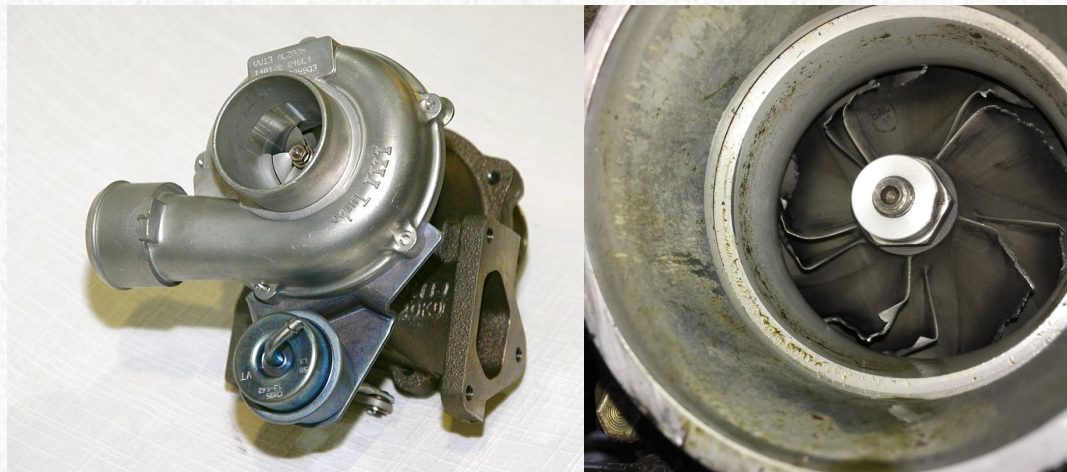


ICE Turbochargers Failures

and Some Features of the Study of Their Causes Using the Fault Tree Analysis



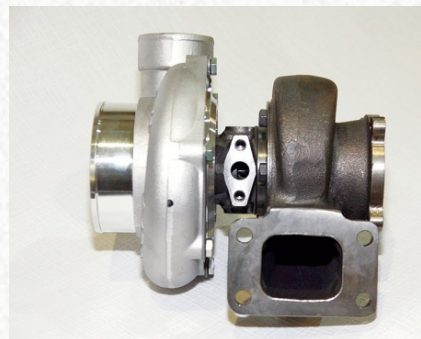
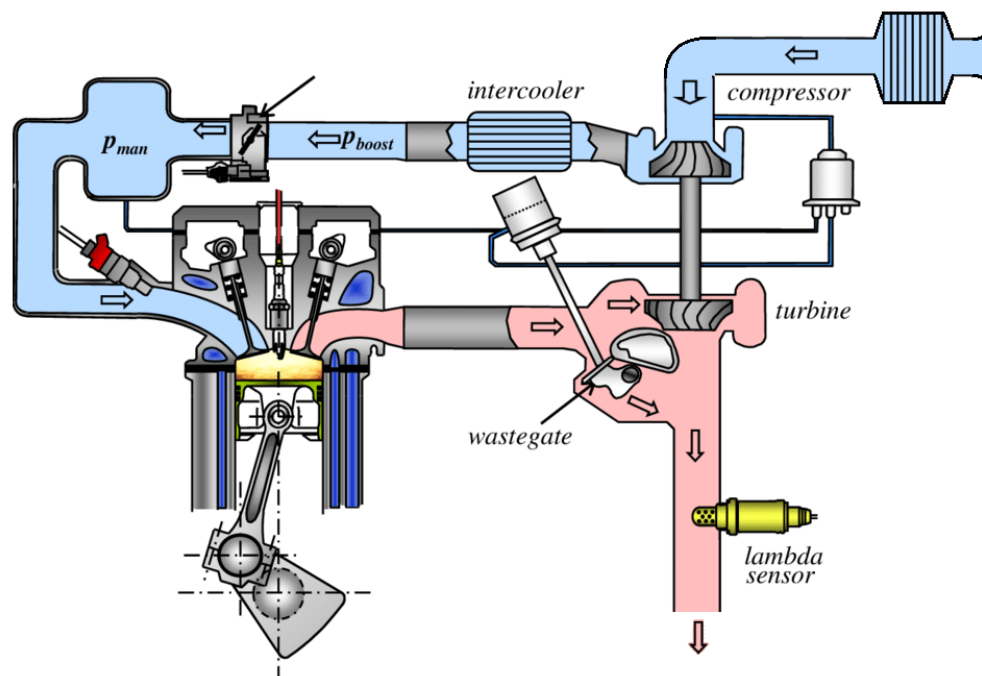
By PhD Alexander Khrulev and Professor Sergey Dmitriev

The 18th Israeli Symposium on Jet Engines & Gas Turbines

November 28, 2019

Turbocharging technology for ICE:

- ❖ **100 years ago** - the first use of a turbocharger on aviation piston ICE to increase altitude (General Electric).
- ❖ **80 years ago** - the beginning of its mass use in aircraft ICE and the first use in automotive ICE to increase the power density.
- ❖ **55 years ago** - the beginning of its mass use in automotive ICE.
- ❖ **20 years ago** – all car diesel engines and a significant part of gasoline ICEs are equipped with turbochargers.

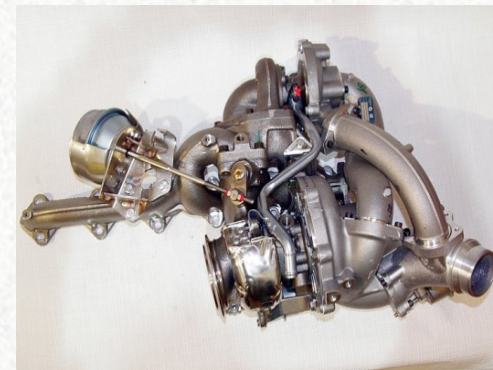


Advantages of turbocharging :

- simplicity, cheapness,
- reliability, efficiency.

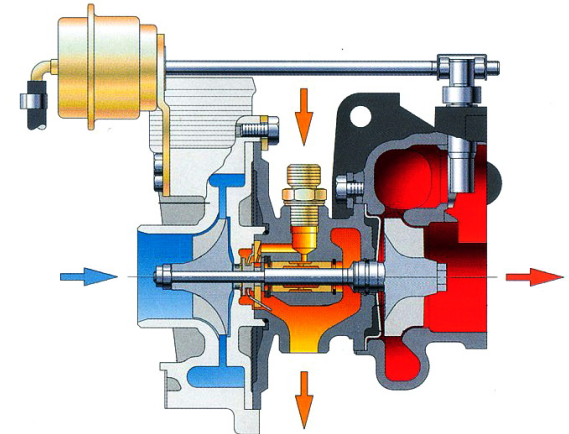
The main task of turbocharging

- Increase of the air supply to the cylinders in order to increase power density (by 30-50%).



