AVL LIST GMBH

HANS - LIST - PLATZ 1
A - 8020 GRAZ, AUSTRIA
TEL. +43 31 6 787 - 0
FAX +43 31 6 787 - 400

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IEA / AMF
ANNEX XIV
DIMETHYL ETHER AS AN AUTOMOTIVE FUEL

R&D TASK 3
DESIGN GUIDELINES FOR DIMETHYL ETHER INJECTION SYSTEMS

Written by

Dr. Herwig Ofner
Fuel & Engine
Management Systems

Approved by

Denis W. Gill
Fuel & Engine
Management Systems

Distribution

Participating Countries Annex XIV of IEA/AMF

IEA / AMF
Annex XIV
Dimethyl Ether as an Automotive Fuel

R&D Task 3
Design Guidelines for Dimethyl Ether Injection Systems

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1. Introduction

The Research and Development (R&D) Task described in this report has been carried out within the activities of the Annex XIV of the IAE/AMF (International Energy Agency / Implementing Agreement on Alternative Motor Fuels). The objective of this Annex XIV is to investigate the introduction of DiMethyl Ether (DME) as an automotive fuel. The work concentrates on subjects which are of general interest and focuses on establishing a fuel quality standard, fuel cost, operational and safety aspects for DME engines and vehicles and environmental issues.

The Annex XVI is supported by the following ten countries: USA, Finland, Norway, Denmark, Netherlands, Sweden, Canada, Japan, France and Austria. France and Austria are not member countries of the Implementing Agreement AMF, but participate via sponsors (France : IFP, PSA and Renault; Austria : AVL List).

An Annex on DME has been created in 1997 and was prepared since 1996. At the 20th IEA Executive Committee meeting in Harwell, England (spring 1996), the decision was made to organise a DME workshop. This was done by TNO Road-Vehicles Research Institute and the workshop was held in November 1996 at the TNO facilities in Delft, Netherlands. In the course of two further workshops (June 1997 in Delft, February 1998 in Naperville, USA), the subjects and the funding of the activities were finalised, thus the "kick off" of the R&D Tasks took place in Naperville. At the fall meeting 1998, which again took place in Delft, many of the Task reports were ready in a draft version. The final version of this report was presented and delivered during the last (5th) workshop in Graz, Austria, which took place in March 1999.

Within theses activities, seven R&D tasks deal with the following subjects :

Task 1 :	Trade-off of fuel quality versus costs
Task 2 :	Safety investigations - DME distribution and handling on vehicles
Task 3 :	Design guidelines for DME fuel injection systems
Task 4 :	DME from renewable feedstock
Task 5 :	Life cycle analysis
Task 6 :	Cost of DME infrastructure
Task 7 :	Operating agent, workshops, newsletter

The following companies (countries) participated in the Task 3 activities :

Advanced Engine Technology Ltd. (Canada)
AVL List GmbH (Austria); Task Leader

AVL Powertrain Eng. (USA)
Renault (France)
Technical University of Denmark (Denmark)

2. Summary

Within the R&D Task 3, general guidelines for the layout and the design of fuel systems for DME were set up. Thus, different types of fuel systems, which fulfil the basic requirements for vehicle application, were assessed. The purpose of the guidelines summarised in this report is to demonstrate and discuss individual items of this new technology.

The work concentrates on the assessment of different system concepts. It demonstrates how far standard engine and fuel injection system technology for Diesel fuel and LPG can be used and shows in which fields new technology is required for DME. Furthermore, the degree of complexity of such systems is demonstrated and possible safety hazards are described.

The assessment is done by a "Failure Mode and Effect Analysis" (FMEA). For this analysis, the individual concepts are prepared according to a standardised scheme. Emphasis is laid on the functional principles and the consideration of all possible system states. It was also agreed among all partners of the task group to include control strategies and basic safety aspects for both the fuel systems and the engine.

During the FMEA meeting, all possible system states were discussed and possible failures and their consequences were listed in the FMEA tables. For the assessment of the failures, their importance was evaluated, the difficulty to detect them and their likelihood to occur. These three criteria were expressed in terms of numbers between 1 and 10. The product of these three numbers is called the "Risk Priority Number (RPN)" and expresses the seriousness of the failure.

At the beginning five different types of systems were proposed by the participants of Task 3:

1. "Shuttle valve concept" in a pump line nozzle diesel injection system (AET Canada)
2. Common rail fuel injection system as published by AVL Austria
3. Common rail fuel injection system as published by AVL Powertrain Engineering USA
4. BOSCH Type diesel common rail system adapted for use with DME (Renault France)
5. "Standard" pump line nozzle diesel injection system adapted for use with DME (TU Denm.)

For the FMEA meeting, only representatives of three systems could get together (systems 1, 2, 5). As these systems represented completely different concepts, it was decided to

generalise them in a way that commonly used components were standardised (e.g. storage tank and DME injection nozzle) and the peculiarities of the individual systems were analysed in more detail. Consequently, it was finally distinguished between the following systems:

System A : "Standard" pump line nozzle diesel injection system adapted for use with DME (TU Denmark.)
System B :"Shuttle valve concept" in a pump line nozzle diesel injection system (AET Canada)
System C : "Common rail" fuel injection system as published by AVL Austria

The FMEA meeting was held on July 9-10, 1998 at AVL Graz (Austria). The FMEA Team was formed by five participants (1 coach from AVL, 2 AVL, 1 AET, 1 TU-Denm.)

3. Conclusions

The conclusions are considered the "Design Guidelines" which represent the results of the task. The assessment method was introduced by Renault (structural analysis) and AVL (system FMEA assessment). It has proven to be a powerful tool and is recommended for further system investigations.

The items listed below have been found during three phases of the work :

Some agreements were already made during the initial phase when the boundary conditions were defined for the individual systems. During that phase, the systems were adapted to the same level of complexity and the participants had to agree on a certain system standard. All participants had practical experience with DME fuel injection systems.

Further conclusions were made at the end of the FMEA meeting.

At the 4th workshop in Delft (Oct. 1998), both the results of the Tasks 2 and 3 were presented and discussed. At that point, further (joint Task 2 and 3) conclusions were agreed which give the most general aspects.

<u>Agreements during definition phase</u>:

- At least for prototype systems, a conditioning system for (low pressure) gaseous DME is required (for preventing DME leakage to escape into the environment and for purging parts of the system after engine shutdown to prevent DME leakage into the engine). Such a conditioning system can be e.g. a purge tank plus compressor or a carbon cartridge with a suitable device for regeneration. Other devices are possible but have not been assessed.

- The basic system control functions (engine start/stop) are considered because they differ from those for standard diesel fuel systems.
- The systems must consider a fuel temperature control (DME cooler).

Conclusions from the FMEA meeting:

I. General:

- It would be beneficial to isolate (separate) the storage tank from the remaining system and the engine whenever possible (quickly reacting shut off device).
- If pipes or hoses break, care should be taken that only a small amount of DME can escape (small fuel volumes, sensors detect damage, shutdown function of system control concept).
- Many malfunctions of system operation originate from dirt and particles in the fuel system, thus high emphasis must be laid on fuel filtering.

II. System concept:

- The common rail concept represents a relatively new technology. However, as the system has been specifically considered for use with DME, there are no areas with very high risks.
- The pump line nozzle concepts are based on a proven technology, but show some areas of concern, mainly at the plunger barrel of the pump (leakage, seizing).
- The common rail concept has a higher potential for redundancy than the pump line nozzle and the shuttle valve concept.

III. DME gas conditioning system:

- If a fuel system is in the development stage, a device for conditioning low pressure gaseous DME is required (a purge tank and a carbon canister were assessed). Such a device is not necessary for engine operation but for system control (start, stop, emergency shutdown).
- The conditioning system must be very well developed, otherwise it represents more of a risk than a safety precaution.
- Carbon canisters should be designed for higher pressures (similar to purge tanks)
- For carbon canisters, the regeneration and regeneration control are relatively complex.
- No experience exists for the regeneration of DME to the intake air of the engine (effects on HC, CO, misfiring).
- Both conditioning devices have been assessed as critical because they represent new technology and are relatively complex.

Joint Task 2 and Task 3 conclusions:

- The technical issues associated with implementing DME in Diesel engines are not insurmountable.
- Three different system concepts have been assessed (pump line nozzle, shuttle valve, common rail). All concepts were found technically feasible.
- The assessments were based on existing Diesel and LPG technology. Areas which require development have been identified.
- On average, the introduction of new technology means higher risks. However, areas of severe concerns can be avoided as the new technology is aligned to the specific requirements of the new fuel.
- On average, the adaptation of proven Diesel fuel and LPG technology for use with DME shows lower risks but also individual items of high concerns. These have to be considered very carefully and the introduction of new technology in these fields is inevitable.

* * * *

4. Objective and Method of the System Assessment

The establishment of design guidelines for systems is like a walk on a tightrope. On the one hand, care must be taken not to go too much into design details of individual components, and on the other hand, the systems must be comprehensively defined. An other question is how to objectively assess the different system concepts.

For the assessment, a "Failure Mode and Effect Analysis" (FMEA) was chosen which is a powerful and well accepted tool within system analysis and quality engineering. Emphasis is laid on the system aspect, thus the system concepts are assessed with respect to their functions. Design details were considered only as far as changes of system states are concerned.

The system analysis was made according to a standardised scheme. For that purpose, exact boundary conditions and system features had to be defined or, in other words, the system demands were clearly established. In a next step, all system functions were listed in the FMEA sheets and these functions finally were assessed by the FMEA group.

