AN INVERSE JET ENGINE MODEL FOR PERFORMANCE PREDICTION AND FAULT DIAGNOSIS IN TRANSIENT OPERATION

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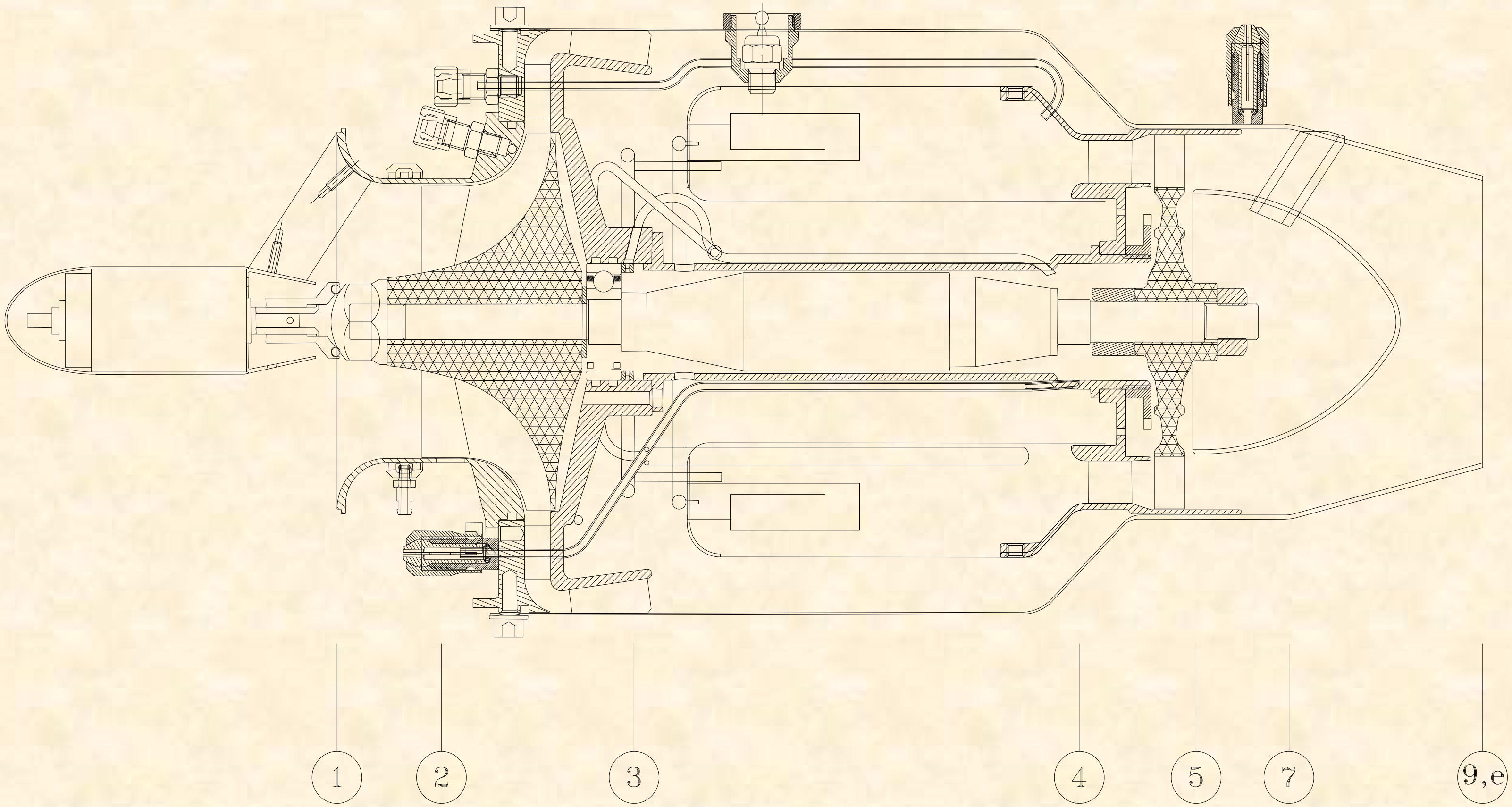
Objectives:

Development of the Inverse Engine Model for

1. Evaluation of the engine maps when not all the effective (realistic) map components are known
2. Transducer or/and engine component map fault detection
3. Real time simulations and control

Single Spool Engine Stations

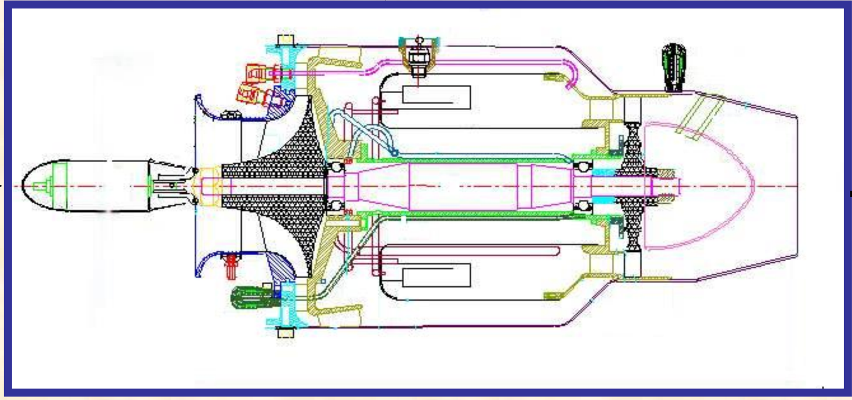


Drawing refers to the AMT Netherlands B.V. Olympus Design.

Typical Closed Loop Engine Control System

H, M

Command: $N_{cor,ref}(t)$



Measured values

Typical measured values : $\dot{m}_f, N, T_{05}, H, M, (T_{03}, P_{03})$

Conventional Dynamic Engine Model

$H, M, \dot{m}_f(t)$

Initial Condition: $N_{t=0}$

Conventional Engine Model

(Using Compressor + Turbine + Nozzle Maps)

$N(t), \dot{m}_a(t)$

$T_{02}(t) \ldots T_{07}(t)$

$P_{02}(t) \ldots P_{07}(t)$

η_C, η_t

$SM(t), \varphi(t)$

Inverse Engine Model

Input Values.

VAL_{in} =

input value number

Input Engine Component Maps.

MAP_{in} =

input map Eqs. number

Inverse Engine Model.

Thermodynamic equations

(**THERM** - thermodynamic equation number).

Output Values.

VAL_{out} =

output value number

Output Engine Component Maps.

MAP_{out} =

input map Eqs. number

To become an inverse engine model the following Complete Inverse Model Conditions must be fulfilled:

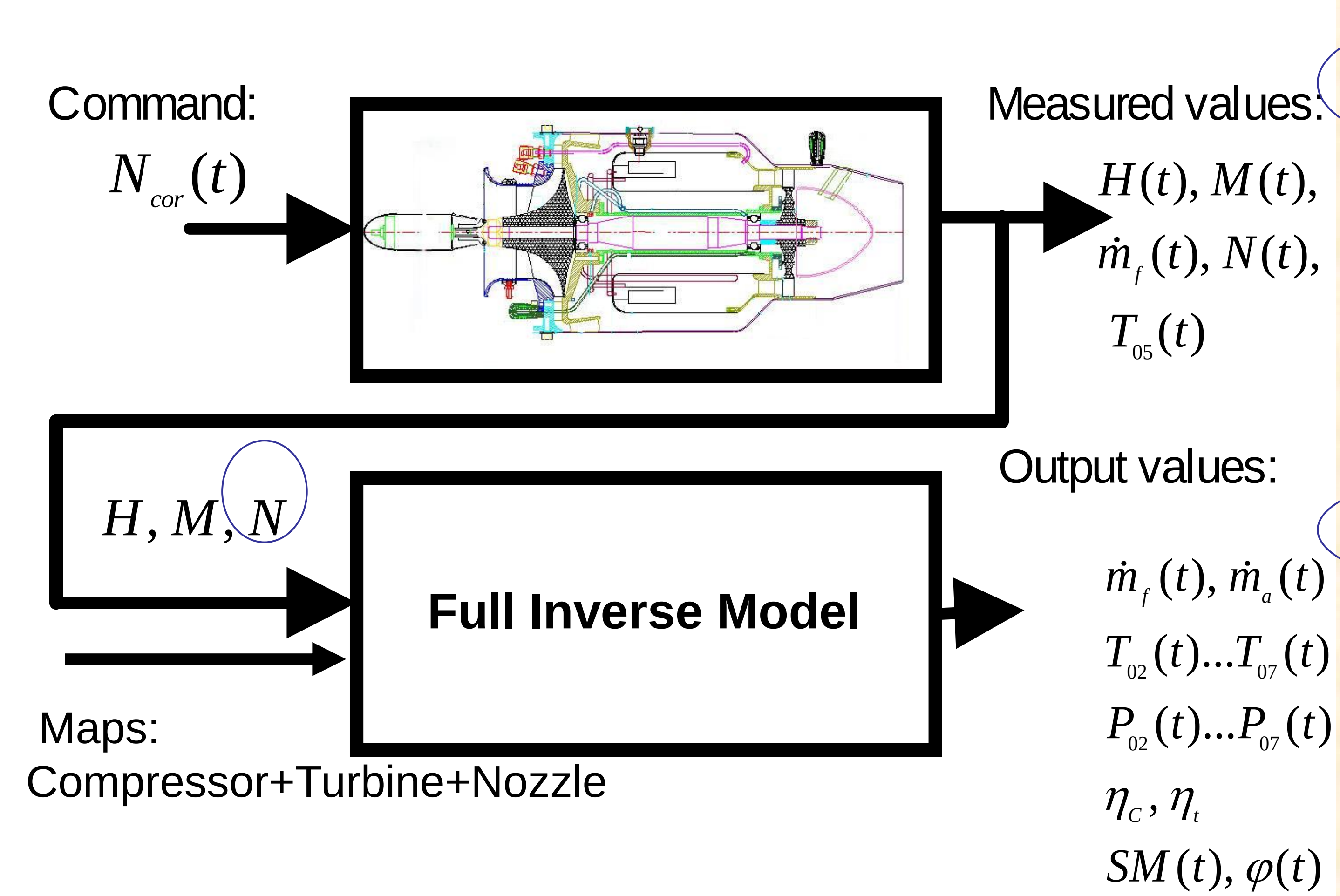
$$MAP_{in} + MAP_{out} = MAP_{total,conv.} \quad (1)$$

