11 – Results of the calculation of the volute temperature state (^{0}?)

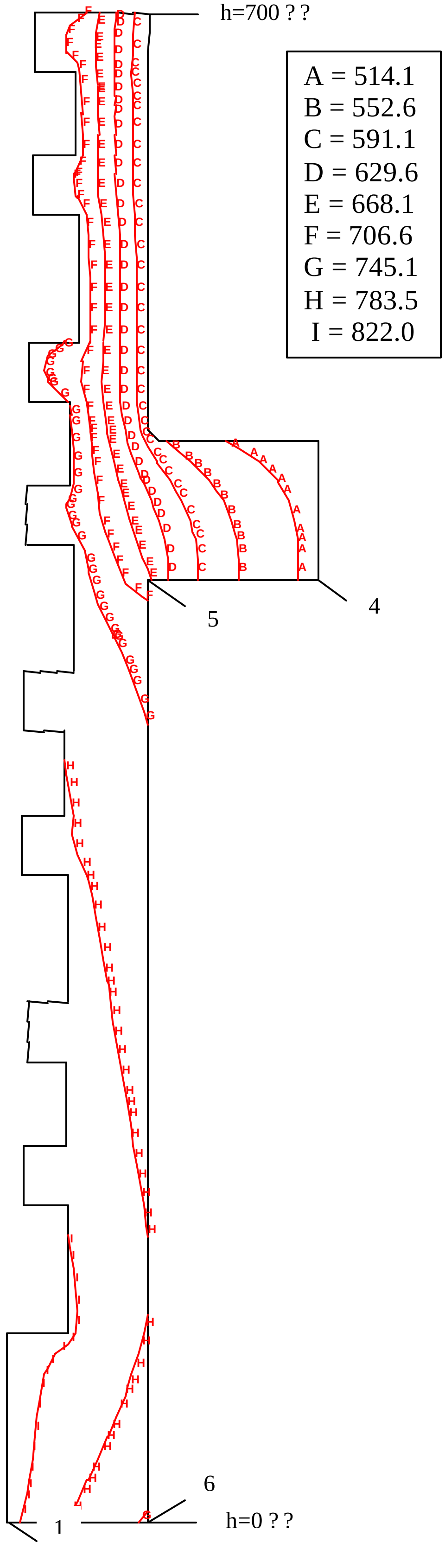


Figure 12 –Results of the calculation of the stator casing temperature state (^{0}?)

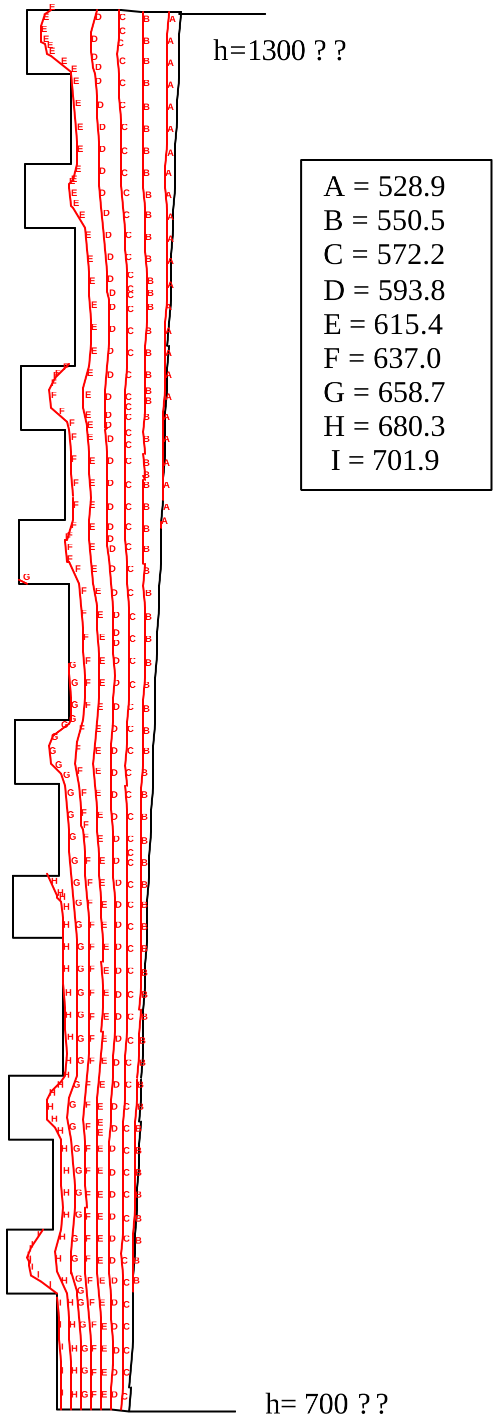


Figure 13 –Results of the calculation of the stator casing temperature state (^{0}?)

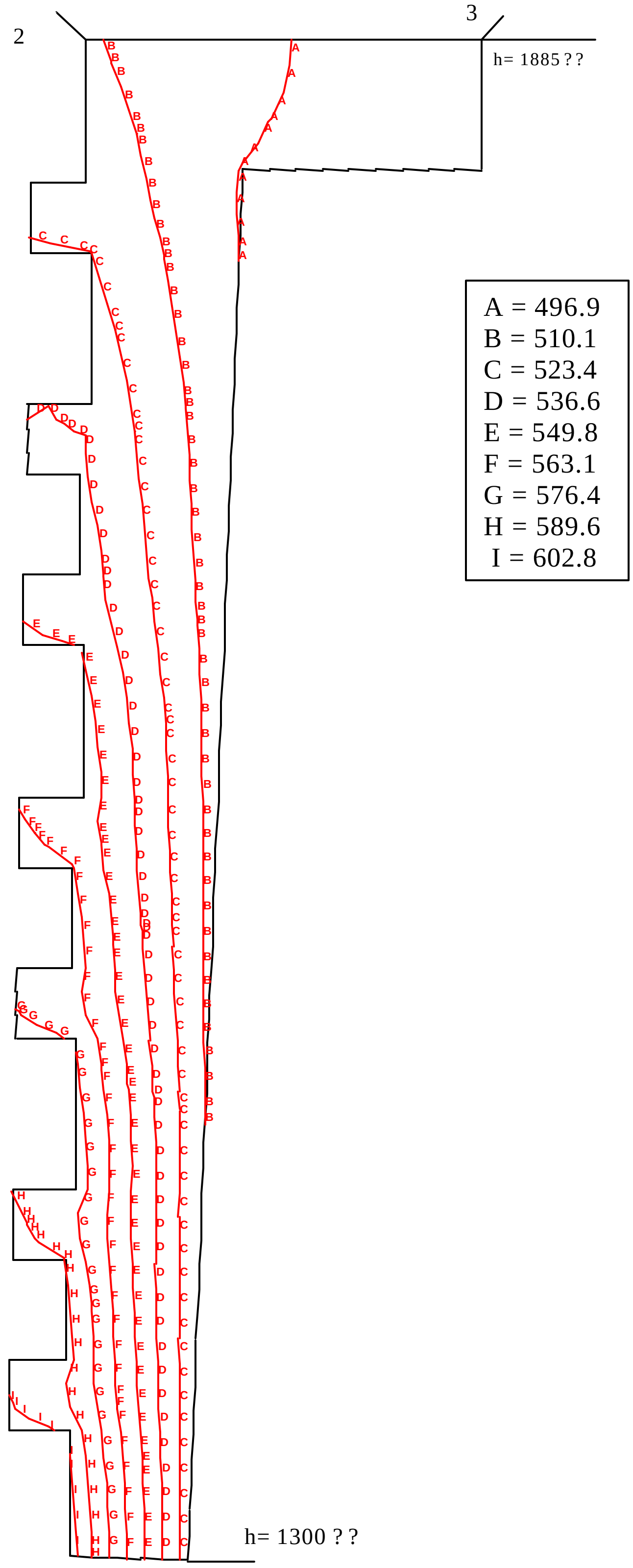


Figure 14 –Results of the calculation of the stator casing temperature state (^{0}?)

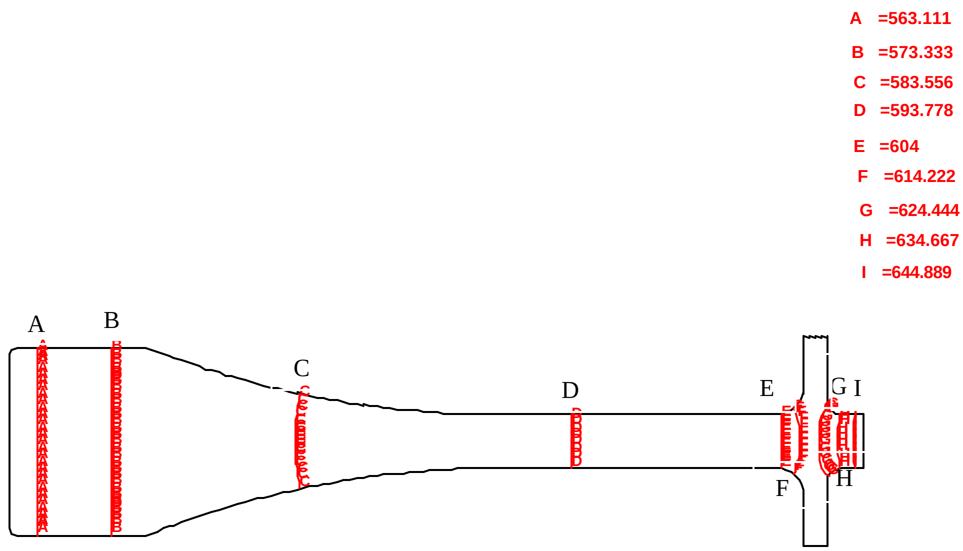


Figure 15 – Temperature (°?) of the first stage turbine disk of the welded rotor in 100% power operation mode

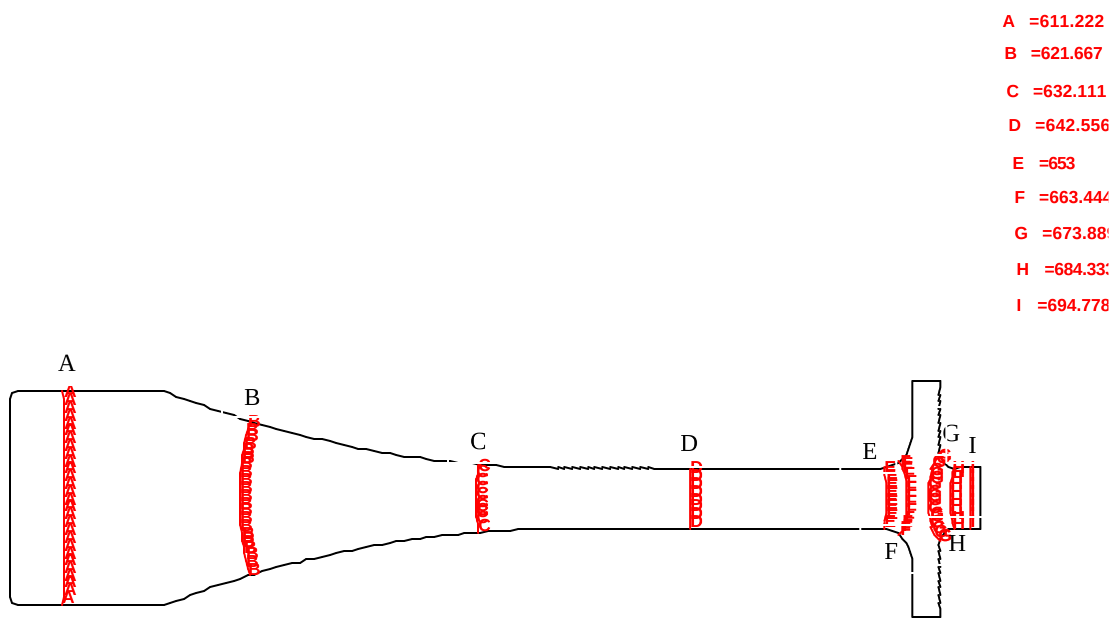


Figure 16 – Temperature (°?) of the first stage turbine disk of the welded rotor in 15% power operation mode