This procedure allows the introduction of personal experience, subjective opinions and spontaneous ideas of the participants. The advantage of having an "international" FMEA meeting was that different concepts were assessed simultaneously. Thus, their analysis was based on the same prerequisites and the evaluated results of the different systems are therefore comparable. The analysis was no "competition" of concepts, but demonstrates advantageous and weak points, shows "forgotten" items but also demonstrates if e.g. safety precautions have been carried too far.

The result of the R&D Task 3 work is a general definition of the demands for a DME fuel system used for automotive application. Furthermore, those areas are identified which require development work for new technology. The conclusions of the system evaluation can be considered as guidelines for the design of such systems.

5. Definition of Boundary Conditions and System Features

With respect to the boundary conditions of the systems, it clearly had to be distinguished between the Task 3 and the Task 2 activities, which deal with the fuel storage and fuel supply on board vehicles and concentrate on safety aspects.

During the Workshop in Naperville (Feb. 1998), Renault Research introduced a method which makes the exact definition of systems possible and also helps to clearly separate the fuel system into individual parts. This method was quickly applied during the meeting and afterwards worked out in more detail (This method has been developed by Renault and is called "Structural Analysis and Design Technique" SADT).

The basic principle of this method is given in Fig. 1. The figure demonstrates the general procedure of the SADT system definition. The key issue is the system's function which is cited in a box. It requires inputs and outputs and provides a certain service. The service is usually (physically) equivalent to one or more outputs, however not all outputs are services. On the top of the box, the parameters which influence (e.g. control) the function of the system are listed and on the bottom the hardware component is given.

Using this principle, a complex system can be split into any degree of details. Its advantage is that individual parts can be detailed to a high degree of complexity, but in the same representation, other parts may remain on the surface. In this way, details can be assessed without losing the overview on the entire system. This kind of representation also helps to define the interactions between the components (or component groups).

The complete system which was subject to both activities (R&D Task 2 and Task 3) is given in Fig.2. In Fig. 3, the same system is split into more detail. The grey area delimits the system which was assessed in the Task 3 activities. This means that all concepts considered the following items:

Physical components (component groups):

- DME fuel injection system (different types of injection systems were defined)
- DME cooler (heat exchanger)
- Conditioning system for (low pressure) gaseous DME which may be leakage or accumulated gas from purging parts of the system. Such a conditioning system can be e.g. a purge tank plus compressor or a carbon cartridge with a suitable device for regeneration.

Some comments to the DME (gas-) conditioning system:

It is difficult to standardise precautionary measures for the prevention of DME leakage into the environment and into the combustion chambers of the engine. On the one hand, it can be assumed that leakage can be avoided (at least for all static seals) if the sealing concepts are suitable for liquefied gases. On the other hand, this is certainly not the case if standard diesel injection components (e.g. injection nozzles, plunger pumps) are applied. The question is, e.g. how much gas may leak into the cylinder without causing unacceptable effects.

If it is considered that at engine shutdown the injector nozzle stays filled with DME (approx. 200 mm3 liquid DME at 5 bar) then, after a while, the fuel will leak over the injector needle seat into the combustion chamber. The DME quantity of only the nozzle would already cause a DME concentration in the cylinder which lies well within the explosion limits*. Therefore it is completely unacceptable if the DME in the nozzle holder and the injection line would additionally leak into the cylinder. Beside the safety issues, it must be considered that for automotive use the DME will contain an odour additive, therefore any leakage would mean a smell nuisance.

At the moment, not enough details are known to estimate an acceptable leak quantity. Therefore, it was agreed that DME leakage should be avoided in all cases. This requires the introduction of special equipment as listed above.

Input streams:

- Fuel supply of liquid DME at a pressure which is above the saturation pressure (referred to the temperature in the storage tank). If held at this temperature, it can be assumed that there is no tendency to cavitation at the intake to an injection pump.
- Gaseous DME (leakage) could also originate from the storage system. This gas would also be conditioned in the low pressure gas conditioning system (optional)

Output streams:

- Liquid DME which is injected into the combustion chamber of the engine (="service")
- Gaseous DME which is mixed to the intake air of the engine (optional)

Parameters:

- Temperature control: All systems must have a fuel temperature control, e.g. surplus liquid DME can be returned over a cooler as indicated in Fig. 3. There can be other solutions, for example the fuel can be returned to the tank, if the heat balance of tank allows such a solution.

- Control functions (necessary):
  - Engine start/stop function (e.g. fuel supply on/off by a solenoid valve)
  - Control of fuel metering (power demand)
  - Timing control (adapted for the low speed of sound of DME)

- Control functions (optional):
  - Special safety control functions
  - Special diagnostic functions

* Explosion limits in air 3.4 – 17% (vol)
Density liquid DME 660 kg/m³ (5 bar, 20 °C)
Density DME gas 1.9 kg/m³ (1 bar, 20 °C)

Additional control and diagnostic functions could improve the safety standard and the engine's operational reliability. Their advantages could possibly be illustrated by the FMEA assessment numbers, however, it should be considered that a too high increase in complexity could also worsen a system.

6. Definition and Assessment of Systems

6.1. Proposed and Assessed Fuel Injection Systems

At the "Kick Off"- meeting in Naperville, the following types of systems were proposed for assessment :

1. "Shuttle valve concept" in a pump line nozzle diesel injection system (AET Canada)
2. Common rail fuel injection system as published by AVL Austria
3. Common rail fuel injection system as published by AVL Powertrain Engineering USA
4. BOSCH Type diesel common rail system adapted for use with DME (Renault France)
5. "Standard" pump line nozzle diesel injection system adapted for use with DME (TU Denm.)

For the FMEA meeting, only representatives of three systems could get together (systems 1, 2, 5). As these systems represented completely different concepts, it was decided to generalise them in a way that commonly used components were standardised (e.g. storage tank and DME injection nozzle) and the peculiarities of the individual systems were analysed in more detail. Consequently it was finally distinguished between the following systems :

System A : "Standard" pump line nozzle diesel inj. system adapted for use with DME (TU Denmark.)
System B : "Shuttle valve concept" in a pump line nozzle diesel injection system (AET Canada)
System C : Common rail fuel injection system as published by AVL Austria

The FMEA meeting was held on July 9-10, 1998 at AVL Graz (Austria). The FMEA Team was formed by :

E. Mungenast	AVL (Austria), Production Engineering, FMEA Coach
H. Ofner	AVL (Austria) , FIE and system hydraulics
R. Schneider	AVL (Austria), Vehicle electronics and control systems
S.C. Sorenson	TU (Denmark), Engine development
G. Webster	AET (Canada), Engine development

The three systems (A,B,C, see above) represent three completely different concepts. System A is a reasonable approach to the problem as it uses "Standard" Diesel fuel equipment. Many authors of published literature used such types of fuel injection systems, at least for basic research work carried out in laboratories and engine test cells. However, one severe problem always was the leakage into pump housing, combustion chamber and to the environment. This has to be prevented by special measures in order to fulfil the boundary conditions.

The system B introduces an interesting approach for preventing the leakage. It contains DME only in some individual parts of the system (injection line, injector). The injection pump delivers Diesel fuel, which, over a "Shuttle Valve" , displaces the DME. Both the pumping, fuel metering and injection control is done with Diesel fuel.

The system C uses a common rail concept which is especially designed for DME. Thus, it represents a comprehensive approach with high flexibility in all control features.

These different principles offered the possibility to start with a simple, well known technology (system A) which successively was extended by special DME equipment (system B and system C). All systems were reduced to their functional principles in order to standardise them and to get comparable degrees of system complexity. The DME storage tank and the fuel injection nozzles were common for all three systems.

6.2. General Principles of Hardware Components

Once the boundary conditions and the system concept have been defined, a (simplified) scheme of hardware components can be set up. The objective of the assessment is the system functions (and no design details), therefore all functions of the components must be determined. For this purpose, the principles of some components must be defined.

Solenoid valves

The solenoid valves are poppet valves as demonstrated in Fig.4. As an example, this figure shows a 2 positions / 3 way valve. It is important that the valve connections are marked (Supply, Exit etc) and that all possible connections are listed. If solenoid valves are applied in a system it must be considered that they have to be actuated. This can be done manually directly by the driver, e.g. by turning the key or pressing a button or indirectly by an electronic controller. If a controller is used, it must be included to the FMEA, however, for reasons of simplicity it is kept in a very general form.

Check valves and mechanical pressure regulators

The principle of check valves and mechanical pressure regulators is given in Fig. 5.

Electronically controlled pressure regulators

The principle of an electronically controlled pressure regulator is also shown in Fig. 5. It consists of an actuator, a sensor and an electronic control unit. Please note that the pressure sensor also includes the cable to the control unit and the control unit also the cable to the actuator!

Fuel system control

The basic engine control features like engine start / stop must also be considered. In most cases, solenoid valves, starter motor, supply pump etc. are actuated according to "actions" like, for example, switching the key off -> on. The basic control features are defined by the state diagram and the state transition diagram. The state diagram defines the individual states (e.g. solenoid valves can be "on" or "off") at different conditions of operation (e.g. "park", "crank engine", or "engine operation"). The state transition diagram defines all possible changes of states (e.g. a change from "crank engine " to "engine operation" is possible but not the vice versa transition). The state definitions are given for all assessed systems in the figures. A state transition diagram is given only once (for system C), but they are analogous for the other systems.