$$VAL_{in} + VAL_{out} = VAL_{total,conv.} \quad (2)$$

$$MAP_{in} + THERM = VAL_{out} \quad (3)$$

$$VAL_{in} \leq VAL_{meas} \quad (4)$$

Full Inverse Engine Model



$\mathrm{MAP_{in}} = 5$

$\mathrm{MAP_{out}} = 0$

$\mathrm{THERM} = 57$

$\mathrm{Eqs_{total,conv.}} = 62$

$\mathrm{VAL_{in}} = 3$

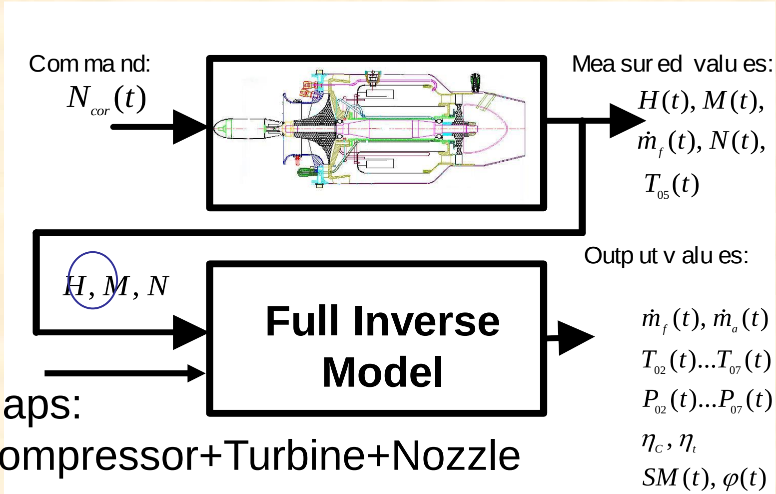
$\mathrm{VAL_{out}} = 62$

$\mathrm{VAL_{total,conv.}} = 65$

$\mathrm{VAL_{meas}} = 5$

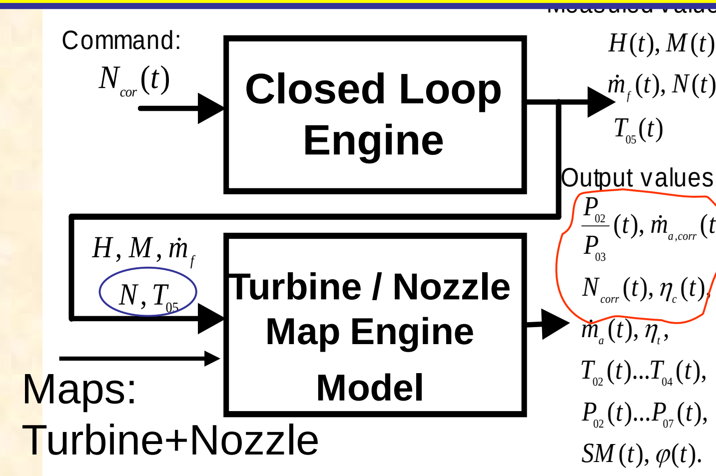
$$\mathrm{MAP_{in}} + \mathrm{THERM} = \mathrm{VAL_{out}} \Rightarrow 5 + 57 = 62$$

Full Inverse Engine Model



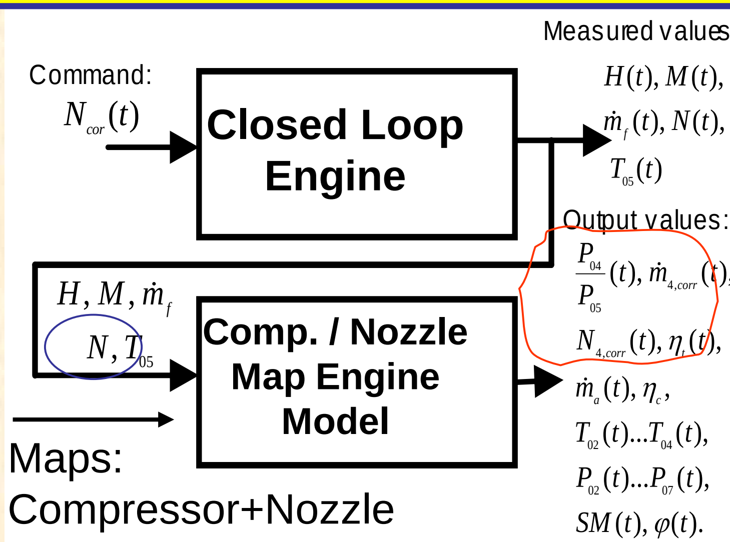
$$\mathrm{MAP_{in}} + \mathrm{THERM} = \mathrm{VAL_{out}} \Rightarrow 5 + 57 = 62$$

Turbine/Nozzle Map Engine Model (without Compressor Map)



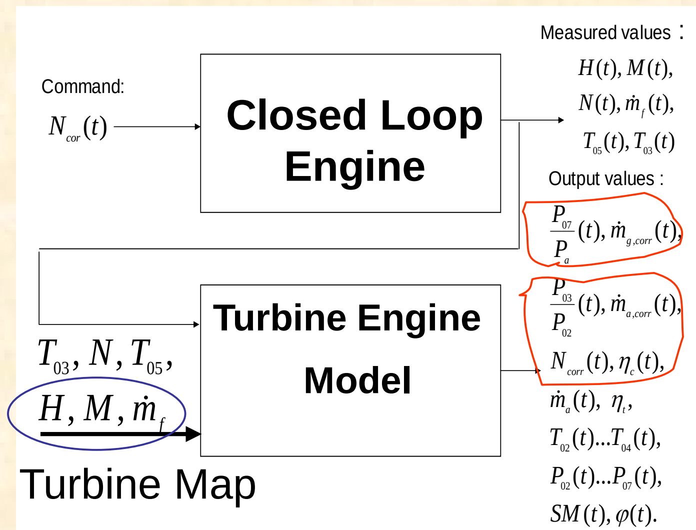
$$\mathrm{MAP_{in}} + \mathrm{THERM} = \mathrm{VAL_{out}} \Rightarrow 3 + 57 = 60$$

Compressor/Nozzle Map Engine Model (without Turbine Map)



$$\mathrm{MAP_{in}} + \mathrm{THERM} = \mathrm{VAL_{out}} \Rightarrow 3 + 57 = 60$$

Turbine Map Engine Model (without Compressor/Nozzle Maps)



$$\mathrm{MAP_{in}} + \mathrm{THERM} = \mathrm{VAL_{out}} \Rightarrow 2 + 57 = 59$$

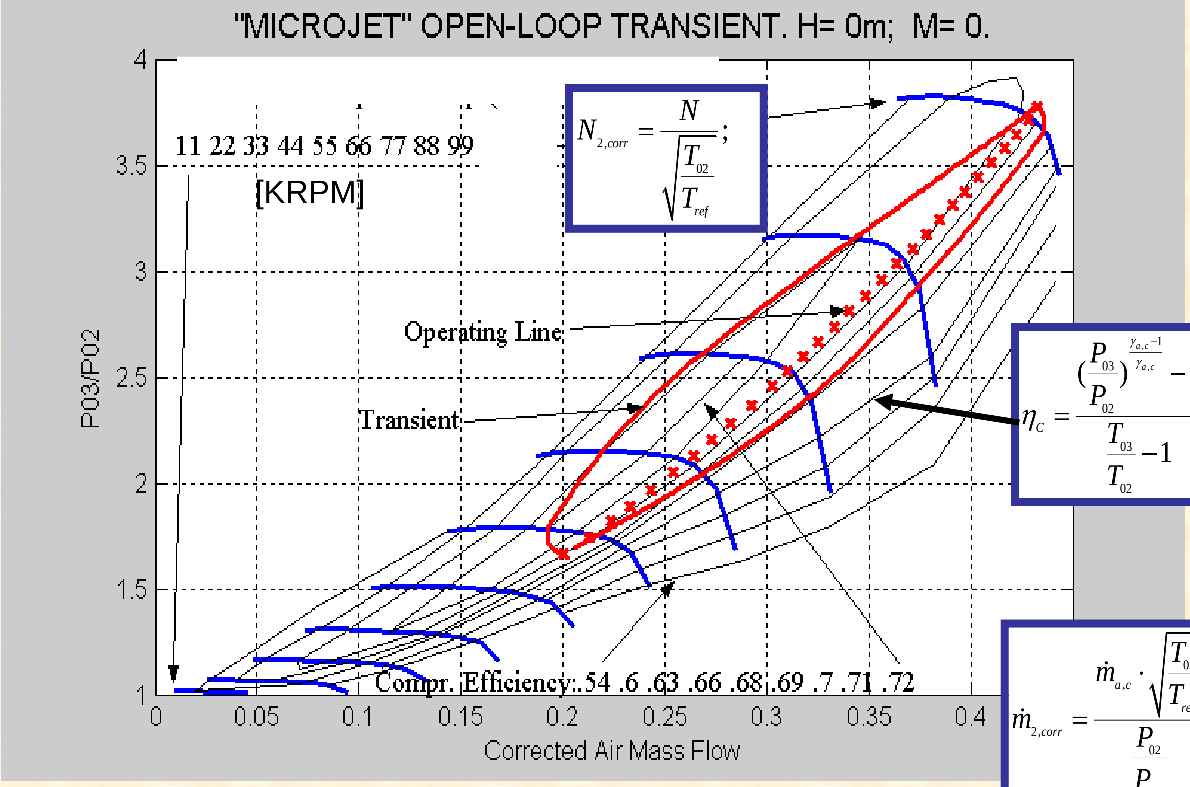
USAGE OF INVERSE ENGINE MODEL

a) Evaluation of effective engine component maps

b) Diagnosis of jet engine component and transducer faults

c) Real-time simulations and control

a) Evaluation of Compressor and Nozzle Maps Using Turbine Map Model (Model without Compressor/Nozzle Maps)



$$N_{2,corr} = \frac{N}{\sqrt{\frac{T_{02}}{T_{ref}}}};$$

$$\eta_C = \frac{\left(\frac{P_{03}}{P_{02}}\right)^{\frac{\gamma_{a,c}-1}{\gamma_{a,c}}} - 1}{\frac{T_{03}}{T_{02}} - 1}$$

$$\dot{m}_{2,corr} = \frac{\dot{m}_{a,c} \cdot \sqrt{\frac{T_{02}}{T_{ref}}}}{\frac{P_{02}}{P_{ref}}};$$

$$N, \dot{m}_{a,c}, T_{02}, T_{03}, P_{02}, P_{03}, \gamma_{a,c}(\bar{T}_{2,3})$$

