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HTR: Identification and review of Turbine candidate materials

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Summary

The different candidates for three turbine applications (disks, blades, first stage stator) have been firstly identified and their chemical composition (specified or typical) are given in table 1 to 3. Taking into account the implications of manufacturing processes (reviewed in paragraph 6) of HTR helium environment (paragraph 7), of cobalt content (paragraph 8), the candidate materials can be separated in the categories, which follow.

1. "High technology materials : the materials are the results of the most recent technology and this technology has to be validated for the size and geometry of HTR turbine. This effort requires the cooperation of a material producer : oxyde dispersion strengthened material for disks as MA6000 (ODS), single crystals for blades as CMSX4 or PWA1483 enter in this category. In addition MA6000 (ODS) is a cobalt free material. CMSX4 and PWA1483 are preferred to CMSX2 for their larger experience in land turbine. PWA 1483 which has an higher chromium content is better in case of carburising or decarburising risks.

2. Materials to be adapted to HTR : These materials are produced by a more conventional fabrication process (forging or casting). The adaptation required is a more performant manufacturing process in order to increase the size or to improve the high temperature properties. HIP Udimet 720 for disks, Directionally solidified cast alloy as MAR M247DS or IN792DS for blades enter in this category. Higher chromium IN792DS is better in case of carburising and decarburising risks.

3. High temperature conventional materials : forged products for disks, conventional cast materials for blades, forged Hastelloy XR for stator enter in this category. Our proposal is to concentrate the effort on the same alloy as in the category 2 but on the reference forged or cast product : forged Udimet 720 for disks, cast MAR M247 or IN792 for blades. It must be recalled that distinct characterisation should be finally performed for HIP Udimet 720 and forged Udimet 720 or for IN792DS and cast IN792. The choice between IN792 from Inco group (higher chromium content) or MAR M247 from Martin Marietta Corporation (higher Al/Cr ratio) is connected to the carburising and decarburising risks. We propose to study cast IN792 rather than cast IN738LC if IN792DS is chosen for category 2.

4. Cobalt free high temperature materials : the alloys mentioned in part 8 enter in this category. For disks it is the wrought Hastelloy XR (as for stator) or a material to be defined if Hastelloy XR must be discarded. For blades it is MAR M004 or SC16 but if coated the blades do not need to be cobalt free.

The categorisation and restricted selection of materials are summarised in table 5.
Single crystals, directionally and conventionally cast alloys must be hot isostatically pressed and characterised in this delivery condition.
The blades must be coated and fatigue testing must be performed taking into account this surface condition.

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1. Introduction

The purpose of this document is to identify the materials proposed for the turbine used in hot helium produced by High Temperature Reactors. The main difficulties are the selections of the material for the hottest parts of the turbine (blades, disks and stator of stage 1) for service in helium gas at 850 °C and this document will be concentrated on the materials for the highest temperatures. Other stages of the turbine will operate at lower temperatures down to 510 °C and the selection of the different materials for these different stages will be mainly a matter of cost optimisation which cannot be examined without discussion with experts of turbine making industry.

As the development of materials for very high temperature (> 800 °C) is a difficult problem which has involved competitions between several alloy producers and several engineering firms producing military and civil aircraft engines or gas turbines the number of materials proposed in reference 14 and 5 is very great (nearly all the designation of the alloys are trade marks used in the complete form or shortened) and is not possible to include such a number of materials in validation programmes covering all the properties important for long time service of HTR turbine. This note will review and categorise the materials identified by their chemical composition considering manufacturing processes (casting, directional solidification, single crystals…) and other implications as HTR helium environment and cobalt content. The design properties at high temperatures will be checked in detail in a future document. In the present note, the comparison of mechanical properties of the candidate materials will be limited to screening remarks found in the literature. The goal of this review, categorisation and comparison is a proposal to restrict as much as possible the number of materials to be studied in more detailed for each of the applications (blades, disks, stator).

2. Candidate materials for turbine disks

2.1 Russian proposal for GTMHR

The proposed materials in reference 1 are two grades of nickel base superalloys : the associated manufacture is casting. The chemical analysis of these materials are indicated in table 1. Both alloys contain chromium cobalt molybdenum tungsten titanium aluminium niobium and vanadium : the differences are in the amount of these additions :

- ♦ more tungsten and niobium for ZhSGF which contains also hafnium,
- ♦ more chromium cobalt molybdenum and titanium but less tungsten for VZhL12U.