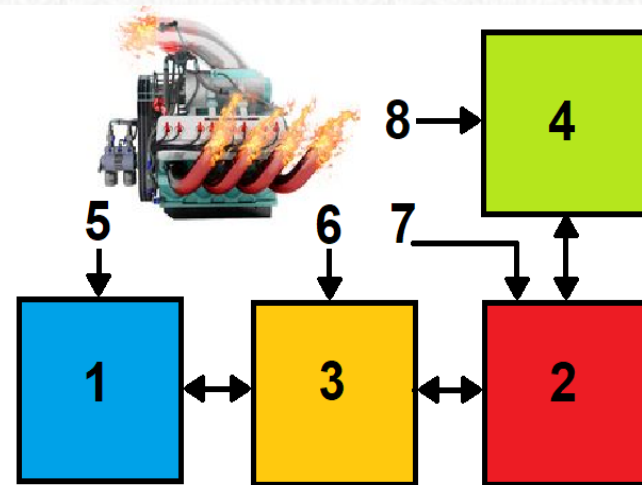
Characteristic features of turbochargers

- ❑ minimal dimensions to reduce acceleration delay with increasing load (turbo-lag),
- ❑ extremely high rotor speeds (over 200,000 rpm),
- ❑ high sensitivity to damage - very fast development of any damage or failure (100,000 cycles per 30 seconds),
- ❑ significant scale of destruction - a large number of damaged parts (secondary damage),
- ❑ strong impact of the engine on turbocharger faults and vice versa,
- ❑ difficulties in determination of failure causes.



Block diagram - 4 main units:

- 1) compressor (wheel and housing),
- 2) turbine (wheel and housing),
- 3) center hub rotating assembly (CHRA), incl. bearings and seals(bearings and seals),
- 4) control system, including driver and control unit (Wastegate valve, VNT - variable nozzle turbine or variable compressor).



External impact on turbocharger (by ICE):

- 5- intake engine system, 6- oil system and engine crankcase,
7- ICE cylinder and exhaust manifold; 8- ICE control system

Features of the problem to determine the causes of the failures

1. During the development of ICE, significant efforts were directed to the research and development of new designs of turbochargers.
2. Such constructions were created, however, they are not 100% reliable, because depending on various conditions, faults and failures continue to arise.
3. During this time, no practically useful methods have been created to reliably find the causes of turbochargers failures.
4. In fact, the obligation to determine the causes of turbochargers failures was given by manufacturers to consumers.

The main difficulty appearing in solving the problem :

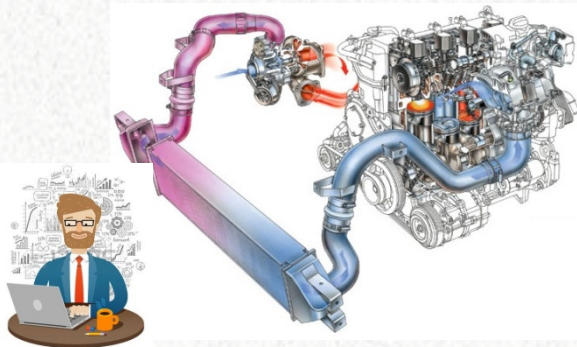
Close interconnection of processes not only inside the turbocharger itself and between its parts, but also of the turbocharger with the engine.

The consequence of the main difficulty :

It is necessary to investigate all cause-effect relationships, clearly separating the cause of the faults from its consequence (incl. secondary damage to parts).

The main questions are :

1. Why do you need to know the faults?
2. Where do they come from?
3. What are their causes?



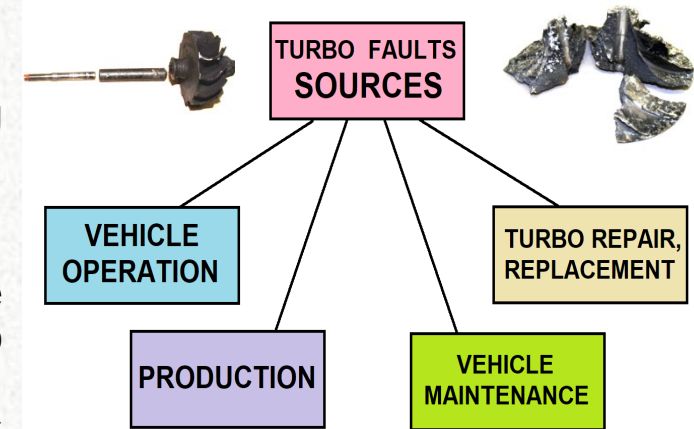
1. Manufacture defects (usually more associated with the defects in secondary production)

a) primary production

- ❑ - quality of materials, machining and assembly, including rotor balancing and electronic control system adjusting

a) secondary production:

- ❖ - recovery (the same as for the primary)
- ❖ - installation (the cause of the failure has not been eliminated - dirt in the oil, in the ducts, intercooler, high pressure in the crankcase, damage to the oil lines, use of sealants, etc.)
- ❖ - ICE service (poor-quality oil, untimely maintenance, abandoned tools and thread components inside engine, etc.)



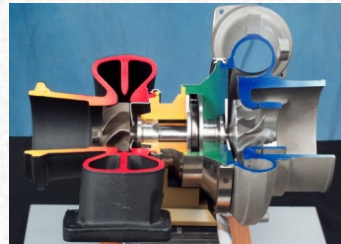
2. Operational faults (often associated with engine)

- ❑ - oil supply failure (low pressure)
- ❑ - oil drain failure (high pressure in the engine crankcase)
- ❑ - dirty oil
- ❑ - inappropriate oil (especially at very low and very high temperatures)
- ❑ - poor air filtration
- ❑ - inlet duct damage (depressurization)
- ❑ - engine components destruction
- ❑ - operational wear
- ❑ - jamming in the driving mechanism (Wastegate, variable nozzles turbine, compressor geometry , etc.)
- ❑ - failure in the turbocharger or ICE control system (control units, connectors, cables)



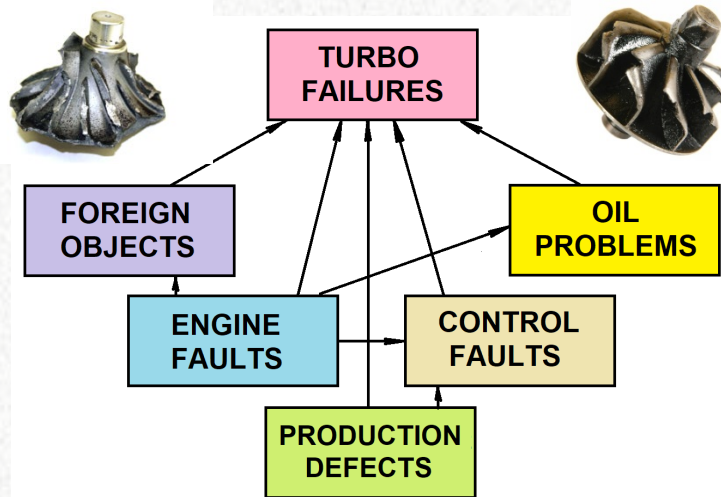
The main causes of the turbocharger faults (types of impacts)

1. Operation at specifications faults.
2. Untimely engine maintenance.
3. Service mistakes.
4. Poor repair (mistakes at recovery or replacing).
5. Manufacturing defects.
6. Operational wear.



