SMALL TURBOJET ENGINE INNOVATION AND TRIZ INSTRUMENTS

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Air Division of PBS, BUT Brno, BUT Brno

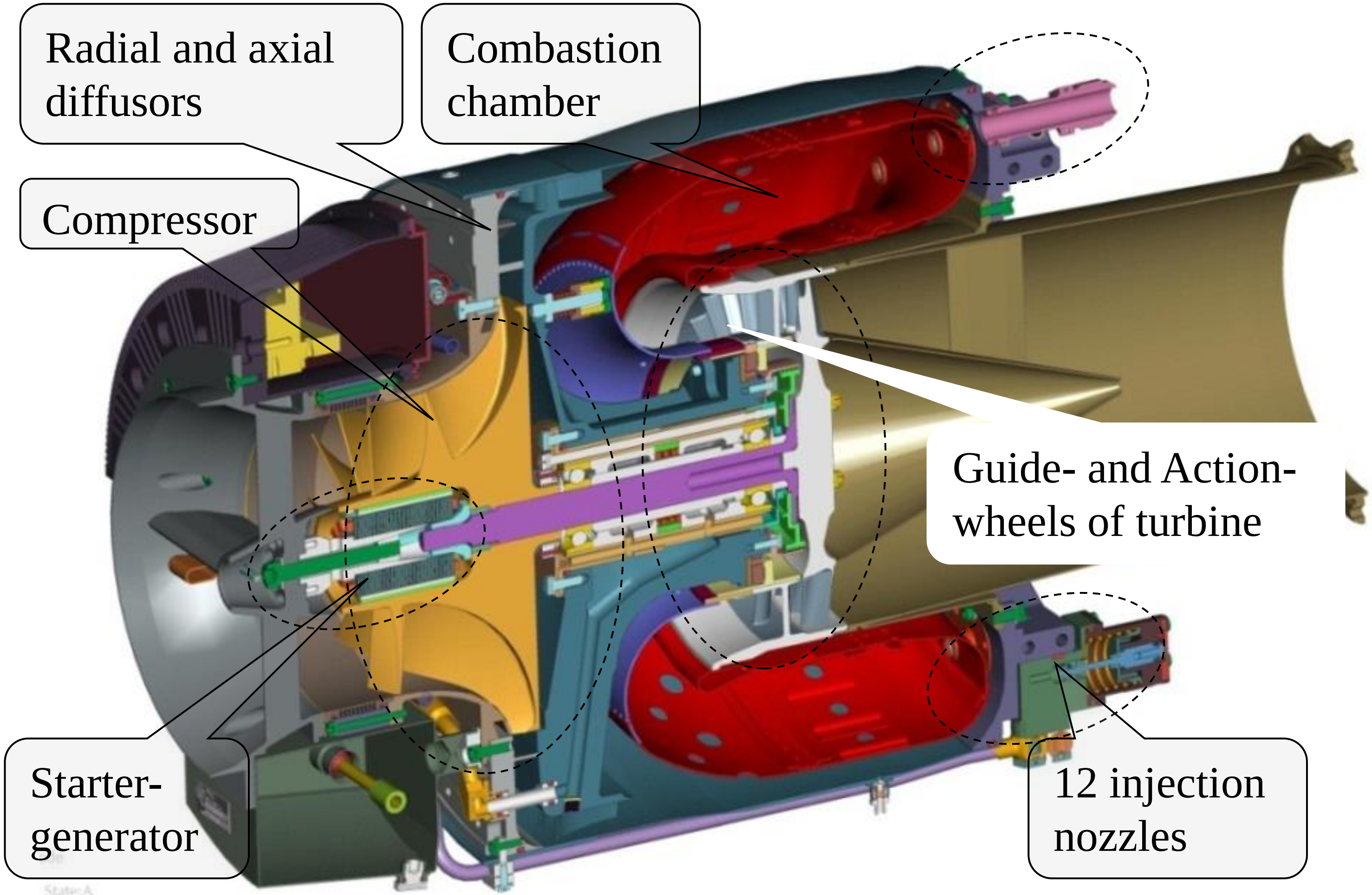


Fig. 1. Small turbojet engine TJ100S-125 [6].

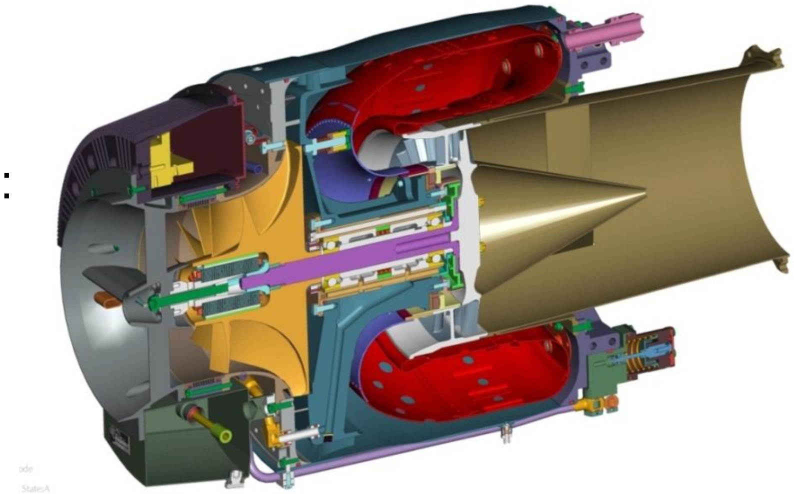
In this article, the turbojet engine is presented as a CASE STUDY:

❑ as an example of **innovative product evaluated** during exhibition,

❑ as a **case of innovation for teaching** the TRIZ methodology to students and engineers.

TJ100S-125
if compare to concurrent small turbojet engines
has several important parametrical advantages:

- weight,
- power,
- reliability,
- cost, etc.



Innovation of real product
was obtained by creative/inventive solutions in which
several instruments TRIZ were used objectively.

❑ **Product evaluation** during competition called **„GOLD MEDAL for BEST INNOVATIVE PRODUCT“** in category **„Commercial product“**

ting Sets

chy exponáty | 1ZM_SSVO | 2ZM_EE | 3ZM_PA | **4ZM_KP** | Rotor | Propagate values | New...

king Criteria: 8N_8MI_8RI_6HF_5DF_10ES_KP Add... **Method:** Quantitative (Weighted decision matr... **Formula:** K = 8*N + 8*MI + 8*RI + 6*HF + 5*DF + 10*Ex

omize Solutions List: ON Custom groups: New... View settings

Solutions	Novost (N)	Míra invence (MI)	Řad inovace (RI)	Hlavní Funkce (HF)	Doplnkové Funkce (DF)	Expertní stanovisko (Ex)	**Rank #**	**Rank Value** Better ⟶
outěž o ZM : User-defined problems and general solutions								
General Solutions								
4. Proudový turbínový motor TJ 100S	6,00	3,00	6,00	5,00	3,00	9,00	1	3914,29
1. Zařízení sekundární metalurgie, V	3,00	3,00	5,00	3,00	7,00	10,00	2	3526,67
25. M2 cusing	4,00	4,00	4,00	1,00	4,00	8,00	3	3072,38
2. ONDRÁŠEK INK JET SYSTEM, S	3,00	3,00	5,00	4,00	5,00	0,00		2503,81
11. H 800								
18. TPS/i								
20. Ložisková jednotka PLC 810-15								
10. Dlouhotočný CNC automat MANU								
14. hybridní orovnávací systém hDD								
9. Indukční tavící pec I 03/13								
24. GAMBIT MAGNUM								
27. Tiskárna 3D FABBSTER C12/V2								

1. Novelty,

2. Level of Invention,

3. Innovation Rank,

4. Differentness Main function,

5. Differentness of Auxiliary fuctions,

6. Expert verdict

1.1. ***NOVELTIES*** of turbojet engines row from TJ100 to TJ100S-125

Engines **TJ100** have been developed since 2002.