2.2 American equivalent material

The Western equivalent material proposed for GTMHR is American alloy MA6000 (Ref 1). The chemical analysis is given in table 1. It is a nickel base superalloy which content chromium, molybdenum, tungsten, titanium, aluminium and tantalum but not cobalt nor niobium. The associated manufacture is power metallurgy. The chemical analysis of reference 1 indicates an ytrium oxide Y_2O_3 content of 1.1 % in this alloy. The product is an oxide dispersion strengthened (ODS) nickel base superalloy. The commercial manufacture can be separated in three essential component processes (Ref 2) :

- mechanical alloying of the powder,
- consolidation by thermomechanical working of the powder to the desired shape,
- critical directional recrystallisation by zone annealing.

Reference 3 which compares different superalloys using a criteria of 1 000 hours life under 140 MPa, points out that the maximum temperature (1 135 °C) is obtained for MA6000. This superiority of MA6000 in strength at very high temperature is probably the main reason for the selection of MA6000 for GTMHR. But this choice does not take into account the manufacture possibility of the disk :

- in gas turbine this material is considered for blades and vanes (Ref 2) but not for disks,
- size of commercial products (60 x 36 mm^2 section bars) is far from needs of GTMHR project (diameter 1 600 mm according to reference 4).

2.3 Materials proposed by CEA

Following the reference 5, the material which combines large diameter manufacturing possibilities and high temperature strength is the nickel base alloy Udimet 720 (commercial designation of Aubert et Duval the French producer of the alloy : PER 72). The chemical composition is given in table 1. Its initial manufacturing process is forging allowed by an excellent workability (Ref 6, 7). The strength is mainly due to γ' $Ni_3(Al,Ti)$ precipitate duplex microstructure (coarse and fine) obtained by heat treatment. But the high temperature strength criteria of reference give a maximum temperature which is 190 °C less than in the case of MA6000 (945 °C for 1 000 h under 140 MPa) and it must be proved that the criteria of high temperature fot GTMHR (180 MPa 850 °C 60 000 h) can be satisfied.

By forging, billet up to 250 mm of diameter were produced (Reference 6) and it is considered that 850 mm will be the maximum diameter which can be obtained by forging. The ability of Udimet 720 to be processed by powder metallurgy and hot isostatic pressing (HIP) has been tested (Reference 7). It is proposed to use HIP processing in order to obtain large diameter disks.

2.4 Material proposed for disks of PBMR

For the hottest parts of turbines for PBMR the material proposed is the nickel base alloy IN100 : the corresponding chemical composition is given in table 1. The strength is due to the dispersion of γ' precipitates. As it is a cast alloy it was firstly proposed for blades. It is not common to use casting for disks due to the fact that the risk of solidification defects increase when the size of the cast product increases. The use of HIP as powder metallurgy or for porosity elimination in the as cast product can improve the quality of disks in IN100 (Ref 8) but such a processing for large diameter disks has to be validated.

3. Candidate materials for turbine blades

3.1 Russian proposal for GTMHR

The Russian proposal as high temperature resisting material is the nickel base alloy Ch120M. The chemical composition is given in table 2 : the material is used as casting or as single crystal.

Three other forged materials named E 929, EI893 and EP800 have been proposed as backup solution if the single crystal solution is given up for cost reason. They are nickel base alloys with chromium, molybdenum tungsten and aluminium. One is cobalt free and in one of them titanium is replaced by niobium.

3.2 American equivalent material for GTMHR

The American product proposed as equivalent to Russian ChS 120M is CMSX2 single crystal. The chemical composition is given in table 2. It is also a chromium cobalt molybdenum tungsten aluminium base nickel alloy. It contents more tantalum (5.8 %) than titanium (1 %) (Ref 9, 10). The single crystals processing eliminates the grain boundary cracking which was observed in directionally solidified alloys : it improves the resistance to thermal fatigue during processing and in service. The single crystal products are used after heat treatment producing convenient distribution of γ' precipitates (Ref 9).

3.3 CEA proposed materials for blades

In fact the alloy CMSX2 was derived from a material which is manufactured by directional solidification and which was considered by CEA (Reference 5) : Ni base alloy MAR M247 with the chemical composition given in table 2. Addition of hafnium and control of zirconium and boron are made to improve the behaviour of grain boundaries and of course are not necessary for single crystals as CMSX2. MAR M247 has a high volume fraction of γ' (Ref 11).