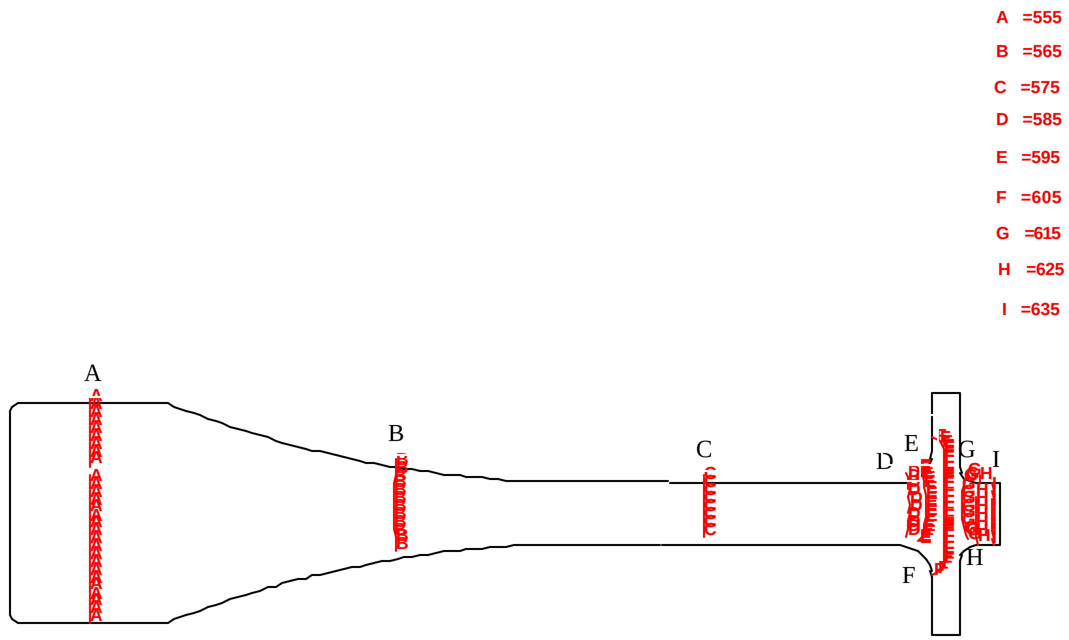


Figure 17 – Temperature (°?) of the second stage turbine disk of the welded rotor in 100% power operation mode

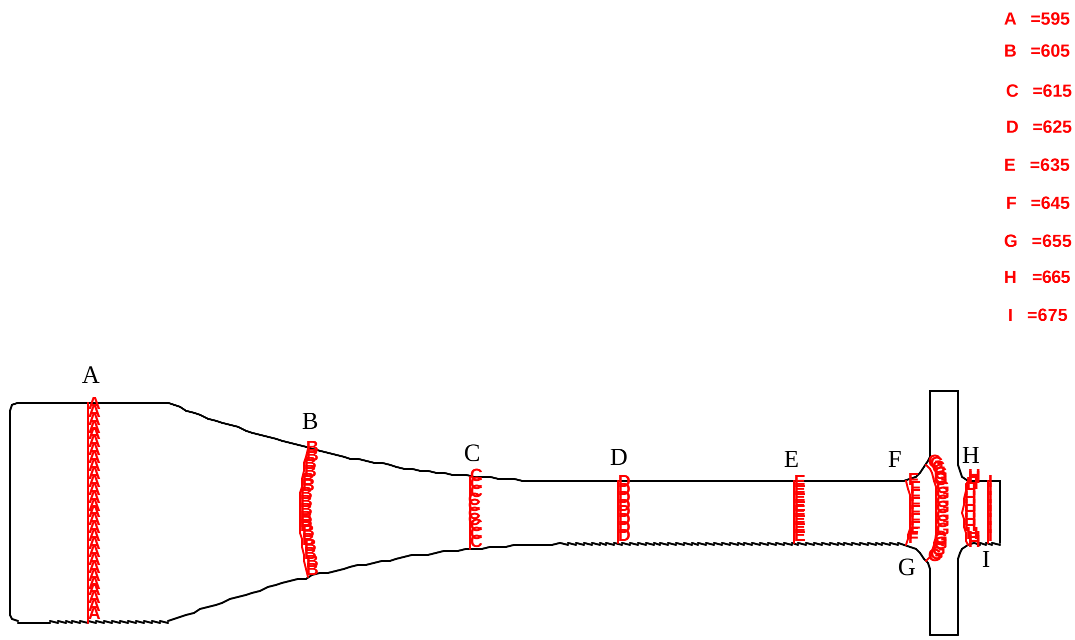


Figure 18 – Temperature (°?) of the second stage turbine disk of the welded rotor in 15% power operation mode

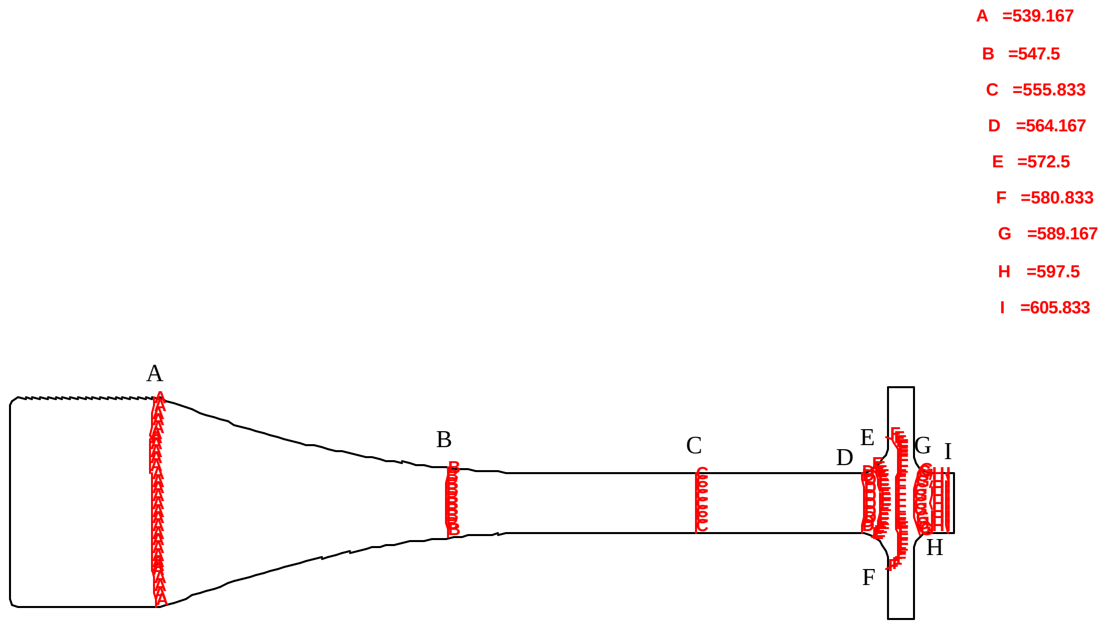


Figure 19 – Temperature (°?) of the third stage turbine disk of the welded rotor in 100% power operation mode

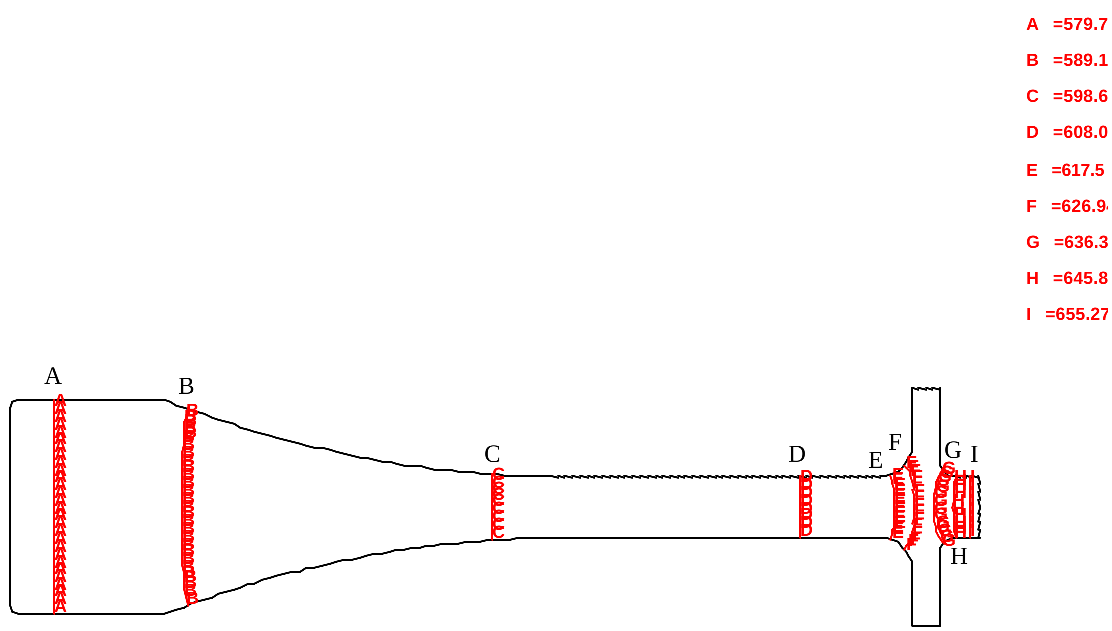


Figure 20 – Temperature (°?) of the third stage turbine disk of the welded rotor in 15% power operation mode

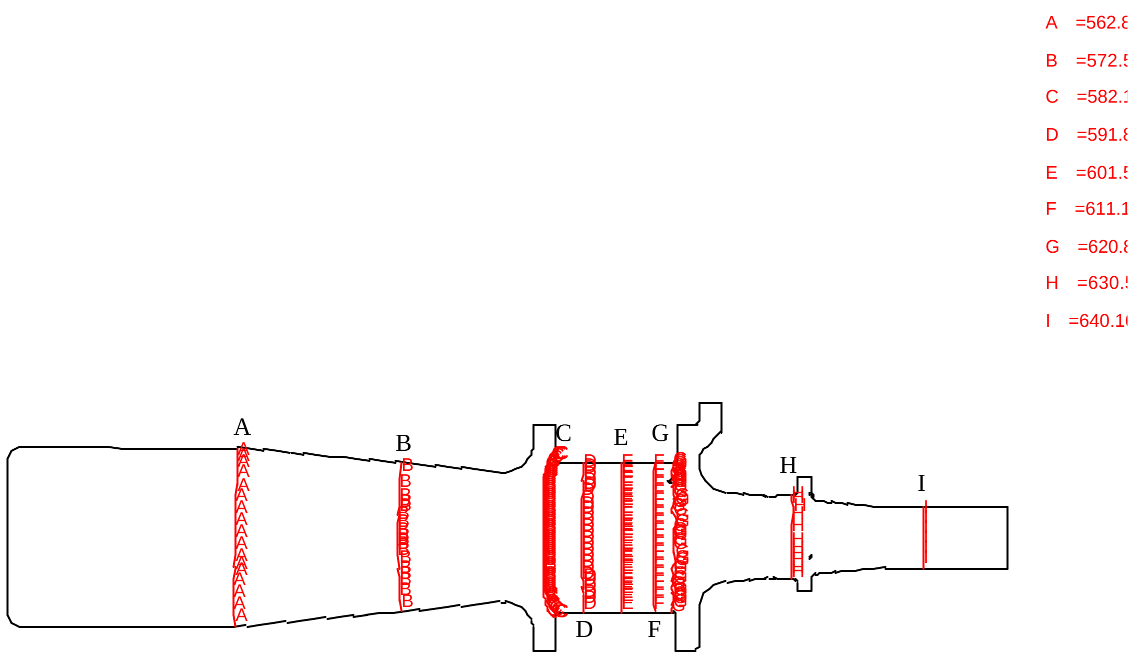


Figure 21 – Temperature (°?) of the first stage turbine disk of the assembled rotor in 100% power operation mode

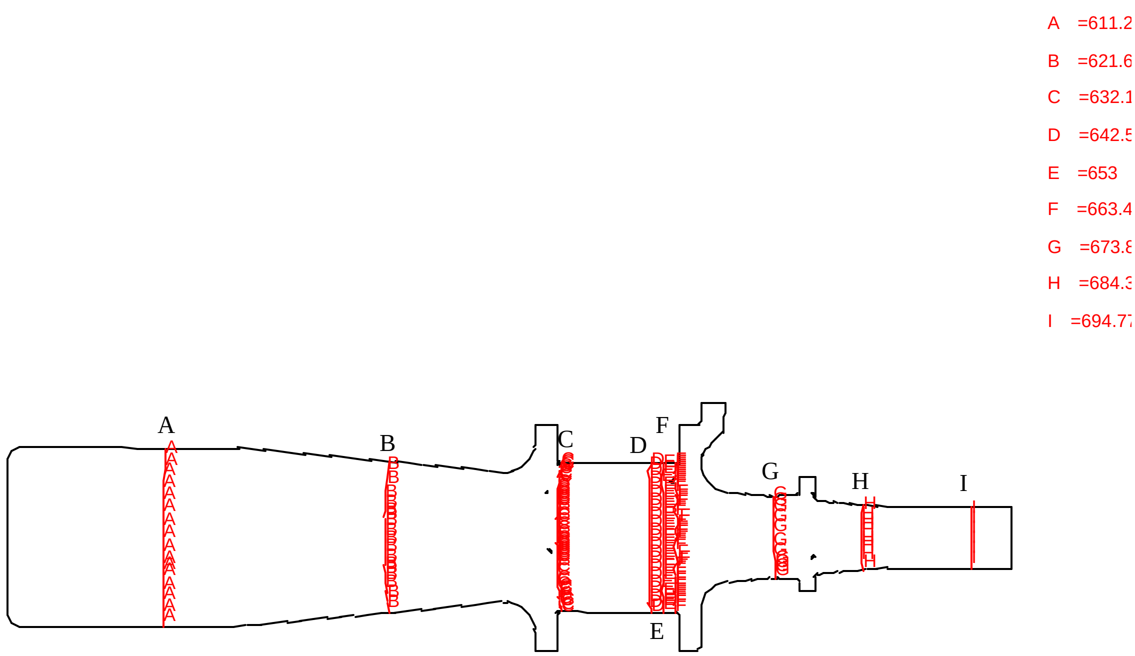


Figure 22 – Temperature (°?) of the first stage turbine disk of the assembled rotor in 15% power operation mode

- volute;
- "HPC - turbine" shaft line
- fastener (fastening of the volute with the turbine stator).