The failure events (the causes of damage, if turbocharger is considered separately)

1. Foreign objects damage (FOD) in compressor or turbine
2. Insufficient oil supply
3. Oil contamination
4. Jamming of the driving mechanism of the control system
5. Control system failure (electrics and electronics)
6. Overspeeding (excess rotor speed)
7. Overheating of turbine, housing



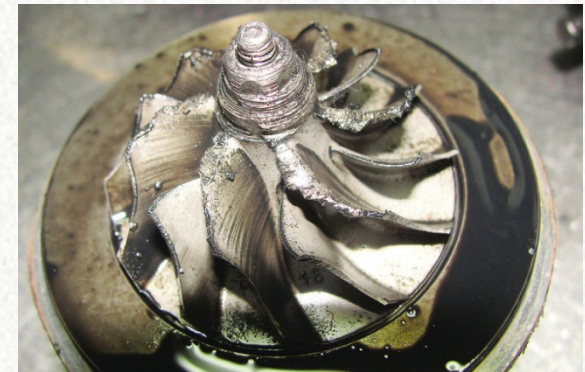
Symptoms

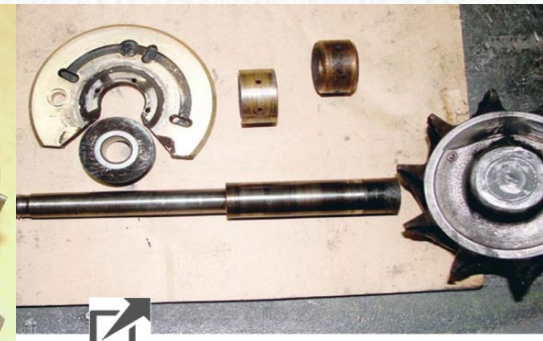
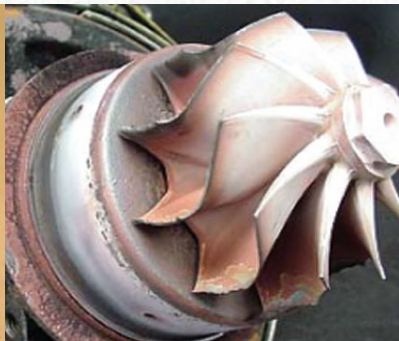
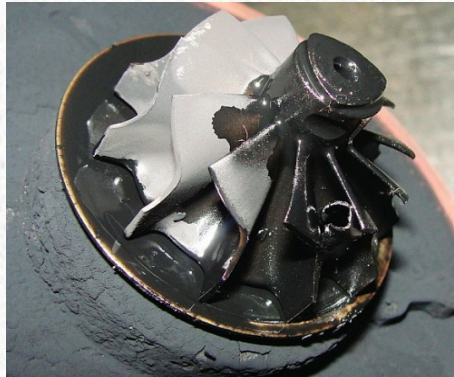
1. **Visible to driver:** loss of engine power, noise, smoke, oil consumption, spontaneous engine speed gain, malfunction indicator lamp (MIL).
2. **Visible to mechanic when servicing the vehicle:** trouble codes, external damage, fluids leakage, sometimes – in intake, exhaust systems and engine cylinders.
3. **Visible to specialist-expert on a partially and completely disassembled turbocharger and engine:** various damage and traces on the details - compressor, turbine, housings, bearing assembly, control system, as well as intake, exhaust systems and engine cylinders.

The main task is to connect the symptoms, events and causes into one system

1. Compressor

- 1) oil in compressor
- 2) blades wear, erosion
- 3) the blades touching the housing (large radial and / or axial play of the rotor)
- 4) blades damage (deformation)
- 5) blade destruction
- 6) rotor nut - loosening or turning out
- 7) wheel destruction





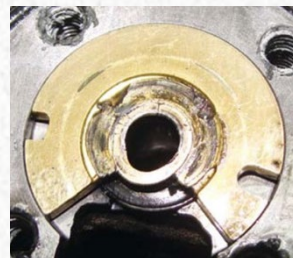
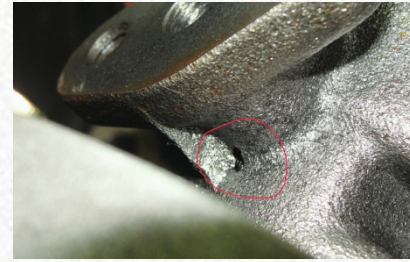
2. Turbine

- 1) oil (carbon deposits) in the turbine
- 2) blades touching the housing (large radial and/or axial play of the rotor)
- 3) blades and/or housing mechanical damage (deformation)
- 4) blades and/or housing overheating
- 5) blade destruction
- 6) shaft destruction (separation from the turbine wheel)

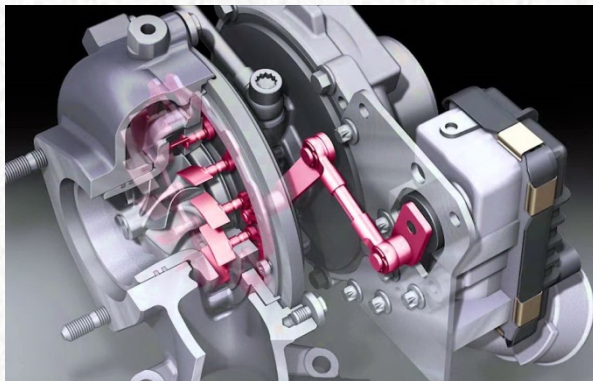
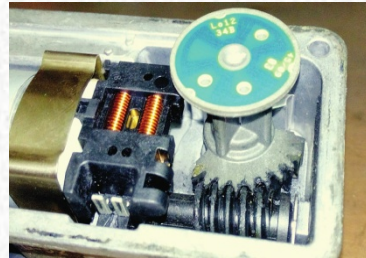
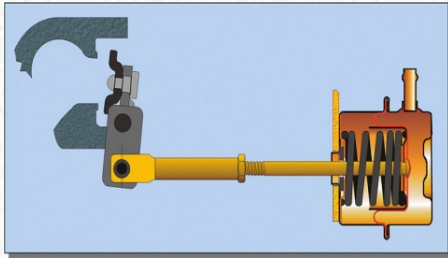


3. Bearing assembly:

- 1) oil and/or coolant leaking in connections
- 2) hoses damage
- 3) wear in bearing bushings and shaft journals
- 4) seal rings - wear and leaking
- 5) dirt and deposits in chambers and holes
- 6) bearings, shaft journals - wear and scuffing,
- 7) bearings, shaft journals - overheating and melting
- 8) thrust bearing - wear and scuffing
- 9) thrust bearing - overheating and melting
- 10) bearing housing - overheating
- 11) shaft deformation
- 12) shaft destruction

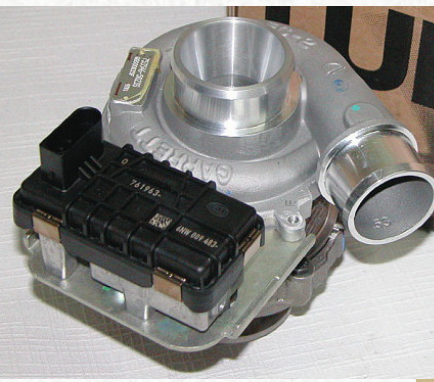
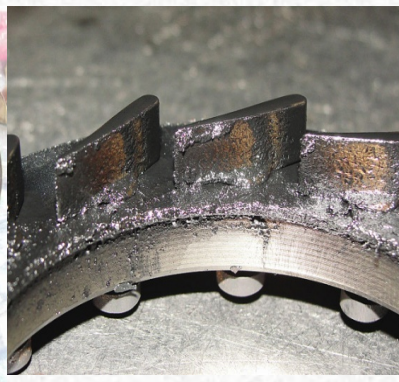