Novelty by the law is protected by Czech utility model [2] and Chinese patent [3].

From the customer's point of view the engine novelty lies especially in parameters "**small size**" and "**small engine weight**".

Innovative engine **TJ100S-125** (follower TJ100) is produced from 2012.

Novelty by the law is protected again by Czech utility model [4] and Czech patent [5].

Utility model fundament consists of **new technology of coating** of integrally cast turbine parts with aluminum that extends significantly the working life of main engine parts.

The patent fundament consists of the **new system of regulation of fuel supply** to the combustion chamber.

From point of view customer´s two latest novelties of the TJ100S-125 turbojet engine can be characterized by improvement of parameters: „**thrust**" and „**operating time**".

Table 1. Main improvements of TJ100S -125 engine

Parametr	Original - **TJ100**	New - **TJ100S 125**
Thrust /N/	1 100	**1 250**
Operating lifetime /hours/	50	**200**

*1.2. **INVENTION** in turbojet engine **TJ100S-125***

The innovative engine with the thrust of 1250 N fulfills the invention criterion (four steps: 1. Takeover; 2. Adaptation; **3. Remodeling**; 4. New model) on the level 3. Remodeling.

3. Level Remodeling means
„***Significant transformation of the known model for several substantial improvements achieved concerning of components, functions and parameters***.

1. The turbojet engine **thrust was increased** by the following improvements:
 - new **compressor** stage with higher air compression efficiency;
 - new type of **combustion chamber** with higher efficiency and lower smoke number;
 - new profiling of **turbine stage** with higher efficiency;
 - the **fuel pump** efficiency increase of 15% (increase of fuel supply with unchanged power input).

2. The turbine **working life was increased** several times using the new developed technology of aluminum coating of guide-wheel and action wheel.

3. The turbine **engine controllability was improved** including the start ability increasing up to the altitude of 6000 m through in principle new controller of bypass nozzle fuel [5] and improved control unit software.

1.3. ***INNOVATION RANK*** *of TJ100S-125 turbojet engine*

The above mentioned **improving of several components**, higher **thrust**, better **controllability**, substantially increased **working life** of the turbojet engine placed the product in the innovation ran **6 – NEW GENERATION** of product, in any case in the level of qualitatively new solution [Souchkov].

INNOVATION RANK (differentness from state of the art, by Valenta [1]) and ***INVENTION LEVELS*** *(differentness from known model / known prototype)*		Solutions by Souchkov
Quantitative (not patentable) solutions	0. Regeneration of producing model	
	1. Quantification of producing model	1 Quantitative
	2. Intensification of producing model	
	3. Reorganisation of producing model	
	4. Adaptation of producing model	
Qualitative solutions (with novelty)	**5. New VARIANT** is distinguished with the change of a partial quality (one or more functions) while maintaining the structural design solution of the generation into which the variant falls. ***Adaptation of known product model****,means* **novelty.**	2 **Qualitative**
	6. New GENERATION is distinguished with the change of more qualities (more or all of the functions) while maintaining the conception of the kind into which the generation falls. ***Remodeling****,of known product model, means* **novelty.**	
	7. New KIND is distinguished with the change of the main function, the design conception is changed, all is changed except the principle of the functioning of the genus into which the kind falls. ***New*** *product model, means* **novelty.**	3 Functional
	8. New GENUS is distinguished with the change of the technological principle of the functioning while remaining in the Clan of the technology. ***New*** *product model*, **novelty.**	4 Principal

1.4. ***MAIN FUNCTION*** *AND* ***PARAMETERS*** *of TJ100S-125 engine in comparision*

In the power category of comparable turbojet engines with the thrust of 1000 – 1500 N, there are significant competitors: SALUT (Russia), Williams Int. (USA), Microturbo (France).

Table 2. Comparison of **TJ100S-125** engine from the competition

Engine producer	**Microturbo**	**Williams Int.**	**SALUT**	**PBS V. Bíteš**
Engine type	TRS 18	WJ 24-8	MD 120	**TJ100S-125**
Max. **thrust** /N/	1 150	1 089	1 177	**1 250**
Engine **speed** 100% 1/min/	47 200	52 000	52 000	59 000
Compression	?	?	(7,2)	5,2
SFConsumption /kg/daNh/	1,2	1,2	(1,04)	1,15
Weight /kg/	37,5	22,68	35	**19,6**
Max. **front diameter** /mm/	303 x 350	292 x 383	265 x 300	**ϕ 272**
Length without exhaust /mm/	600	501	750	**488**
Control unit	External analog	Hydro-mechanical	External analog	Integr. FADEC +convertor 1 kW
Manner of start	Electrical	By air	By air / pyrocartidge	Electrical
Altitude /m/	10 000	12 000	10 000	10 000
Time to general repair /hrs/	?	25	15	**200**
Lubricating system	Autonomous	Lossy	By fuel	Autonomous
Thrust / weight ratio /daN/kg	3,07	4,80	3,36	**6,38**

1.5. ***DIFFERENTNESS OF AUXILIARY FUNCTIONS** of TJ100S-125*

• A unique design with a built-in starter-generator in the compressor body allows the user smooth engine start in the range of ambient temperatures from –40°C to +50°C by means of 28V battery, current consumption up to 100 A.

• Competitive engines started by air require ground equipment including compressor and pressure vessels, which increases the cost by up to 30% of engine price. Weight, total mobility and flexibility of such a solution are low.

• Unique opportunity of in-flight electric start allows to restart the engine either by instruction of the pilot or automatically based on the selected program. Experience confirms the need for this functionality, which reduces the occasion of total loss of the flying device.

• Engine has the air take-off behind the compressor, which allows the user:

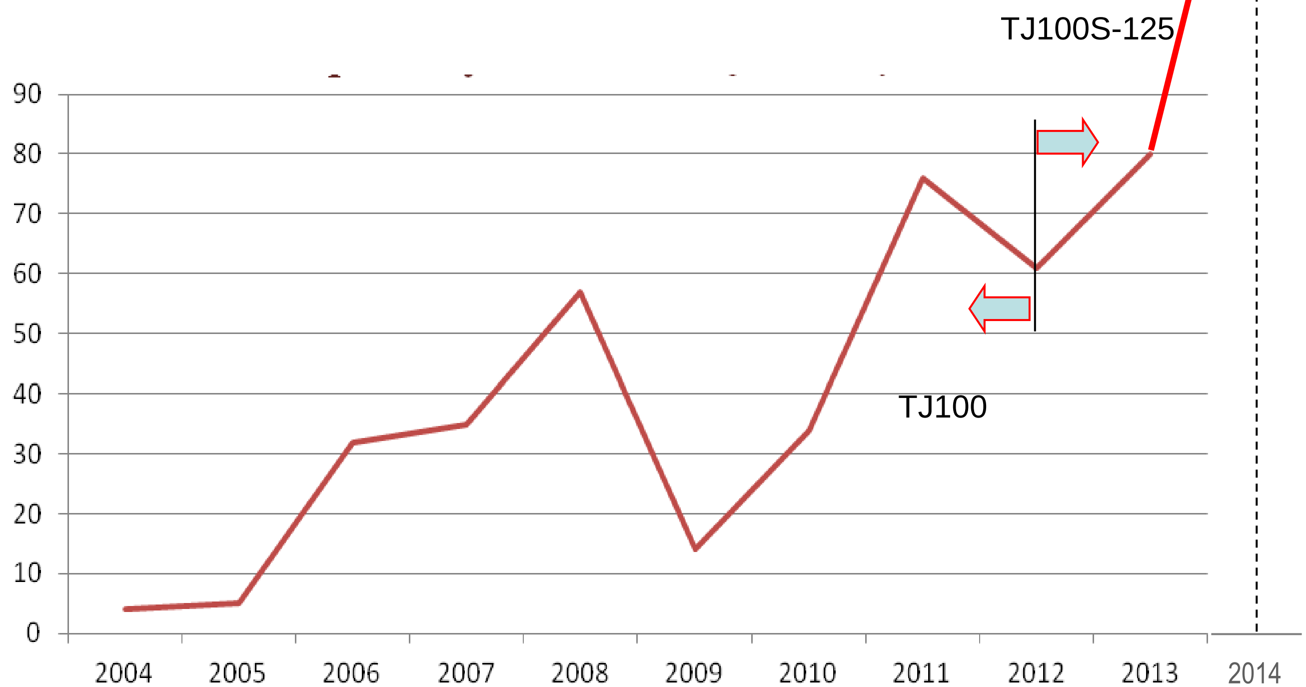
- to pressurize fuel tanks; - to heat or to blow-off board systems; - to inflate landing bags.

• Digital control system enables to program the engine functions according to customer needs, and to record all error messages for the last two hours of engine operation.

Using the monitoring software can easily trace any defects.

• A control system monitors the real engine operation and by the algorithm evaluates the residual source in hours and cycles.

• A control system transmits via bus the engine operation data (speed, temperature, voltage, current), and allows control of either by the pilot or remote-control of flying device.



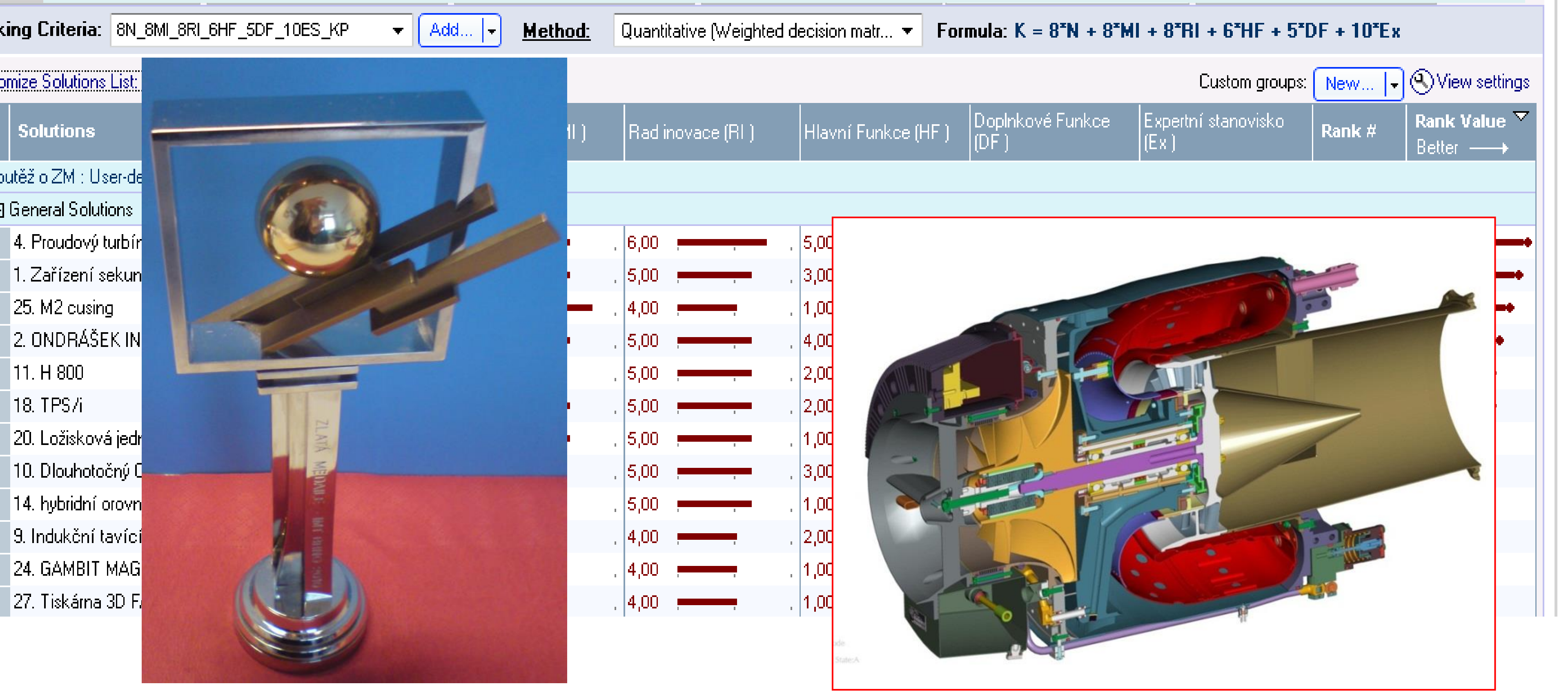
Progress of sold engines TJ100 and then TJ100S-125 (civil or military application)

Existing users

Table 3. List of existing users (15.5.2014, 30.8.2014)

Country	**COMPANY OR INSTITUTIONS**	**Number of sold engines (15.5.2014)**	**Number of sold engines (30.8.2014)**
United Arab Emirates	ATS	187	220
China	3 R&D, 2 Universities, 2 Companies	126	126
Russia	SOKOL, Rosoboronexport	61	82
USA	SONEX, Carlton, BD, Microturbo	9	9
Spain	INTA	7	15
Saudi Arabia	Research institute	6	6
Czech Republic	VZLÚ	1	3
Denmark	Xiroco	1	1
Italy		1	1
Suma		399	463

GOLD MEDAL competition for **BEST INNOVATIVE EXHIBIT in category „Commercial product“.**



(International Machinery Trade Fair in Brno, September, 2013).

❑ Case of turbojet engine innovation for teaching the TRIZ methodology to students and engineers

Problem situation with numerous contradictions can be visualized when chain of causes, so called RCA+ diagram is composed [8].