6.3. Definition of Component Functions and Guidelines for Assessment

The component functions are defined and cited into special FMEA sheets. These are tables which show the functions, the potential failure of the function and it's effects and causes. In this well ordered list, the individual functions and failures can be assessed (from the FMEA team). This means that the team gives evaluation numbers to the O (=occurance of a failure), I (=importance) and D (=detectability) of the individual items. These numbers result in the "Risk Priority Number" (RPN = O*I*D). Evaluation guidelines are listed in Fig.6.

There are some additional aspects which should be realised:

- No combination of failures is considered.
- Mechanical and electrical failures are generalised and depend on the individual component.

- The fuel injection systems are considered for multi cylinder applications. Therefore, the stop of fuel delivery does not necessarily mean stop of engine.
- Seals are contact seals (e.g. O-rings), fixed metal fittings (e.g. clamping rings) or narrow gaps (e.g. plunger / plunger barrel).
- Safety risks according to leakage do not distinguish between high or small amounts of leakage.

6.4. System A – Pump Line Nozzle DME Injection System

The scheme is given in Fig. 7. The fuel is stored in a pressure tank where the DME is kept at saturated state. From there, the liquid fuel is delivered to the fuel injection system by a supply pump. A solenoid valve (V1) closes / opens the connection from the tank to the system. V1 is a 2 positions / 3 way valve as demonstrated in Figure 4. If V1 is "off", it closes the connection between tank and system and opens the system to the gas conditioning system. If V1 is "on ", DME can be supplied from the storàge tank into the system and the connection to the gas conditioning system is closed.

In their principle, both the injection pump and the injection nozzle are standard diesel fuel injection equipment. That is why e.g. the pump camshaft housing must also be ventilated to the gas conditioning system because an undefined amount of DME leaks via the gap between plunger and barrel into this chamber.

As gas conditioning system, a charcoal canister is considered. For regeneration, air is supplied to the canister and the DME – air mixture is added to the intake air of the engine. The regeneration must be controlled because no DME may escape during engine shut-down. Furthermore, the DME which is added to the intake air must be carefully metered.

6.5. System B – Shuttle Valve DME Injection System

The shuttle valve concept avoids the problem of DME leakage into the pump housing by separating the DME from the pump (and thus also from the fuel metering device, timing control etc., see Fig. 9). The injection pump delivers diesel fuel to the shuttle valve which transmits the injection pulse to the DME.

For the system assessed, the same storage device (tank and V1) and the same gas conditioning system as described for the Jerk pump system (system A) was considered.

6.6. System C – Common Rail DME Injection System

The storage tank and the fuel shut-off device (V1) is identical to those described in system A and B, see Fig. 11.

For conditioning the low pressure gaseous DME, a "purge system" is applied. The purge tank is a pressure tank in which the pressure is kept below saturation pressure in order to keep the DME in a gaseous state. After engine shutdown, the liquid DME which is in the fuel injection system, is expanded into this tank and thus evaporates. For controlling the pressure in the purge tank, a compressor is installed which recompresses the gas into the storage tank. This compressor operates in an on / off mode and is automatically controlled by a control unit. As soon as the purge tank pressure sensor detects a certain "maximum" pressure level, the controller switches the compressor "on" and stops it as soon as a "minimum" is reached again.

In the fuel system, the supplied liquid DME is cooled in a heat exchanger and afterwards delivered to two fuel pumps. The high pressure pump (hp_p) is driven by the engine and builds up the rail pressure (approx. 250 bar). The rail pressure is controlled by an electronically controlled pressure regulator (hp_epr).

The second pump (circulation pump c_p) builds up the residual pressure in the injectors and circulates the fuel for cooling purpose. The residual pressure is adjusted by a mechanical pressure regulator (pr_2).

The fuel injection is controlled by the injection solenoid valve (inj_V). This valve closes the high pressure to the injector if it is in "off" state and, at the same time, opens the injectors to the "control line". If the valve is "on", it opens the high pressure to the injectors and closes the "control line".

The fuel injectors are standard Diesel fuel injection nozzle holder / nozzle configurations.

The system is described in more detail in published literature (e.g. SAE 981158 "Dimethyl Ether as Fuel for CI Engines – A New Technology and its Environmental Potential"). For this FMEA it had to be simplified, however the principle has stayed the same.

7. List of Figures, Appendix

Fig.	
1	General structure for definition of system
2	Overview of DME fuel system
3	Boundary conditions for DME fuel injection system
4	Design principles of solenoid valves
5	Design principles of electronic pressure regulator and mechanical pressure regulator
6	Specific RPN evaluation rules
7	Scheme of system A "jerk pump"
8	Definition of system states, system A
9	Scheme of system B "shuttle valve"
10	Definition of system states, system B
11	Scheme of system C "common rail"
12	Definition of system states, system C
13	State transition diagram, system C

Appendix A: FMEA evaluation tables

A1	DME storage and supply (systems A,B,C)
A2	DME injection nozzle (systems A,B,C)
A3	Injection system (system A)
A4,5	Control system (system A
A6	DME gas conditioning system (system A)
A7,8,9	Injection System (system B)
	Control + gas conditioning system analogous system A
A10,11,12	Injection system (system C)
A13,14,15	Control system (system C)
A16,17	DME gas conditioning system (system C)

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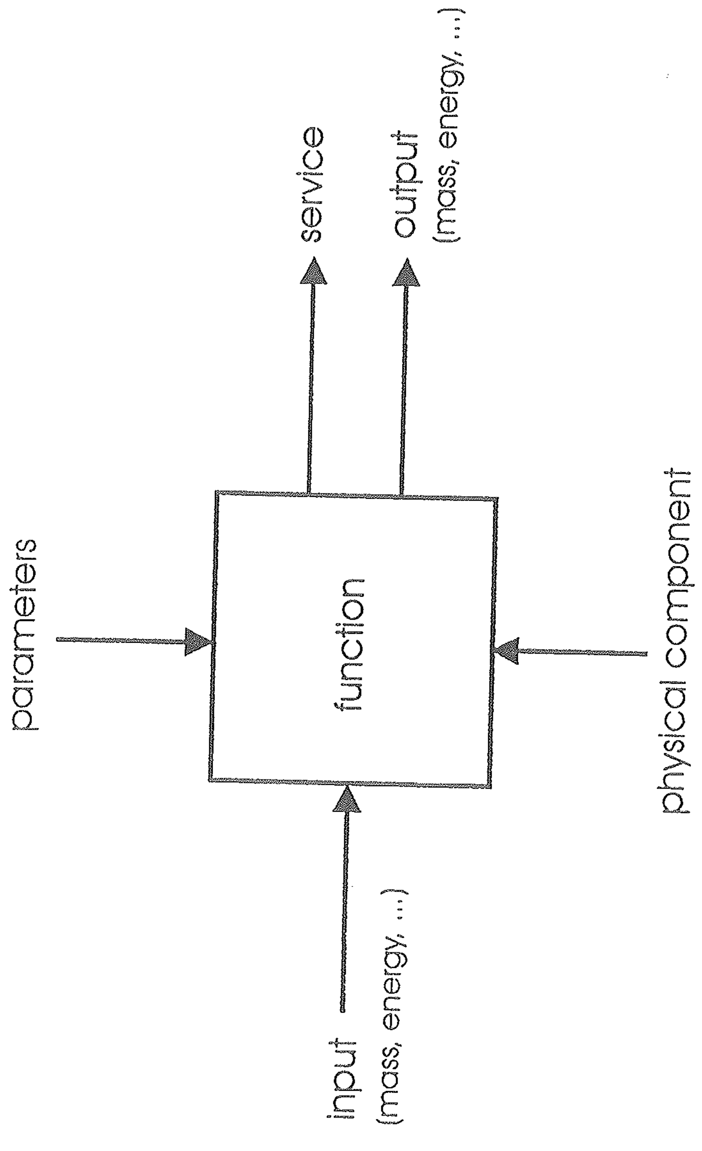