Duration of the RP operation at different levels of electric power within the control range is:

- with the maximal load 100 % N_{nom} – 85 % per year (7000 h per year);
- with the load not less than 80 % N_{nom} – 5 % per year;
- with the load not less than 50 % N_{nom} – 5 % per year;
- with the minimal load 15 % N_{nom} – 5 % per year.

For calculation of stresses in the most stressed TC elements the following modes are accepted:

- operation during maximal load (100 % power mode, mode No.1). The calculational duration of operation is accepted as 57000 h. The duration includes operation with the load not less than 80 % N_{nom} and with the load not less than 50 % Nnom;
- unit operation at the 15 % power mode (mode No.2). The calculational duration of operation is 3000 h;
- TC operation mode involving increase of the rotor nominal rotation speed by 20%, and short-period (approximately, up to 5 min) increase of coolant temperature in the turbine outlet up to 830 °? (complete loss of power mode – mode No.3). The coolant temperature in the turbine outlet with the 120% N_{nom} is about 600 °? .

Stressed state of the turbine components is determined by methods used in calculation of aviation turbines and with the use of finite elements method (a special computer program) in the axial-symmetric and 3-dimensional approximation.

Calculational loads are centrifugal forces, torques, weight loads, pressure drops, gas dynamic forces and temperature fields.

During determination of strength margin the following requirements are used: "Codes for NPP Equipment and Piping Strength Analysis …" PNAE G-7-002-86 /6/, for all the categories of said stresses.

The results of the calculation and components design have been analyzed by the Russian leading design institutes on gas-turbine plants. Some of the received remarks are allowed for in that Product and will be considered further on.

The analysis showed that all the considered turbine elements in the high level of temperatures, that cause structural materials creep, have a quite high stress level. All that with the specified 60000 h lifetime puts high requirements to the mechanical characteristics of the used structural materials, the key requirements being the ultimate long-term strength and creep.

Based on the results of the analysis, input requirements have been formulated for materials properties of the turbine structural elements under consideration.

The basic requirements for strength properties of materials are given in Table 1.

Table 1 – Minimal values of the material mechanical properties for the turbine most stressed components and elements

Values in MPa

Turbine component	Calculational temperature, °?	Yield strength $R^{T}_{p0.2}$	Ultimate strength R^{T}_{m}	Ultimate long-term strength duting time t , RTmt			Creep strength, $R^{T}_{\Delta\varepsilon/60000}$
				10000 h	60000 h	100000 h	
Operation blade	550	216	374	281	-	177	-
	600	179	310	-	-	-	-
	830	176	304	228	-	140	128/164
Nozzle blade	550	245	424	-	318	-	-
	850	139	240	-	180	-	-
Turbine disk for the assembly structure (cooled)	650	422	731	-	392	-	270/295
	700	171	297	-	143	-	174/200
Turbine disk for the assembly structure (non-cooled)	800	422	731	-	392	-	-
	820	171	297	-	143	-	74/100
Turbine disk for the welded structure (cooled)	650	251	434	-	364	-	270/295
	700	171	297	-	143	-	174/200
Turbine disk for the welded structure (non-cooled)	800	251	434	-	364	-	-
	820	171	297	-	143	-	74/100
Stator	600	96	165	-	96	-	-
	830	30	52	-	30	-	40/-
	850	15	26	-	15	-	20/-
Volute	750	60	104	-	110	-	-/80
	850	30	52	-	30	-	-/40
Fastener	650	120	-	-	180	-	100/-
Shaft line	500	309	536	-	273	-	-

Note – The creep strength values in the numerator is given for deformation as 0.2% and in the denominator for deformation as 1 % on the 60000 h basis.

Apart from the strength characteristics, plasticity parameters are also important to provide details operability in cyclic stressing ($?^{?}$ - extension strain, Z^{T} - compressive strain, $a_{?}$ - impact strength), fatigue resistance characteristics (for example, static and cyclic deformation diagram, fatigue curves in stressing with the specified deformations and material ultimate resistance with the specified cycle number and others) are also important.

These characteristics together with the physical properties of the turbine structural materials (density, elasticity module, linear expansion coefficient) must be determined.

6.1.2 Based on results, technical requirements were determined for turbocompressor key components with account of the spefified lifetime, maximum loads and safety factors.

The preliminary selection of the candidate materials is made for the above-mentioned TC components, based on the required values of long-term ultimate strengths and creep.

TC components candidate materials are, according to that Product, those indicated in Table 2.

Table 2 – TC components candidate materials

Component	Material
Nozzle blades and operation turbines	ZhS6, ZhS40, (ZhS26, ZhS32, ZhS36 – with cobalt)
Turbine rotor disks	EI698M, EP741??, EP975ID, EP962E, EP202
Inlet volute, beyond turbine diffuser	ChS-57, EP99ID, EP202
Turbine stator casing	EP99ID, ChS-57, VZhL-14H, EP202
Shaft line	EP517, EP975ID, EP741NP, EP962E
Fastener	EI893, EI698

6.1.3 It was shown that to find out the possibility of getting details with the required sizes from the selected high-temperature alloys that have low manufacturability in hot process, it is necessary to perform experimental activities for adjustment of the manufacturing technology.

6.1.4 To confirm the operability of the selected materials during specified lifetime qualification tests and investigations are required with the specified operational parameters.

The issue of confirming the operability during 60000 h is of special difficulty.

6.1.5 Bearing in mind that high-temperature alloys, containing cobalt, possess increased high-temperature properties and are more manufacturable, it is necessary to clear out its allowed content in the used materials during details manufacturing.

6.2 Stage ?-2. Analysis of adapted modern technologies of turbocompressor key elements manufacture.

Works under this stage resulted in issuance of research work report “Analysis of modern manufacturing technology of turbocompressor key components” (Product 02.03-35.2?, Inv.No.0206091).

Summary of this report is given below:

6.2.1 This work briefly handles history of occurrence of modern materials for manufacturing of turbocompressor key components, which is closely connected to occurrence and development of jet engines in aircraft construction.

For such purposes the most advanced materials are superalloys used at temperatures closed to melting temperatures.

Nowadays they use three basic classes of superalloys according to their basis: nickel, cobalt and on the basis of iron.

6.2.2 The report provides analysis of world and Russian experience in using structural materials and manufacturing technologies for turbine key components in aircraft and industrial turbine construction.

It is noted that in domestic and foreign practices high-temperature nickel alloys are applied, which based on their processing technology are divided into deformable and foundry ones. Deformable alloys are used for manufacturing high-loaded parts, such as disks, shafts, rings (stators), and foundry ones are for manufacturing the operating and directing blades. Lately granulated alloys are also applied rather widely.

The report takes up domestic and foreign (first of all, USA’s) experience in application of deformable and foundry alloys for manufacturing high-loaded parts.

The accent is made on the analysis of influence of chemical content on the level of mechanical and technological properties of the alloys under consideration.

Importance of alloy weldability is noted, specifically, for large-sized turbocompressor components, and also ways of improving this characteristic, including ways of increasing resistance of metals against cracking in near-weld zone are described.

6.2.3 A close connection is shown between heat resistance (high-temperature strength) characteristics of alloys and technology of making materials and products from them that causes a necessity of the comprehensive solution for material authority and technological issues.

6.2.4 Consideration of selection criteria for the materials started in the product 02.03-35.1? and selection of materials for turbocompressor components is continued.

Characteristics of various alloys for turbocompressor components, and in particular, those indicated in tables 3, 4, 5, are listed and discussed.

Table 3 – Temperature ?$^{\gamma'}$ and long durability of foundry blade materials for aviation gas–turbine engines

Alloy	?$^{\gamma}_{red}$, ^{0}?	s_{1000}^{800}, MPa	s_{1000}^{820}, MPa	s_{1000}^{870}, MPa	S_{60000}^{800}, MPa	S_{60000}^{850}, MPa
ZhS6	1185	380	-	-	209*	146*
ZhS6K	1200	420	-	-	208*	152*
ZhS6U	1225	480	-	-	247*	171*
In713LC	1180	350	330	205	180*	124*
M22	1220	420	-	285	256*	174*
TRW1800	1215	-	420	-	-	190*
MarM200	1200	-	420	-	-	168*
MarM247	1220	-	450	305	-	218*
* the given values are obtained by extrapolation.						

Table 4 – Calculational characteristics of corrosion-proof high-temperature alloys for blades of stationary gas-turbine plants

Alloy mark	Structure	?'-phase amount, %	?$^{\gamma}_{red}$, ^{0}?	?=?$_{L}$-T$_{S}$, ^{0}?	s_{1000}^{800}, MPa	s_{60000}^{800}, MPa	s_{60000}^{850}, MPa
ChS-70-VI	equiaxial	43.0	1165	105	380	200	135
In738LC	equiaxial	46.0	1170	95	375	183	104
Rene 80	equiaxial	45.5	1185	98	379	222	152
In 792	equiaxial	59.0	1190	80	395	230	151
DS-16	columnar	65.4	1161	120	340	175	115
DSgTD-111	columnar	58.0	1144	85	350	205	125
In 792 LC	columnar	61.9	1200	91	419	236	154
TsNK-7	columnar	47.8	1185	104	365	185	110
SC-16	mono	43.4	1177	103	397	226	152
?WA-1483	mono	60.0	1163	99	410	242	161
ChS120VI	mono	54.2	1240	84	475	260	215
TsNK8 MP	mono	53.5	1247	100	405	225	155

Table 5 – Long durability of nickel alloys for turbine casing components

Alloy mark	Long durability, MPa					
	$s_{1000}^{?}$			$s_{10000}^{?}$		
	700 ^{0}?	800 ^{0}?	850 ^{0}?	700 ^{0}?	800 ^{0}?	850 ^{0}?
VZh98	140	60	-	85	40	-
ChS-57	-	70	48	95	42	30
EP99-ID	500	250	-	210	80	-
EP202	398	204	133	326	153	82
VZhL-14?	-	205	140	-	-	-
Hastelloy ?	159*	78*	49*	-	-	-
Nimonik 263	430*	165*	92*	-	-	-
Inkonel 617	240*	100*	68*	-	70	45
* the given values are obtained by extrapolation.						

6.2.5 Nature of influence of cobalt upon operational and technological properties of materials is discussed; the advisability of works for determination of its allowable contents in the materials used for manufacturing of TC components is substantiated.

Based on results of the analysis of foreign and domestic literature, the role of cobalt in high-temperature nickel alloys is characterized in table 6.

Table 6 – Positive influence of cobalt on characteristics of superalloys

Mechanical	Structural
1. Improves technological plasticity 2. Increases time before energized destruction 3. Enhances durability by increasing resistance to oxidation and corrosion	1. Reduces energy of packing defects 2. Reduces solubility Al and Ti in gamma -matrix 3. Increases a volume fraction of gamma-phase 4. Increases ? at which fusion starts 5. Increases solubility of carbon 6. Stabilizes an alloy

6.2.6 Absence of practical experience in manufacturing of TC components of the required sizes and experimental verification of their serviceability in conditions operation during the specified lifetime is noted. A necessity to perform qualification tests and investigations of materials with involving specialized material authority institutes is emphasized.

6.2.7 The enterprises, possible manufacturers of TC materials and components, are proposed.

6.2.8 Results of the report allow drawing a conclusion as to a principal practicability of manufacturing the TC components in Russia after appropriate R&D is complete.

6.3 Stage A-3. Selection of materials and technological methods of turbocompressor parts manufacture.

Results of works required by this stage are summarized in the research work report “Selection of materials and production process methods of turbocompressor components“ (Product 02.03-35.3A, Inv.No.0210250).