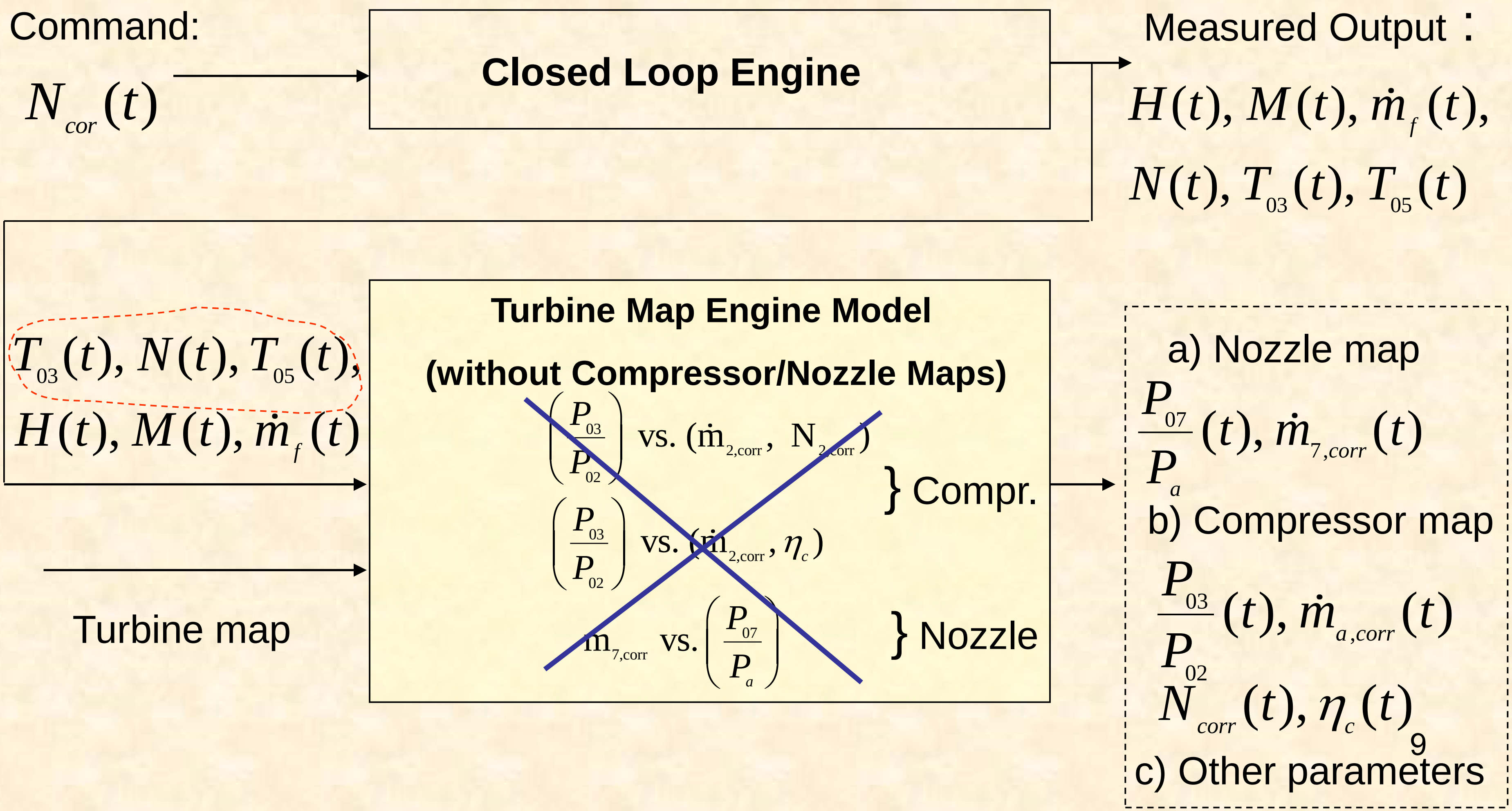
Nozzle map:

$$\dot{m}_{7,corr} \text{ vs. } \left(\frac{P_{07}}{P_a}\right)$$

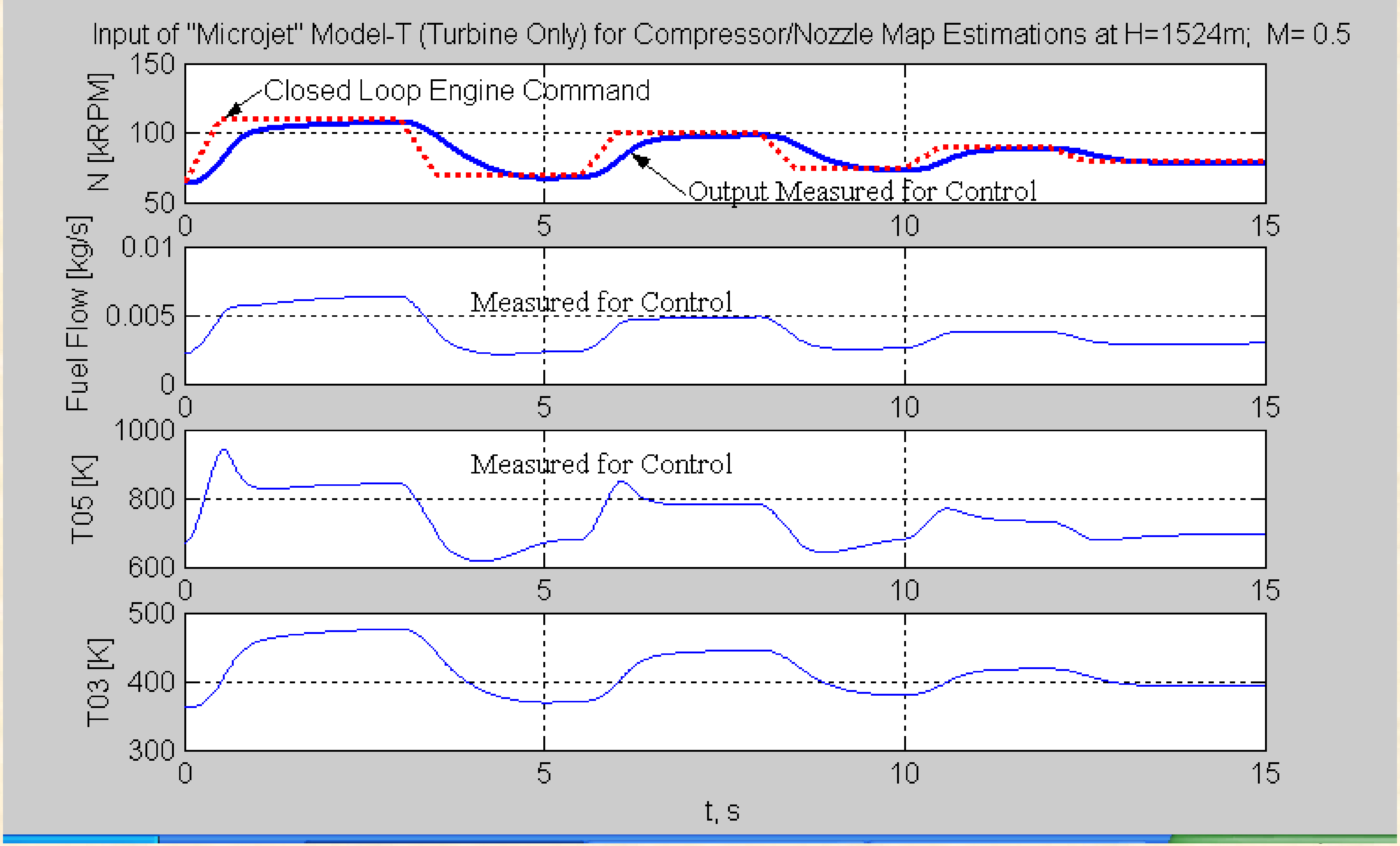
$$\dot{m}_{7,corr} = \frac{\dot{m}_g \cdot \sqrt{T_{07}}}{P_{07}} \Rightarrow$$

$$\dot{m}_g, T_{07}, P_{07}, P_a,$$

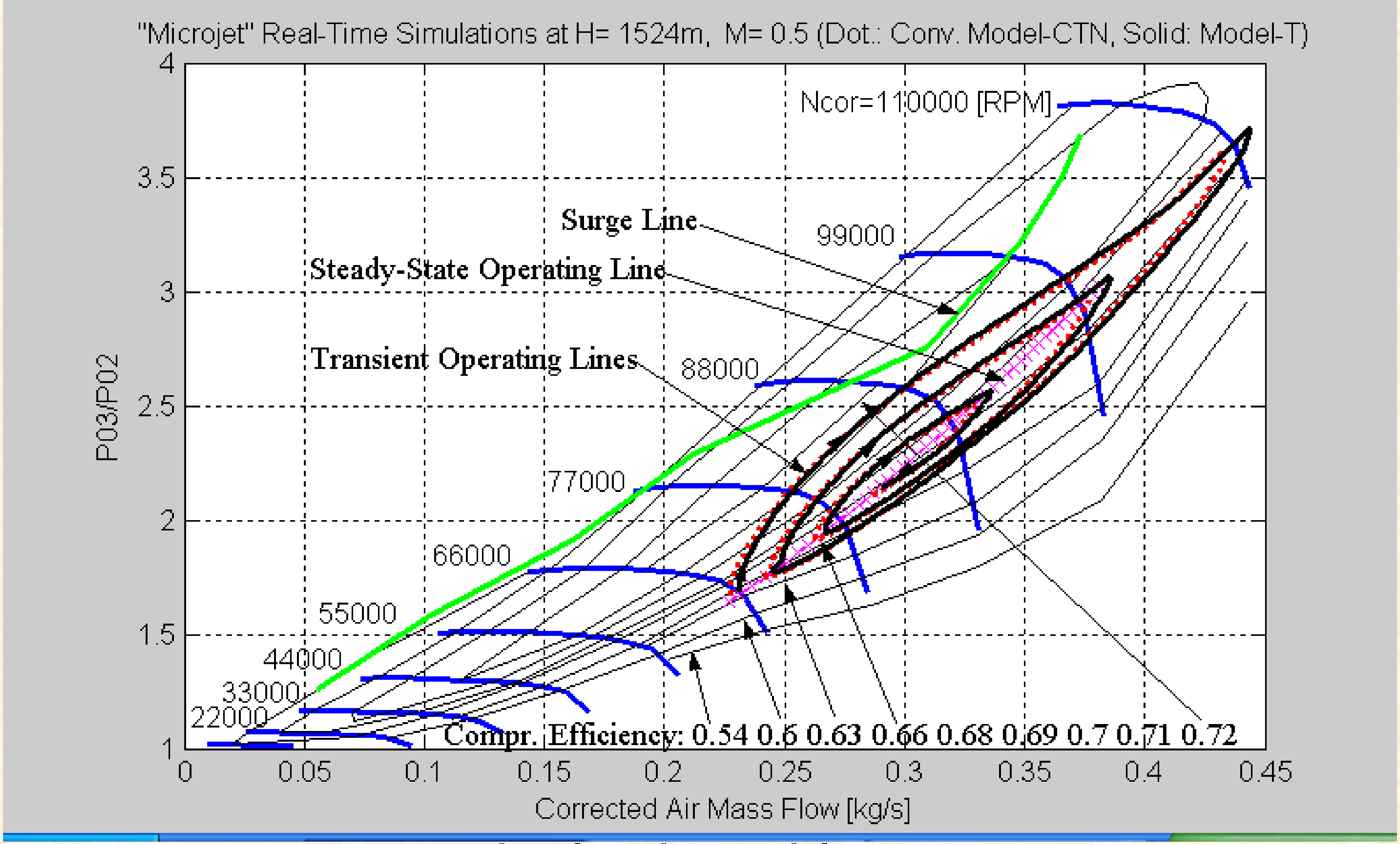
Evaluation of Compressor and Nozzle Maps Using Turbine Map Engine Model (without Compressor/Nozzle Maps)