System analysis ; general structure

Fig. 1 : General structure for definition of system

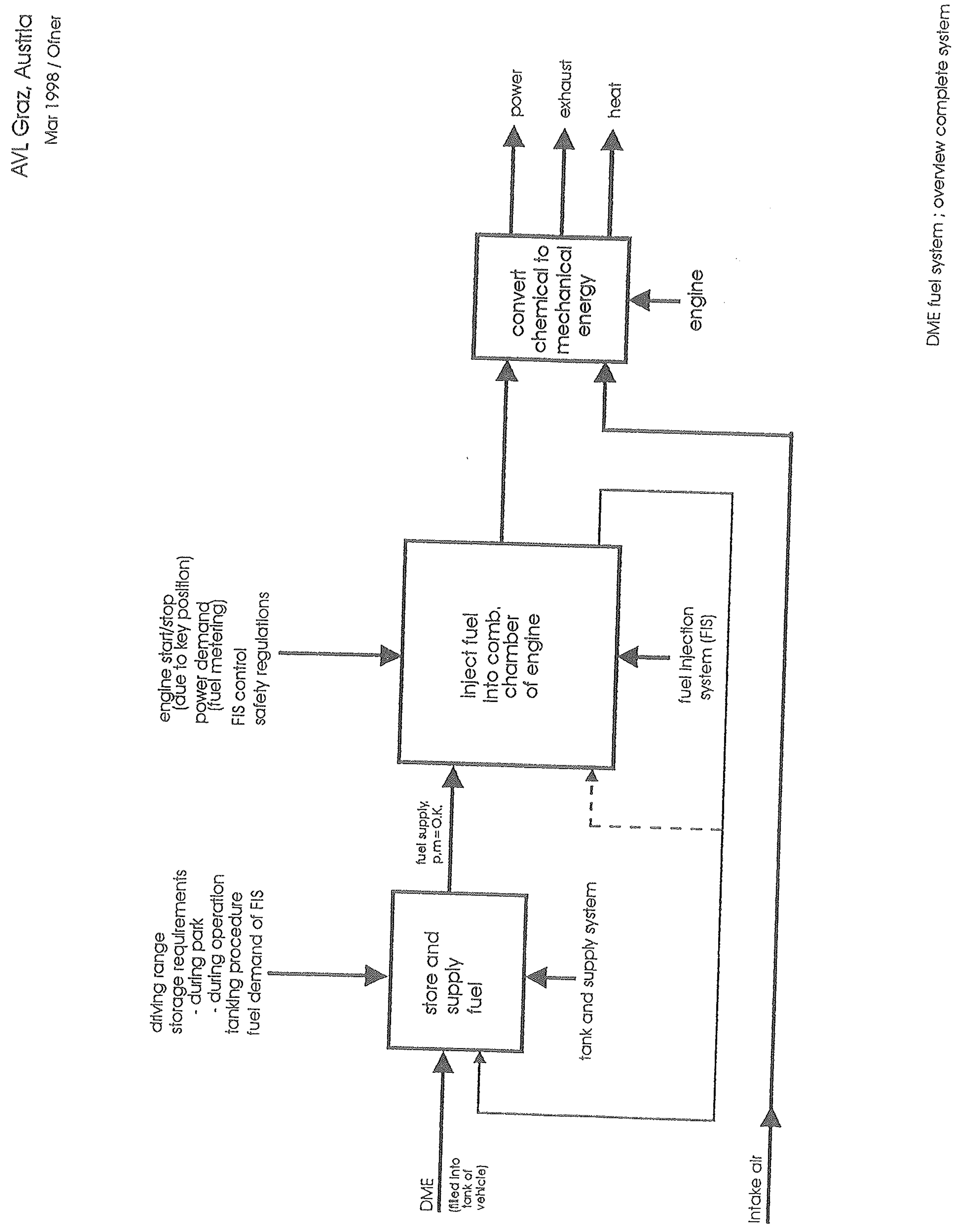


Fig. 2 : Overview of DME fuel system

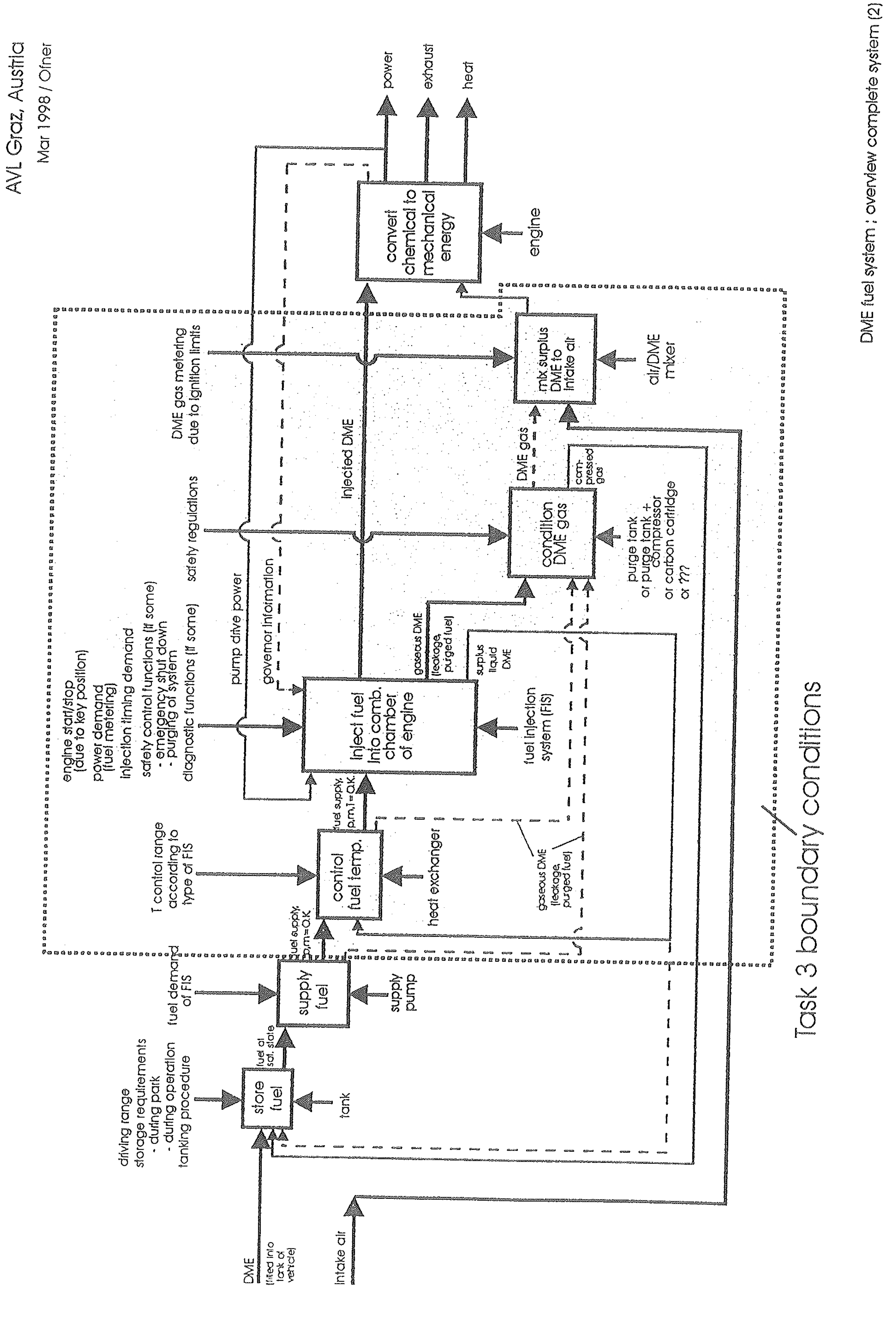
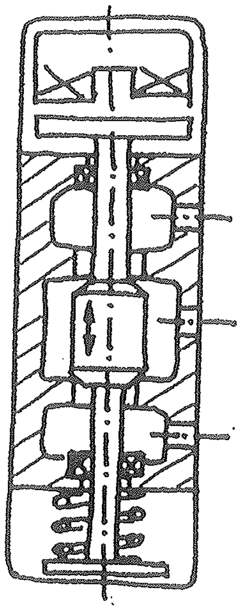


Fig. 3 : Boundary conditions for DME fuel injection system

2 position / 3 way solenoid valve



Assessed valve body positions of 2 position / 3 way solenoid valve (V1) :

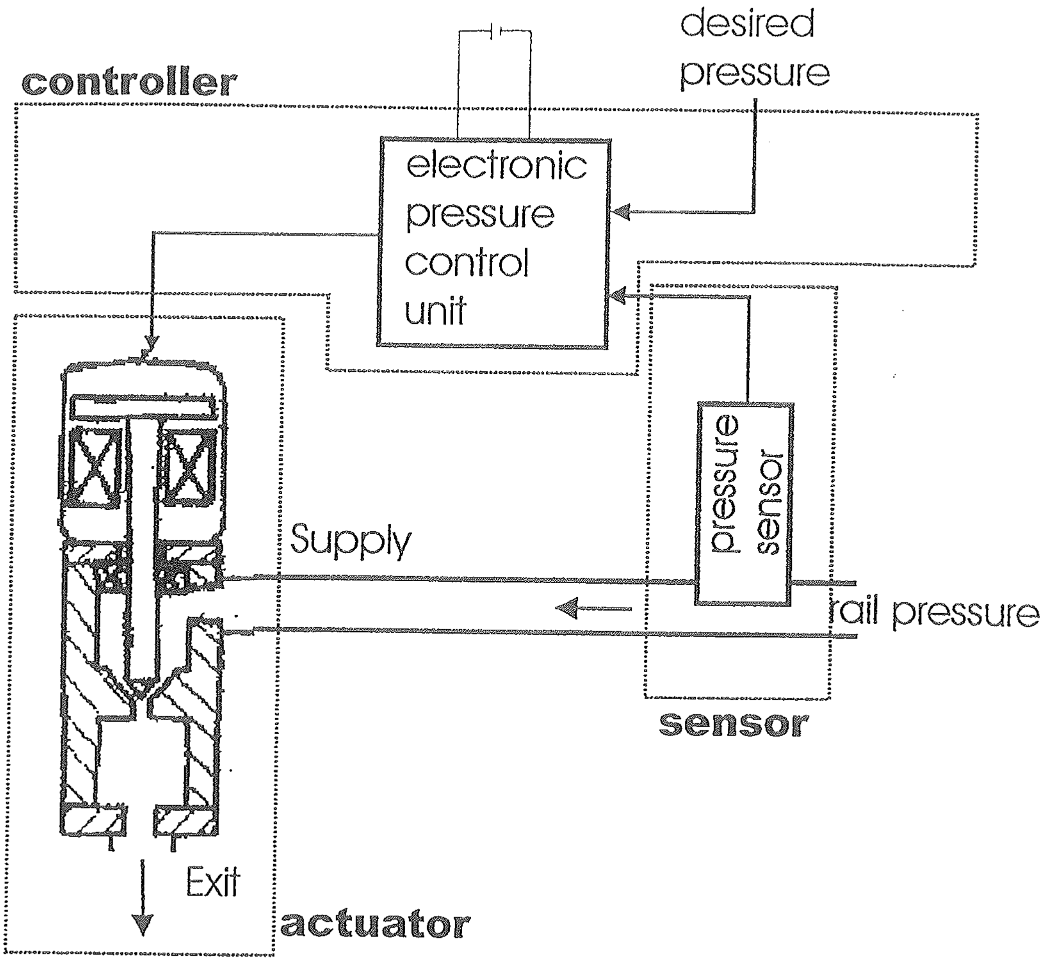
SE	SD	ED	valve body	
closed	closed	open	at lower seat	(valve not powered)
open	closed	closed	at upper seat	(valve powered)
open	open	open	between seats	
closed	closed	closed	blocked	

