Proposal: IAPWS Guideline on the Fast Calculation of Steam and Water Properties With the Spline-Based Table Look-Up Method (SBTL)

Project of the IAPWS Task Group "CFD Steam Property Formulation"

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IAPWS Annual Meeting 2015, June 28 - July 3, Stockholm, Sweden

Development of the new IAPWS-Guideline

Progress:

- **Draft IAPWS Guideline was discussed in Moscow 2014**

  Content:

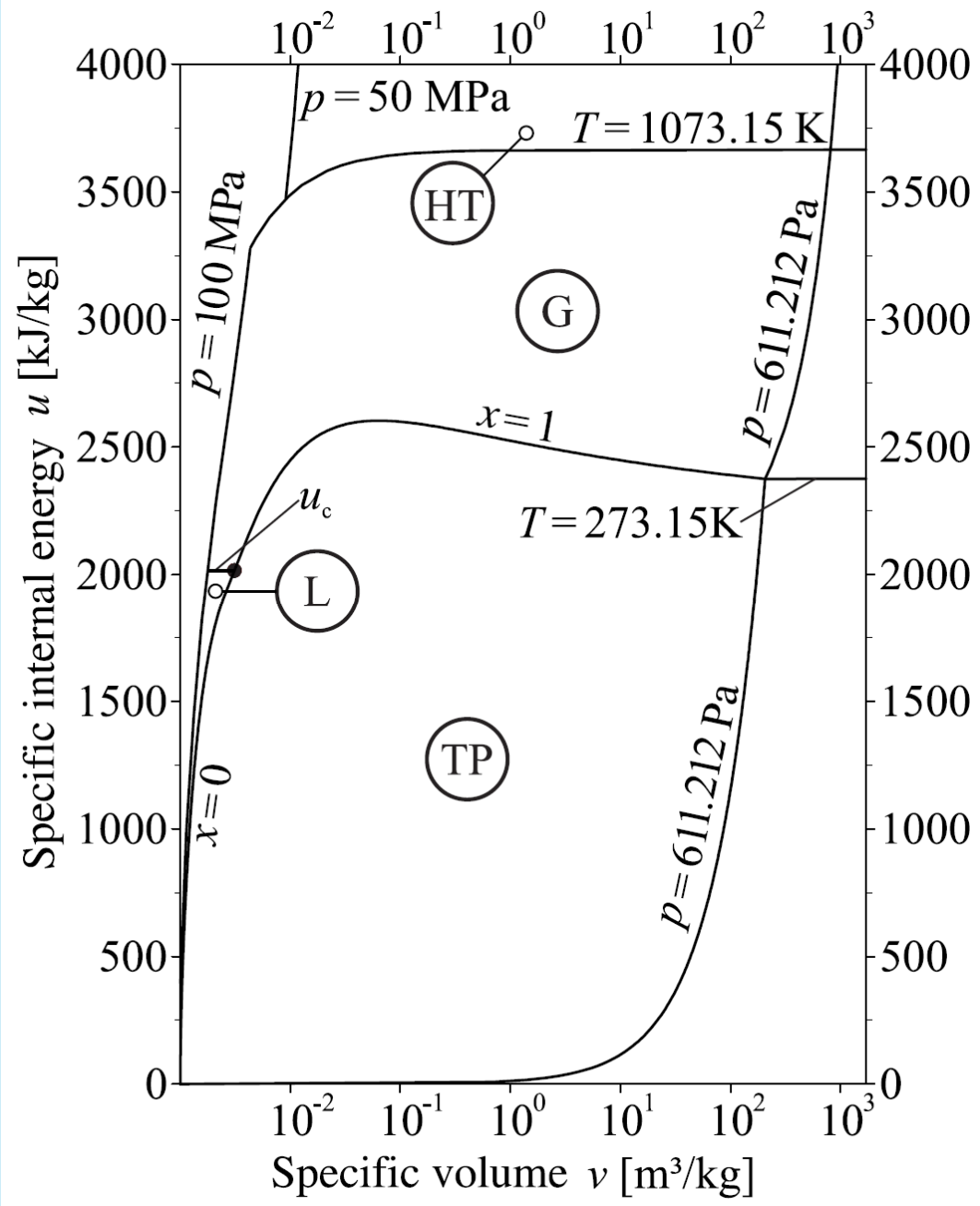
  - **Fundamentals of the SBTL method**
  - **SBTL functions based on IAPWS-IF97:**
    - **(*v*,*u*) spline functions with inverse spline functions of (*p*,*v*) and (*u*,*s*)**
    - **(*p*,*h*) spline functions with inverse spline functions of (*p*,*T*), (*p*,*s*), and (*h*,*s*)**
  - **Deviations from IAPWS-IF97**
  - **Computing time comparisons with IAPWS-IF97**
  - **Application of the SBTL in Computational Fluid Dynamics (CFD)**
  - **Application of the SBTL in heat cycle simulations**