Evaluation of Compressor and Nozzle Maps Using Turbine Map Model (without Compressor/Nozzle Maps) (Continued)



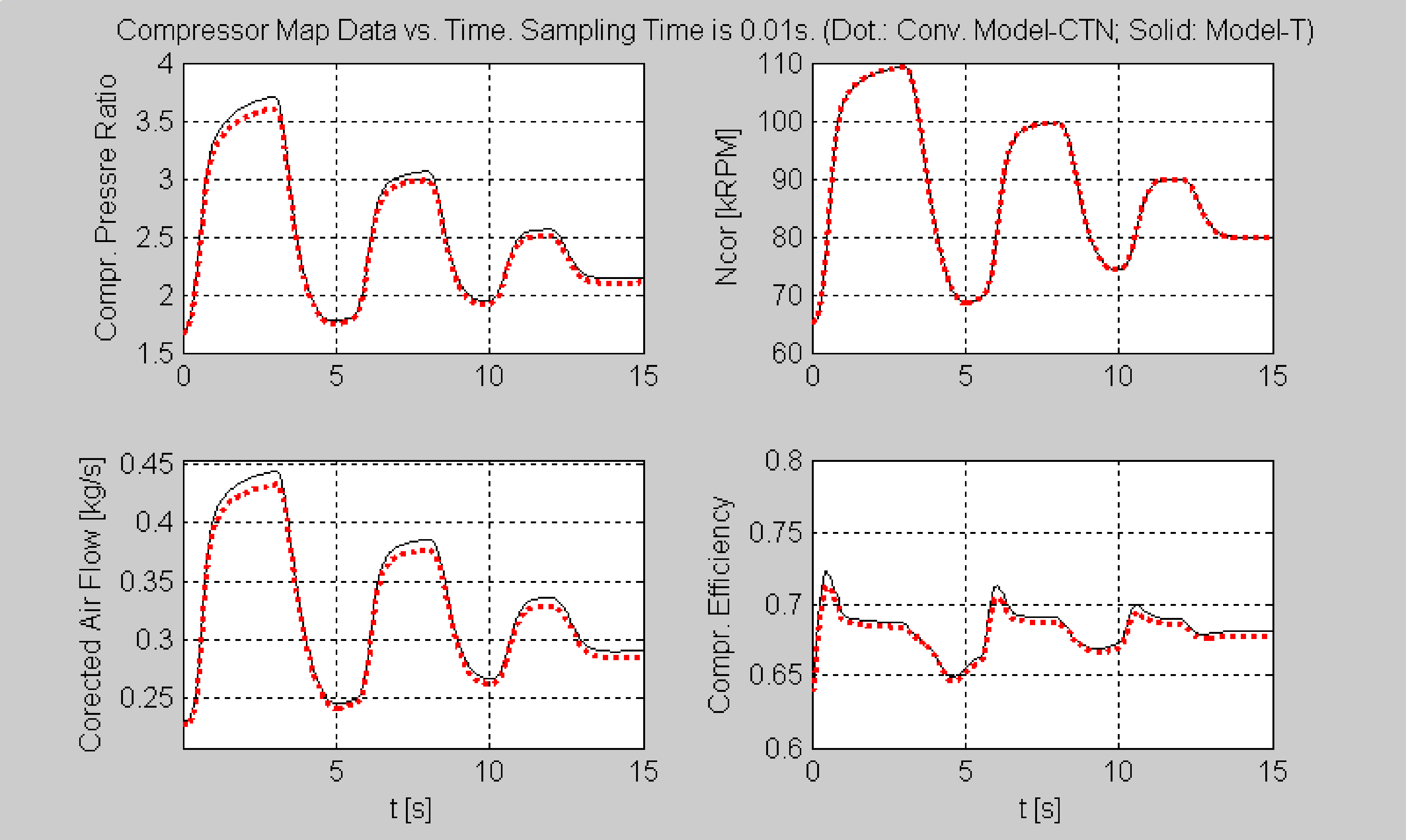
Evaluation of Compressor and Nozzle Maps Using Turbine Map Model (without Compressor/Nozzle Maps) (Continued)



Conventional engine model

Inverse T-Model (without compressor and nozzle maps)

Evaluation of Compressor and Nozzle Maps Using Turbine Map Model (without Compressor/Nozzle Maps) (Continued)



Conventional engine model

Inverse T-Model (without compressor and nozzle maps)

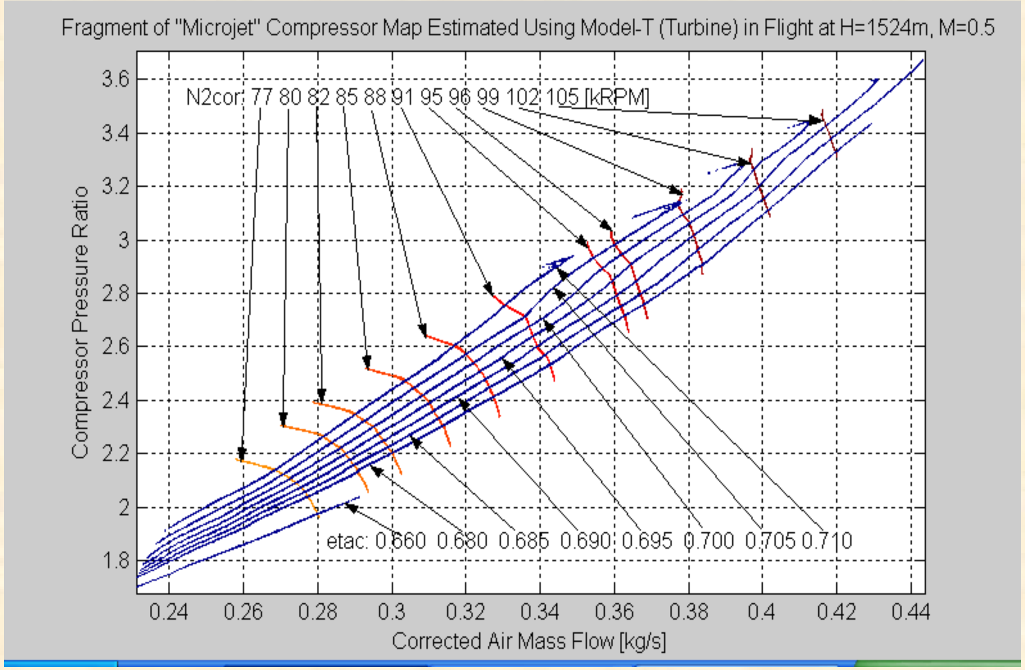
Evaluation of Compressor Map Fragment

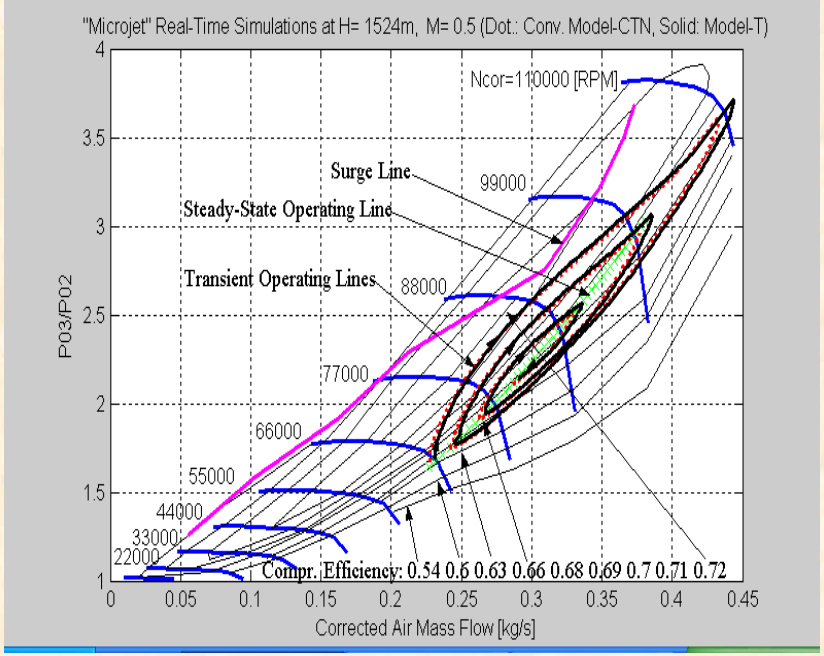
Compressor Map Data Matrix (1500X4):