Three grades which are manufactured by casting have been mentioned in reference 5 as more promising for the blades. The first one 713LC have been used for the fabrication blades for the German project HHV (a full scale test turbine driven by HTGR – type helium). Alloy 713LC is a chromium molybdenum aluminium and niobium nickel base alloy (Table 2) : it is a low cobalt alloy. Another alloy MAR M004 was derived from alloy 713 LC by addition of hafnium which produces a toughness improvement. The corresponding chemical analysis is given in table 2. The third cast alloy M21 is a relatively low chromium nickel base alloy (table 2) with tungsten aluminium and niobium.

3.4 Material proposed for blades of PBMR

Ni alloy IN100 is the proposed material for blades of PBMR as for the highest temperature disks. As it is produced by casting this material seems more appropriate to the fabrication of blades than for the fabrication of large diameter disks.

3.5 Other materials proposed by HTRM partners

Two other cast superalloys were proposed by HTRM partners as worthwhile to be studied for blades : IN738 and IN792. Their chemical analysis appear very similar (table 2) with chromium cobalt, molybdenum, tungsten, titanium, aluminium and tantalum alloying. IN792 contains hafnium and more tantalum than IN738 (IN738 LC is presumably a low carbon variant of IN738). Following the criteria of reference 3, IN792 has an advantage of 30 °C in high temperature strength when compared to IN738. This corresponds to a small advantage of 10 °C of IN792 against IN100. The directionally solidified (DS) version of IN792 produce a further improvement in high temperature strength which is estimated to 25 °C.

Additional proposal have been made by Framatome - Gmbh CMSX4 and PWA1483 for single crystals and SC16 for cobalt free single crystal blades : the chemical composition of these alloys are given in table 2.

4. Candidate Materials for turbine stator

4.1 Russian proposal for GTMHR turbine stator

The Russian material for GTMHR turbine stator is a chromium tungsten molybdenum base nickel alloy called ChS57. Amounts of zirconium (0-15 %) and ytrium (0.05 %) are mentioned. It is not clarified whether or not these elements are present in oxide particles. If it is the case, this alloy must be categorised as an ODS alloy.

4.2 Western proposal for turbine stator

Ni alloy Hastelloy X can be proposed as nearly equivalent to the Russian ChS57 alloy. The corresponding specified chemical analysis is given in table 3. The specified chemical analysis of the low cobalt version of Hastelloy X (developed in Japan and called Hastelloy XR) is also given in table 3. The reference 4 indicates for Hastelloy XR mechanical properties which can be favourably compared to those of ChS57 alloy. Consequently there is no reason to not select the XR version of Hastelloy X (see paragraph 8.3).

5. Comments on the choice of nickel base alloys

All the proposed materials in part 2, 3 and 4 above are nickel base superalloys. This selection corresponds to the reference to an existing industrial experience : that of aero-engines and that of gas turbines. Up to now, nickel base superalloys are the material used for these machines and tentative other solutions have started only for small parts or for tiles used as thermal protecting devices.

As these industries used nickel base superalloys up to 90 % of the melting point of the alloys, new refractory materials are investigated for the future in particular compositions based on Nb – Ti – Cr – Al – Si (Ref 3) which look promise. But the development of such alloys are far from an industrial issue.

Molybdenum alloy (TZM with 0,50 % titanium and 0,08 % zirconium) has been studied in Germany for helium turbine blades. This alloy have several draw back :

- Mo-TZM is brittle at temperatures up to 350-440 °C,
- oxidation resistance is poor and air ingress will produce massive oxidation,
- microstructure is heterogeneous in the prototypical blades and low strength areas were found in fatigue and creep.

This alloy was not considered by American partners of GTMHR project. In addition due to the oxidation sensitivity there is no hope of cooperative development of TZM alloy with aero-engines and gas turbine industries.

6. Candidate materials for HTR turbine : implications of manufacturing processes

6.1 Casting

It is not the practice to use cast parts for large disks in aero-engines.

The implication of casting as manufacturing process is the acceptability of this process for disks in HTR and (Russian grade Zh56F and VZhL12U proposed for GTMHR and proposed grade IN100 for PBMR). This implies the non destructive and destructive examinations of defects of a prototypical disks and fracture mechanics assessment of the defects : as other solutions exist, we suggest to eliminate cast products from list of candidate materials for disks.