In this case we are interested about causes leading to the desired parameter **thrust/weight,**

which well represents the achieved quality of turbojet engine design

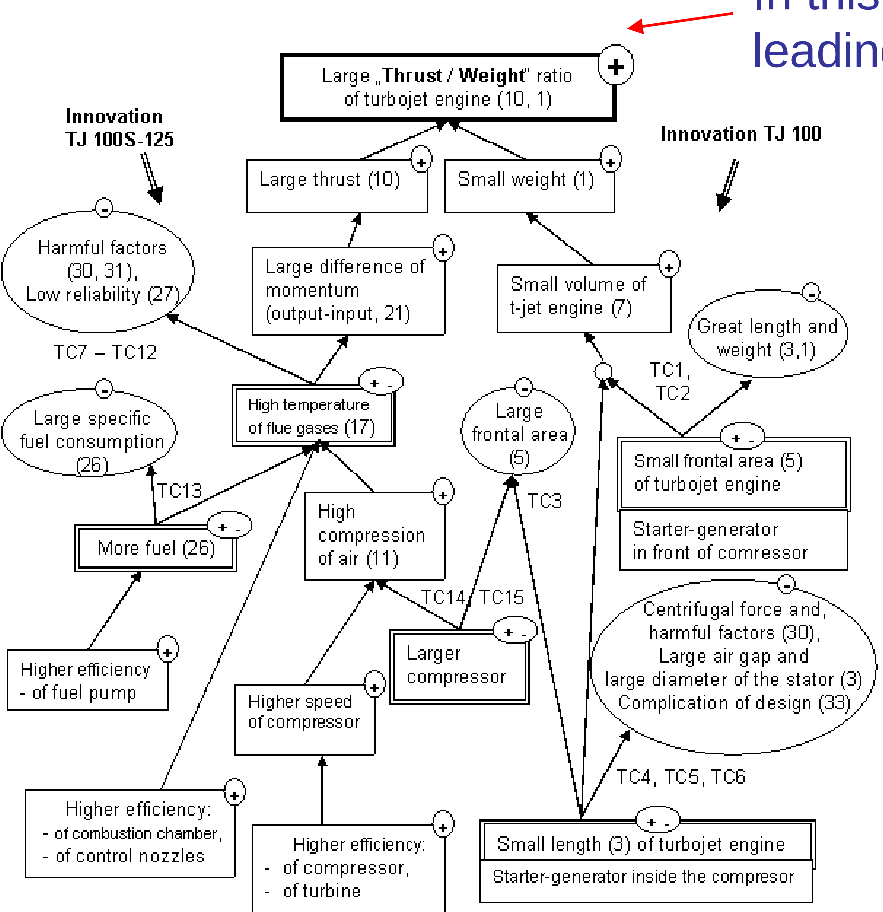


Fig.3 RCA+ diagram of problem situation

2. Where and how TRIZ was used

2.1. Contradictions and inventive principles in turbojet engine TJ100

2.1.1. „One inside the other“

Reducing the **volume** of turbojet engine (volume, 7th row in Altschuller table)
by small frontal area (electric machine located outside- ***in front of the compressor***)
leads to the extension of the built **length** (length, 3th column in Altshuller table)
and total **weight** (1th column in Altshuller table).
Possible formulations of technical contradictions (TC):

TC1: volume 7/3 length – recommended heuristic principles (HP): **1**, **7**, 35, **4** and
TC2: volume 7/1 weight – recommended heuristic principles (HP): **2**, 26, 29, **40**.

Whereas the TC1 and TC2 formulations are only verbal models of the problem being dealt with, visual models of the same problem/contradictions being solved are more illustrative. Visual models can be found in the right upper part of RCA+ diagram (Fig. 3) which is a relatively complete map of the problem situation [7].

"Segmentation" (HP1), "One inside the other" (HP7) and "Extraction of harmful property" (HP2) could be imaginative and were objectively applied.

One object (starter-generator) was built <u>inside</u> the other (compressor), and so were <u>extracted</u> worsening length/weight parameter.

In solution TJ100 both built-up **volume**, smaller frontal **area** and reducing the **length** were achieved, as well as the **weight** of the engine was reduced.

Word formulation of TC1 and TC2 are only **verbal models.**

Visual models of TC1 an TC2 inside complete problem situation are much better for effective communication in team work.

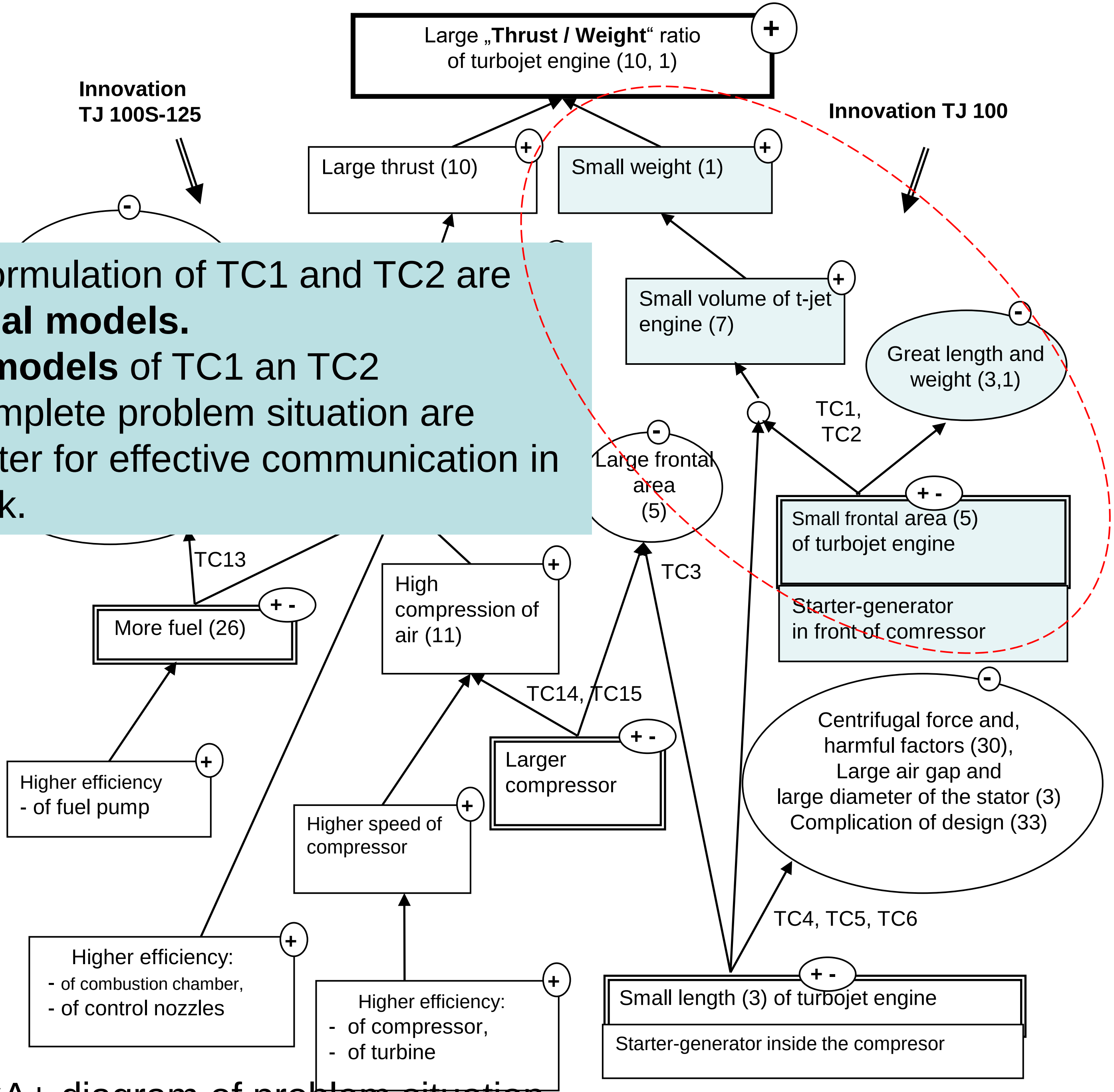


Fig. 3 RCA+ diagram of problem situation

2.1.2. Several times „vice versa“

However, to reduce the overall built-up **volume** (7) by integration of starter-generator inside the turbojet engine (one inside the other), as mentioned above, in a conventional way (powered static stator and rotating rotor with permanent magnets), leads to extinction of the frontal **area** (5), extinction harmful action of centrifugal **force** on the rotor magnets (30), extinction of the air **gap** between rotor and stator, extension of inner **diameter** (3) and **weight** of the stator and compressor impeller, which **complicates** (33) the use of such a construction.