4. The symptoms of turbocharger faults (4/4)



4. Control system

- 1) Wastegate valve damage, jamming
- 2) Wastegate actuator diaphragm damage
- 3) vacuum tubes damage
- 4) Wastegate actuator mechanism damage
- 5) variable nozzle turbine (VNT) vanes - damage, overheating
- 6) variable nozzle vanes mechanism - jamming
- 7) control unit failure (electrics and/or electronics)



Specialized failure handbooks (incl. troubleshooting):

- ❖ lists of possible causes and symptoms of faults
- ❖ standard views of damage for comparison with real objects

Features of application:

- ❑ no manufacturing defects
- ❑ in some cases it is difficult to understand which damage is primary and which is secondary

Consequence from features of application

- handbooks are not a universal tool and demand special training
- it is impossible to find manufacturing defect with the handbooks



Turbocharger fault tables:

- ❑ dozens of causes may correspond to some faults
- ❑ extremely laborious practical use of the tables (necessity to check lots of causes)

Possible Cause	Trouble and Symptoms											
	Lacks Power	Black Smoke	Excessive Oil Consumption	Blue Smoke	Noise	Excessive Oil - Compressor	Excessive Oil - Turbine	Drag or Bind in Rotor Assy	Excess Rotor play	Damaged Comp. Wheel	Damaged Turb. Wheel	
 Dirty Air Cleaner Element	•	•		•	•	•						
Plugged Crankcase Breathers			•			•	•					
Air Cleaner Element Missing or loose to Turbo					•			•				
Collapsed or restricted air pipe to Turbo	•	•		•								
Restricted or Damaged Boost Tube	•	•		•		•						
Foreign Object Between Air Cleaner & Turbo	•	•			•			•				
Foreign Object in Exh. Sys. From Engine	•	•					•	•	•	•	•	•
Turbocharger Flanges, Clamps, or Bolts Loose	•	•		•		•			•	•	•	•
Inlet Manifold Cracked, Loose Gaskets/Hoses	•	•			•							
Exh. Manifold Cracked, Burned/Blown Gasket	•	•			•							
Restricted Exhaust System					•							
Oil Lag at Start-up									•	•		
Insufficient Lubrication									•	•		
Contaminated Lube Oil									•	•		
Improper Type Lubricating Oil Used									•	•		
Restricted Oil Feed Line							•	•				
Restricted Oil Drain Line			•				•					
Turbine Housing Damaged or Restricted	•	•			•						•	
Turbocharger Seal Leakage						•						
Worn Journal Bearing	•	•	•						•	•	•	•
Excess Dirt build-up on Comp. Housing					•				•	•		
Excess Carbon Build-up behind Turb. Wheel	•	•							•	•		
Too Fast Acceleration at Initial Start-up, Oil Lag												
Too Little Warm-up Time										•	•	
Fuel Pump Malfunction	•	•										
Worn or Damaged Injectors	•	•										
Valve Timing	•	•										
Burned Valves	•	•										
Worn Piston Rings	•	•										
Burned Piston(s)	•	•										
Leaking Oil Feed Line									•	•		
Excessive Engine Pre-Oil						•						
Excessive Engine Idle									•	•		
Coked or Sludged Center Housing									•	•		
Oil Pump Malfunction									•	•		
Oil Filter Plugged									•	•		
Oil Bath Air Cleaner: Inlet screen restricted	•	•	•	•	•							
Oil Bath Air Cleaner: Oil Pull /Viscosity Low	•	•	•	•	•							
Boost Control Malfunction: Wastegate	•	•	•	•	•							
Boost Control Malfunction: VNT	•	•	•	•	•							
Boost Control Malfunc: Eng. Mgmt. System	•	•	•	•	•							

Inadequate lubrication is one of the most frequent causes for turbochargers to fail. If the turbocharger is not sufficiently supplied with oil, damage will occur within a very short time. This is due to the very high speeds of the turbocharger.

EFFECTS

- The impeller and turbine wheel can strike the turbocharger housing on account of bearing damage (Fig. 1). This can be discovered from wear marks on the housing (Fig. 2).
- If the turbocharger speed increases too fast, the engine will not perform properly, the rotating assembly no longer reaches the maximum speed and can no longer build up the full boost pressure as a result. The reason for this is the speed friction caused by the inadequate lubrication.
- The exhaust system emits black smoke. These are the effects of the engine not being loaded with enough air and a corresponding too rich fuel-air mixture.
- The first shaft exhibits clear discoloration (Fig. 3), which arises from friction and the resultant high temperatures between the shaft and the bearings. The cause of this is inadequate lubrication. If the temperature exceeds a certain level, the bearing material will become disintegrated on the shaft (Fig. 4) or the bearing might even become completely fused to the shaft.
- A broken shaft shank (Fig. 5) is the result of operating the turbocharger for a prolonged time without enough oil. The shaft will rotate until it has turned out and break.
- A bearing that has permanently incorporated in the bearing housing becomes fused to the shaft, the bearings might turn out of position in the bearing housing (Fig. 6).
- The first shaft exhibits clear discoloration between the shaft and the bearings. The cause of this is inadequate lubrication. If the temperature exceeds a certain level, the bearing material will become disintegrated on the shaft (Fig. 4) or the bearing might even become completely fused to the shaft.
- The rotating assembly can emit a large imbalance owing to the contact with the housing, which might result in the shaft bearing housing (Fig. 7).
- Due to incorrect oil or fuel soot, the bearing housing can become carbonized.
- The rotor bearings have fretted.
- The seal bearings exhibit fretting marks or carbon deposits.
- Blocked oil bearings can cause too great a speed of rotation, whereby the bearing collar might also be damaged.

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Logical-probabilistic method - construction and analysis of the fault tree