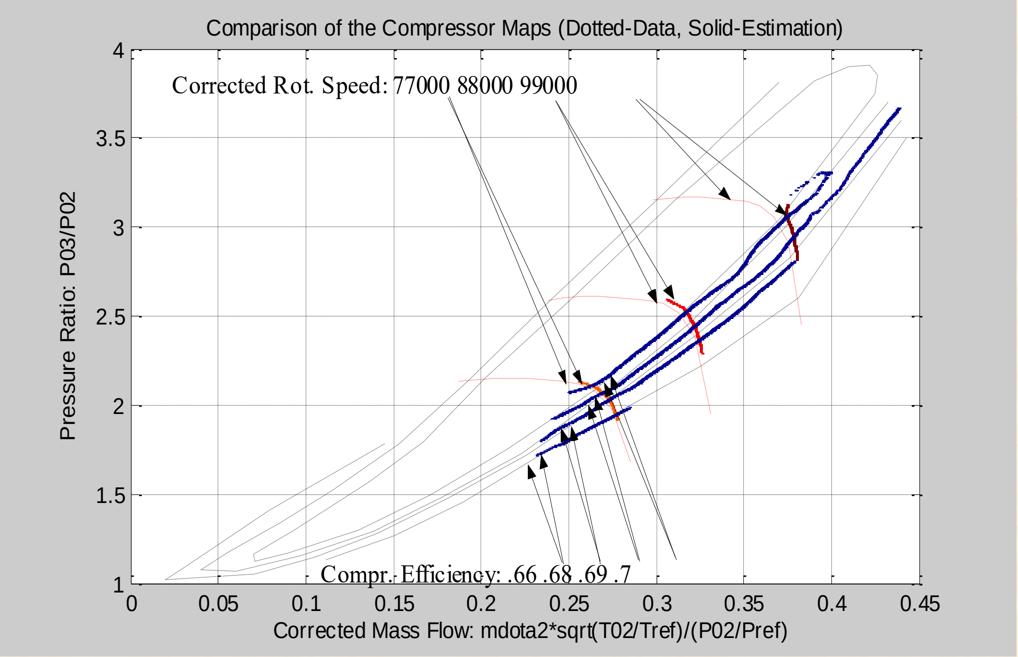
$$\frac{P_{03}}{P_{02}}(t),\ \dot{m}_{a,corr}(t),$$

$$N_{corr}(t),\ \eta_c(t)$$

$\Rightarrow$





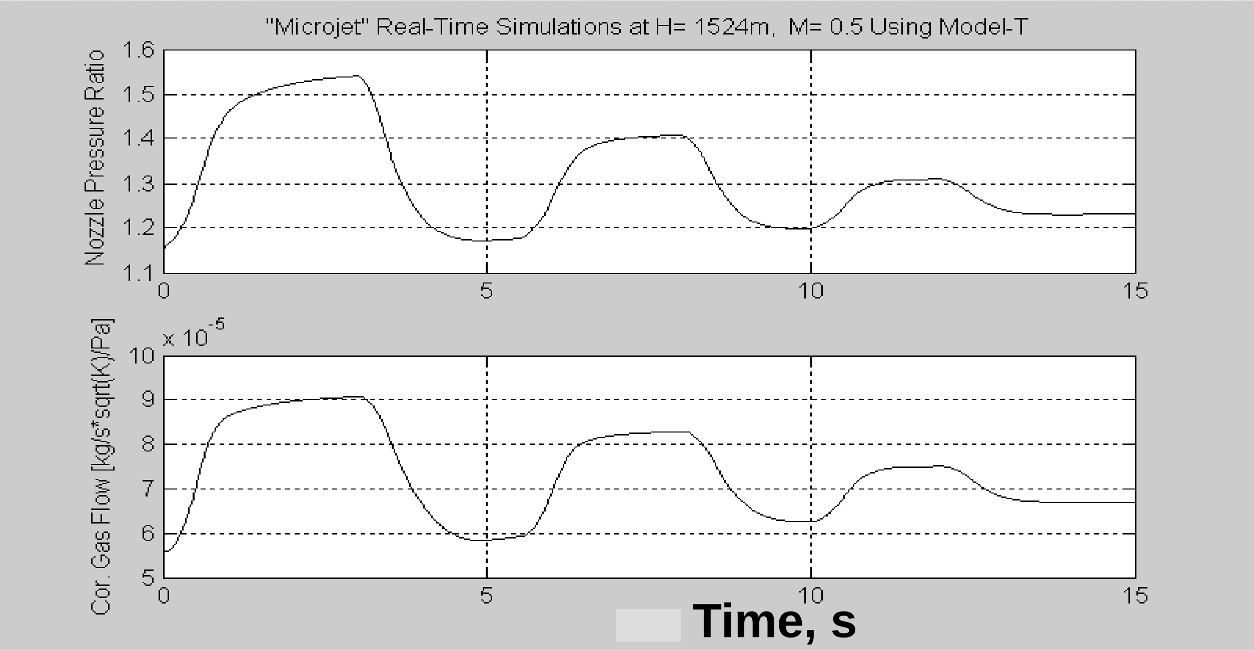


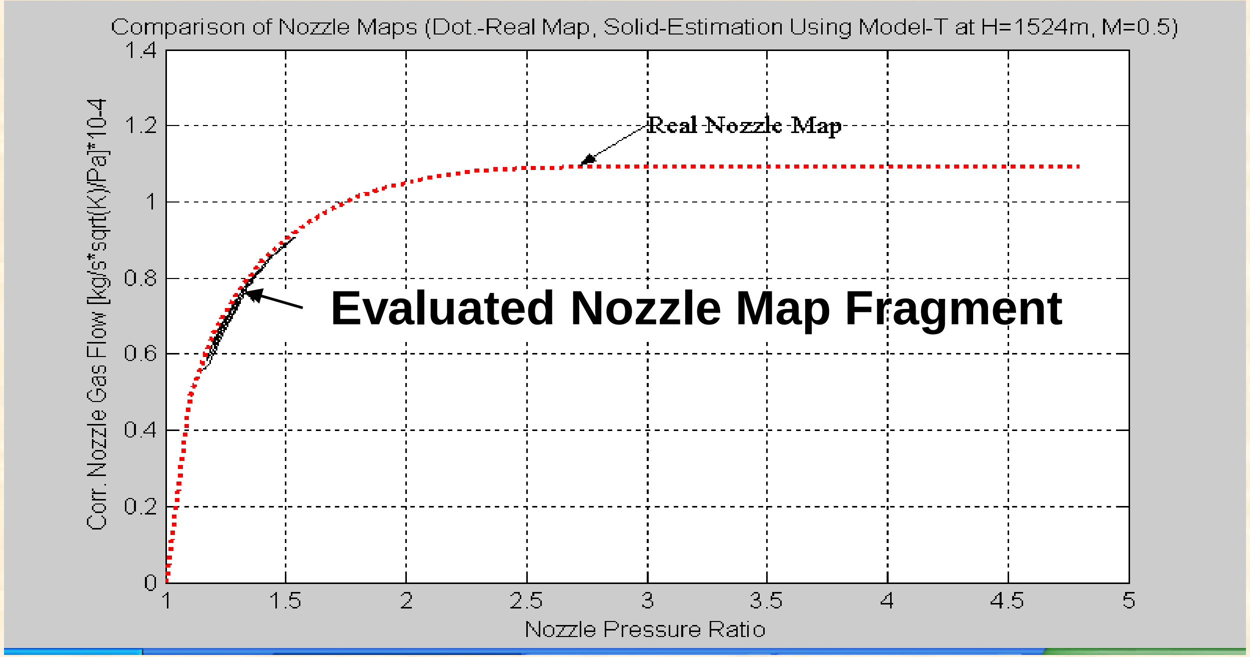
Evaluation of Nozzle Map Fragment

$$\frac{P_{07}}{P_a} \longrightarrow$$

$$\dot{m}_{7,corr} = \frac{\dot{m}_g \cdot \sqrt{T_{07}}}{P_{07}} \rightarrow$$

$$\dot{m}_{7,corr} \text{ vs. } \left(\frac{P_{07}}{P_a}\right)$$





Measurement Error

Results depend on:

- **accuracy of the engine model**
- **algorithm of computer solution**
- **measurement error.**

The thermodynamic model is considered as precise.

A measurement error has two components: random and bias.

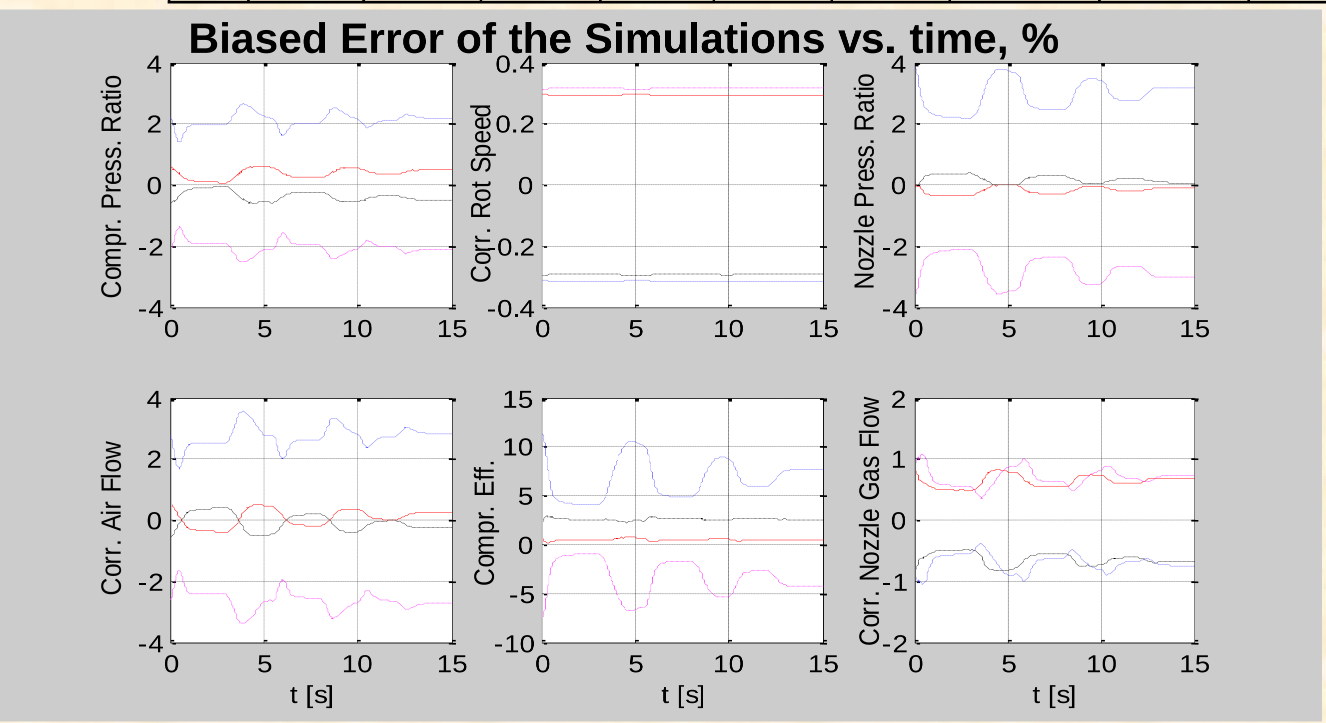
Random errors do not significantly affect the map evaluation result

(can be filtered during interpolation process).