Contents of this report may be briefed as follows:

6.3.1 This work offers key technological procedures for manufacture of the following turbocompressor components: nozzle and working blades, discs, stator, volute, and shaft line, fixing and tightening parts of the turbine.

Two technological procedures have been selected for blades manufacture, and they are represented in Figures 23, 24 in diagram form.

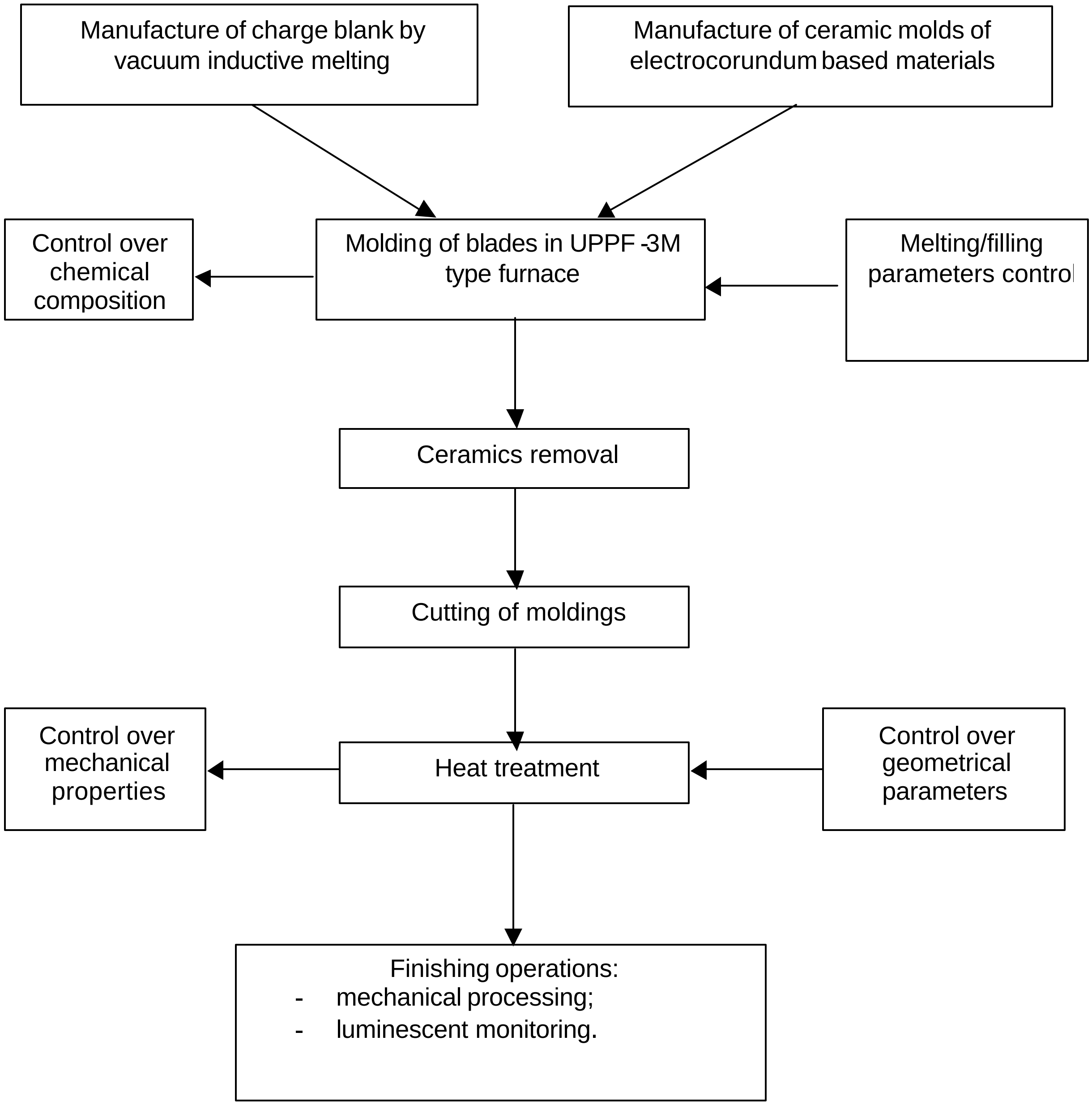


Figure 23 – Technological Procedure of Manufacture of Plant Turbine Blades with Equiaxial Structure

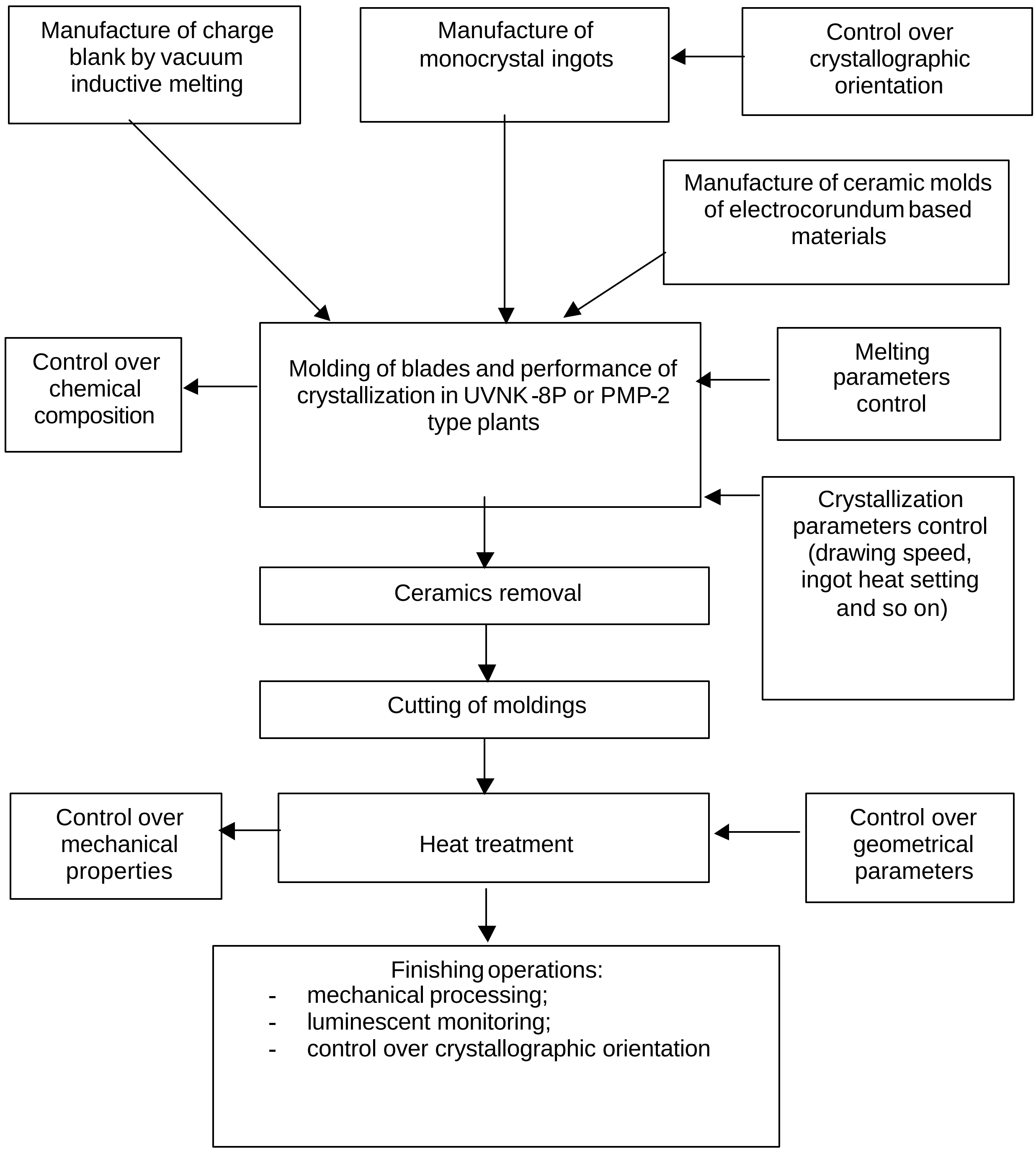


Figure 24 – Technological Procedure of Manufacture of Plant Turbine Blades with Monocrystal Structure

6.3.2 As technological procedures of rotor discs manufacture, forming on powerful presses and granule metallurgy with application technology are considered.

The most widespread method of industrial manufacture of large-diameter turbine rotor disc blanks is the forming on powerful presses.

Here are the main stages of the manufacturing technology:

- melting of ingots using VIM+VAR doplex-process (vacuum inductive melting and vacuum arc remelting);
- first stage of plastic deformation of ingot with making forged bar or extruded bar of ˜ 600 mm diameter and 1500–2000 mm length on hydraulic presses by applying 5000 t·f force;
- making of blanks of the required geometry (of 1000–1500 mm diameter) by upset of forged or extruded bars on the presses by applying 10000- 30000 t·f force;
- mechanical processing of discs and cutting of special V-shaped slots for working blades.

Since 1995 using this technology OAO VILS has been manufacturing large-sized molds of 1200 mm, 1250 kg weight of EI698VD alloy for sets of DG80 and DG90 type gas turbine plant turbine discs /3/.

During last decade OAO VILS has developed manufacturing technologies for large-sized discs by direct upset of ingots using VIM+VAR out of more complicatedly doped heat-resistant (high-temperature) alloys (containing 45–50% of g'- phase) of EK79 and EP975 type.

Practical experience in using alloys of EI698VD, EP975ID type and this technology in Russian enterprises allows us to hope for their successful application for plant turbine.

Occurrence of liquation processes during crystallization of large ingots represents a main reason for chemical and microstructure heterogeneity of large-sized half-finished articles and instability of mechanical properties of high-temperature materials used.

Granule metallurgy /4,5/, which combines liquid melt consolidation in form of micro ingots, i.e. granules with high cooling rate (10^3–10^4 ^{0}C/sec), with their subsequent compacting by hot isostatic pressing, makes it possible to avoid shortcomings of molded structure of large ingots. Besides, such technology causes a necessity to make articles out of high-temperature alloys with more intense doping, as well as to shape precise blanks, in terms of configuration close to the finished article and requiring no plastic deformation. This, in its turn, decreases consumption of charge materials and, accordingly, the prime cost of finished articles.

To implement this technology alloy EP741NP and new experimental alloy EP962E represent the most promising materials.

The main obstacle for using the granule technology for turbine discs manufacture is the limited workspace of domestic gas static vessels.

Technologies, which have not found widespread application for manufacture of discs for land-based gas turbine power plants, are discussed in brief.

6.3.3 Difficulties in or even impossibility of manufacturing of large-sized parts (for volute, stator, and shaft line) using the following technologies are noted:

- VIM+VAR ingot deformation;
- granule metallurgy.

The development of principal manufacturing technology for large-sized turbine units with the help of welding has been started.

6.3.4 Technological procedures have been selected with account of marks of materials regarded as candidate ones for above listed turbocompressor components: ZhS6, ZhS40, ChS57, EI698U.VD, EI437BU.VD, EP517 and more heat-resistant EP975ID, EP741NP, EP962E, EP99ID, EI765VD.

6.3.5 A necessity to solve a problem concerning applicability of cobalt-containing alloys has been confirmed.

6.3.6 Optimization issues for service properties of the most loaded turbocompressor components at the expense of structural and technological solutions have been considered.

6.3.7 Type-dimensions and number of blanks of models of turbocompressor full-scale parts required for tests have been determined.

6.4 Stage ?-4. Purchase of materials and manufacture of billets for pilot experimental activities performance

Results of works under this stage are summarized in research work report “Manufacture of blanks to perform pilot-experimental activities on development of turbocompressor materials” (Product 02.03-35.4? , Inv.No. 0210251).

Contents of the report may be briefed as follows:

6.4.1 This work offers recommendations on changing (within valid documentation for the delivery) the chemical composition of alloys ZhS6, EP99ID, EP741NP and EP975ID, which ensures their phase and structural stability and stability of their service characteristics.

Narrowing of concentration limits of main chemical elements within the framework of the valid specifications for delivery of high-temperature materials represents a quite effective measure aimed at stabilizing their service properties.

Such narrowing of limits expressed in practice as a decrease of upper concentration limit of some main components of the materials under consideration, correlates with computer calculations of their phase stability by Md – Phacomp /6/, which showed for alloys EP741NP, EP975NP and ZhS6 at upper alloying limit $M\overline{dt}$ = 1.017, 1.013 and 0.998, accordingly, and $M\overline{dt}_{cr}$ = 0.991 for critical value.