6.2 Directionally solidified products

This manufacturing process has two implications. Firstly the success of this process is bound to a specific alloys and to a specific geometry of the blades : blades in DS alloys were found difficult to fabricate in particular when the thermohydraulic or cooling design results are thin walled airfoil. The implication is that the development of blades in DS grades as (MAR M247DS or IN792 DS) requires a precise sizing and design of the blades and cooperation with a producer of DS products in order to demonstrate the manufacturing possibility of DS alloy blades for HTR turbine (and to precise the cost of this solution).

The second point is the anisotropy produced by DS process : it means that design material data must be characterised with reference to the specimens orientations. In the cases where anisotropy is important :

- this effect must be treated in the design rules and in particular anisotropic thermal expansion coefficient and anisotropic modulus of elasticity,
- the material data of the DS alloy differ from those of the cast alloy of the same chemical composition.

The two implications concern MAR M247 DS and IN100 or IN792 in the DS version of the blades.

6.3 Single crystals

For single crystal blades, the implications are the same than for DS blades The improvement gained with single crystals as compared with DS alloy is also the result of solidification under, larger thermal gradient. This is more difficult with larger size of blades. The discussion with a producer of single crystals blades is even more important as the size and geometric complexity of such blades are increasing from year to year and an up to date knowledge of industrial manufacturing possibility must be taken into account in the development of HTR projects.

Concerning the anisotropy, the length of the blade corresponds to a crystallographic direction (<001> within 6° according reference 9). For some properties as fatigue crack growth rates (Ref 10), differences appear in the propagation of (001) [110] cracks and (001) [100] cracks : the behaviour of the material can be fully anisotropic and not orthotropic.

These implications concern CMSX2, CMSX4 and PWA1483 blades and Ch120M in the single crystal version for blades.

6.4 Oxide dispersion strengthened products

The first implication of this manufacturing process is the manufacturing possibility of products of required size for HTR turbine. As pointed in 2.2 extruded bars in MA6000 (ODS) seem to be very far the diameter required for GTMHR turbine disks. Active cooperation with a producer of ODS alloys is necessary to fabricate prototypic products demonstrating the viability of ODS solution for disks. The other implication of ODS is that it produces a material which has design material properties quite different from those of the matrix alloy.

These implications concern the MA6000 candidate material for disks and the Russian alloy ChS57 if it is confirmed that ytrium and zirconium are present in the alloy as oxide dispersed particles.

6.5 Powder metallurgy and Hot Isostatic Pressing

This fabrication process is applied to :

- forged alloys to increase the size over the limit of forgeability,
- cast alloys to increase the size over the limit of castability.

In both cases, the powder is produced by an atomisation process. The first implication of this process is the hot isostatic pressing (HIP) facility which should be sized to treat large diameter disks. This point concerned Udimet 720 and other forged candidate materials for large disks.

The second implication of HIP is that it produces materials with design properties different from those of the corresponding forged or cast alloy.

6.6 Hot Isostatic Pressing of Cast alloy

Hot isostatic pressing (HIP) of cast alloy can be used to reduce porosities of the as cast alloy (conventionally cast or directionally cast or cast as a single crystals, Ref 12). This process can be delicate to optimise but if seems to be necessary to improve the thermal fatigue behaviour of the as cast or DS or single crystal products.

7. Helium environment consideration and coating

7.1 Implications of HTR helium environment

All the turbine candidate material of parts 2 to 4 were developed for aero-engines or gas turbines. Among criteria for selection of alloys in these machine are :

- resistance to hot corrosion,
- resistance to oxidation.

Hot corrosion is elevated corrosion due to the composition of the gas resulting from fuel combustion (sodium, potassium, sulfur,…). This type of corrosion is not encountered in HTR helium.

Concerning oxidation, the reaction occurs in HTR helium from CO, CO_2, H_2O and CH_4 impurities. The surface layer is formed from chromium and other metallic elements under oxidizing condition. Oxidation can also produce the growth of a sublayer of internal oxidation which can be the origin of the major part of metal loss.

As indicated in reference 14 in the case of Inconel 617, the HTR helium environment can be carburizing or decarburizing depending of temperature, content of helium impurities and alloy. Concerning the effect of the environment, it seems that the case of low aluminium and titanium alloys is different from the case of large volumic fraction of γ' produced by large amount of aluminium or aluminium + titanium.