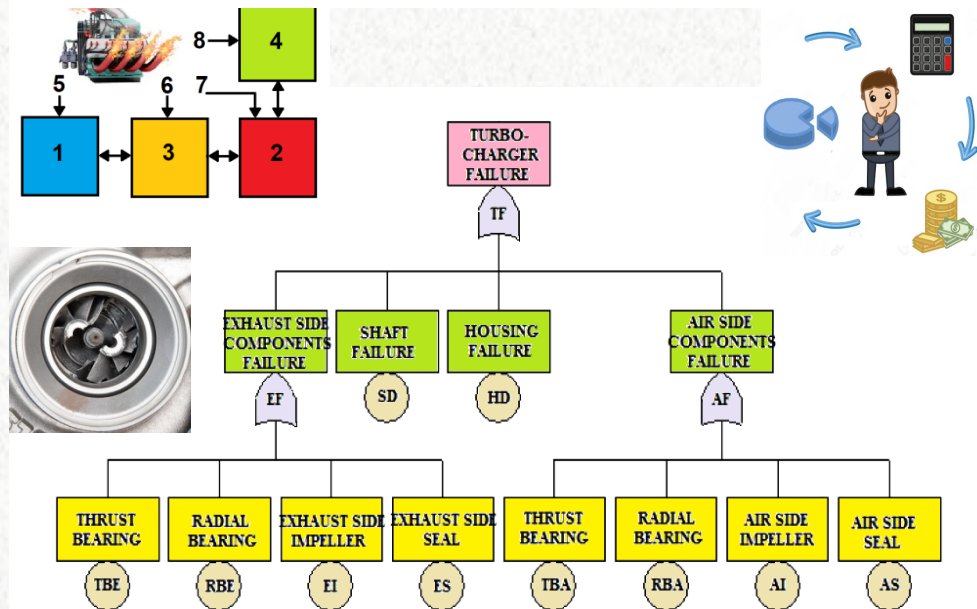
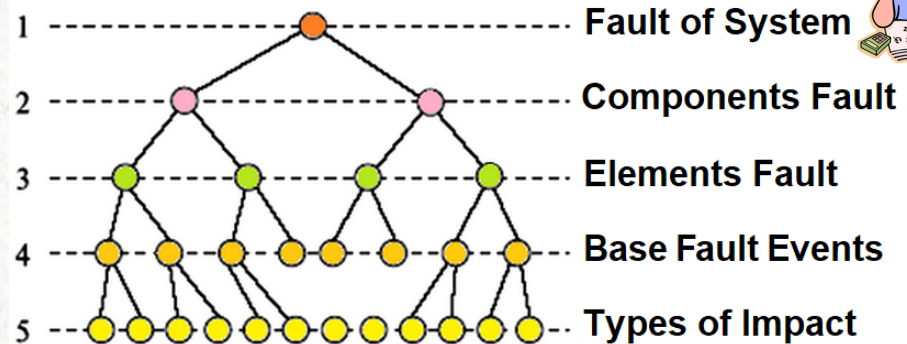
The **fault tree** is a multi-level graphological structure (graph) of causal relationships in the system obtained as a result of tracing dangerous situations in order to find possible causes of their occurrence.

Failure tree compilation :

- 1) final (emergency) state of the system,
- 2) subsystems (components, elements) and related events that can lead to system failure,
- 3) the effects that trigger these events.

The fault tree use - to analyze the reliability of the system:

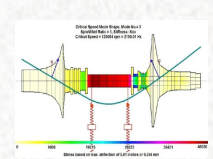
1. **Qualitative (logical) analysis** - search all possible combinations of basic or elementary events that can lead to the investigated event (failure) occurrence.
2. **Quantitative analysis** - calculation of the probability of the final event (failure) based on the data on the occurrence probabilities of the basic events (used only in design)



The fault tree of analyzed engine's turbocharger

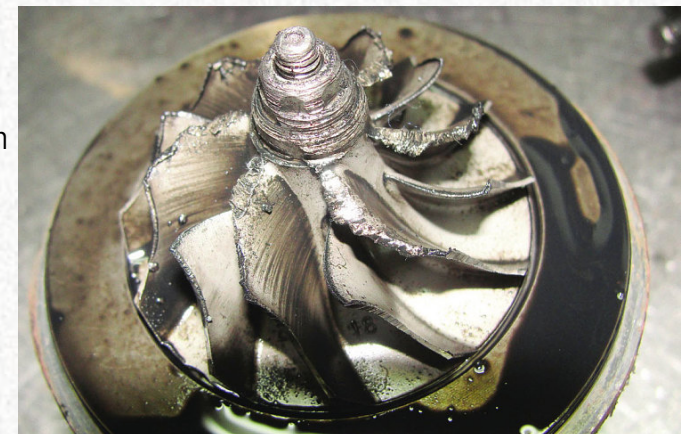
An example: FT forming for the problem of the failure cause determination - foreign object getting into compressor

1. **Failure of system** - turbocharger inoperability
2. **Failure of components** - compressor, turbine with shaft, bearing assembly with seals:
 - ✓ - rotor shaft - fatigue failure
 - ✓ - o-rings damage and / or destruction (oil leaking from the turbocharger)
3. **Failure of elements** - compressor wheel with blades, turbine wheel with blades and shaft, housings, bearing bushings with seals:
 - a) **direct damage:**
 - -compressor wheel blades deformation and / or destruction (the shaft nut and the threaded shaft - blades edges are damaged by a foreign object, damage done to the compressor housing)
 - b) **secondary damage:**
 - - bearings overheating and seizure
 - - o-rings wear, damage (oil in the compressor housing, turbine)
 - - turbine damage (the blades touching the housing, overheating, increased noise).



4. Failure events:

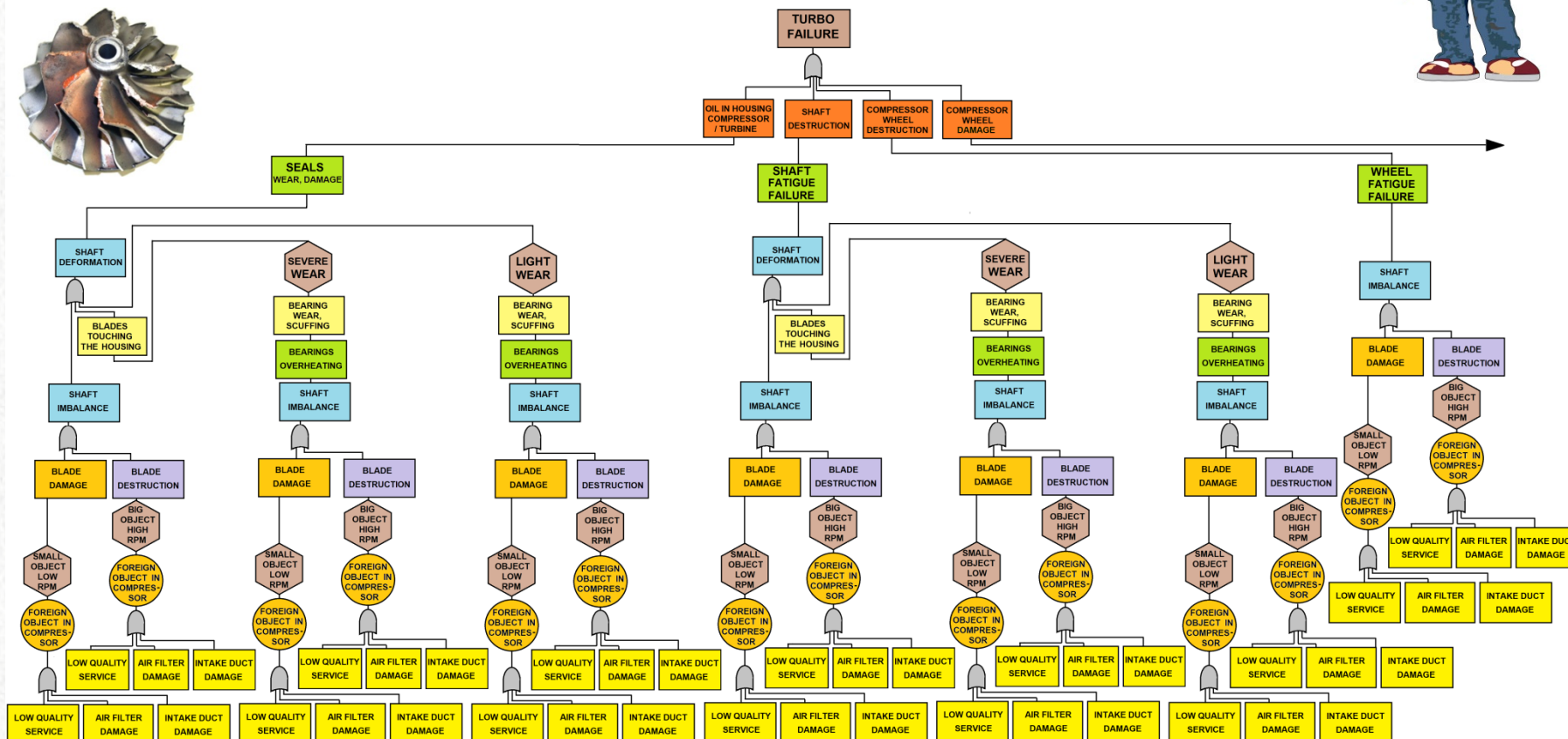
- a) **primary:**
 - - compressor blades and housing damage (visually)
- b) **secondary:**
 - ❖ - increase in residual imbalance and backlash of the rotor, rise of vibration acceleration
 - ❖ - increase of radial loads on the bearings
 - ❖ - oil film break, the bearings passing to semi-dry friction mode
 - ❖ - the blades touching the housing