2 position / 2 way solenoid valve; Normal Closed;
(same principle as above but no Drain port)

Assessed valve body positions of 2 position / 2 way solenoid valve :
(valves for regeneration of charcoal V2, V3) :

SE	valve body	
closed	at lower seat	(valve not powered)
open	at upper seat	(valve powered)

Fig. 4 : Design principles of solenoid valves



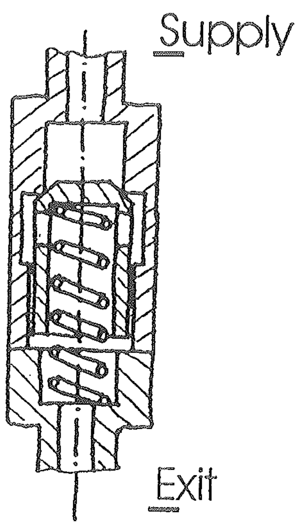


Fig. 5 : Design principles of electronic pressure regulator and
mechanical pressure regulator (= same principle as check valve)

Graz, 08.07.1998
„FMEA/EU-DME.doc"
E. Mungenast

Subject: Specific RPN-Evaluation roles for R&D Task 3 „Design Guidelines"

To tune the general FMEA evaluation system to the concerned application the following items are changed according to our experience and the current task:

1. Occurrence of failure

High	7
neutral, no agreement	5
Low	2

2. Importance of failure

Safety for public	10
Leakage	8
Engine destruction	9
Break down	7
Service necessary, now	5
later	4

3. Detection of failure

Like in general system

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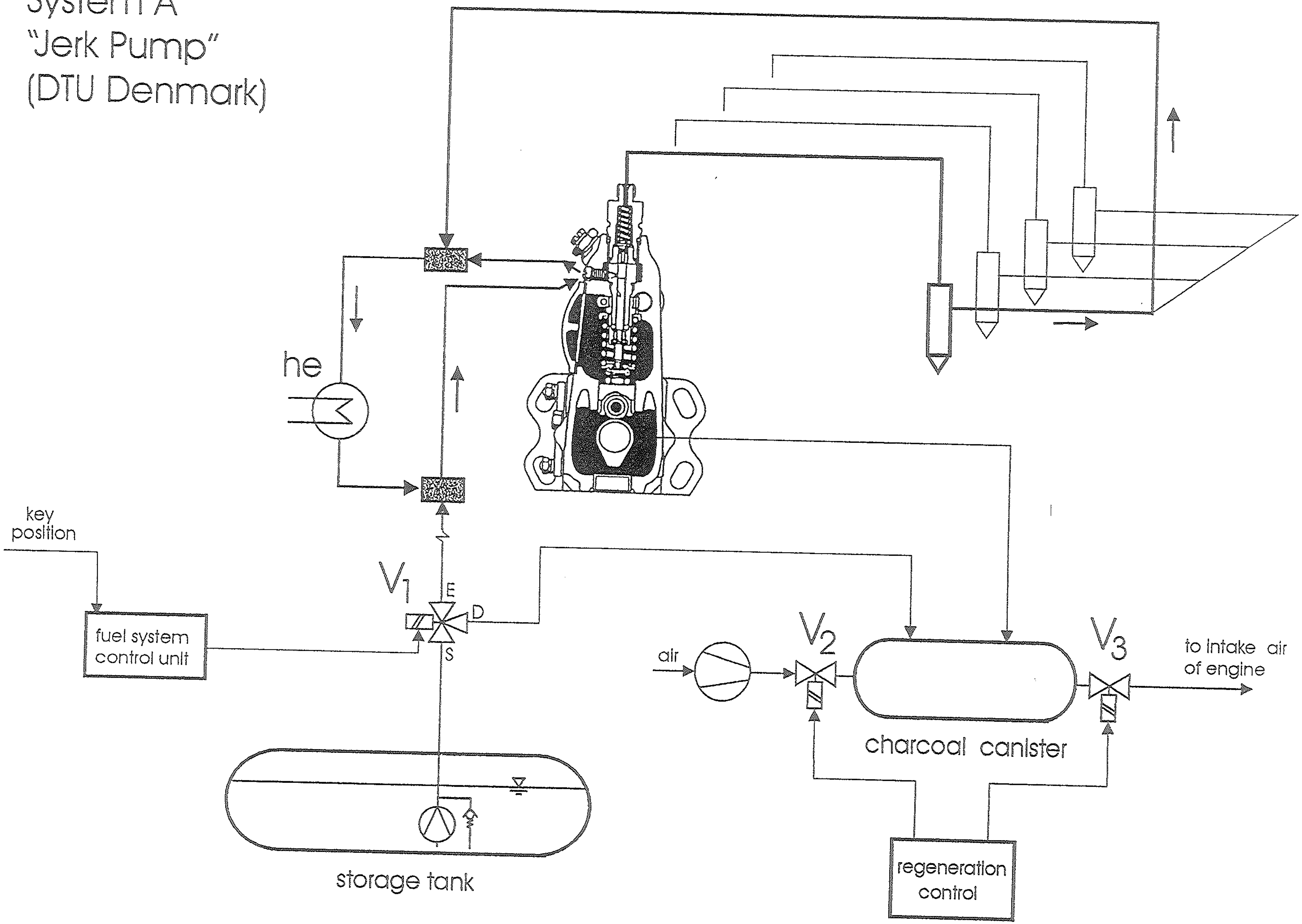
Fig. 6

System A
"Jerk Pump"
(DTU Denmark)



State	Key	Speed	Pedal	V1 (system filling)	Fuel Supply Pump	Charcoal Regeneration (V2,V3,Air)	Starter Motor
Park	Off	Low	-	Off	Off	Off	Off
Ready for Start	On	Low	-	On	On	Off	Off
Crank Engine	Start	Low	-	On	On	Off	On
Engine operation "low"	On	High	Low	On	On	Off	Off
Engine operation "high"	On	High	High	On	On	On	Off

System A (Jerk Pump) : Definition of system states

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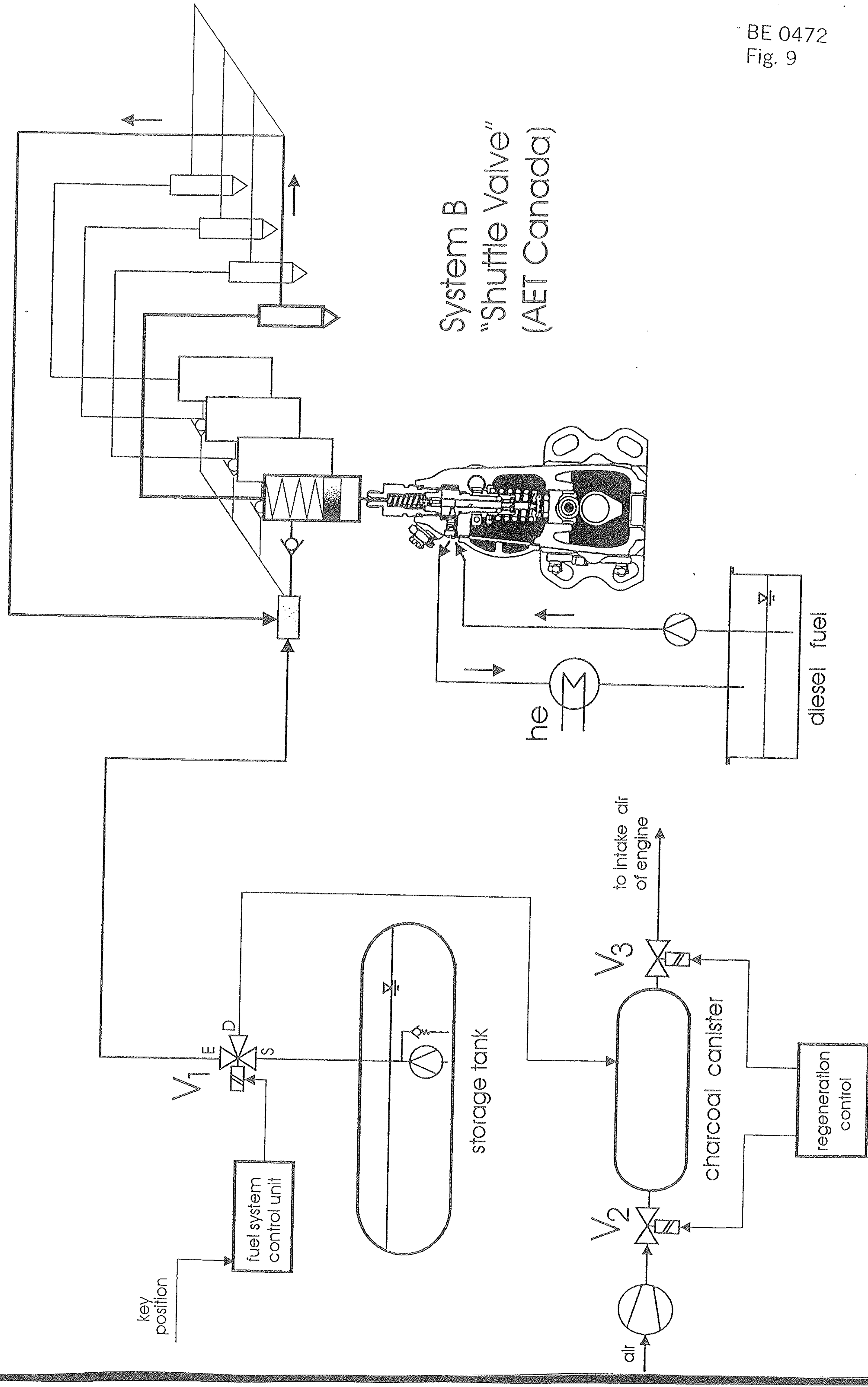
Fig. 9