Possible formulations of technical contradictions (TC):

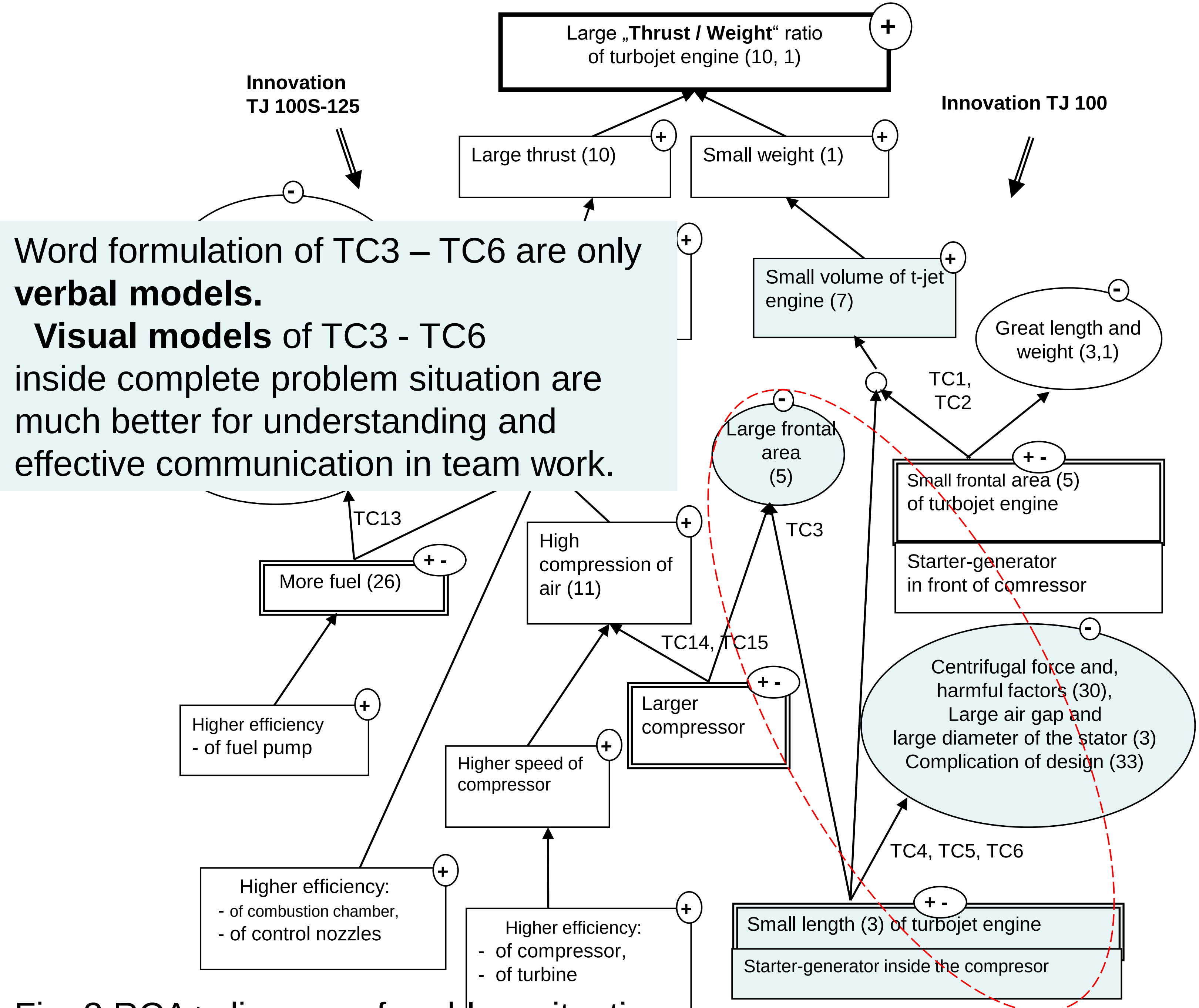
TC3: volume 7/5 area: HP: 1, **7**, **4**, 17
TC4: volume 7/30 harmful effects on magnets: HP: **22**, 21, 27, 35
TC5: volume 7/3 diameter: HP: 1, **7**, **4**, 35
TC6: volume 7/33 complication: HP: 15, **13**, 30, 12

Again, it is useful to supplement verbal problem models (TC3-TC6), by visual models of partial problems being solved. Visualization of TC3-TC6 in Fig. 3, right side.

Principles: introduce “Asymmetry” (HP4), “One inside the other” (HP7), “Converting harm into benefit” (HP22) “Inversion” (HP13), could be inspirational and were objectively applied.

In the new solution of TJ100, the stator is placed inside the rotor, which is built-up in the compressor impeller. Permanent magnets are not on the surface of the rotor, but conversely on the internal diameter of the outer rotor. Magnets are not centrifuged as usual from the rotor surface, but conversely are pushed to the internal surface of the outer rotor.

Objectively and multiple times used heuristic principles “inversion”, “asymmetry” and “converting harm into benefit” led to the creation of TJ100 with **small dimensions**, **low weight** and therefore to the higher indicator of design quality – **thrust / weight**.



Word formulation of TC3 – TC6 are only **verbal models.**
Visual models of TC3 - TC6 inside complete problem situation are much better for understanding and effective communication in team work.

Fig. 3 RCA+ diagram of problem situation

2.1.3 **PARTIAL CONCLUSION** concerning of TJ 100 turbojet engine.

New solution of very compact engine can be evaluated in terms of TRIZ such as:
- **Overcoming several contradictions** (TC1-TC6) by combinations of several inventive/heuristic principles;
- Effective **merging of two systems** (compressor, starter generator), originally as a “tandem” up to the level of fusion - “one inside the other” [9];
- **Partially “trimmed” electric machine**, now built-up inside the compressor [9].

However, TJ100 (2002) engine has been further improved up to the variant TJ100S-125 (2012) by raising the **engine thrust**.

2.2. Innovative engine **TJ100S-125**

In the new engine TJ100S-125 the **working life** and the reliability of exposed engine components are increased, especially of turbine guide-wheel and action-wheel [4].

In the new engine TJ100S-125 **higher thrust**, **better controllability** and start ability are achieved at a lower specific fuel consumption [5].

Such improvements are usually contradictional, **either one or the other** is possible.

How the improvements were achieved?