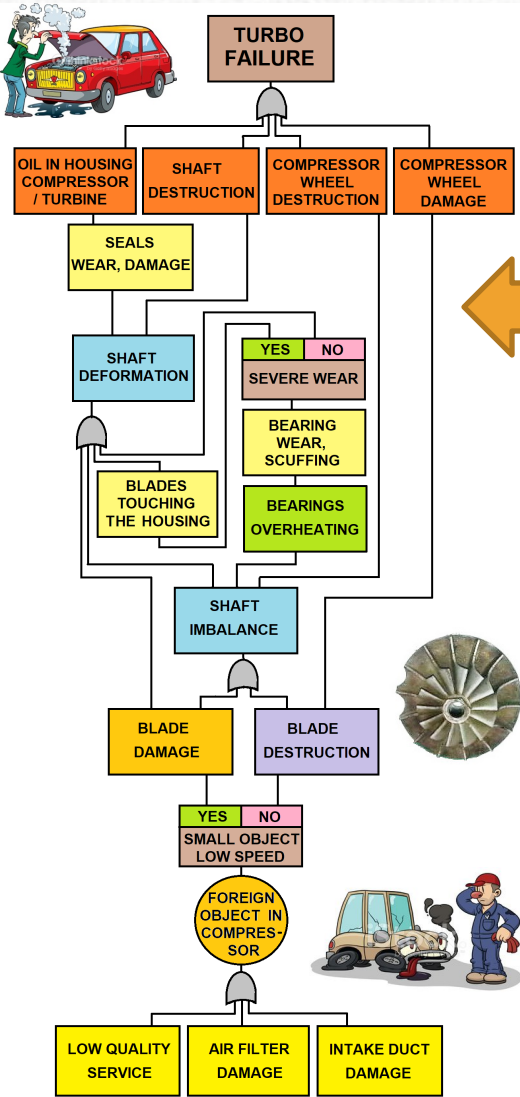


5. **Types of impacts** - ways of foreign object ingress:
 - - object was left in the intake system during repairs
 - - it hit through a destroyed air filter
 - - it has got through damaged intake duct

Foreign object getting in compressor: Standard fault tree

1. Each event and / or failure has a logical connection with only one subsequent event
2. Excessively bulky construction
3. Suitable for calculating reliability estimates, but poorly suited for logical analysis to determine the cause of a malfunction



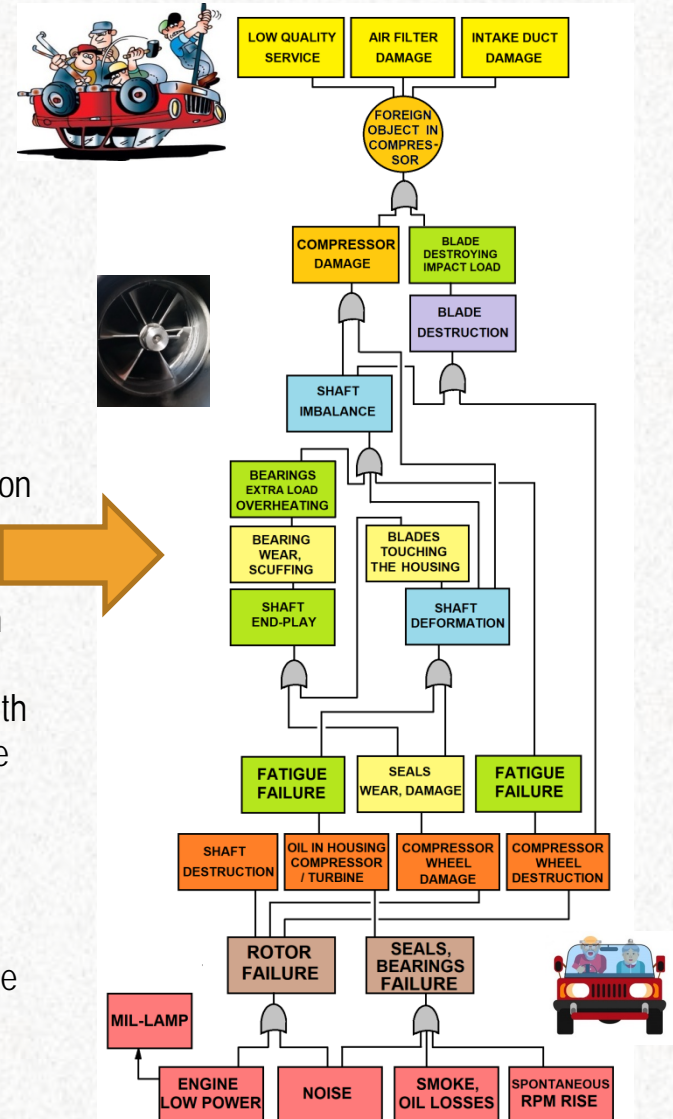


Modified Fault Tree

- ❖ Each current event can have a logical connection with several subsequent processes (events) at once.
- ❖ Not entirely consistent with the task of determination the fault cause in the direction of analysis.