As for alloys ZhS40 and EI698U.VD, then they have rather modern (narrow) alloying limits, phase and structural stability ($M\overline{dt}$ < 0.991), and their use for turbine blades and discs does not require changes to be included in technological documentation for their delivery.

6.4.2 Technological procedures have been considered for melting of candidate and prospective high-temperature alloys under consideration for turbine key components in vacuum-induction furnaces and at vacuum arc remelting.

6.4.3 Information has been provided as to manufacture of pilot lot of granules of alloys EP741NP and EP962E for reprocessing by granule metallurgy methods.

As per the work, ~ 55 kg of granules of alloys EP741NP and ~ 45 kg of granules of experimental alloy EP962E have been got. Granules have been obtained by a method of dispersing of rotating electrode of 75 mm diameter, being cast after materials melting in vacuum induction furnace.

6.4.4 Based on dimensions of turbocompressor components, experience, technological capabilities and a necessity to minimize costs of work, dimensions of open inductive melting and vacuum inductive melting electrodes have been recommended.

6.5 Stage ?-5. Development and manufacture of test lot of welding materials for TC elements of welding design

Results of works under this stage are summarized in research work report "Development and manufacture of welding materials pilot batch for welding structure turbocompressor components" (Product 02.03-35.5A, Inv.No.0210252).

Contents of the report may be briefed as follows:

6.5.1 Selection of welding methods and equipment for making turbocompressor welded structures has been made.

The analysis of existing design solutions and manufacturing technology for turbocompressor design components has shown that one of the main ways of increasing manufacturability, metal use factor, decreasing labor and energy intensity of the article will be application of welding.

The main welding process is automated argon-arc welding by nonconsumable electrode without/with using additives. As many-year practice of MMPP "Salyut" and other associations shows, it is a quite reliable method to get original structures of gas-turbine engines by high-energy stream welding method. This method makes it possible to get a joint with the large relation of weld depth to its width, achieving 30:1 with minimum deformations.

Electron-beam welding process will be widely used for manufacture of turbocompressor stator, shaft line and volute, as there is a necessity to join parts mechanically processed in full, practically, with fine precision. Manufacture of gas turbine welded large-sized parts, such as casings, rings, has been successfully mastered at large-scale production enterprises long ago, in particular, at MMPP "Salyut". The said units are welded at domestic plants of ELU-5, ELU-9, ELU-10, ELU-20 type.

According to requirements specified for turbocompressor components and their design features, a part of them, namely: volute and stator, shall be manufactured out of weldable nickel alloys. At the first stage of work weldability of selected welded alloy EP99ID by argon-arc and electron-beam welding will be evaluated. Subject to results gained, a type of welding for the alloy under investigation will be selected.

6.5.2 100 kg of hot-rolled rod of 40 mm diameter were obtained for experimental works.

During argon-arc welding of articles of alloy EP99ID, as adding material nickel alloy EP533 or basic alloy EP99 are used. Experiments for evaluation of weldability will be performed on samples of 20x50x250 mm dimensions. Blanks of such dimensions will be welded together by two types of welding to get plates of 20x100x250 mm dimensions. Further on, out of these plates samples will be manufactured, which will have a welded joint for performance of mechanical tests.

To get blanks of 20x50x250 mm dimensions, samples of 200 mm length have been cut off from the rod of 40 mm diameter, which have been upset by, approximately, 30 mm thickness at 1130 °C. Flat blanks obtained were hot rolled into samples of the required dimensions. So, 6 blanks of 20x50x250 mm dimensions designed for further argon-arc and electron-beam welding were obtained.

6.5.3 Experiments and investigations of technological parameters have been performed for alloy EP99ID. As adding material wire Sv 08X20N57M8V8T3R (EP533) has been used. During the first series of experiments, optimum values of clearance have been selected. Welding has been performed by vertical beam (single-pass and double-pass types).

6.5.4 Scope of control tests has involved:

- metallographic investigations of welded joints of alloy EP99ID and measuring microhardness of welded joints along the melted zone and in fusion zone;
- determination of change in alloy constituent elements in various zones of welded joint using spectrum analysis;
- mechanical tests for short-term rupture, 100-hour long-term durability at 850 ^{0}C and impact strength. Impact strength tests are performed for Menazhe samples (knife cut shall be made in the weld and near-weld zone).

6.6 Stage ?-6. Development of manufacturing technological processes for nozzle and rotor blades of selected materials

Results of works under this stage are summarized in research work report “Manufacturing technology development of turbocompressor nozzle and rotor blades” (Product 02.03-35.6A, Inv.No. 0210253).

Contents of the report may be briefed as follows:

6.6.1 Manufacturing technology of blades by “precise melting in vacuum” method has been developed.

Increase in quality of foundry high-temperature alloys is ensured by their melting in vacuum inductive furnaces with overheating. This process has been given a name of temporary heat treatment. Melting shall be performed in tamped melting-pots of lining mixtures on the basis of electrocorundum, magnesite, electrocorundum-magnesite mixtures, or of alumel magnesia spinel, and also in ceramic melting-pot.

Additional burdening of vacuum melting alloys is necessary. Application of temporary heat treatment significantly increases stability of long durability, operational characteristics of melted parts and enhances quality of melting.

6.6.2 Optimum parameters of equiaxial-structure blades melting technology are discussed.

6.6.3 Optimum parameters of manufacturing technology of monocrystal blades by method of guided crystallization are discussed.

6.6.4 Design of needed melting tooling is discussed. Algorithm and main stages are described for design of melting tooling after receiving drawings for blades being manufactured.

6.7 Stage ?-7. Development of manufacturing technology for rotor discs of selected materials.

Results of works under this stage are summarized in research work report “Manufacturing technology development of turbocompressor rotor discs” (Product 02.03-35.7?, Inv.No. 0210254).

Contents of the report may be briefed as follows:

6.7.1 Deformation thermomechanical parameters have been refined for manufacturing turbine discs by forging and forming methods as applied to alloys EP741NP and EP962E.

6.7.2 Investigation of technological parameters in deformation (forming) temperature range for alloy EP975ID has been performed.

6.7.3 Thermomechanical parameters of manufacture of melted blank of alloy EP975ID have been determined.

6.7.4 Manufacturing technological process for rotor discs by powder metallurgy using hot isostatic pressing has been developed as applied to alloys EP741NP and EP962E.

6.8 Stage ?-8. Development of manufacturing technology for turbocompressor shaft line

During performance of works under this stage, it has been shown that shaft line model can be developed by two technological procedures:

1. By granule metallurgy method, i.e. by hot isostatic pressing of granules of alloy EP741NP;
2. By method of mechanical processing of extruded bar of high alloy EP975ID.

Reasons, which determine the complexity of applying these approaches to manufacture of a real shaft line, have been discussed.

Topicality of the task (indicated in Stage ?-3) for manufacturing this complicated and large-sized component of several parts with the help of welding has been confirmed.

Advisability of using the most heat-resistant weldable nickel based alloy EP99ID as a shaft line material has been noted.

In view of the above, three technological procedures have been tried out for manufacturing the shaft line model:

- hot isostatic pressing (HIP) of granules of alloy EP741NP;
- hot pressing of ingot obtained by vacuum inductive melting (VIM) method with vacuum arc remelting (VAR) with further mechanical reprocessing out of alloy EP975ID;
- method of welding individual components of nickel heat-resistant weldable alloy EP99ID.

To implement the planned approach several works have been performed.

6.8.1 Development of deformation thermomechanical parameters has been confirmed and given definite expression for any blanks of alloy EP975ID, previously discussed in stage A-7, where a necessity to use preliminary pressing for this alloy as a method of increasing material plasticity and a possibility of its further forming, was noted.

6.8.2 Manufacturing technology for extruded bars has been confirmed and given definite expression, including homogenization of melted (VIM + VAR) blank under the following conditions: 1200 ± 10 ^{0}C, 6 - 8 hour exposure, air cooling and further pressing on hydraulic press by applying 6300 f·t at 1120 ± 20 ^{0}C temperature from 365 mm diameter to 170 mm diameter with further mechanical processing into 160 mm diameter.

The final operation is heat treatment.

6.8.3 Technological procedure for shaft line individual components deformation has been developed.

6.8.4 Technological procedure for shaft line individual components manufacture by powder metallurgy method using hot isostatic pressing has been developed.

6.8.5 Technological procedure options have been developed for manufacture of shaft line model by welding individual deformed components together. Taking into account lower temperature and stress requirements for materials discovered in the process of works compared to those declared earlier during conceptual design, now there is a real opportunity to use less durable cobalt-free alloys EP517, EI437BU.VD, EP202 for shaft line manufacture.

6.9 Stage ?-9 Development of manufacturing technology for turbocompressor stator

As it was noted, one of the stator models will be manufactured of alloy EP99ID by square section profile bending method with subsequent welding. Instead of the profile a sheet blank can be used, which is of no principal importance. It should be noted that using the bending method with subsequent welding at OAO Kulebaksky metallurgical works equipment one could manufacture parts of diameter up to 2400 mm. This factory possesses such experience and experience in working with alloy EP99ID.

Welding technology for individual components of alloy EP99ID has been developed and experimental investigation of this process has been performed as applied to models.

As for a possibility to manufacture a stator by the powder metallurgy method, then workspace of existing gas static vessels makes it impossible to manufacture parts of diameter = 1100 mm. Nevertheless, this method is quite applicable for purposes of manufacture of this type of parts, just as like for shaft line manufacture.

6.10 Stage ?-10 Development of manufacturing technology for turbocompressor volute of selected materials

Taking into account “volute” geometrical parameters and design, apparently, it can be manufactured only by welding. It is impossible to manufacture individual components of the “volute” in gas static vessels available in the country nowadays, since diameter of their workspace is lower than even central shell of volute.

Cylindrical shells (2 pieces) can be manufactured by unrolling or bending methods with further welding. Apparently, it is advisable to manufacture tapered shells (2 pieces) by forming method. The main goal for this stage of work is to adjust welding technology, in our case, for alloy EP99ID (at helium temperature ~ 850 °C) and work out an opinion concerning manufacturing technology for individual components (and also their number and geometry).

Bending and manufacturing technology for individual elements of alloy EP99ID with application of welding are similar to those indicated in It.6.9.

6.11 Stage ?-11. Manufacture of turbocompressor components models by developed technological processes.

Works for this stage and issuance of a report for them are now in progress.

As required by Task No.02.03-035.11 the following works shall be performed:

6.11.1 Cutting of ingots for subsequent deformation.

6.11.2 Manufacture of turbine and nozzle blades models.

6.11.3 Manufacture of turbine disc models.

6.11.4 Manufacture of components for shaft line, stator, volute models.

6.11.5 Manufacture of shaft line, stator, volute models with application of welding.

6.11.6 Heat treatment of manufactured blanks of models.

6.11.7 Quality evaluation of TC model samples and test components manufactured by developed technologies by control methods adopted in present-day gas-turbine building.

As of June 30, 2002 as result of works for manufacture, a disc model of deformable alloy EP975ID, two blanks of 267x45 mm diameter and one blank of 325x61 mm diameter were obtained.

As result of works for manufacture of a disc model of high-temperature granulated alloys by methods of HIP and HIP with subsequent deformation (forming), four blanks have been obtained. One has been made out of granules of alloy EP741NP and three of granules of alloy EP962E.

In accordance with sections 6.11.4, 6.11.5 the followings have been developed each in one model: shaft line model of granulated alloy EP741NP (HIP method) and of alloy EP975ID (mechanical processing of extruded bar), stator model of weldable alloy EP99ID with application of welding. Manufacturing technology for volute shall not differ from that for stator, and that is why volute model has not been manufactured at this stage of work.

Heat treatment of manufactured models of turbocompressor components has been performed in chamber electric furnaces of SNO type, with temperature maintenance precision in workspace amounting to ± 10 ^{0}C, according to optimum modes for used alloys.

6.12 Stage A-12. Tests of TC manufactured models and components

To perform tests including microstructure investigations and determination of the level of mechanical properties during tensile, long-term durability, creep and fatigue tests at temperatures 20, 650, 750, 800 and 850 ^{0}C, procedures were proposed for comprehensive investigations and, accordingly, cutting of obtained models of turbocompressor components.

In accordance with the developed procedures, thermally treated models were cut into blanks by section (18 – 22) x (18 – 22) mm and length 70 - 150 mm, from which samples for mechanical tests were manufactured.

Blanks were cut using anodic-mechanical saw and emery cutting-off machines, in which required emulsive cooling was used. Samples for mechanical tests were manufactured at electroarc process stations with subsequent machining at turning lathes.

Manufacture of samples (their geometry) and their tests will be performed according to the following GOSTs. Samples for tensile tests at room or elevated temperatures were manufactured and will be tested as per GOSTs 1497-84 and 9651-84, accordingly. Impact strength samples are as per GOST 9454-78. Long-term durability samples are as per

GOST 10145-81, creep samples are as per GOST 3248-60 and fatigue strength samples are as per GOST 25502-79.