For HTR in Japan a low titanium and low aluminium alloy was developed in order to improve the behaviour in HTR helium environment (Ref 13) : it is the modified Hasteloy XR of table 3 which in addition has an as low as possible cobalt content. The reduction of titanium and aluminium suppress internal oxidation and intergranular attack. Decarburization and carburisation reactions can also occur over a critical temperature depending of the alloy and of H_2O, CO, CH_4 concentrations (Ref 14). It must be pointed out that internal oxidation, intergranular attack and carburization or decarburization have been observed in low Ti + Al containing alloys : alloy 800H (Ti + Al $\leq$ 1 %), Hastelloy X (Ti + Al $\leq$ 0.65 %) and Inconel 617 (Ti + Al $\leq$ 1.3 %).

The implication of HTR helium environment is that for low Al + Ti alloys, the (Ti + Al) content must be reduced as it is in the Japanese grade of Hastelloy (Hastelloy XR). Many candidate materials for turbine disks and blades have high contents in aluminium (or Ti + Al) : 6 % < Ti + Al < 8 %. In this case, no intergranular attack and no internal oxidation occur and in many cases protective oxide scales are observed. An exception may be M21 alloy (Ref 15) which is titanium free and has a low chromium content (3-6%) : a weight gain greater than in 713LC alloy indicates that the oxide layer is not protective in the environment of the tests.

Concerning γ' hardened alloys for blades the question of the quality of oxide layer is the more important problem. It seems that less than 6,5% of Cr it is not enough. For the γ' alloys containing more than 6,5 % of Cr, it is not clear if the behaviour of alloy in HTR helium environment is better (The approximate values of Al /Cr are given in table 4 for the different candidate alloys for blades) :

- for chromium rich alloys promoting $Cr_2 0_3$ formation ; (for these alloys Al /Cr $\leq$ 0,4),
- for aluminium rich alloys promoting $Al_2 0_3$ formation (for these alloys Al /Cr $\geq$ 0,5).

The development of the use of single crystals which are the highest performance for blades indicates.

- The use of PWA1480 for aeroengine in 1982 (Réf. 17). PWA1480 has a ratio Al /Cr = 0.5. Then the development of CMSX2 and CMSX4 (Al /Cr = 0.69 and 0.86) correspond to an improvement of the creep strength (Réf. 18).
- The first single crystals to be used for blades in land base turbine is CMSX4 in 1990 (Réf 17 and 19).

Reference 17 indicates there was a need to develop more corrosion resistant alloys for industrial gas turbines than for an aircraft turbine : this seems mainly due to hot corrosion resistance needs with the use of a fuel of lower chemical quality. The improvement of corrosion resistance is obtained by using higher chromium alloys as IN738 (Al /Cr = 0.21), IN792 (Al /Cr = 0.28) and for single crystals PWA1483 (Al /Cr = 0.29). PWA1483 single crystals were used satisfactorily for hot blades of gas turbine.

Although hot corrosion due to fuel impurities is not encountered in HTR helium, carburizing or decarburizing can be very detrimental to the materials in service at high temperature. In these situations chromium oxide forming material or coating is better, chromium acting as "carbon getter".

Table 4 indicates also that aluminium oxide former alloys as CMSX2, CMSX4, MAR M247, MAR M004 have low values of Ti/Al ratio (Ti/Al < 0.2), whereas chromium oxide former alloys have a Ti/Al ratio not very different from 1 (PWA1483, SC16, IN792) resulting in Ti/Cr ratio between 0.22 and 0.34.

The implication of HTR helium environment for γ' hardened alloy is the choice of chromium rich alloys (PWA1483, IN792 and SC16) if carburizing or decarburizing conditions cannot be excluded by the control of helium quality. In the opposite case, aluminium oxide former materials can be considered (CSMX4, MAR M247DS and MAR M004).

7.2 Coating

Initially coating was used to protect gas turbine hot section components from oxidation and hot corrosion. Aluminide coating were successfully developed for resistance to oxidation and used. Improvements for resistance to hot corrosion were obtained by the development of metal, chromium, aluminium and ytrium coatings (MCrAlY, metal M being nickel, cobalt or iron) (Ref 3).