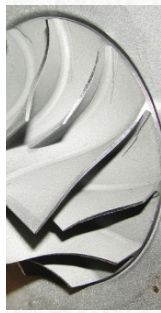
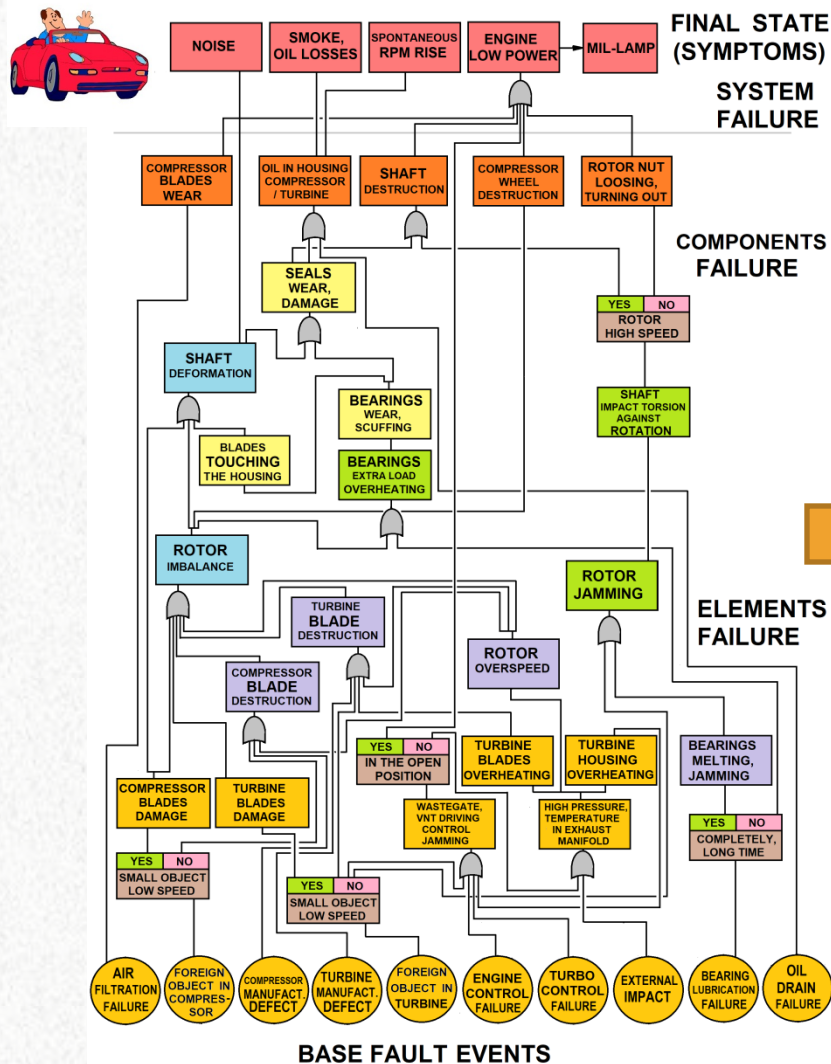
Reversed fault tree

- ❑ Each event can have a logical connection to several previous and several subsequent events.
- ❑ Logically, the analysis does not go from basic events to failure, but rather from failure to basic events in accordance with the direction of the search for the failure cause.
- ❑ Failure can be divided by signs of its occurrence, visible in the vehicle operation.
- ❑ A process that triggers the failure can be added to each event, which facilitates logical analysis.

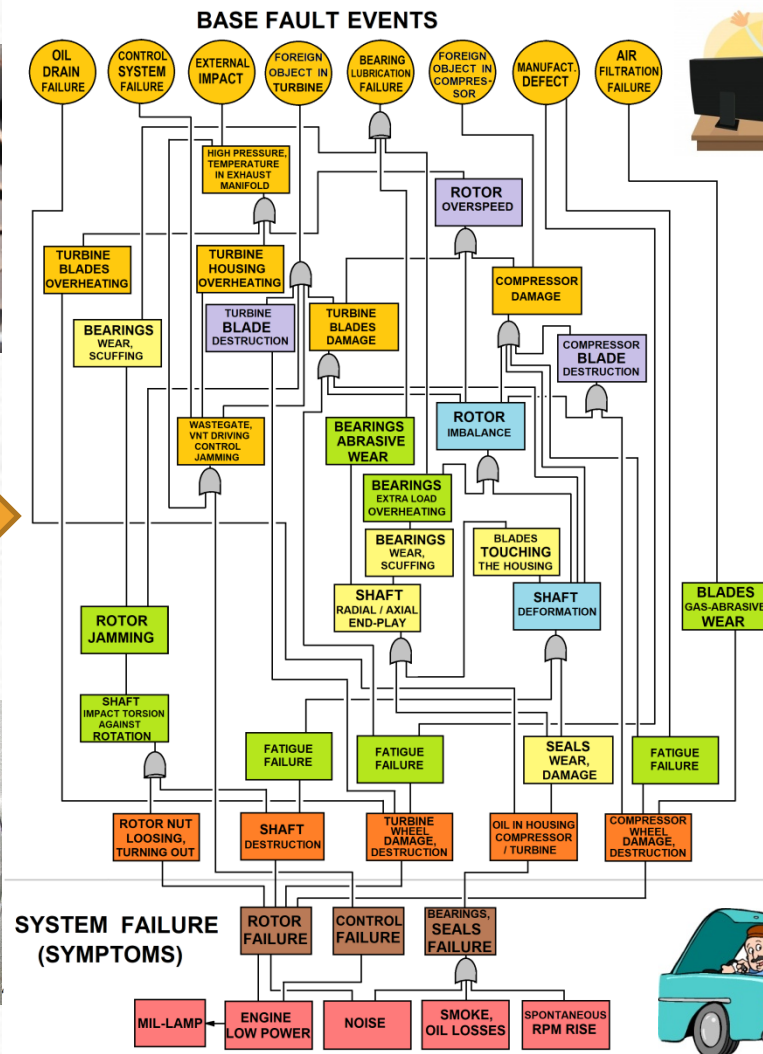


6. Method for determination of the failure causes of turbochargers (2/4)

Modified general turbocharger fault tree



Structural-logical diagram of the turbocharger failures (reversed fault tree)



Basic events causing failures and types of impacts as the causes of failures

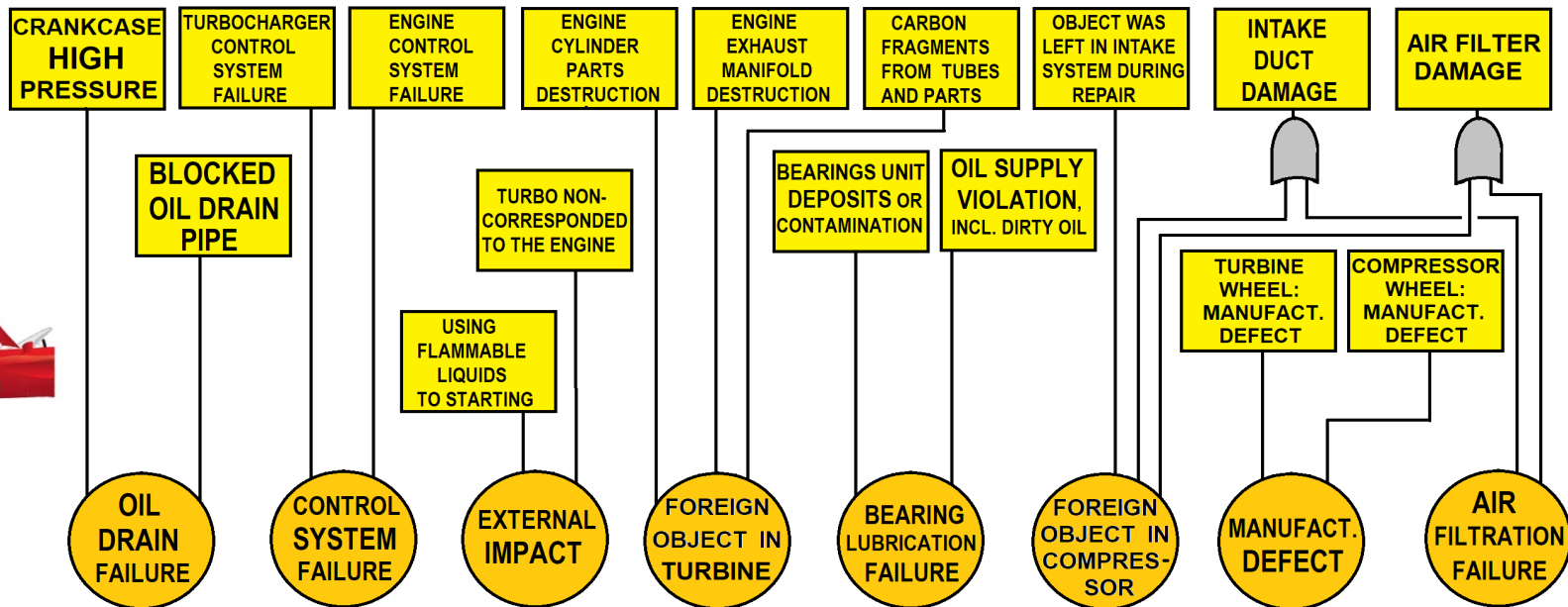


- ❑ compiling a list of basic events (failure events)
- ❑ compiling a list of impacts on the turbocharger (causes of failure)
- ❑ correlation between basic events and impacts