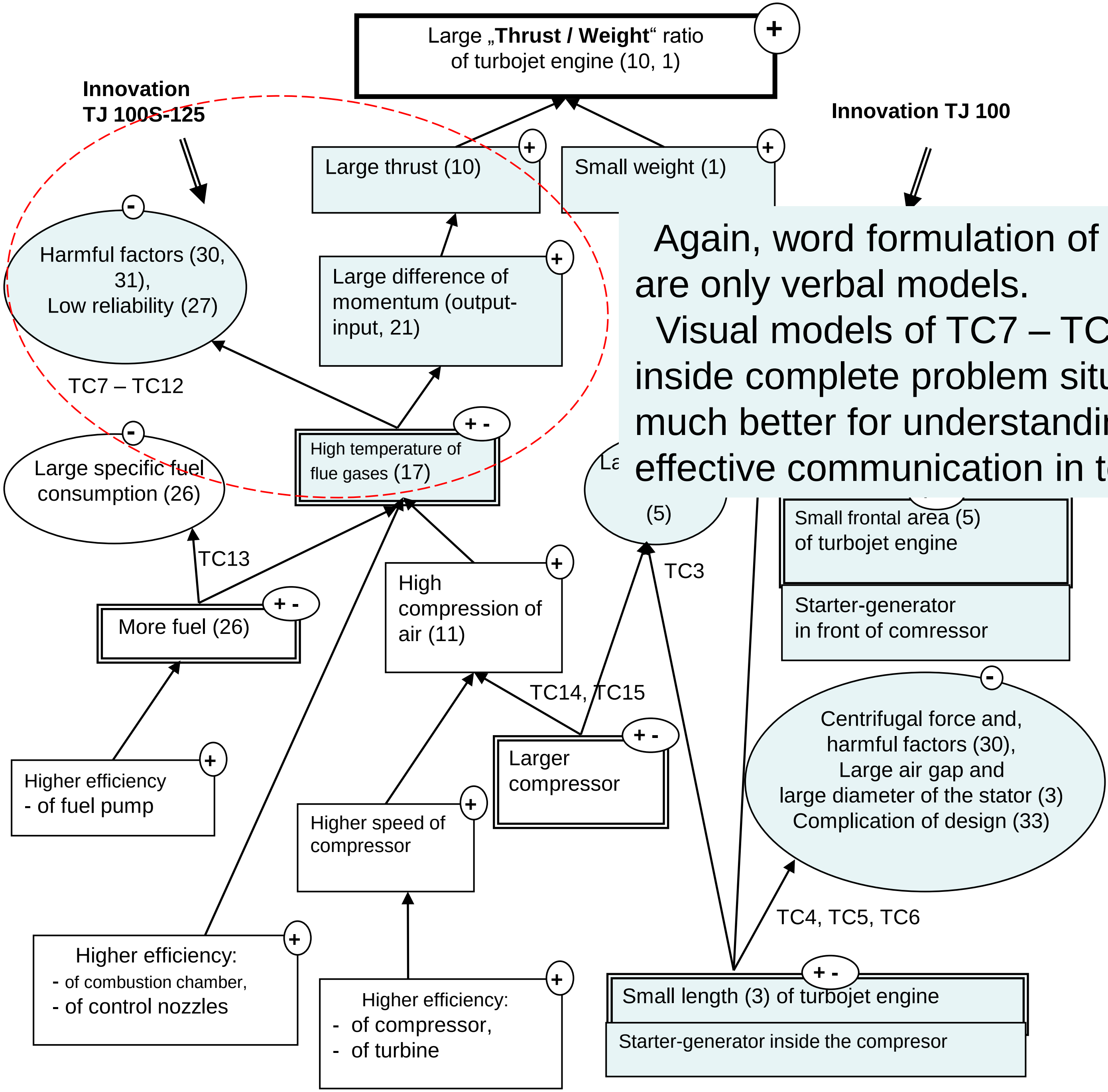
*2.2.1 **Thrust** versus engine **reliability** of TJ100S-125*

Increase of engine power or **thrust** (21 or 10) **by** higher exhaust gas **temperature** leads to higher **oxidation** (harmful factors, 30) and shortening of the **working life** (31) and reducing the **reliability** (27) of exposed components: combustion chamber, guide-wheel and action-wheel. Variants of contradictions:

TC7: power 21/30 harmful factors: HP: 19, 22, **31**, 2
TC8: power 21/31 harmful factors: HP: 26, **10**, **34**
TC9: power 21/27 reliability: HP: 19, **24**, 26, **31**
TC10: force 10/30 harmful factors: HP: **1, 35, 40**, 18
TC11: force 10/31 harmful factors: HP: 13, **3, 36**, 24
TC12: force 10/27 reliability: HP: **3, 35, 13,** 21

Heuristic principles: Porous materials (HP31), Extraction of harmful property (HP2), Preliminary action (HP10), Establish a mediator (HP24), Segmentation (HP1), Change of physical-chemical parameters (HP35), Composite (HP40), Phase transitions (HP36), Local quality (HP3), could be inspirational and several were objectively applied.

Increase of engine power or **thrust was achieved** by higher flue gas temperature but **without shortening of service** life and reducing the reliability,
thanks to **newly developed technology of coating** the exposed parts [4].
See Fig. 3, left side.



Again, word formulation of TC7 – TC12 are only verbal models.
Visual models of TC7 – TC12 inside complete problem situation are much better for understanding and effective communication in team work.

Fig. 3

2.2.2 ***Temperature*** *versus* ***fuel consumption*** *of TJ100S-125 engine*

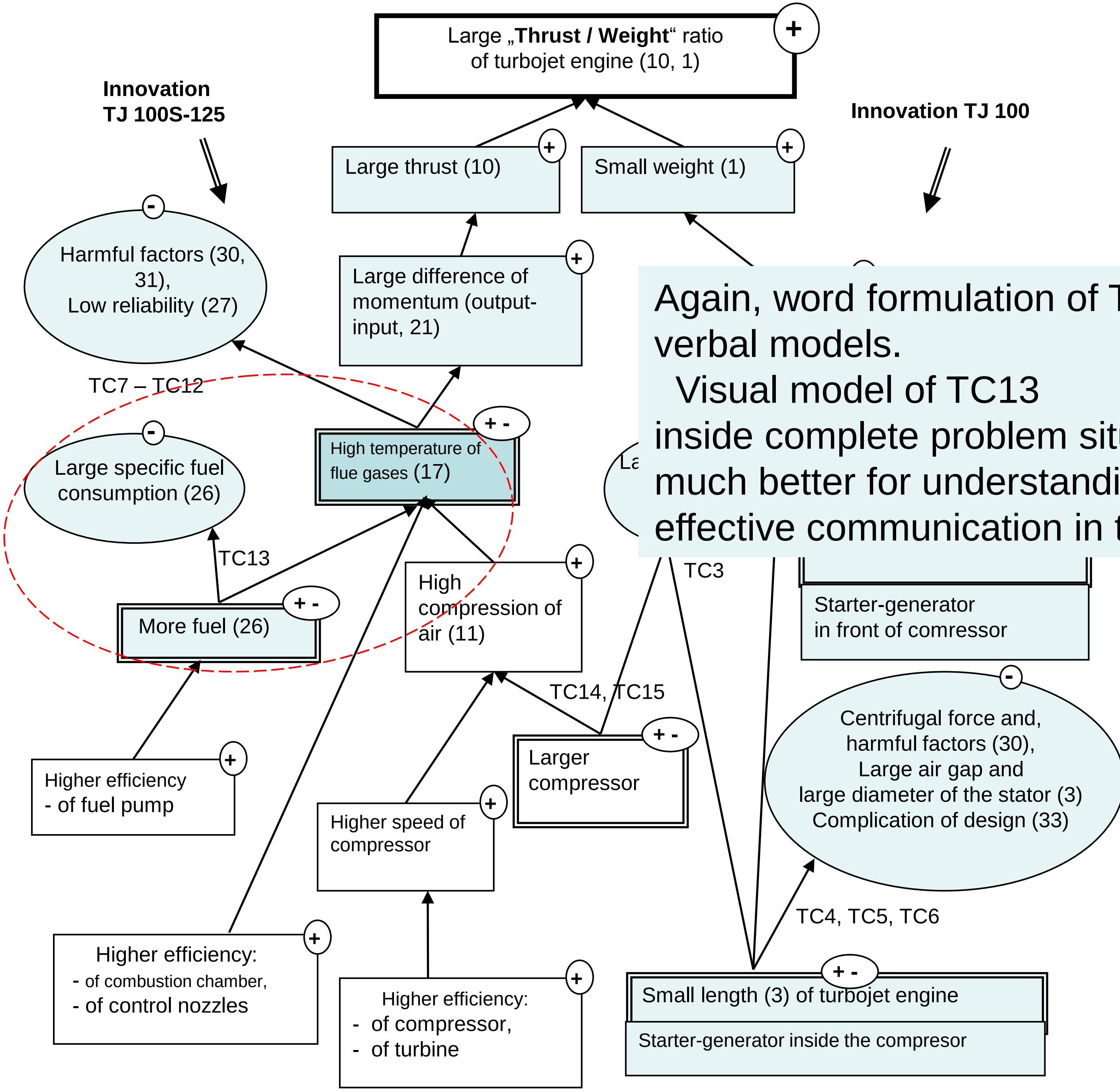
Increase of flue gas temperature (17) by greater quantity of fuel leads to undesirably high specific fuel consumption (26). Possible formulation of technical contradiction:

TC13: temperature 17/26 fuel quantity: HP: **3, 17**, 30, 39

Heuristic principles: Local quality (HP3) and Shift to another dimension (HP17) could be inspirational and were objectively applied.

Higher temperature was achieved by greater quantity of fuel but without higher specific fuel consumption (SFC), thanks to **higher efficiencies** of fuel **pump** and combustion **chamber**, by new regulation of **nozzles** and by **improved fuel dispersion** [5].

See Fig. 3, left side.



Again, word formulation of TC13 is only verbal models.
Visual model of TC13 inside complete problem situation is much better for understanding and effective communication in team work.

2.2.3 ***Temperature*** *and* ***compression of air*** *versus* ***geometry*** *of compressor*

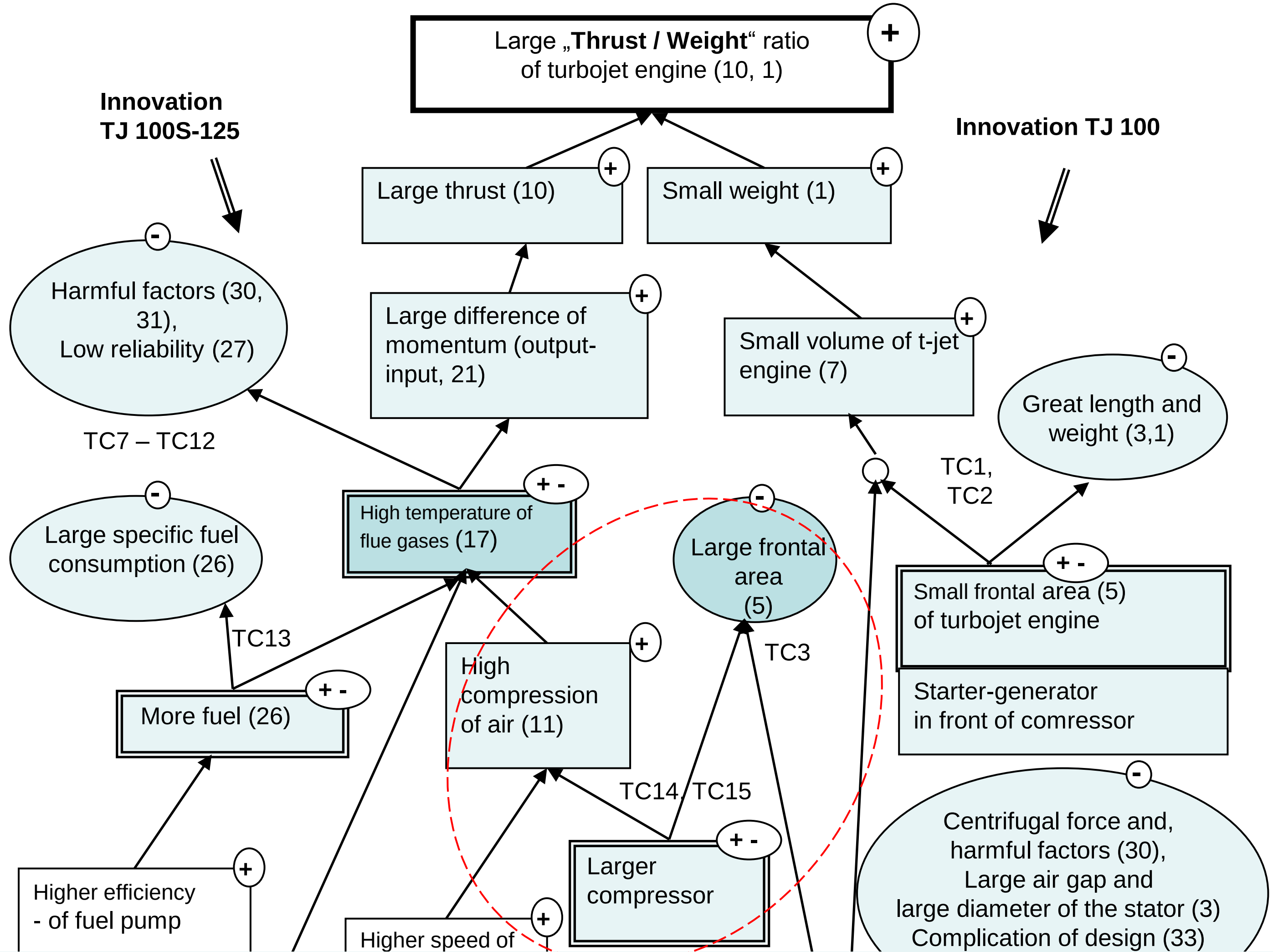
Increase of flue gas **temperature** (17) **by** higher air **compression** (11) in larger compressor could lead to undesirable increase in engine **diameter** and engine frontal area (5). Possible formulation of contradiction:

TC14: temperature 17/5 area: HP: **3**,35,39,18 and
TC15: pressure11/5 area: HP:**10**,**15**,36, 28.

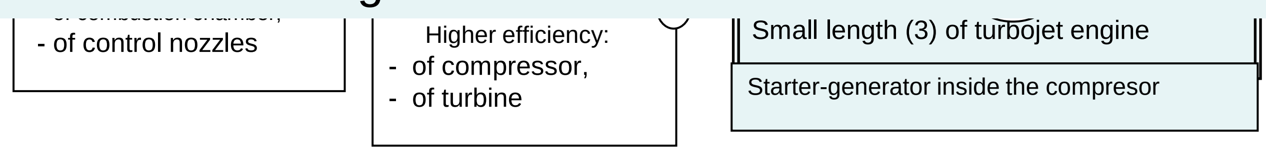
Heuristic principles: Local quality (HP3), Change of phys.-chem. parameters (HP**35**), Preliminary action (HP10) and Dynamics (15) could be inspirational and were applied.

Higher temperature of flue gas was achieved by **higher air compression** but without extension of compressor and frontal area, thanks to **higher compressor speed** and optimization of most components: both diameters and **blades geometry** of compressor, radial and axial **diffusers**, combustion **chamber**, and **guide and action-wheels** of the turbine.

See Fig. 3, in the midle.