As for base materials, the contents of chromium and aluminium determine the propensity of the coating to be chromium oxide former or aluminium oxide former. For the same considerations as for base materiel, chromium rich coating is preferred in case of long life industrial engine as gas turbine and HTR turbine if carburizing and decarburizing conditions have to be taken into account. In addition coating of a Cr oxide former alloy by Cr oxide former coating is more easy than coating an Al oxide former alloy by Cr oxide former coating. For thermal fatigue performance, fatigue can initiate in the coating and propagates into the superalloy : differences in fatigue lifes can be observed with the same coating on different superalloys. Better thermal fatigue performance are obtained when interdiffusion between the coating and the substrate is limited.

The conclusion are

- Coating is necessary for long life turbine blades,
- A base material with adequate corrosion resistance is regarded as essential even in case of coating.
- Coating must be of the same type (chromium oxide former or aluminium oxide former) than the base alloy.

A last implication of coating is that in case of coating, it is not the cobalt and tantalum of the alloy which is important for contamination but those of the coating.

Move recently thermal barrier coating (TBC) were developed for turbine blades (Ref 16). It is a second layer deposited on MCrAlY layer which can increase the temperature difference between gas and superalloys up to 100 °C. The composition of TBC is zirconia + yttria (around 7 %°). It is a porous layer and the choice of the MCrAlY coating metallic bounding layer for environment reasons is the same as in absence of TBC. For both layers, the deposition process are electron beam physical vapour deposition (EP-PVD) or plasma spray : the first being better but more expensive.

The implication of the TBC + MCrAlY coating for the selection of materials turbine blades is that for the same gas temperature an alloy less resisting to high temperature can be used. The choice of the best coating remains to be made for HTR helium environment and its durability to be assessed.

8. Cobalt (and tantalum) free turbine materials

The action to evaluate the amount of cobalt (and tantalum) which can be transferred from cobalt and tantalum alloyed turbine materials to the core through the helium circuit is not finished and the conclusion about the maximum allowable cobalt content in the turbine alloys is not known. The implication of this action can result in a decision of using only cobalt free materials in the HTR turbine. The present paragraph examines the simplification of such a decision on the selection of candidate materials for the HTR turbine.

8.1 Cobalt free material for turbine disks

For disks (table 1), there is no cobalt free proposed material except MA6000 which is an ODS alloy with the associated fabrication problem for large diameter (paragraph 6.4)

Although the cobalt problem seems to be less important for disks than for blades (smaller total surface and less erosion loss with a lower differential velocity of the gas) it is desirable to consider for disks a forged cobalt free material : there are no reasons to discard Hastelloy XR from disk application.

8.2 Cobalt free materials for turbine blades

In table 2, the number of cobalt free materials is very limited. The majority of cast alloys contents between 8 and 16 % cobalt : it is the case for IN100, IN792, IN738LC, and 713LC. Excluding M21 alloy which seems not very convenient for HTR helium environment, the cobalt free material to study for blades is MAR M004 (low chromium) or SC16 (high chromium). But if coated, the blades do not need to be cobalt free.

8.3 Cobalt free stator material

In the case of stator, the proposal is to restrict the selected cobalt free material to Hastelloy XR which appear satisfactory from the test in Japan when compared to standard Hastelloy X. One advantage of this selection is that this material can be used also for Reactor Vessel and Hot duct internals and that high temperature characterisation can be at least partly used for both applications.

9. Conclusion

The different candidates for three turbine applications (disks, blades, first stage stator) have been firstly identified and their chemical composition (specified or typical) are given in table 1 to 3. Taking into account the implications of manufacturing processes (reviewed in paragraph 6) of HTR helium environment (paragraph 7), of cobalt content (paragraph 8), the candidate materials can be separated in the categories, which follow.

1. "High technology materials". The materials are the results of the most recent technology and this technology has to be validated for the size and geometry of HTR turbine. This effort requires the cooperation of a material producer : oxide dispersion strengthened material for disks as MA6000 (ODS), single crystals for blades as CMSX4 or PWA1483 enter in this category. In addition, MA6000 ODS is a cobalt free material. CMSX4 and PWA1483 are preferred to CMSX2 for their larger experience in land turbine. PWA1483 which is higher in chromium is better in case of carburizing or decarburizing risks.