Item No	Item Description	Item Status	Item Category	Item Type	Item Sub-Type	Item Code	Item Date	Item Author	Item Reviewer	Item Approved
1	Check for oil leaks	OK	Oil Leaks	Leak	Oil Leak	101	2023-10-27	John Doe	Jane Smith	Yes
2	Check for oil leaks	OK	Oil Leaks	Leak	Oil Leak	102	2023-10-27	John Doe	Jane Smith	Yes
3	Check for oil leaks	OK	Oil Leaks	Leak	Oil Leak	103	2023-10-27	John Doe	Jane Smith	Yes
4	Check for oil leaks	OK	Oil Leaks	Leak	Oil Leak	104	2023-10-27	John Doe	Jane Smith	Yes
5	Check for oil leaks	OK	Oil Leaks	Leak	Oil Leak	105	2023-10-27	John Doe	Jane Smith	Yes
6	Check for oil leaks	OK	Oil Leaks	Leak	Oil Leak	106	2023-10-27	John Doe	Jane Smith	Yes
7	Check for oil leaks	OK	Oil Leaks	Leak	Oil Leak	107	2023-10-27	John Doe	Jane Smith	Yes
8	Check for oil leaks	OK	Oil Leaks	Leak	Oil Leak	108	2023-10-27	John Doe	Jane Smith	Yes
9	Check for oil leaks	OK	Oil Leaks	Leak	Oil Leak	109	2023-10-27	John Doe	Jane Smith	Yes
10	Check for oil leaks	OK	Oil Leaks	Leak	Oil Leak	110	2023-10-27	John Doe	Jane Smith	Yes

TYPES OF IMPACT



BASE FAULT EVENTS

Verification of the reversed fault tree on a specific failure case

Cummins / Holset turbocharger of Cummins ISF3.8 turbodiesel, failure after recondition and short operation.

Visual inspection:

- the turbine housing has traces of overheating (discoloration) and corrosion,
- destruction in the compressor.

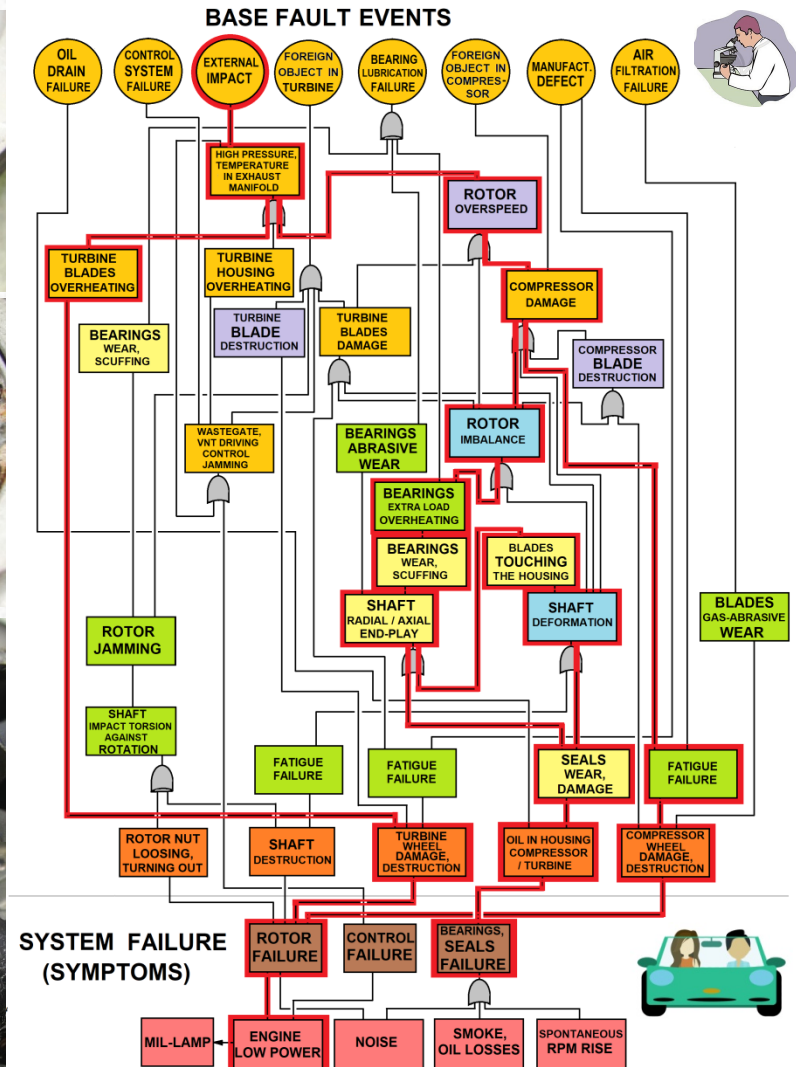
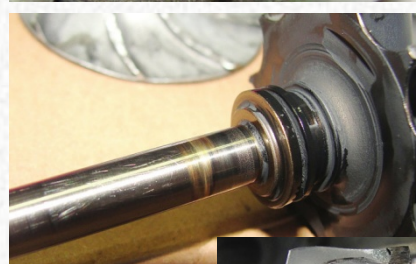
Disassembling turbocharger housings:

- engine oil in turbine and compressor housings;
- the compressor wheel is destroyed along the hub into two parts;
- the internal surfaces of the compressor housing are damaged and deformed;
- the turbine blades have signs of overheating and are damaged due to contact with the turbine housing in axial and radial directions.

Disassembling the bearing unit:

- particles of the material of the bearings were detected on the rotor shaft journals;
- the working surfaces of the bearings have traces of semi-dry friction and wear;
- the o-seal of the bearing housing on the side of the turbine wheel is damaged.

Conclusion - the failure cause is rotor overspeeding that occurred from the installation of a smaller-sized turbocharger that was unfit for the engine.





1. **Despite great success in the development of highly efficient turbochargers for the ICE, the existing methods for determination of failure causes are too complicated and/or not effective for practical use.**
2. **On the other hand, the well-known method of fault tree analysis (FTA) does not quite fit the tasks for studying the causes of turbocharger faults.**
3. **The performed research demonstrates that the faults of the ICE turbochargers can be analyzed with the means of the modified, or reversed, fault tree.**
4. **The verification conducted on real failure events has demonstrated that the proposed method can be applied with the accuracy sufficient for practice as well as with minimal time consumption.**

Thanks for attention!

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