Known biases can be eliminated or corrected, however unknown biases are not correctable.

Measurement Bias

No	Measured bias (constant): $\frac{\Delta X}{X_{max}}\%$						Maximal error of Turbine Map Model output due to the measured bias: $\frac{\Delta Y}{Y_{max}}\%$					
							Compressor map				Nozzle map	
	ΔH	ΔM	$\Delta \dot{m}_f$	ΔN	ΔT_{03}	ΔT_{05}	$\Delta(\frac{P_{03}}{P_{02}})$	$\Delta \dot{m}_{a,corr}$	ΔN_{corr}	$\Delta \eta_C$	$\Delta(\frac{P_{07}}{P_a})$	$\Delta \dot{m}_{g,corr}$
1	0.5	0.5	1	0.3	0.6	0.6	0.5	0.5	0.3	0.5	-0.5	0.75
2	-0.5	-0.5	-1	-0.3	-0.6	-0.6	-0.5	0.5	-0.3	2.5	0.5	-0.75
3	0.5	0.5	1	-0.3	-0.6	-0.6	2.5	3.5	-0.3	10	4	-1
4	-0.5	-0.5	-1	0.3	0.6	0.6	-2.5	-3.5	0.3	-7	3.5	-1



test No.1: Positive input biases

test No.2: Negative input biases

test No.3: Combined sign of input biases

test No.4: Combined sign of input biases

b) Diagnosis of jet engine component and transducer faults

The Problem Formulation:

Consider a single spool jet engine. Assume that seven values X_1 to X_7 are available for diagnostic purposes (for example, $H, M, \dot{m}_f, N, T_{03}, P_{03}, T_{05}$).

A single transducer fault or/and single engine component (compressor or turbine) fault could be present in the engine at any instance.

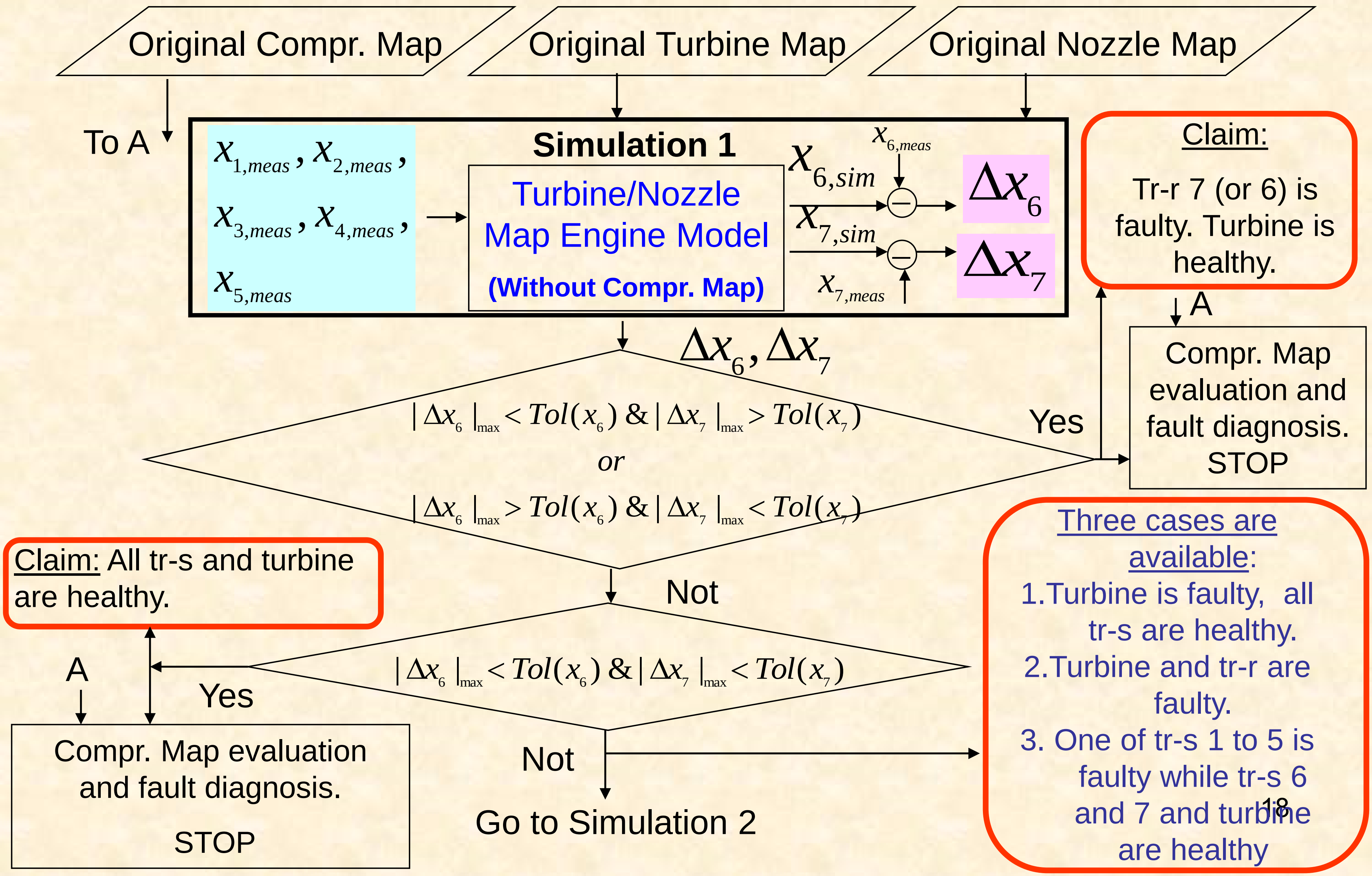
The following 3 cases are possible:

1) One transducer fault (7 combinations).
2) One engine component fault (2 combinations: *compressor or turbine*).
3) Combined single engine component and single transducer fault (14 combinations).

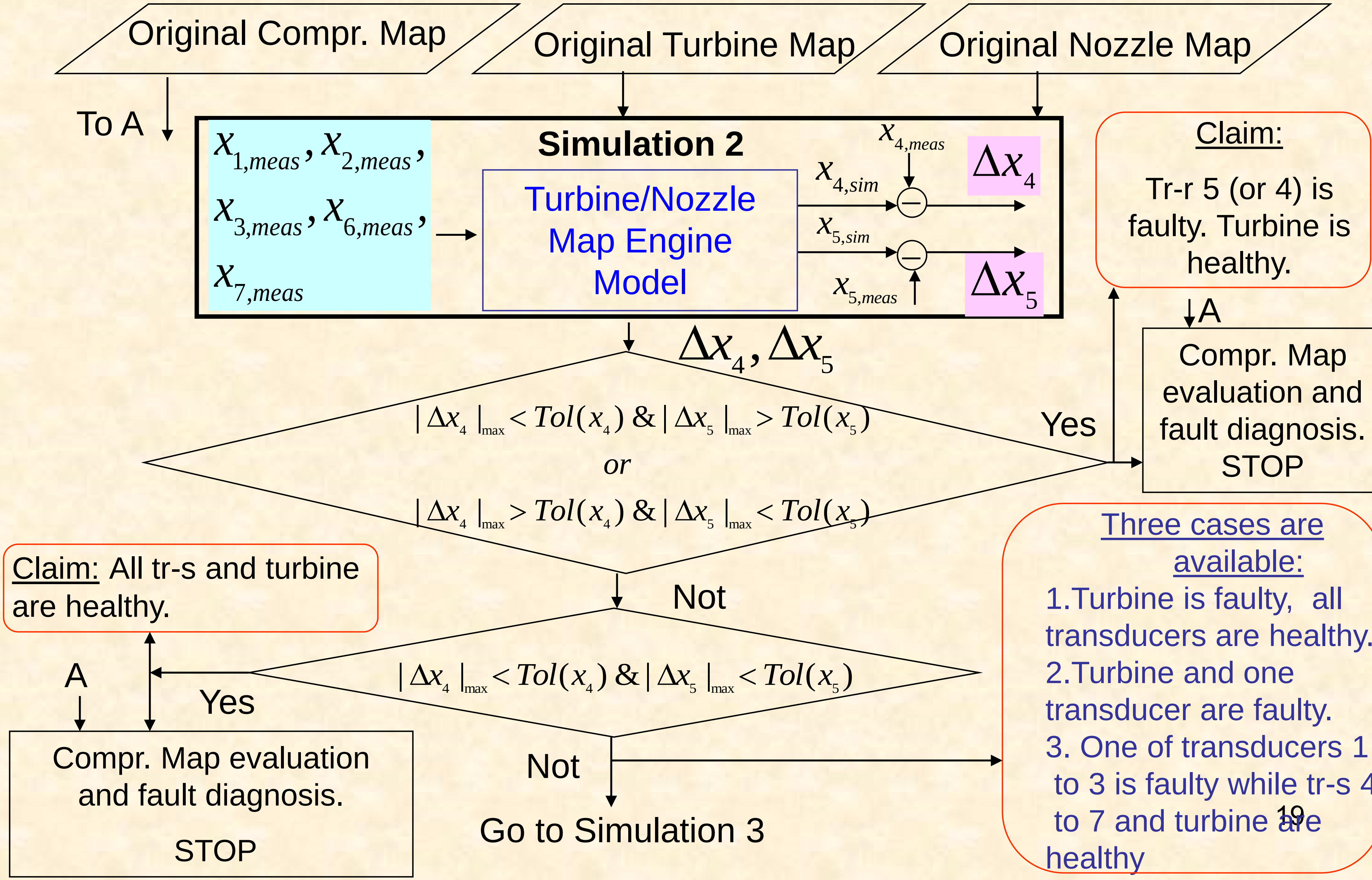
In all: 23 fault combinations.