2. Materials to be adapted to HTR. These materials are produced by a more conventional fabrication process (forging or casting). The adaptation required is a more performant manufacturing process in order to increase the size or to improve the high temperature properties. HIP Udimet 720 for disks, Directionally solidified cast alloy as MAR M247DS or IN792DS for blades enter in this category. Higher chromium IN792DS is better in case of carburizing or decarburizing risks.

5. High temperature conventional materials. Forged products for disks, conventional cast materials for blades, forged Hastelloy XR for stator enter in this category. Our proposal is to concentrate the effort on the same alloy as in the category 2 but on the reference forged or cast product : forged Udimet 720 for disks, cast MAR M247 or IN792 for blades. It must be recalled that distinct characterization should be finally performed for HIP Udimet 720 and forged Udimet 720 or for IN792DS and cast IN792. The choice between IN792 from Inco group (higher chromium content) or MAR M247 from Martin Marietta Corporation (higher Al/Cr ratio) is connected to the carburizing and decarburizing risks. We propose to study cast IN792 rather than cast IN738LC if IN792DS is chosen for category 2.

6. Cobalt free high temperature materials : the alloy mentioned in part 8 enters in this category. For disks it is the wrought Hastelloy XR (as for stator) or a material to be defined if Hastelloy XR must be discarded. For blades it is MAR M004 or SC16 but if coated the blades do not need to be cobalt free.

The categorisation and restricted selection of materials are summarised in table 5.

Single crystals, directionally and conventionally cast alloys must be hot isostatically pressed and characterised in this delivery condition. The blades must be coated and fatigue testing must be performed taking into account this surface condition.

The information on Russian proposed materials are not sufficient to categorise them : refering to the proposed Western equivalent material which are generally the highest temperature material, they must be put in the High technology material category.

Table 1

Candidate materials for turbine disks

(% mass)	C	Cr	Co	Mo	W	Ti	Al	Nb	Ta	Hf	V	B	Zr	Other
Zh56F	≃ 0.11	≃ 5.5	≃ 9.4	≃ 0.9	≃ 12	≃ 1.0	≃ 5.3	≃ 1.6	-	≃ 0.9	≃ 0.9			
V2HL12U	≃ 0.17	≃ 9.5	≃ 13.5	≃ 3.1	≃ 1.4	≃ 4.4	≃ 5.4	≃ 0.75	-	-	≃ 0.75			
Inconel MA6000 (ODS)	≃ 0.05	≃ 15	-	≃ 2	≃ 4	≃ 2.5	≃ 4.5	-	≃ 2	-		≃ 0.01	≃ 0.15	Y_2O_3 : 1.1
Udimet 720 (F or HIP)	0.03 0.04	17.5 18.5	14 15.5	2.75 3.25	1.1 1.4	4.75 5.25	2.25 2.75	-	-			0.03 0.04	0.025 0.050	
IN 100 (C)	≃ 0.18	≃ 10	≃ 15	≃ 3	-	≃ 3	≃ 4.7	-			≃ 1	≃ 0.014	≃ 0.06	