Again, word formulation of TC14, TC15 are only verbal models. Visual model of TC14, TC15 inside complete problem situation are much better for understanding and effective communication in team work.



*2.2.4 **Expensive** and **cheap**, **resistant** and **low-resistant** material*

Causes of the mentioned TC7-12 could be formulated inside, it means numerous causal **physical contradictions** (PCs) with contradictory demands on the individual parts could be formulated on quantity of fuel, on flue gas temperature, on size of frontal area (diameter) of the compressor, possibly also on the material quantity or quality. Then so called separations could be used to solution of PCs.
The key PC could be formulated inside of TC7-12.

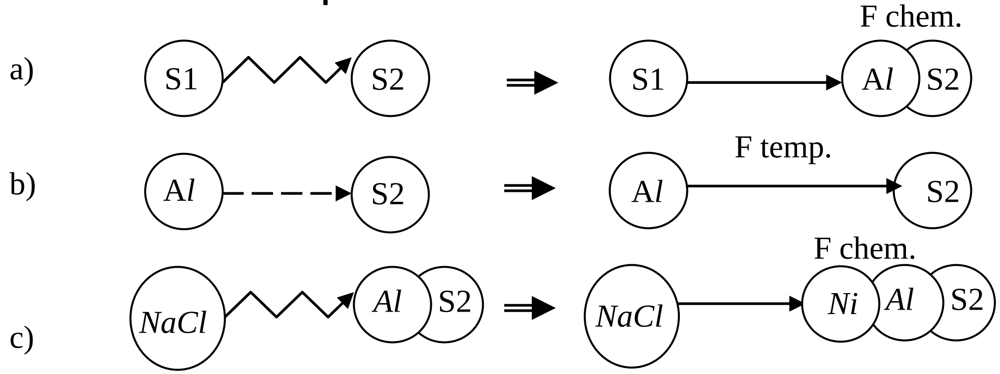
PC: **exposed parts**, guide and action wheels of the turbine,
must have a **high melting point** for prolongation of working life (reliability),
but they must have also a
low melting point for maintaining the cheapness of originally used material (Inconel).

Physical contradiction was solved by **separation in space** and by **structural change of the surface**; both in accordance with **standard solution models**, as it is known from Sub-Field analysis (see 2.2.5) and thanks to **new technology of coating** (2.2.6).

2.2.5 ***Standard solutions*** *– three times*

In the innovated engine TJ100S-125 by utility model No. 25292 “Design of flow parts of turbojet engines” [4] – the standard way of softening of harmful interaction between two substances was applied, as it is known from Sub-Field analysis.

The harmful heat effects of **exhaust gas** (S1) on the **exposed components** (guide-wheel and action-wheel, S2) were limited by introduction of **external supplement** (protective coating) on the components surface, namely two times. Standard paterns of Sub-Field analysis are shown in Fig. 4.



a) A casting made of nickel-based super alloy Inconel 713 LC (S2) was first coated by “external supplement” – aluminium layer (Al) by new developed technology CVD “Out of pack” [4].
b) Then the diffusion of Al inside alloy Inconel 713 LC was reinforced by heat action. These coating and diffusion improved the thermal oxidation resistance of cheap super alloy (S2) against harm action of hot gases (S1). Fig. 4a, b.
c) Now there is prepared further improvement of resistance of external Al supplement, again by external supplement, namely by Ni coating for increase the corrosion resistance, especially against NaCl (Fig. 4c). It is motivated by requirements of naval forces to apply TJ100S-125 engines for air targets starting from the aircraf carriers.

*2.2.6 **Merging of two alternative methods** of coating*

Protective Al coating was deposited by new developed technology of coating [4]. In terms of TRIZ the new developed method merges two alternative coating methods. The existing two coating methods, „**CVD-Chemical Vapour Deposition**“ and „**Pack cementation**“, were merged into a new method „**CVD-Out of Pack Cementation**”, which combines advantages and suppresses disadvantages of both alternative methods, as shown in Table 4.

Table 4. Merging of two alternative methods of coating in one new method

Method of coating	Contactless gas deposition (**CVD**)	Contact gas deposition (**Pack cementation**)	**New Contactless gas deposition** (**CDV - Out of Pack**)
Components in contact with the powder	+ (separation)	- (contact)	+ (separation)
External generator of deposit gas	- (existence)	+ (absence)	+ (absence)
Adhering of the powder on the components	+ (non-adhering)	- (adhering)	+ (non-adhering)
Release of gases inside the retort	- (outside)	+ (inside)	+ (inside)

Protective **Al coatings** against oxidation as well as **Ni coatings** against corrosion, both **deposited by the new method**, allowed to increase the **thrust** (temperature of gases) and also significantly extend the **working life** (reliability) of the engine. Those are contradictory goals usually solved only through compromise, optimization.

In the new engine TJ100S-125 the contradiction was overcome, the **thrust was improved**; **working life and reliability** were significantly **increased**.

2.2.7 Dynamism

The **engine controllability was improved** thanks to the fact that the amount of injected fuel depends now almost linearly only on the pump speed [5].
The pump efficiency was increased by 15%.
The fuel pressure and number of injection nozzles increased, the quality of injected fuel spray was improved.
The engine restart ability was improved up to 6 000 m.

2.2.8 **PARTIAL CONCLUSION** concerning of **TJ 100S-125** turbojet engine.

New solution of TJ100S-125 engine can be evaluated in terms of TRIZ as follows:
- Successful **overcoming of numerous contradictions** (TC7-TC16, Fig. 3, left side),
- Standard **solutions of three substance conflicts** (Fig. 4 a, b, c),
- **Merging of two coating methods** to a new method CDV Out of Pack (Table 4),
- **Increasing of controllability** of fuel injection and the **dynamism** of the whole engine.

3. Conclusion

The innovation of small turbojet engine was evaluated two times.

First, the innovation of turbojet engine TJ100S-125 was evaluated by 16 experts from universities and research institutions – the members of evaluation committee - on the base of five criteria (novelty, invention, rank of innovation, difference of the main and additional functions) **in the competition for the Gold Medal** at the International Engineering Fair in Brno, 2013.

Then the chief designer of Air division and secretary of the evaluation committee **looked for deeper causes**, which led the inventor to successful innovation.

Several causes were identified and described:
- **overcoming numerous contradictions**,
- **using of standard solution patterns**,
- **merging of two alternative devices** and
- **merging of two alternative methods**.

4. Super conclusion

The question arises how much TRIZ methodology was or was not used during improvements of the small turbojet engines.

The contradictory answer is: “**yes and no**”;
it means objectively and intuitively and partly **yes**,
subjectively and consciously and completely **not**.

The main designer and the director of the Air Division PSB Velká Bíteš, inventor and first author of this paper used **objectively** and intuitively several solving tools known from the TRIZ methodology. **Subjectively**, he did not know TRIZ methodology completely, he was only informed two times about existing TRIZ instruments
(1998- informative 2 h presetation, 2004- short 6 h seminar).
While innovating the engine he used lifetime knowledge and experience of designer, regardless of numerous sceptical views of dubious people around.

However, the contradictory statement “yes and no” is not in contradiction with the fact that the TRIZ methodology can be studied, mastered, practically applied and hence should be used as instrument in education as well as
in technical creative work.
Therefore, it remains a **permanent challenge** for MATRIZ colleagues to strengthen the subjective creative intuition in education and practice with the objective analytical and synthetic TRIZ methodology.

Thank you for attention