6.13 Stage ?-13. Summarization of test results and bench-scale investigations for turbine materials and key components as per the program of first year works.

A draft qualification tests program was developed for candidate materials as per RF GAN Regulations (Appendix No.1), which is now being proposed to the collaborators for concurrence.

One of the problem issues in qualification of materials for turbocompressor high-temperature components is a necessity to increase the upper temperature limit for application of procedures recommended by PNAE ?-7-002-86 "Codes for .... Strength Analysis". For this purpose, it is advisable to utilize experience in creating and operating gas-turbine aviation and stationary plants.

At the present time samples tests and materials investigations are underway in compliance with the developed program of first year works within the framework of ISTC Project No.1313 (Appendix No 2).

6.14 Works for Work Plan stages ?-8, ?-9, ?-10, ?-11, ?-12, ?-13 are continuing as materials are purchased and will be reflected in Products 02.03-35.8A, 02.03-35.9A, 02.03-35.10A, 02.03-35.11A, 02.03-35.12A, 02.03-35.13A.

6.15 A list of purchased equipment is provided in Appendix No. 3.

7 Current Status of Technical Progress

Substantially, works under the project were performed in accordance with the plan. At the same time, a lag from deadlines was allowed to happen, which is associated with several circumstances.

7.1 In accordance with Section 4 of ISTC-OKBM Agreement, payments of project costs and budget structure are expressed in US dollars. As it was agreed at the stage of Work Plan preparation, US dollars also cover specialists' participation, costs for materials and enterprises' services. ISTC Project #1313 is funded by ?U in Euro. As a result of change in the dollar-to-euro exchange rate at opening of the project funding and according to Agreement, Section 11, It.3, correction was made to decrease the budget. This required repartition of duties among the participants, search for new executors, for a cheaper supplier of materials and services on investigations and tests of materials, and, as a result, led to a delay in completing Stages ?-1, ?-2, ?-4.

7.2 Selection of materials for tests and investigations under ISTC Project # 1313 is determined by temperature-stressed state of turbine units and parts during operation, which depends upon turbocompressor design. During design several diagram options were considered with various coolant parameters and associated various temperature and stress conditions for turbocompressor key components. The final selection of design diagram could considerably change the selection of materials and manufacturing technologies. In conditions when funds for the materials are limited, executors responsible for Project # 1313 were forced not to run financial risk, until key operating parameters of individual units of the turbocompressor are determined. This led to a delay in completing Stages ?-1, ?-3, ?-4, ?-6, ?-7, ?-8, ?-9, ?-10.

7.3 During performance of the Work Plan a problem was discovered concerning purchase of raw materials associated with a necessity of 100 % prepayment for their cost to manufacturing plants, additional time for their delivery and obligatory minimum application norms for the scope of delivery, which are 500^{+} kg of metal.

ISTC procurement office does not uses any prepayment system in its practice, and, moreover, 90-120 kg of alloy is quite sufficient for purposes of complying with the ISTC Project#1313 work plan at the stage of materials selection. These mentioned circumstances led to a delay in completing Stages ?-4, ?-5, ?-11, ?-12, ?-13.

7.4 During development of input data for materials of turbocompressor high-temperature components and analysis of available heat-resistant materials as prospective ones for tests, it was found out that most of them in their composition contain cobalt within the range from 8% to 18%, which during operation is converted into radioactive isotope with a long half-life period, and due to such reason is not desirable for application in nuclear plants, since it leads to further difficulties during operation caused by induced activity, repair and unit replacements, and subsequent disposition.

That is why in support of works under ISTC Project # 1313 a decision was taken to update one of the well-known cobalt-containing alloys, by decreasing its cobalt contents down to the certain minimum allowable level established by experiments with samples. This experimental alloy was given a conventional name MSK, whose test program is provided in Appendix No.4.

7.5 Owing to correction made to decrease the budget (see It.7.1), and shortage of time for tests it was proposed to exclude the Task for Evaluation of Selected Materials

Stability to Carbon Saturation from Stage ?-13. That would not affect expected results of the project, since this activity may be performed at the subsequent stages of industrial mastering of candidate materials.

7.6 In view of what was stated in It.7.1, 7.2, 7.3, and 7.4 a revised schedule of work under ISTC Project # 1313 (Appendix No.5).

7.7 Estimated Total Participation and Grant Payment under ISTC Project # 1313 during First Year Work is provided in Appendix 6.

8 Cooperation with Foreign Collaborators

8.1 Cooperation with Foreign Collaborators has started with preparation of the Work Plan after approval of project funding by the ISTC Governing Board. In particular, comments of the experts group (GA – R. Schleicher, James Lindqren, ORNL – Syd Ball, Framatome – ANP – Eric Brenil, FE – Fumio Okamoto) were taken into account for proposed Work Plan and some stages of work were revised. San Diego, California, November, 1999.

8.2 Project 1313 Work Plan was reviewed at the ISTC preliminary contact expert group meeting attended by Project Collaborators: M. Lecomte, FA-ANP, A. Jhenoy, GA. San Diego, California, February 2001.

8.3 Progress information was presented at the ISTC project experts meeting for GT-MHR and FPS work areas, in Petten with participation of M. Lecomte, FA-ANP.

8.4 Status of completing the Work Plan was regularly reported at working group meetings for the project in Nizhny Novgorod in 2001 and 2002.

9 Problems Revealed and Proposals concerning their Elimination

9.1 Problems revealed during the performance of works under the Project are described in Section 7 of the present report. They caused a delay in completing the Work Plan. By the end of period reported only one problem is left unresolved: purchase of raw materials. By July 1, 2002 heat resistant alloys EP975ID, EP941NP and EP99ID were purchased for a total cost amounting to 39$?. Out of them the models were manufactured, samples were cut and now qualification tests are on in accordance with the program of the first year work. Residual materials have been ordered, intermediate firms have been determined, and now manufacture and purchase of materials intended for tests are in progress, including new advanced alloys for turbocompressor blades and discs. There is no doubt that this problem will be resolved as well.

9.2 OKBM has prepared and submitted to ISTC a well-grounded proposal for extension of Project #1313 by 5 months without additional funding, by having this extension agreed upon by M. Lecomte, a collaborator from Framatome – ANP.

9.3 To evaluate appropriateness of turbocompressor high-temperature components materials for 60000 hours lifetime, it is necessary to perform sufficiently representative long-term durability and creep tests on the basis of 6000 hours and more. It is scheduled in the calendar plan of Project 1313 to perform tests on the basis of 3000-5000 hours, and owing to the problem of purchasing some materials, such basis is non-practicable for these materials. For this reason, OKBM, as a lead institute under the Project, had to apply to collaborators and ISTC Agreements Department concerning additional prolongation of Project #1313 by 4-5 months without changing the scope of funding till July 2003.

10 Prospects for Further Development of Developed Technology\Research Study

10.1 Project # 1313 represents an initial stage in selection, development, tests and investigations of advanced heat-resistant materials for manufacture of high-temperature components of high-performance turbocompressor. Overall results of first year works are provided in Section 6 of the present report.

Upon completion of the overall project, a stage of development of industrial manufacturing technology for specific turbocompressor components, based on principal technologies and obtained data on materials properties, will take place, and qualification tests will be continued as per respective programs.

10.2 Obtained results of the project may be used for creation of turbocompressors of various purposes and other components operating in similar conditions, for their application in gas turbine building, nuclear mechanical engineering and the other branches of industry.

OKBM First Deputy Director,

Chief Engineer V.I. Kostin

Project # 1313 Manager A.A. Romantsov

Appendix 1

DRAFT QUALIFICATION TESTS AND INVESTIGATIONS PROGRAM FOR METALLIC MATERIALS OF TURBOCOMPRESSOR KEY COMPONENTS

The Program is prepared according to "Rules for Design and Safe Operation of NPP Equipment and Piping" PNAE G-7-008-89 and "Codes for NPP Equipment and Piping Strength Analysis" G-7-002-86 in consideration of analysis results for temperature and stressed state performed in Product 02.03-35.1A, specified lifetime, maximum loads and safety factor.

0.1 General

0.1.1 Qualification tests of materials apply to the following turbine components:
- working blades;
- nozzle blades;
- rotor discs;
- "HPC - turbine" shaft line;
- turbine stator;
- volute.

0.1.2 Operating fluid is helium coolant of turbine inlet temperature 850 ^{0}C and outlet one 510 ^{0}C.

0.1.3 Specified total lifetime of the turbocompressor (TC) is 60000 hours. Operation time of turbine components at various calculational operating modes is determined according to the reactor plant (RP) operation model:
- with the maximal load 100 % N_{nom} – 85 % per year (6000 h per year);
- with the load not less than 80 % Nnom – 5 % per year (~ 350 h per year);
- with the load not less than 50 % Nnom – 5 % per year (~ 350 h per year);
- with the minimal load 15 % Nnom – 5 % per year (~ 350 h per year).

0.1.4 For stressed-state analysis for turbocompressor components under consideration the following operating modes were adopted:
- operation at the maximal load (100% power, mode No. 1) with calculational duration of work 57000 h;
- operation at 15% of plant power (mode No. 2) with calculational duration of 3000 h;
- TC operation involving increase of the rotor rotation speed by 20%, and short-period (approximately, up to 5 min) increase in helium turbine outlet temperature up to 850 ^{0}C (complete loss of power mode – mode No.3).

0.1.5 Parent metal and metal of welded joints (stator, volute, shaft line and discs for welded option) undergo tests.

0.1.6 Data interpolation and extrapolation may be performed as per recommendations of PNAE G-7-008-86, or by other physically validated method.

1.1 Main tests for working blades material

1.1.1 Tensile tests with determination of the following mechanical characteristics: R^T_m – temporary resistance; $R^T_{p0.2}$ – yield strength; A^T – extension strain; Z^T - compressive strain.

Said characteristics are defined at 20 ^{0}C, within the range 500 – 850 ^{0}C every 50 ^{0}C, and for $?_{max}$ + 25 ^{0}C and $?_{max}$ + 50 ^{0}C as required by GOST 1497-84, GOST 9651-84, GOST 11150-84.

1.1.2 Evaluation of influence of isothermal exposures upon mechanical properties at tension at 750, 800 and 850 ^{0}C with duration up to 10000 h as per GOST 10145-81.

1.1.3 Long-term durability tests on the basis up to 6000 h within the range 500 – 850 ^{0}C every 50 ^{0}? , and for $?_{max}$ + 25 ^{0}? and $?_{max}$ + 50 ^{0}? as per GOST 3248-81.

1.1.4 Creep tests within the range 500 – 850 ^{0}? (every 50 ^{0}?) with drawing isochronous creep curves in coordinates σ - e (stress – residual deformation) and determining the rate of steady creep.

1.1.5 Cyclic strength evaluation is performed based on bending test results with rotation speed f = 50 Hz on the basis up to $2 \cdot 10^7$ cycles at 20, 500, 600, 700, 750, 800 and 850 ^{0}C.

1.1.6 Corrosion resistance evaluation in helium coolant is performed for the change in weight, carbon concentration and depth of damaged layer in samples after thermal exposures at 750 and 850 ^{0}C. Exposure duration is selected subject to possible extrapolation of test results to 60000 h lifetime.

Corrosive action of additives (oxygen, carbon) contained in helium is evaluated based on tensile and high-cycle fatigue test results at 20, 750, 850 ^{0}? temperature of samples previously held in coolant.

1.1.7 Determination of the following physical properties of materials: E - elasticity module; α - linear expansion coefficient; λ - heat conductivity factor; ? – thermal capacity coefficient; ρ - density.

Said characteristics (except for ρ) are determined within the range 20 – 800 ^{0}C every 100 ^{0}? , and for 850 ^{0}? .

1.1.8 Crystallographic orientation evaluation for material of working blades with monocrystal structure.

1.1.9 Evaluation of practicability of enhancing the service properties of heat-resistant material selected for working blades at the expense of “hot” isostatic pressing (HIP).

1.1.9.1 Selection of optimum HIP mode (9 modes – 3 temperatures and 3 exposures):

- by mechanical properties at tension at 20 ^{0}? ;
- by long-tem durability level at 850 ^{0}C on the basis of 100 h.

Note: to ensure the effectiveness of HIP, coating is applied to the samples by gas circulation method (aluminizing).

1.1.9.2 Investigations of structure and mechanical properties of materials after HIP.

1.1.10 Investigation of structure and service properties of material of pilot working blades of turbine (including blades exposed to HIP).