F : Forged

C : Cast

ODS : Oxide Dispersion Strengthened

HIP : Hot Isostatic Pressed

Udimet : trademark of Special Metals Corporation

Inconel, MA : trademark of Inco group of companies

Table 2
Candidate materials for turbine blades

(% mass)	C	Cr	Co	Mo	W	Ti	Al	Nb	Ta	Hf	V	B	Zr
Ch120M (C or SC)		≃ 11.7	≃ 7.5	≃ 1	≃ 6.5	≃ 4.3	≃ 4	≃ 0.8	-				
EI929 (F)	-	9 12	12 16	4 6	4.5 6.5	1.4 2	3.6 4.6	-	-				
EI893 (F)	-	15 17	-	3.5 4.5	8.5 10	1.2 1.6	1.2 1.6	-	-				
EP800 (F)	-	12 13.5	8.5 10.5	5 6	4 6	-	4.2 4.9	1.5 2	-				
CMSX2 (SC)	≤ 0.03	≃ 8	≃ 4.6	≃ 0.6	≃ 7.9	≃ 1	≃ 5.5	-	5.8				
CMSX4 (SC)		≃ 6.5	≃ 9	≃ 0.6	≃ 6	≃ 1.0	≃ 5.6		≃ 6.5	≃ 0.1			
PWA1480 (SC)		≃ 10	≃ 5		≃ 4	≃ 1.5	≃ 5		≃ 12				
PWA1483 (SC)	≃ 0.080	≃ 12.3	≃ 8.5	≃ 1.9	≃ 3.8	≃ 4	≃ 3.6		≃ 5	< 0.01		< 0.003	< 0.01
SC16 (SC)		≃ 16		≃ 3.0		≃ 3.5	≃ 3.5		≃ 3.5				
MAR M247 (C or DS)	0.13 0.17	8 9	9 11	0.5 0.8	9.5 10	0.9 1.2	5.3 5.7		2.8 3.8	1.2 1.6			
M21 (C)	~ 0.1	~ 6	-	~ 2	~ 10.5	-	~ 6	1.5				~ 0.02	~ 0.1
MAR M004 (C)	≃ 0.065	≃ 11.86	-	≃ 4.42	-	≃ 0.6	≃ 5.95	≃ 1.6	≃ 0.3	≃ 1.3			
713LC (C)	≃ 0.07	≃ 12	≃ 0.04	≃ 4.65	-	≃ 0.74	≃ 5.8	≃ 2				≃ 0.09	≃ 0.1
IN100 (C) or (DS)	≃ 0.18	≃ 10	≃ 15	≃ 3	-	≃ 3	≃ 4.7			-	≃ 1	0.014	0.06
IN792 (C) or (DS)	≃ 0.11	≃ 12.15	≃ 9.25	≃ 1.8	≃ 3.78	≃ 4.10	≃ 3.45	-	≃ 3.75	≃ 0.52		0.01	0.09
IN738LC (C)	0.09 0.13	15.7 16.5	8.0 9.0	1.5 2.0	2.4 2.6	3.2 3.7	3.2 3.7	0.6 1.1	1.5 2.0	-		0.007 0.012	0.03 0.08

(F) : Forged
(C) : Conventionally, cast
(DS) : Directionallly solidified
(SC) : Single crystal

CMSX is a trade name of Cannon Muskegon Corporation
MAR M is a trade name of Martin Marietta Corporation
PWA is a trade name of Pratt and Withney

Table 3

Candidate materials for first stage stator

(% mass)	C	Cr	Co	Mo	W	Ti	Al	Nb	Ta	Hf	V	B	Zr	Fe	Mn	Si
ChS57	≤ 0.05	≃ 19		≃ 6	≃ 2.5		≤ 0.15	-	-	-	-					
Hastelloy X	0.05 0.15	20.5 23	0.5 2.5	8 10	0.2 1.0	≤ 0.15	≤ 0.50	-	-	-	-	≤ 0.01	-	17.0 20.0	0.6 1.1	≤ 1.0
Hastelloy XR	0.05 0.09	20.5 23	≤ 0.10	8 10	0.2 1.0	≤ 0.05	≤ 0.05	-	-	-	-	≤ 0.01	-	17.0 20.0	0.6 1.1	0.2 0.5

Hastelloy is a trademark of Cabot Corporation

Table 4

Candidate materials for turbine blades : values of Al/Cr, Ti/Al and Ti/Cr ratios

	Al/Cr	Ti/Al	Ti/Cr
Ch120M	0.34	1.1	0.37
CMSX2	0.69	0.18	0.12
CMSX4	0.86	0.18	0.15
PWA1480	0.50	0.3	0.15
PWA1483	0.29	1.1	0.33
SC16	0.22	1	0.22
MAR M247	0.65	0.19	0.12
M21	1		
MAR M004	0.50	0.1	0.05
713LC	0.48	0.13	0.06
IN100	0.47	0.64	0.3
IN792	0.28	1.19	0.34
IN738	0.21	1	0.21

Table 5

Proposed restricted selection of candidate materials in the different categories

	Disks	Blades	Stator
Conventional High temperature materials	Forged Udimet 720	cast IN792 (1) cast MAR M247 (2)	Hastelloy XR
Materials to be adapted to HTR	HIP Udimet 720	cast IN792 DS (1) cast MAR M247 DS (2)	
High technology materials	Inconel MA6000 (ODS)	PWA1483 (1) CMSX4 (2)	
Cobalt free high temperature material	Hastelloy XR(3)	SC16 (1) (4) MAR M004 (2) (4)	Hastelloy XR

(1) to be chosen taking into account carburizing and decarburizing risks

(2) to be chosen if carburizing/decarburizing is excluded

(3) To be confirmed

(4) Only in case of uncoated blade development.