System B
"Shuttle Valve"
(AET Canada)
he
diesel fuel
to intake air of engine
V3
charcoal canister
regeneration control
V2
air
key position
fuel system control unit
V1
E
D
S
storage tank

State	Key	V1 (DME system filling)	DME Fuel Supply Pump	Diesel Fuel Supply Pump (+lubrication system)	Charcoal Regeneration (V2,V3,Air)	Starter Motor
Park	Off	Off	Off	Off	Off	Off
Ready for Start	On	On	On	Off	Off	Off
Crank Engine	Start	On	On	On	Off	On
Engine operation	On	On	On	On	On	Off

System B (Shuttle Valve) : Definition of system states

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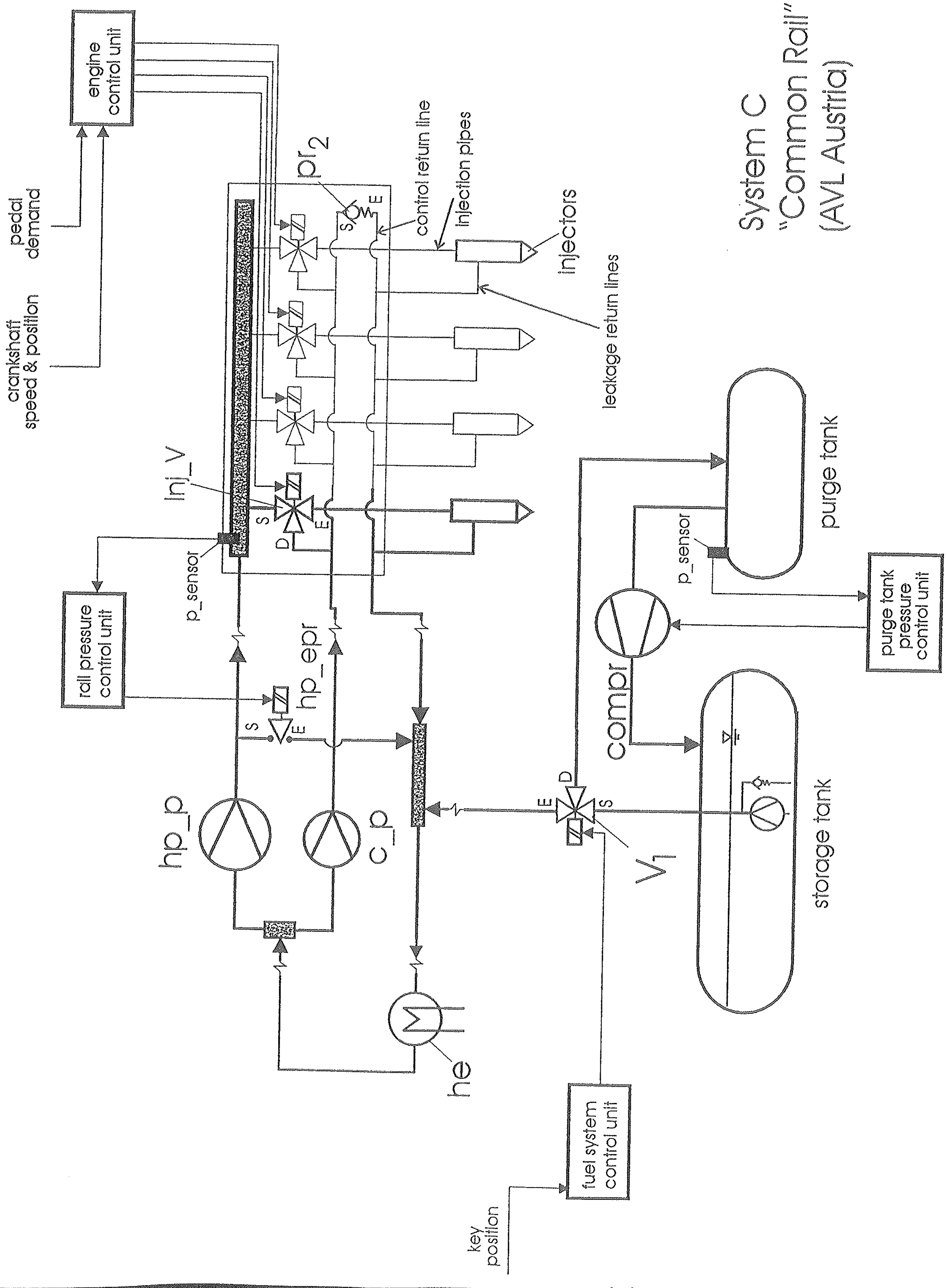
Fig. 11

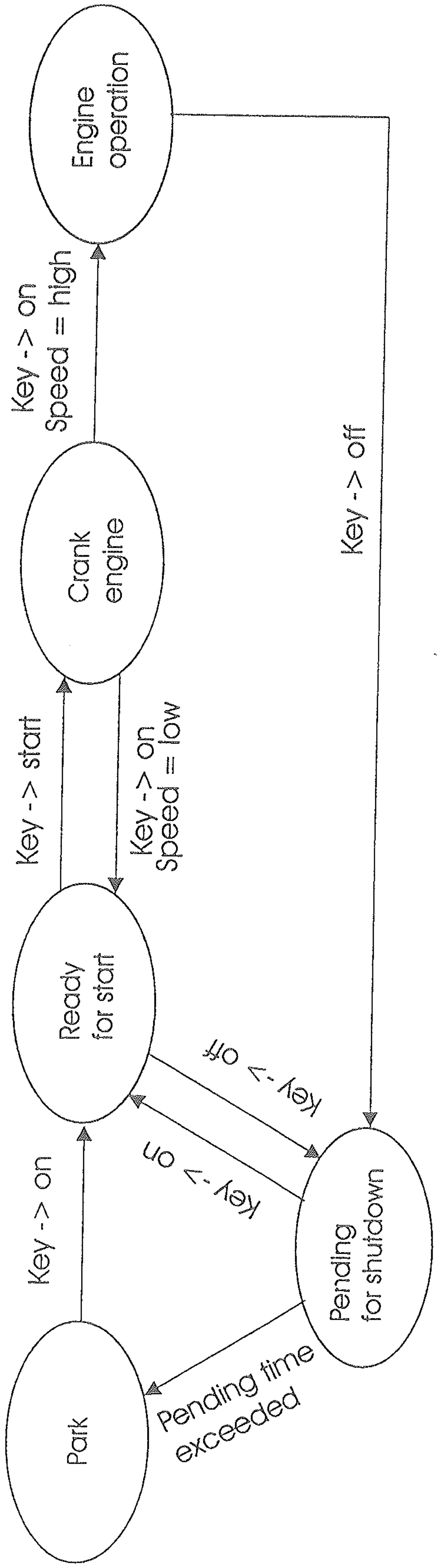


System C
"Common Rail"
(AVL Austria)

State	Key	V1 (DME system filling)	DME Fuel Suppl. Pump	Circu-lation Pump	Control Units			Starter Motor
					Rail Pressure	Engine Control	Purge Compres.	
Park	Off	Off	Off	Off	Off	Off	Off	Off
Ready for Start	On	On	On	Off	On	On	On	Off
Crank Engine	Start	On	On	On	On	On	On	On
Engine operation	On	On	On	On	On	On	On	Off
Pending for shutdown	Off	On	Off	Off	Off	Off	Off	Off

System C (Common Rail) : Definition of system states

BE 0472
Fig. 13



State transition diagram; System C

DME Storage and Supply (A+B+C)

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	I	D	RPN	Comments
1. Fuel storage system (storage tank + assy., supply pump,								
pipes to fuel injection system)								
Fu.1: Delivers liquid DME from storage tank to fuel injection system on engine (supply pump = ON). DME pressure is approx. 5 to 15 bar above saturation pressure	Fuel delivery rate too low ; supply pressure too low	DME pressures in system drop, partial evaporation of DME, unstable engine operation, engine stops	Failures in hydraulic part of supply pump (valves, plungers, diaphragms, sealings, etc.)	5	7	2	70	
			Mechanical or electrical failures in drive of supply pump					
			Supply line blocked					
Fu.2: Stops fuel delivery during engine stop (supply pump = OFF); protects tank + pipes from excessive pressure (e.g. by pressure reliefe valves)	Fuel delivery during engine shutdown;	No effects on system if V1, V3 and injection solenoid valves are O.K.	Mechanical or electrical failures in control valves of storage tank	3	4	9	108	
	Excessive pressure due to temperature increase (e.g. in supply line)	Break of components (e.g. supply line), DME escapes from system	Pressure reliefe valves do not work					

DME Injection Nozzle (A+B+C)

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
2. Fuel injection nozzle								
Fu.1: Opens orifice to combustion chamber for fuel injection if pressure inside nozzle has exceeded Needle Opening Pressure (NOP)	Orifice stays closed	No fuel injection	Needle hangs in closed position (mechanically)	2	4	5	40	
			Pressure in nozzle spring chamber (=needle back pressure) has increased, e.g. due to blocked ventilation line	1	4	5	20	
Fu.2: Closes orifice to combustion chamber if pressure inside nozzle is below NOP	Orifice is open even if nozzle pressure is below NOP	Continous (uncontrolled) fuel injection	Needle hangs in open position (mechanically)	7	10	4	280	Severe safety issue ! OBD, Emergency shutdown !
			Particles at needle seat					
			Leakage					

DTU Jerk Pump (A) ; Inj. Sys.