1.2 Tests of materials for nozzle diaphragm blades

It.1.2.1, 1.2.2, 1.2.3, 1.2.4, 1.2.6, 1.2.7, 1.2.9 and 1.2.10 are similar to It.1.1.1, 1.1.2, 1.1.3, 1.1.4, 1.1.6, 1.1.7, 1.1.9 and 1.1.10.

1.2.5. Cyclic strength evaluation is performed based on low-cycle fatigue test results in non-isothermic mode (thermal fatigue). Test conditions: 850 ^{0}C, 2 hours ? = 400 ^{0}C until cracks of 0.5 mm depth appear.

1.3 Tests of materials of assembly-structure rotor discs

It.1.3.1, 1.3.2, 1.3.3, 1.3.4, 1.3.5, 1.3.6, 1.3.7, 1.3.9, 1.3.10 are similar to It.1.1.1, 1.1.2, 1.1.3, 1.1.4, 1.1.5, 1.1.6, 1.1.7, 1.1.9, 1.1.10 with replacing “turbine working blades” with “rotor discs”.

1.4 Qualification tests for welded-structure rotor discs

1.4.0 All tests shall be performed for parent metal and welded joint metal.
It. 1.4.1, 1.4.2, 1.4.3, 1.4.4, 1.4.5, 14.6, 1.4.7, 1.4.9 and 1.4.10 are similar to It.1.3.1, 1.3.2, 1.3.3, 1.3.4, 1.3.5, 1.3.6, 1.3.7, 1.3.9 and 1.3.10.

1.5 Test of materials of stator, volute, and their welded joints

1.5.0 All tests shall be performed for parent metal and welded joint metal.

1.5.1 Tensile tests with determining $R^T{}_m$, $R^T{}_{p0.2}$, A^T and Z^T.
$?_{test}$ – from 20 ^{0}? up to 850 ^{0}?, every 50 ^{0}?, and for $?_{max}$ + 25 ^{0}? and $?_{max}$ + 50 ^{0}?.

1.5.2 Evaluation of influence of isothermal exposures upon tension characteristics. Aging tests shall be performed at 750 and 850 ^{0}C with duration of up to 10^4 h (500, 1000, 3000, 5000 and 10000 hours).
Determination of mechanical properties at tension shall be performed at 20 ^{0}C, within the range 500 – 850 ^{0}C every 50 ^{0}C, and for $?_{max}$ + 25 ^{0}C and $?_{max}$ + 50 ^{0}C as required by GOST 1497-84, GOST 9651-84, GOST 11150-84.
1.5.3 Long-term durability tests shall be performed on the basis of 6000 h within the temperature range 500 – 850 ^{0}C, every 50 ^{0}?, and for $?_{max}$ + 25 ^{0}? and $?_{max}$ + 50 ^{0}?.
1.5.4 Creep tests shall be performed within the temperature range 500 – 850 ^{0}?, every 50 ^{0}?.
According to test results, isochronic curves are constructed in coordinates “σ - e” for 10, 10^2, $3 \cdot 10^2$, 10^3, $3 \cdot 10^3$, 10^4, $3 \cdot 10^4$ and $6 \cdot 10^4$ hours up to e = 5%, and dependence of the rate of steady creep upon stress within the range 500 – 850 ^{0}? is determined.

1.5.5 Evaluation of cyclic strength shall be performed based on fatigue tests within the range of number of cycles 10^2 - $2 \cdot 10^7$.
Test temperature is 20 ^{0}? and within the range 500 – 850 ^{0}?, every 50 ^{0}? for parent metal and every 100 ^{0}? for welded joints.
Low-cycle fatigue tests (N < 10^4 cycles) shall be performed at temperatures up to 800 ^{0}? in hard loading mode.

For high-cycle fatigue bending tests are performed at rotation speed f = 50 Hz.

1.5.6 Corrosion resistance in helium coolant is evaluated according to the change in weight, carbon concentration and depth of damaged layer in samples after exposures at 650, 750 and 850 ^{0}? in helium with specified contents of additives. Exposure duration is selected subject to possible extrapolation of test results to 60000 h lifetime.

Corrosive action of helium coolant is evaluated also by:

- short-term tension characteristics at 20 ^{0}? and at exposure temperatures;
- results fatigue tests for bending and rotation.

1.5.7 Determination of the following physical properties of materials: E - elasticity module; α - linear expansion coefficient; λ - heat conductivity factor; C - thermal capacity coefficient; ρ - density.

Said characteristics (except for ρ) are determined within the range 20 – 900 ^{0}C every 100 ^{0}? , and for 850 ^{0}? .

1.6 <u>Tests of materials of shaft line and their welded joints</u>

1.6.0 All tests shall be performed for parent metal and welded joint metal.

1.6.1 Tensile tests with determining $R^T{}_m$, $R^T{}_{p0.2}$, A^T and Z^T.
$?_{test}$ – from 20 ^{0}? up to 500 ^{0}C every 50 ^{0}C, and for $?_{max}$ + 25 ^{0}? and $?_{max}$ + 50 ^{0}? .

1.6.2 Evaluation of influence of isothermal exposures upon tension characteristics. Aging tests shall be performed at 750 and 850 ^{0}? with duration of up to 10^4 h (500, 1000, 3000, 5000 and 10000 hours).

Determination of mechanical properties at tension shall be performed at 20, 400, 450, 500 and 550 ^{0}? .

1.6.3 Long-term durability tests shall be performed on the basis of 6000 h within the temperature range 400 – 500 ^{0}? , every 50 ^{0}? , and for $?_{max}$ + 25 ^{0}? and $?_{max}$ + 50 ^{0}? .

1.6.4 Creep tests shall be performed within the temperature range 400 – 550 ^{0}? , every 50 ^{0}? .

According to test results, isochronic curves are constructed in coordinates "σ - e" for 10, 10^2, $3 \cdot 10^2$, 10^3, $3 \cdot 10^3$, 10^4, $3 \cdot 10^4$ and $6 \cdot 10^4$ hours up to e = 5%, and dependence of the rate of steady creep upon stress within the range 500 – 850 ^{0}? is determined

1.6.5 Evaluation of cyclic strength shall be performed based on fatigue tests within the range of number of cycles 10^2 - $2 \cdot 10^7$.

Test temperature is 20 ^{0}? and within the range 400 – 550 ^{0}? , every 50 ^{0}? for parent metal and every 100 ^{0}? for welded joints.

Low-cycle fatigue tests ($N < 10^4$ cycles) shall be performed at temperatures up to 500 ^{0}? in hard loading mode.

For high-cycle fatigue bending tests are performed at rotation speed f = 50 Hz.

1.6.6 Corrosion resistance in helium coolant is evaluated according to the change in weight, carbon concentration and depth of damaged layer in samples after exposures at 400, 500 and 550 ^{0}? in helium with specified contents of additives. Exposure duration is selected subject to possible extrapolation of test results to 60000 h lifetime.

Corrosive action of helium coolant is evaluated also by:

- short-term tension characteristics at 20 ^{0}? and at exposure temperatures;
- results fatigue tests for bending and rotation.

1.6.7 Determination of the following physical properties of materials: Ε - elasticity module; α - linear expansion coefficient; λ - heat conductivity factor; C - thermal capacity coefficient; ρ - density.

Said characteristics (except for ρ) are determined within the range 20 – 500 ^{0}C every 100 ^{0}? , and for 550 ^{0}? .

Appendix 2

DRAFT TESTS AND INVESTIGATIONS PROGRAM FOR MATERIALS OF TURBOCOMPRESSOR ROTOR AND STATOR COMPONENTS WITHIN THE FIRST YEAR WORK UNDER ISTC PROJECT # 1313

It is quite obvious that the above qualification tests program (see Appendix 1) cannot be fulfilled within ISTC Project # 1313. In this connection a tests and investigations program has been developed, whose purpose is to confirm the correctness of materials selection for said turbine components in terms of their manufacturing technology and compliance with technical requirements set forth in Products 02.03-35.1A, 02.03-35.2A (see Table 1 of the body).

Tests and investigations of materials for working and nozzle blades

1.1 Tensile tests at 20, 550, 600, 700, 750, 800, 850 and 900 ^{0}C.
A number of samples are 24 for each material.

1.2 Long-term durability tests at 750, 800, 830, 850 and 900 ^{0}? with specifying two stress levels for duration order. Time basis for the tests is 3000 hours (100, 500, 1000 and 3000 hours). A number of samples are 120.

1.3 Creep tests at 750, 800 and 850 ^{0}? for the purpose of ensuring the calculability of creep strength at residual deformation 0.2% for 6000 hours.
A number of samples are 30.

1.4 Tensile tests of samples after HIP at temperature 20, 800 and 850 ^{0}? .
A number of samples are 9
A number of blades are 2
A total number of samples are 18

1.5 Investigation of pilot models of blades.
A number of blades are 5 (or 10…) pieces.

2 Tests and investigations of materials for stator and volute

2.1 Tensile tests with determining $R^T{}_m$, $R^T{}_{p0.2}$, A^T and Z^T.
Test temperature: 20, 500, 550, 600, 650, 700, 750, 800 and 850 ^{0}? .
A number of samples are (3 x 9) = 27 pieces for parent metal tests and the same number for welded joints.
Total: 54 samples.
Note: According to data listed in Table 1 of the body, it is supposed that the same heat-resistant alloy will be used for stator and volute (for example: ChS-57).
2.2 Long-term durability tests.
Test temperature: 550, 600, 650, 750 and 800 ^{0}? .
Test basis: 3000 hours (100, 500, 1000, 3000).
A number of samples: 60 pieces for parent metal 60 pieces for welded joints.
Total (presumably): 120 samples.

2.3 Creep tests with determining creep strength at residual deformation 0.2% and 1% for 60000 hours.

$?_{test}$ = 750,830 and 850 ^{0}? .

A number of samples are 30 pieces for parent metal and 30 pieces for welded joints.

Total: 70 samples.

2.4 Endurance tests on the basis of $2 \cdot 10^7$ cycles.

$?_{test}$ = 20, 750 and 850 ^{0}? .

A number of samples are 45 + 45 pieces (parent metal and welded joints.).

Total: 90 samples.

2.5 Evaluation of physical properties: ? , ?, C, a and ? at 20 – 850 ^{0}? .

A number of samples are 8 pieces.

2.6 As an alternative material, whose applicability is studied, within the framework of ISTC Project # 1313 tests of EP99ID are performed.

2.6.1 Tensile tests as per GOST 1497-84 and GOST 9651-84 at 20, 650 and 850 ^{0}? , in 3 samples per a point.

2.6.2 Long-term durability tests as per GOST 10145-81 at 650 and 850 ^{0}? , in 3 samples per a point.

Limits of long-term durability are forecasted on the basis of 60000 hours.

2.6.3 Alloy microstructure investigations.

3 Tests and investigations of materials for turbine rotor discs

3.1 Tests and investigations of samples of alloy EP975ID as material for turbine rotor discs manufactured by forming the blank out of previously extruded bar.

3.1.1 Tensile tests as per GOST 1497-84 and GOST 9651-84 for samples of alloy EP975ID at 20, 600, 650, 700, 750, 800 and 850 ^{0}? in 3 samples per a point.

3.1.2 Long-term durability tests at various stress levels as per GOST 10145-81 at 650, 750 and 850 ^{0}? , in 6 samples per a point.

Calculational forecasting of limits of long-term durability on the basis of up to 100000 hours.

3.1.3 Creep tests as per GOST 3248-60 at 650, 750 and 850 ^{0}? , in 6 samples per a point.

3.1.4 Fatigue tests as per GOST 25502-79 – 4 samples at 800 ^{0}? and 8 samples per a point at 850 ^{0}? .

3.1.5 Microstructure investigations.

3.1.6 Electronic microscope investigation in initial state and after long-term tests.

3.2 Tests and investigations of samples of alloy EP741NP as material for rotor discs manufactured by granule HIP technology

3.2.1 Tensile tests as per GOST 1497-84 and GOST 9651-84 of samples of alloy EP741NP at 20, 650 and 850 ^{0}C – in 3 samples per a point.

3.2.2 Long-term durability tests at various stress levels as per GOST 10145-81 at 650, 750 and 850 ^{0}? – in 3 samples per a point.

Calculational forecasting of limits of long-term durability on the basis of 60000 hours.

3.2.3 Fatigue tests as per GOST 25502-79 at 650, 750 ^{0}? – in 5 samples per a point.

3.2.4 Creep tests as per GOST 3248-60 at 850 ^{0}? – in 3 samples per a point.

3.2.5 Microstructure investigations.

3.2.6 Electronic microscope investigation in initial state and after long-term tests.

3.3 Tests and investigations of samples of alloy EP741NP as material for rotor discs manufactured by HIP technology with subsequent deformation

3.3.1 Tensile tests as per GOST 1497-84 and GOST 9651-84 at 20, 650, 750 and 850 ^{0}? – in 3 samples per a point.

3.3.2 Long-term durability tests as per GOST 10145-81 at 650, 750 and 850 ^{0}? – in 4 samples per a point.

Calculational forecasting of limits of long-term durability on the basis of up to 60000 hours.