OBJECTIVE: to isolate the degraded transducer and/or to evaluate the relevant engine component map.

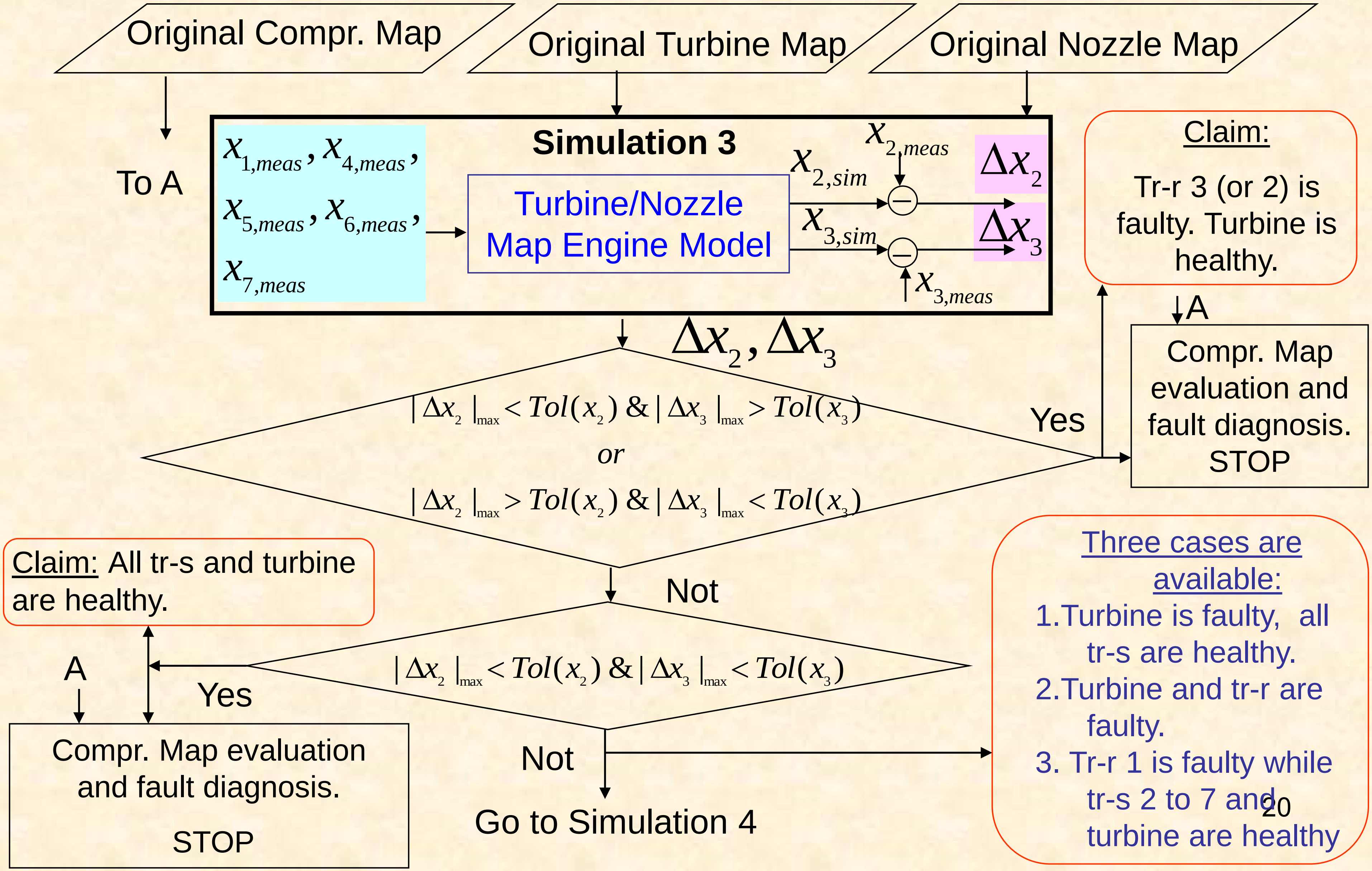
Algorithm of Transducer or/and Engine Component Fault Detection: Step 1 Using Turbine/Nozzle Map Engine Model (Without Compr. Map)



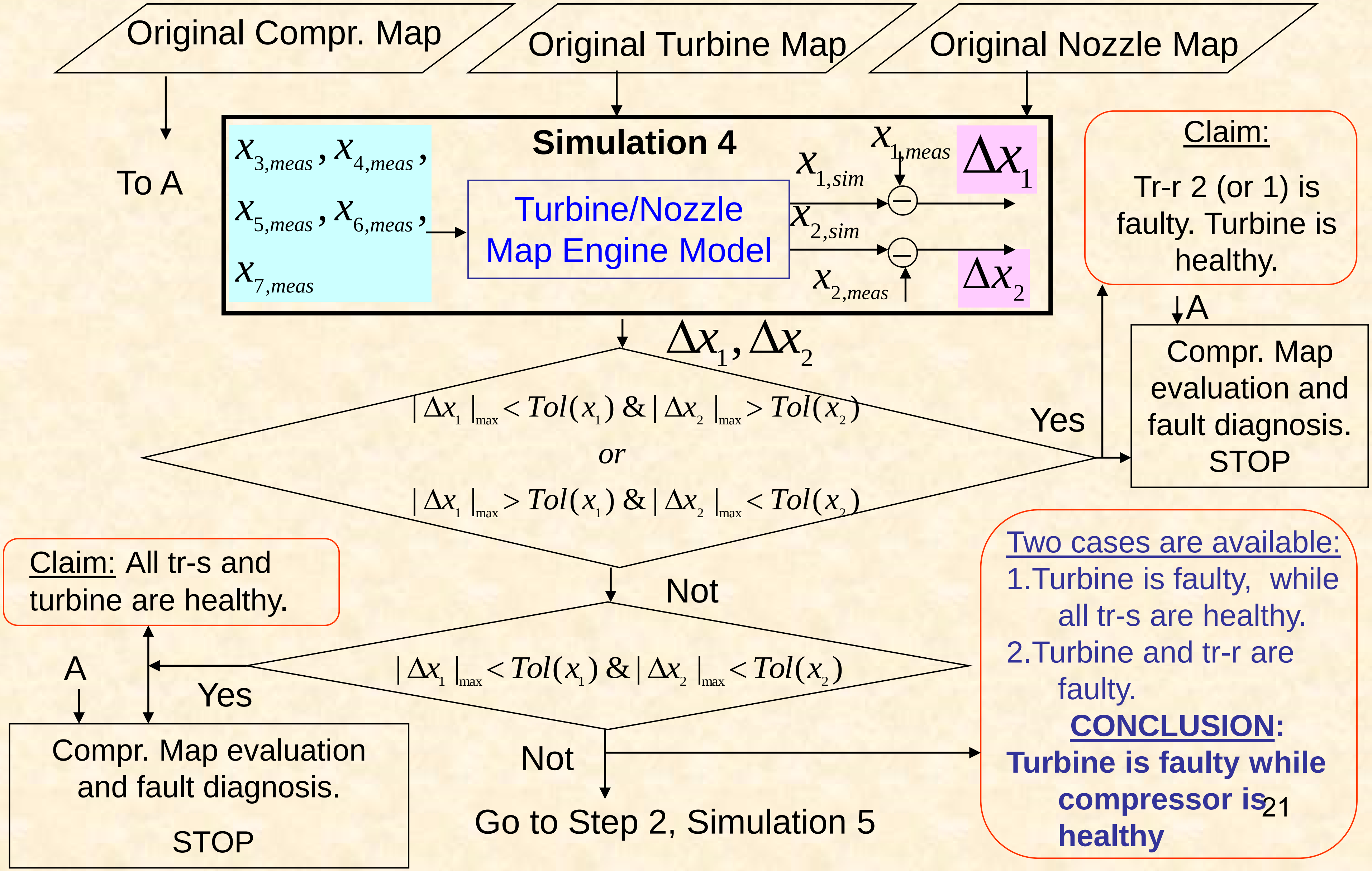
Algorithm of Transducer or/and Engine Component Fault Detection: Step 1 Using Turbine/Nozzle Map Engine Model (Continued)



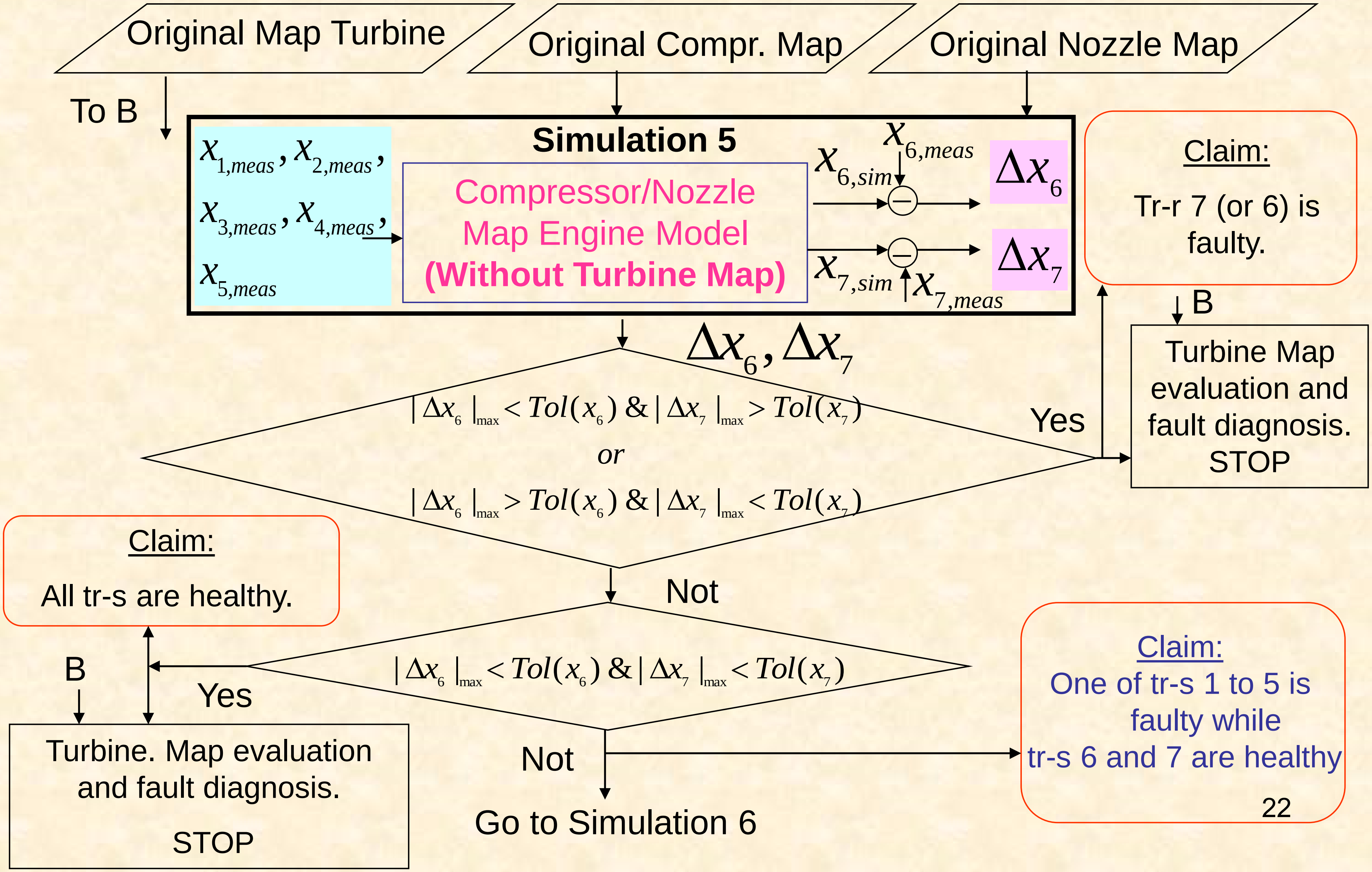
Algorithm of Transducer or/and Engine Component Fault Detection: Step 1 Using Turbine/Nozzle Map Engine Model (Continued)