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
3.(A) Fuel injection system								
3.1 High Pressure Jerk pump								
Fu1: Delivers fuel to the nozzle	Does not deliver because of plunger seizure	Unstable engine operation, Loss of engine control	Plunger seizure	8	10	4	320	Materials and Lubricants must be developed
	Does not deliver because of leakage at plunger	Unstable engine operation, leakage of DME into pump housing	Wear of Plunger	8	8	8	512	
Fu2: Generatre the high pressure fuel to the engine	Does not generate adequate pressure	Unstable engine operation, leakage of DME into pump housing	Wear of Plunger	8	8	8	512	
		Unstable engine operation, leakage of DME into pump housing	Overheating of the pump	5	7	3	105	
Fu3: Meter the fuel	Does not meter the fuel	Unstable Operation	Plunger seizure	8	10	4	320	
		Engine Stops	Mechanical failure on rack	3	7	3	63	
3.2: Fuel injection control devices								
Fu1: Shut off fuel injection (zero metering)	Does not work	Unstable operation	Mechanical Failure	8	10	4	320	
		Engine does not stop	Mechanical Failure				.	
Fu2: Control the injection timing	Does not work	Lower engine performance	Mechanical Failure	2	5	8	80	
3.3 Delivery Valve								
Fu1: Determines the residual pressure in the line	Does not work	Loss of Performance	Damage to valve seat	7	5	8	280	Critical for Wear

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	Evaluation I	Evaluation D	Evaluation RPN	Comments
4.(A) Fuel control system								
4.1 Solenoid valve V1: (2 position / 3 way valve)								
Fu. 1: Fuel supply shut off (not powered) cl.SE, cl.SD, op.BD	op.SE, cl.SD, cl.ED	Uncontrolled filling of fuel system	Valve body hangs in open SE position (mechanically)	2	6	8	96	
			Valve powered (e.g. short cut to ground)					
	op.SE, op.SD, op.BD	Short circuit storage to purge tank and uncontroled filling of fuel system	Valve body hangs between seats	6	10	8	480	Filter in supply line ! Take care on seals at valve body !
			Leakage					
	cl.SE, cl.SD, cl.ED	Filling and purging of system is disabled	Blocked by particles	2	7	2	28	
Fu. 2: Fuel supply switched on (valve powered) op.SE, cl.SD, cl.ED	cl.SE, cl.SD, op.ED	No fuel supply	Valve not powered (electrical failures)	5	7	2	70	
			Valve body mechanically blocked					
	op.SE, op.SD, op.ED	see Fu. 1					s.a.	
	cl.SE, cl.SD, cl.ED	see Fu. 1					s.a.	

DTU Jerk Pump (A) ; Fuel Contr.

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	I	D	RPN	Comments
4.2. Fuel Control Unit								
1. Park -> Ready to Start	does not change state							Changes of system states are given in the STATE TRANSITION DIAGRAM
2. Ready to Start ->Park	-- " --							System changes due to state transitions are given in the STATE DIAGRAM
3 Ready to Start -> Crank	-- " --							No numbers were specified because changes of system states refere to individual components which were assessed elswere (e.g. functions of V1 etc.)
4. Crank - > Ready to Start	-- " --							
5. Crank -> Engine Operation rack low	-- " --							
6. Crank -> Engine Operation rack high	-- " --							
7. Engine Operation rack low -> Engine Operation rack high	-- " --							
8. Engine Operation rack high -> Engine Operation rack low	-- " --							
9. Engine Operation rack high -> Park	-- " --							
10. Engine Operation rack low -> Park	-- " --							

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
5. Evaorpative/Leakage control System								
5.1 Air Source for Regeneration								
Fu1: Supply Regeneration Air to Canister	No Supply air	High Emisions, canister breakthrough	Plugging	3	6	8	144	
5.2 Canister								
Fu1: Temporary storage of purged and leaked DME from system	Disabled Temporary Storage of purged DME	Slightly high combustion emissions for a short time	Poisonsing/deterioration of activated Charcoal	3	6	8	144	
5.3 Air Inlet Valve (V2)								
Fu1: Control the purge time	Does not	Small amount of leakage to the environment and the engine	Hydraulic, electrical failure, sticking	3	10	9	270	
5.4 Air Outlet Valve (V3)								
deliver of DME into the intake manifold (breakthrough of canister)	Does not	Small amount of leakage to the environment and the engine	Hydraulic, electrical failure, sticking	3	10	9	270	

System/item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	Evaluation I	Evaluation D	Evaluation RPN	Comments
3.(B) Fuel injection system								
3.1 Diesel fuel supply system (tank, supply pump, ...)								
Fu1: Delivers diesel fuel from the tank to the injection pump	Fuel delivery rate too low / supply pressure too low / fuel aeration	Insufficient diesel drawn into injection pump causing reduced shuttle valve displacement, erratic engine operation, engine shutdown	Mechanical / hydraulic failure	2	7	2	28	
			Supply line and/or filters blocked					
			Fuel tank empty					
			Air leak in diesel fuel supply line or pump					
Fu2: Delivers diesel fuel to the shuttle valves for lubrication	Fuel delivery rate too low / supply pressure too low / fuel aeration	Reduced shuttle valve lubrication resulting in increased shuttle valve wear and potential seizure	Mechanical / hydraulic failure	2	7	2	28	
			Supply line and/or filters blocked					
			Fuel tank empty					
			Air leak in diesel fuel supply line or pump					
Fu3: Stops fuel delivery to the shuttle valve at engine shutdown	Fuel delivery during engine shutdown	diesel fuel mixed to DME	Mechanical / hydraulic failure	2	7	2	28	
		charcoal poisoned by diesel fuel						

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	I	D	RPN	Comments
3.2: Diesel fuel injection pump								
Fu1: Supplies high pressure diesel fuel to activate shuttle valve system	Does not supply ...	Erratic engine operation	Insufficient diesel fuel supplied to tank	4	10	4	160	
		Engine does not start / operate	Aeration of diesel					
		loss of engine control	Seizure of plunger					
			Insufficient lubrication of pump					
Fu2: Genegates high pressure diesel / DME	Does not generate ...	Erratic engine operation	Insufficient diesel fuel supplied to tank	2	7	3	42	
		Engine does not start / operate	Aeration of diesel					
			Cavitation (DME)					
Fu3: Meters the fuel	Does not generate ...	Unstable operation	Plunger seizure	8	10	4	320	
		Engine stops	Mechanical / hydraulic failure					
3.3: Fuel injection control devices (rack of diesel pump)								
Fu1: Shut off fuel injection (zero metering)	Does not work	Unstable operation	Mechanical Failure	8	10	4	320	
		Injection does not stop						
Fu2: Control the injection timing	Does not work	Lower engine performance	Mechanical Failure	2	5	8	80	

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System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	I	D	RPN	Comments
3.3 Shuttle valve Diesel fuel / DME								
Fu1: Displacement of shuttle valve causes rapid buildup of DME pressure	Shuttle valve stays open	No DME delivery to nozzle, engine does not start / operate	Shuttle valve seizure from insufficient lubrication	6	7	2	84	
	Shuttle valve stays closed							
Fu2: Provides a sealed interface between diesel fuel and DME	Shuttle valve leaks	Erratic engine operation	Valve seat wear	7	6	4	168	
		Diesel mixed to DME	Excessive clearance between shuttle valve and barrel					
			Deposits on valve seat					
			Valve seat wear					
3.4 DME high pressure check valve								
Fu1: Valve opens at minimal pressure differential to allow DME from supply line to enter high pressure injection line	Check valve stays closed	DME does not transfer from supply line into high pressure injection line	Blockage of check valve	3	5	8	120	
	Shuttle valve stays closed	Erratic engine operation	Seizure of check valve					
Fu2: Check valve closes at minimal pressure differential preventing injection pulse in the high pressure injection line from transferring into DME supply line	Check valve leaks / stays open	High pressure injection pulse weakened as a portion of pulse enters low pressure supply line	Pour fuel lubricity causes excessive wear at the valve seat	6	5	8	240	
		Erratic engine operation	Deposits on valve seat					
			Seizure of check valve					

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	Evaluation I	Evaluation D	Evaluation RPN	Comments
3.(C) Fuel injection system								
3.1 Injection solenoid valve inj V (2 position / 3 way solenoid valve)								
Fu. 1: High pressure fuel supply to injectors shut off (not powered) cl.SE, cl.SD, op.ED	op.SE, cl.SD, cl.ED	Uncontrolled fuel injection	Valve body hangs in open SE position (mechanically)	2	10	5	100	
			Valve powered (e.g. short cut to ground)					
	op.SE, op.SD, op.ED	Continuous fuel flow from high pressure rail into control line, high pressure can (possibly) not be held	Valve body hangs between seats	3	7	8	168	
			Leakage					
			Bouncing					
Fu. 2: Fuel injection switched on (valve powered) op.SE, cl.SD, cl.ED	cl.SE, cl.SD, op.ED	No fuel injection	Valve not powered (electrical failures)	6	5	8	240	OBD !!!
			Valve body mechanically blocked					
	op.SE, op.SD, op.ED	see Fu. 1						
	cl.SE, cl.SD, cl.ED	see Fu. 1						