3.3.3 Fatigue tests as per GOST 25502-79 at 650, 750 ^{0}? – in 11 samples at various stress levels.

Construction of fatigue curve at 650 ^{0}? .

3.3.4 Microstructure investigations

3.4 Tests and investigations of samples of experimental alloy EP962E as material for rotor discs manufactured by granule HIP technology

3.4.1 Tensile tests as per GOST 1497-84 and GOST 9651-84 at 20, 650, 750 and 850 ^{0}? – in 3 samples per a point.

3.4.2 Long-term durability tests as per GOST 10145-81 at 650, 750 and 850 ^{0}? – in 3 samples per a point.

Calculational forecasting of limits of long-term durability on the basis of 60000 hours.

3.4.3 Fatigue tests as per GOST 25502-79 at 650, 750 ^{0}? – in 5 samples per a point.

3.4.4 Microstructure investigations.

3.5 Tests and investigations of samples of experimental alloy EP962E as material for rotor discs manufactured by granule HIP technology with subsequent deformation

3.5.1 Tensile tests as per GOST 1497-84 and GOST 9651-84 at 20, 650, 750 and 850 ^{0}? – in 3 samples per a point.

3.5.2 Long-term durability tests as per GOST 10145-81 at 650, 750 and 850 ^{0}? – in 3 samples per a point.

Forecasting of limits of long-term durability on the basis of 60000 hours.

3.5.3 Fatigue tests as per GOST 25502-79 at 650, 750 and 850 ^{0}? – in 4 samples per a point.

3.5.4 Creep tests as per GOST 3248-60 at 650, 750 and 850 ^{0}? – in 5 samples per a point.

3.5.5 Microstructure investigations.

4 Tests and investigations of materials for shaft line

4.1 Tests and investigations of samples of alloy EP975ID as material for shaft line obtained by mechanical processing of extruded bar

4.1.1 Tensile tests as per GOST 1497-84 and GOST 9651-84 at 20, 400, 500 and 550 ^{0}? – in 3 samples per a point.

4.1.2 Long-term durability tests as per GOST 10145-81 at 500 and 550 ^{0}? – in 4 samples per a point.

4.1.3 Microstructure investigations.

4.2 Tests and investigations of samples of alloy EP741NP as material for shaft line manufactured by granule HIP technology

4.2.1 Tensile tests as per GOST 1497-84 and GOST 9651-84 at 20, 400, 500 and 550 ^{0}? – in 3 samples per a point.

4.2.2 Long-term durability tests as per GOST 10145-81 at 500 and 550 ^{0}? – in 3 samples per a point.

4.2.3 Microstructure investigations.

Appendix 3

List of Equipment to be stored at the Recipient Institution
Project Agreement # 1313

Name of Recipient Institution OKBM									
Name of Responsible Person for overall equipment: Lev N. Skatov									
Item #	Name	Type	Serial #	ISTC #	Price, $	Delivery date	Storage place	Responsible person	Remarks
1.	Computer	PC Intel Pentium 4 1500MHz/512MB RAM/ 40GB HDD/3,5"/ Video 64MB/ CD-RW 32r/8w/4rw/ Keyboard/Mouse/ Monitor 19" CTX GF-100TXR		2001AK000172	987.00	November, 2001	room 317, 01, 15, Burnakovsky proezd Nizhny Novgorod	Sergey N. Chirkunov	
2.	Computer	PC Intel Pentium 4 1500MHz/512MB RAM/ 40GB HDD/3,5"/ Video 64MB/ CD-RW 32r/8w/4rw/ Keyboard/Mouse/ Monitor 19" CTX GF-100TXR		2001AK000170	987.00	November, 2001	room 317, 01, 15, Burnakovsky proezd Nizhny Novgorod	Yevgeny O. Leushin	
3.	Computer	PC Intel Pentium 4 1500MHz/512MB RAM/ 40GB HDD/3,5"/ Video 64MB/ CD-RW 32r/8w/4rw/ Keyboard/Mouse/ Monitor 19" CTX GF-100TXR		2001AK000171	987.00	November, 2001	room 325, 01, 15, Burnakovsky proezd Nizhny Novgorod	Alexey A. Romantsov	

4.	Computer	PC Intel Pentium 3 1300MHz/512MB RAM/ 40GB HDD/3,5”/ Video 64MB/ CD-RW 40r/24w/16rw/ Keyboard/Mouse/ Monitor 19” CTX GF-100TXR	2001AK000169 875.00	November, 2001	room 317, 01, 15, Burnakovsky proezd Nizhny Novgorod	Alexey N. Sozinov	
5.	Printer	Hewlett Packard Laser Jet 1220	499.00	November, 2001	room 317, 01, 15, Burnakovsky proezd Nizhny Novgorod	Yevgeny O. Leushin	
6.	Printer	Hewlett Packard Laser Jet 1220	499.00	November, 2001	room 325, 01, 15, Burnakovsky proezd Nizhny Novgorod	Alexey A. Romantsov	

List of Equipment to be stored at the Recipient Institution
Project Agreement # 1313

Name of Recipient Institution OKBM									
Name of Responsible Person for overall equipment: Stanislav M. Ufimtsev									
Item #	Name	Type	Serial #	ISTC #	Price, $	Delivery date	Storage place	Responsible person	Remarks
1.	Copier Toner	CANON	NP-6416	PHC 16258	1,070.00 5×9.00	October, 2001	room 625, 33, 15, Burnakovsky proezd Nizhny Novgorod	Vyacheslav V. Cherepennikov	
2.	Copier Toner cartridge	CANON	FC-226 E-30	UUF 69933	268.00 90.00	October, 2001	room 512, 33, 15, Burnakovsky proezd Nizhny Novgorod	Vadim S. Danilovsky	
3.	Copier Toner	CANON	NP-6416	PHC 19287	1,070.00 5×9.00	October, 2001	room 317, 01, 15, Burnakovsky proezd Nizhny Novgorod	Sergey N. Chirkunov	
4.	Copier Toner cartridge	CANON	FC-226 E-30	UUF 80061	268.00 90.00	October, 2001	room 325, 01, 15, Burnakovsky proezd Nizhny Novgorod	Sergey N. Bakin	

Appendix 4

DRAFT INVESTIGATIONS PROGRAM FOR DEVELOPMENT OF TECHNOLOGICAL PARAMETERS OF MANUFACTURE OF DISC BLANKS OF NEW EXPERIMENTAL ALLOY MSK

The present program has been prepared with the purpose of development of new granulated heat-resistant alloy with minimum cobalt contents.

Work program calls for development of deformation thermomechanical parameters, which will ensure satisfactory form changing of materials; development of heat treatment modes for deformed model blanks, which will ensure the specified level of mechanical properties; quality evaluation for deformed model blanks manufactured by developed parameters by means of investigation of the structure and mechanical properties.

Table – Contents of investigations

It.No.	Measures	Note
1	Melting of initial electrodes, manufacture of granules, reprocessing and charging granules into capsules, hot isostatic pressing (HIP) of granules, getting of compacted blanks	5 blanks, height: 170 mm, diameter: 145 mm, weight: 23.4 kg (each)
1.1	Determination of chemical composition of obtained blanks	
1.2	Turning of compacted blanks	End diameter of blanks, height: 160 mm, diameter: 130 mm
2	Development of optimum homogenizing anneal, which will ensure formation of specified structure type and satisfactory plasticity of materials	One blank is used
2.1	Investigations of initial structure of blanks after HIP, evaluation of critical points of alloy	
2.2	Performance of homogenizing annealing of initial blank in various modes	2 modes are used
2.3	Investigation of material structure after homogenizing selection of the optimum mode	
3	Investigation of rheological characteristics of initial material and material homogenized for the optimum mode	Cylindrical samples are used (in 18 pcs. For each state)
3.1	Deformation of cylindrical samples for contraction. Construction of dependences of deformation resistance upon temperature for material state under investigation. Selection of the optimum annealing mode and deformation thermomechanical parameters	
4	Manufacture of disc model blanks according to the selected optimum modes of homogenizing annealing and deformation thermomechanical parameters	4 deformed blanks are obtained
5	Development of the optimum heat treatment modes for deformed blanks	2,5 blanks are used and cut into templates

5.1	Study of blank macro- and microstructure after deformation	For one template
5.2	Heat treatment according to various experimental modes	5 modes are used
5.3	Manufacture and tests of samples after each heat treatment mode	12 samples for each mode
5.4	Selection of the optimum heat treatment mode	
5.5 5.6	Heat treatment according to the selected optimum mode for disc blanks Performance of tests in accordance with procedure given in Section ? – 13 for deformed alloy EP741NP	For remaining 1.5 disc blanks Total: 30 samples
5.7	Evaluation of microstructure, investigation of phase composition	
6	Submittal of recommendations for investigations of developed experimental alloy MSK as material for turbocompressor discs manufacture	

REVISED ACTIVITY SCHEDULE ON PROJECT 1313 Appendix 5

	Name of activity	First year												Second year											
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
? -1	Development, output and concordance of input data for structural materials needed for manufacture of TC elements key units.	—	—	—	—	—	—																		
? -2	Analysis of adapted modern technologies of turbocompressor key elements manufacture.	—	—	—	—	—	—																		
? -3	Selection of materials and technological methods of TC parts manufacture.							—	—	—															
? -4	Purchase of materials and manufacture of billets for pilot-experimental activities performance.							—	—	—	—	—	—	—	—	—	—	—	—						
? -5	Development and manufacture of test lot of welding materials for TC elements of welding design.							—	—	—	—	—	—												
? -6	Development of manufacturing technological processes for nozzle and rotor plates of selected materials.							—	—	—	—	—	—												
? -7	Development of manufacturing technology for rotor discs of selected materials.							—	—	—	—	—	—												
? -8	Development of manufacturing technology for shaft line of selected materials.							—	—	—	—	—	—	—	—	—									
? -9	Development of manufacturing technology for stator of selected materials							—	—	—	—	—	—	—	—	—									
A-10	Development of manufacturing technology for volute of selected materials.							—	—	—	—	—	—	—	—	—									
? -11	Manufacture of turbocompressor components models by developed technological processes.								—	—	—	—	—	—	—	—	—	—	—	—					
? -12	Tests of TC manufactured models and components.								—	—	—	—	—	—	—	—	—	—	—	—	—				
? -13	Bench-Scale investigations of structure and mechanical properties of material and model samples of turbine key components manufactured by developed technologies.							—	—	—	—	—	—	—	—	—	—	—	—	—	—	- -	- -	- -	- - ►
A-14	Report on results of performed activities and definition of directions of their further development.																	—	—	—	—	—	—	—	—

Appendix 6

Estimated Total Participation and Grant Payment under ISTC Project #1313 during First Year Work

Period	Category I		Category II		Category III		Category IV	
	Man/ days	Grant $	Man/ days	Grant $	Man/ days	Grant $	Man/ days	Grant $
1st quarter	863,0	24 835	144,0	4 195	303,0	4 715	327,0	4 905
2nd quarter	972,0	26 410	125,0	3 235	100,0	1 605	420,0	6 990
3rd quarter	636,0	18 117	152,0	3 760	107,0	1 775	378,0	6 204
4th quarter	369,0	10 665	70,0	2 100	65,0	1 086	133,0	2 546
TOTAL	***2 840,0***	***80 027***	***491,0***	***13 290***	***575.0***	***9 181***	***1 258,0***	***20 645***

List of Sources Used

1 A.I. Abramov, V.I. Izvekov, N.A. Serihin, Turbogenerator Designing, M., “Visshaya Shkola”, 1990.

2 Coolant Thermophysical Characteristics, Leningrade, 1964

3 PNAE G-7-002-86 Codes for NPP Equipment and Piping Strength Analysis. Energoatomizdat, M., 1989.

4 Bondaryov B.I., Garibov G.S. and others. “Granule Metallurgy of Heat Resistant Alloys Propels the Progress in Gas Turbine Building”. Gas Turbine Technologies. 2000, No. 5, pp. 20 – 25.

5 Jaribov J.S., Baslavsky L.S., Zinoviev V.A. “Impronement in Duck Allay Qnahty Due to Application of Powder Metallurgy Method and H.JP. In book Procudiass of the Conference on Powder Metallurgy. May – June 1998. Las – Vegas, USA, p. 5 – 26.

6 J.S. Zhang, Z.Q. Hu, Y.Murate, M. Morinaga and N. Yukawa. Metall. Trans. A., 1993, vol 24A pp. 2251 – 64.