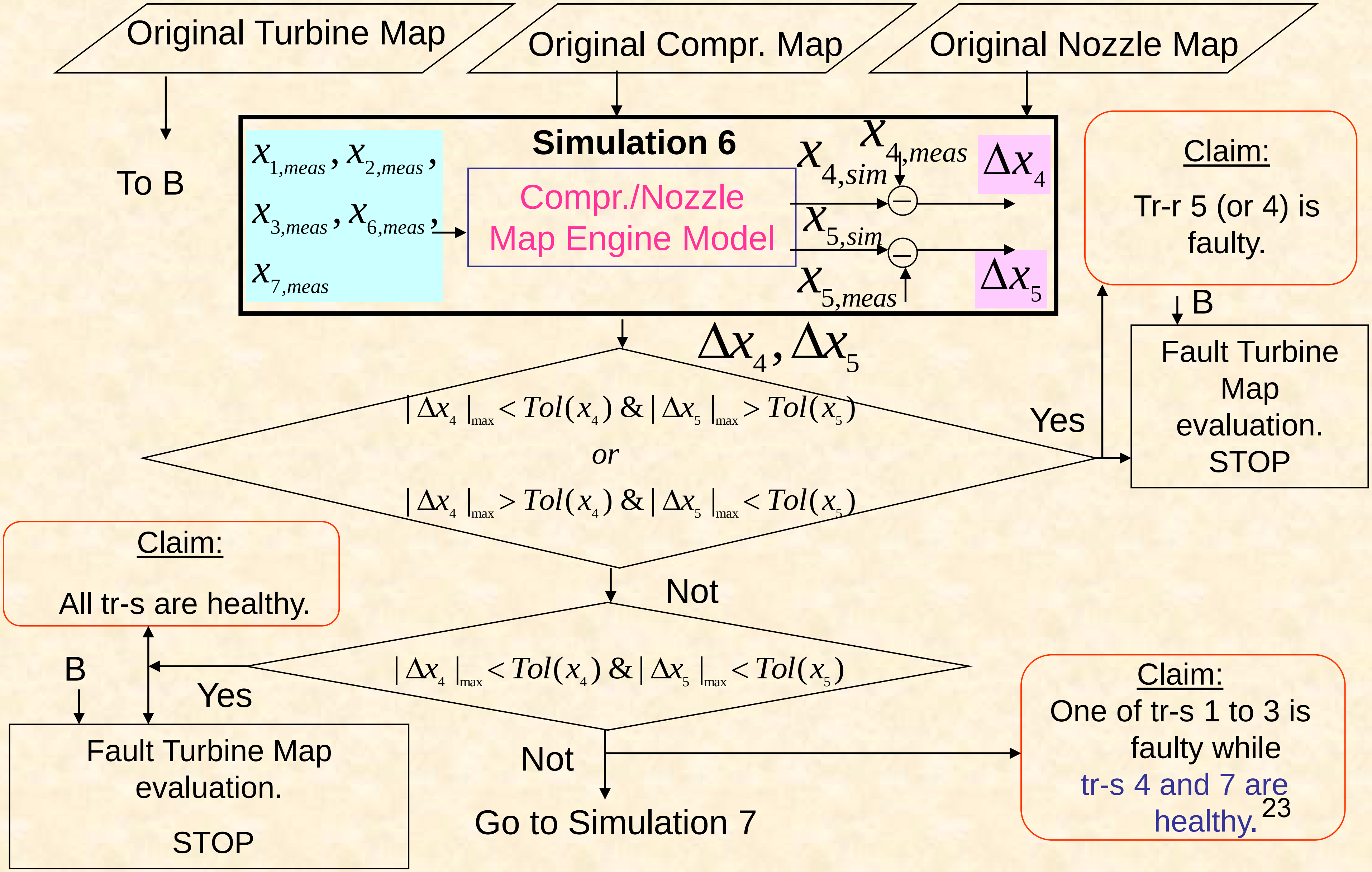
Algorithm of Transducer or/and Engine Component Fault Detection: Step 1 Using Turbine/Nozzle Map Engine Model (Continued)



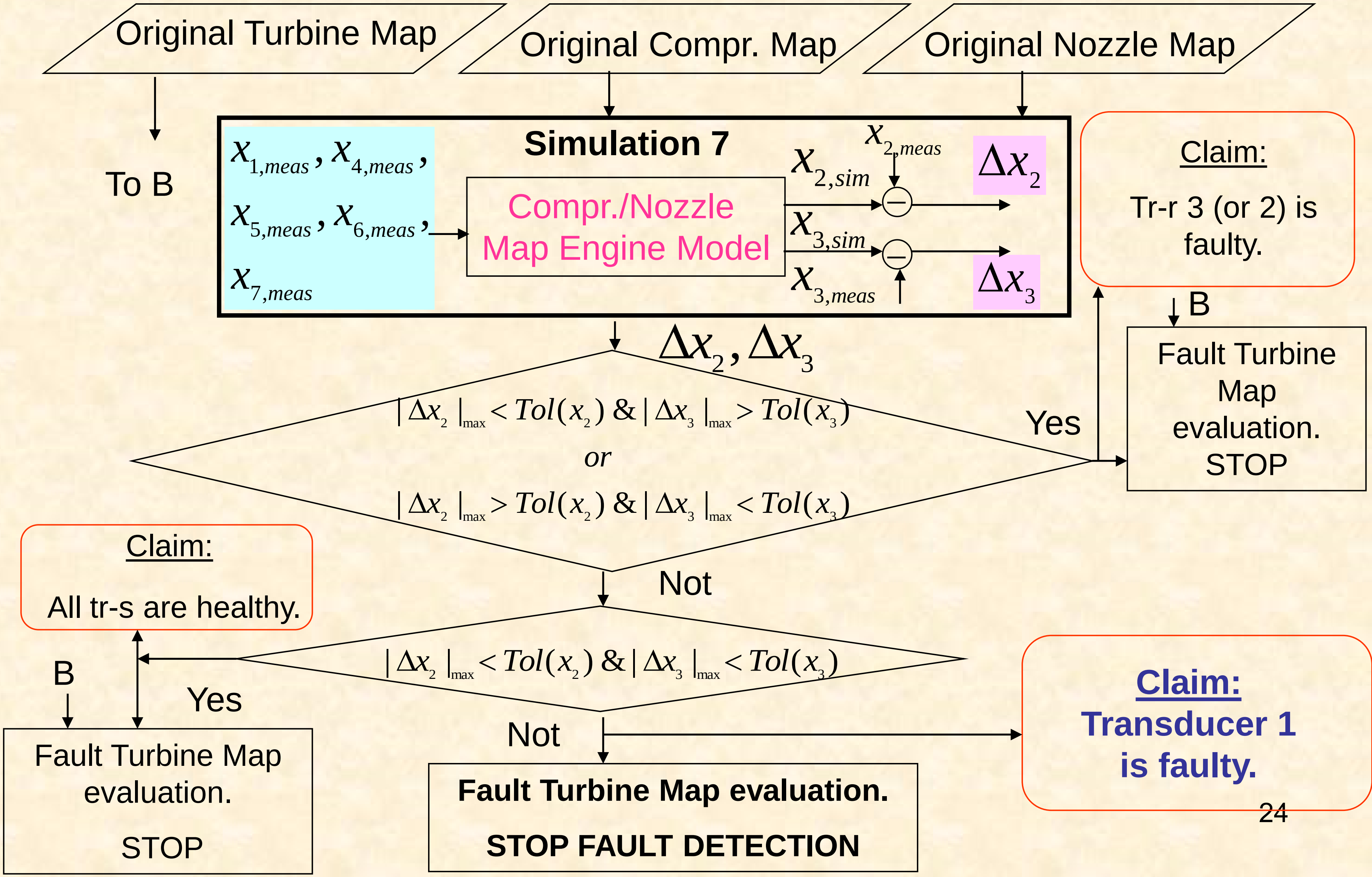
Algorithm of Transducer or/and Engine Component Fault Detection. Step 2: Using Compr./Nozzle Map Engine Model (Without Turbine Map)



Algorithm of Transducer or/and Engine Component Fault Detection: Step 2 Using Compr./Nozzle Map Engine Model (Continued)



Algorithm of Transducer or/and Engine Component Fault Detection: Step 2 Using Compr./Nozzle Map Engine Model (Continued)



Conclusions:

1. Advantages of the inverse engine models:

a) Inverse engine model may be built even when not all the engine component maps are known

b) CPU time decreases significantly in comparison with the conventional model.

2. The inverse engine models may be used for:

a) Evaluation of effective jet engine component maps using data acquisition during transient engine operation

b) Transducer and/or engine component fault diagnosis

c) Real-time simulations and engine control.

3. An universal computer program can be developed for inverse engine model solutions (as Gasturb-9, Dyngen etc.).