System/item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	Evaluation I	Evaluation D	Evaluation RPN	Comments
3.2 Engine control system								
3.2.1 Engine speed and position sensor (plus sensor wheel etc.)								
Fu. 1: Detects speed and position of engine crankshaft (possibly additionally of camshaft), converts it into electrical signal and transmits it to engine control unit	Detects wrong speed and position	Engine control fundamentally disturbed	Sensor device (or parts thereof) damaged (mechanically)	2	4	5	40	
	Wrong conversion of speed and position to electrical signal		Wrong calibration					
	Transmits wrong (or no) signal to engine control unit		Electrical failure (broken cable, shortcut to ground, loose contact)					
3.2.2 Fuel temperature sensor								
Fu. 1: Detects temperature in high pressure rail, converts it into electrical signal and transmits it to engine control unit	Detects wrong temperature	Wrong fuel temperature compensation disturbed performance of engine	Temperature sensor damaged (mechanically)	2	5	6	60	
	Wrong conversion temperature to electrical signal		Wrong calibration					
	Transmits wrong (or no) signal to engine control unit		Electrical failure (broken cable, shortcut to ground, loose contact)					

AVL CR (C) ; Injection System

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
3.2.3 Engine control unit								
Fu. 1: Controls duration of injection (=fuel metering) as function of driver demand, speed, fuel temperature	Disabled control	Disturbed engine operation (performance) and safety hazard (e.g. speed, cylinder pressure, exhaust gas temp. too high)		2	10	2	40	
Fu. 2: Controls engine speed (max. speed, idle speed)	Disabled control	-- " --						
Fu. 3: Limits full load quantity (as function of speed)	Disabled control	-- " --						
Fu. 4: Controls injection timing (as function of temperature, speed, injection duration)	Disabled control	-- " --						
Fu. 5: Controls start quantity	Disabled control	-- " --						

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	I	D	RPN	Comments
4.(C) Fuel control system								
4.1 Solenoid valve V1: (2 position / 3 way valve)								
Fu. 1: Fuel supply shut off (not powered) cl.SE, cl.SD, op.BD	op.SE, cl.SD, cl.BD	Uncontrolled filling of fuel system	Valve body hangs in open SB position (mechanically)	2	6	8	96	
			Valve powered (e.g. short cut to ground)					
	op.SE, op.SD, op.BD	Short circuit storage to purge tank and uncontroled filling of fuel system	Valve body hangs between seats	6	10	8	480	Filter in supply line ! Take care on seals at valve body !
			Leakage					
	cl.SE, cl.SD, cl.BD	Filling and purging of system is disabled	Blocked by particles	2	7	2	28	
Fu. 2: Fuel supply switched on (valve powered) op.SE, cl.SD, cl.BD	cl.SE, cl.SD, op.BD	No fuel supply	Valve not powered (electrical failures)	5	7	2	70	
			Valve body mechanically blocked					
	op.SE, op.SD, op.BD	see Fu. 1					s.a.	
	cl.SE, cl.SD, cl.BD	see Fu. 1					s.a.	
4.2 pr2 (mechanical pressure valve)								
Fu. 1: Enables fuel circulation (from c_p) into rail, supply of cool fuel to injectors - open SB	Closed SB	Uncontrolled built up of residual line pressure - if NOP is reached -> fuel injection !	Valve body hangs in closed SB position (mechanically)	2	10	8	160	Safety valve for circulation pump (max pressure limitation) !
Fu. 2: Controlls residual pressure in control line and injectors -> pressure difference between SB controlled by spring	Pressure difference between SB lower than specified	Residual pressure in injectors too low, partial evaporation of fuel, reduced engine power output	Valve body hangs in open SB position (mechanically)	7	5	8	280	
			Broken spring					
	Pressure difference between SB higher than specified	No effect	Valve body hangs at position with too small flowarea (mechanically)					
			Pieces and particles reduce flowarea					
			Leakage					

AVL CR (C) ; Fuel Control

System/item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	I	D	RPN	Comments
4.4 fuel system control unit								
Fu. 1:Key off>on (change state from "park" to "ready for start")	Does not change state	V1 not switched ON	Failures in hardware + software of fuel CU, disconnection of component (cable, connector)					No numbers were specified because system components (e.g. V1) individually assessed !
		Fuel supply pump not switched ON	--- " ---					
		Circulation pump not switched ON	--- " ---					
		Rail pressure CU not switched ON	--- " ---					
		Purge press. CU not switched ON	--- " ---					
		Engine CU not switched ON	--- " ---					
Fu. 2:Key off>on (change state from "pending for shutdown" to "ready for start")	Does not change state	Fuel supply pump not switched ON	--- " ---					
		Circulation pump not switched ON	--- " ---					
		Rail pressure CU not switched ON	--- " ---					
		Purge press. CU not switched ON	--- " ---					
		Engine CU not switched ON	--- " ---					
Fu. 3:Key on>off (change state from "ready for start" to "park")	Does not change state	Fuel supply pump not switch. OFF						
		Circulation pump not switch OFF	--- " ---					
		Rail pressure CU not switch OFF	--- " ---					
		Purge press. CU not switch OFF	--- " ---					
		Engine CU not switched OFF	--- " ---					
Fu. 4:Pending time exceeded (change state from "pending for shutdown" to "park")	Does not change state	V1 not switched OFF	--- " ---					
Fu. 5:Key on>start (change state from "ready for start" to "crank engine")	Does not change state	Starter motor not switched ON	--- " ---					
Fu. 6:Key start>on & engine not operating (change state from "crank engine" to "ready for start")	Does not change state	Starter motor not switched OFF	--- " ---					
Fu. 7:Key start>on & engine operating (change state from "crank engine" to "engine operation")	Does not change state	Starter motor not switched OFF	--- " ---					
Fu. 8:Key on>off & engine operating (change state from "engine operation" to "pending for shutdown")	Does not change state	Fuel supply pump not switch. OFF	--- " ---					
		Circulation pump not switch OFF	--- " ---					
		Rail pressure CU not switch OFF	--- " ---					
		Purge press. CU not switch OFF	--- " ---					
		Engine CU not switched OFF	C. cntrl V1 S --- " ---					

AVL CR(C) ; Aux. Components

System/item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	I	D	RPN	Comments
5.(C) Auxiliary Components								
5.1 hp_p (high pressure pump)								
Fu.1: Builds up rail pressure	Not capable to build up rail pressure	Reduced power output	Failures in hydraulic part of pump (valves, plungers, sealings, etc.)	6	7	3	126	New technology !
		If pressure below a certain limit (approx.NOP) engine cannot be operated	Mechanical failures in pump drive					
5.2 c_p (circulation pump)								
Fu. 1: Produces residual pressure in injectors	Not able to produce the desired residual pressure	Residual pressure in injectors too low, partial evaporation of fuel, reduced engine power output	Failures in hydraulic part of pump (valves, plungers, sealings, etc.)	6	5	5	150	New technology !
			Mechanical or electrical failures in pump drive					
Fu. 2: Enables fuel circulation in rail for cooling purpose	No (or too low) fuel circulation	Uncontrolled heating of fuel, partial evaporation of fuel, unstable fuel injection, reduced power output	Failures in hydraulic part of pump (valves, plungers, sealings, etc.)	6	5	5	150	
			Mechanical or electrical failures in pump drive					

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	Evaluation I	Evaluation D	Evaluation RPN	Comments
5.3 Purge tank pressure control system								
5.3.1 Compressor								
Fu.1: Delivers DME from purge tank into storage tank	Does not deliver DME from purge tank into storage tank	Pressure in purge tank increases, reaches saturation pressure, condenses, tank filled with liquid DME	Mechanical failures in compresso or compressor drive	2	10	10	200	
			Failures in power supply to compressor (electric, pneumatic...)					
5.3.2 Pressure sensor for purge tank pressure control system								
Fu.1: Detects pressure in purge tank and transmits signal to pressure control unit if a maximum or a minimum value i reached	Does not detect maximum pressure	Compressor is not actuated, see 5.3.1. Fu.1	Pressure sensor damaged (mechanically)	2	10	10	200	
			Wrong calibration					
			Signal (electric or pneumatic) not transmitted to pressure control unit (broken cable or hose, loos contact etc.)					
	Does not detect minimum pressure	Compressor is continuously working and evacuates purge tank	Pressure sensor damaged (mechanically)					
			Wrong calibration					
			Signal (electric or pneumatic) not transmitted to pressure control unit (broken cable or hose, loos contact etc.)					
5.3.3 Purge tank pressure control unit								
Fu.1: Receives signal for maximum purge tank pressure and actuates compressor	Misinterpretation of signal	Compressor is not actuated, see 5.3.1. Fu.1	Mechanical, electrical, pneumatical failure in controller	2	10	10	200	
	Does not actuate compressor		Failure in signal transmission to compressor power supply (electronic, pneumatic)					
Fu.2: Receives signal for minimum purge tank pressure and stops compressor	Misinterpretation of signal	Compressor is continuously working and evacuates purge tank	Mechanical, electrical, pneumatical failure in controller					
	Does not stop compressor		Failure in signal transmission to compressor power supply (electronic, pneumatic)					