⇨ **Additional content (added after the meeting 2014):**

- **SBTL functions for metastable-vapor region based on IAPWS-IF97**
- **SBTL functions based on IAPWS-95 (*v*,*u*) and (*p*,*h*) for pressures up to 1000 MPa and temperatures up to 1273 K**

Spline Functions of (*v*,*u*) and Inverse Functions Based on IAPWS-IF97

Range of validity:



Regions:

L – liquid region

G – gas region

273.15 K ≤ *T* ≤ 1073.15 K

0.611212 kPa ≤ *p* ≤ 100 MPa

HT – high-temperature region

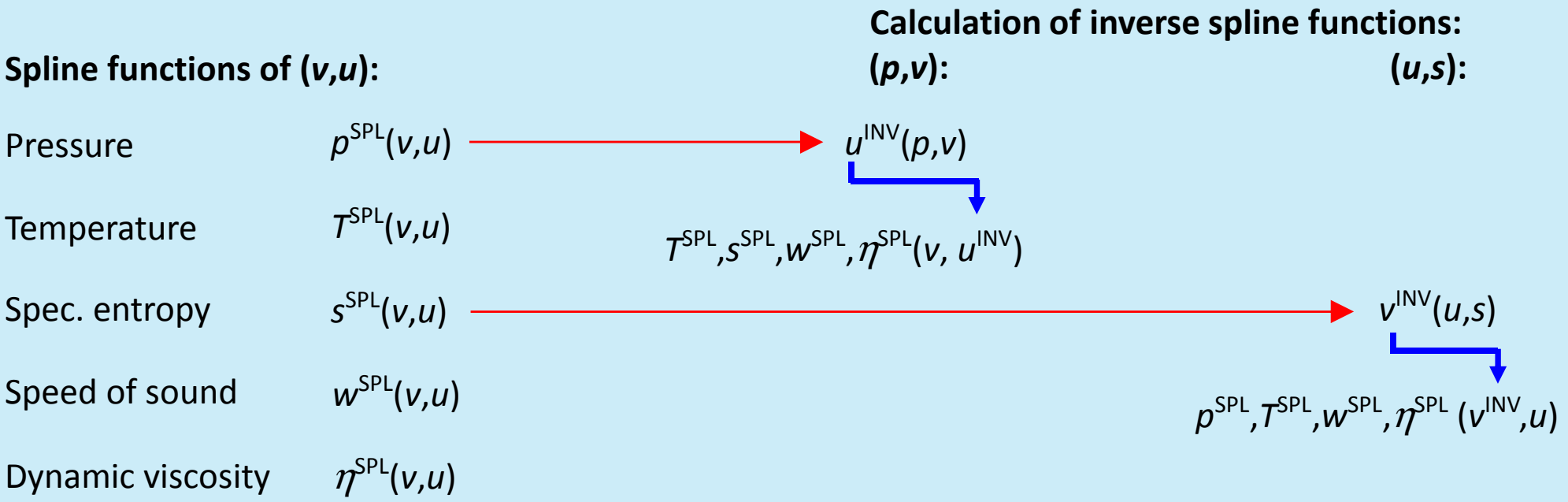
1073.15 K ≤ *T* ≤ 2273.15 K

0.611212 kPa ≤ *p* ≤ 50 MPa

TP – two-phase region

273.15 K ≤ *T* ≤ 647.096 K

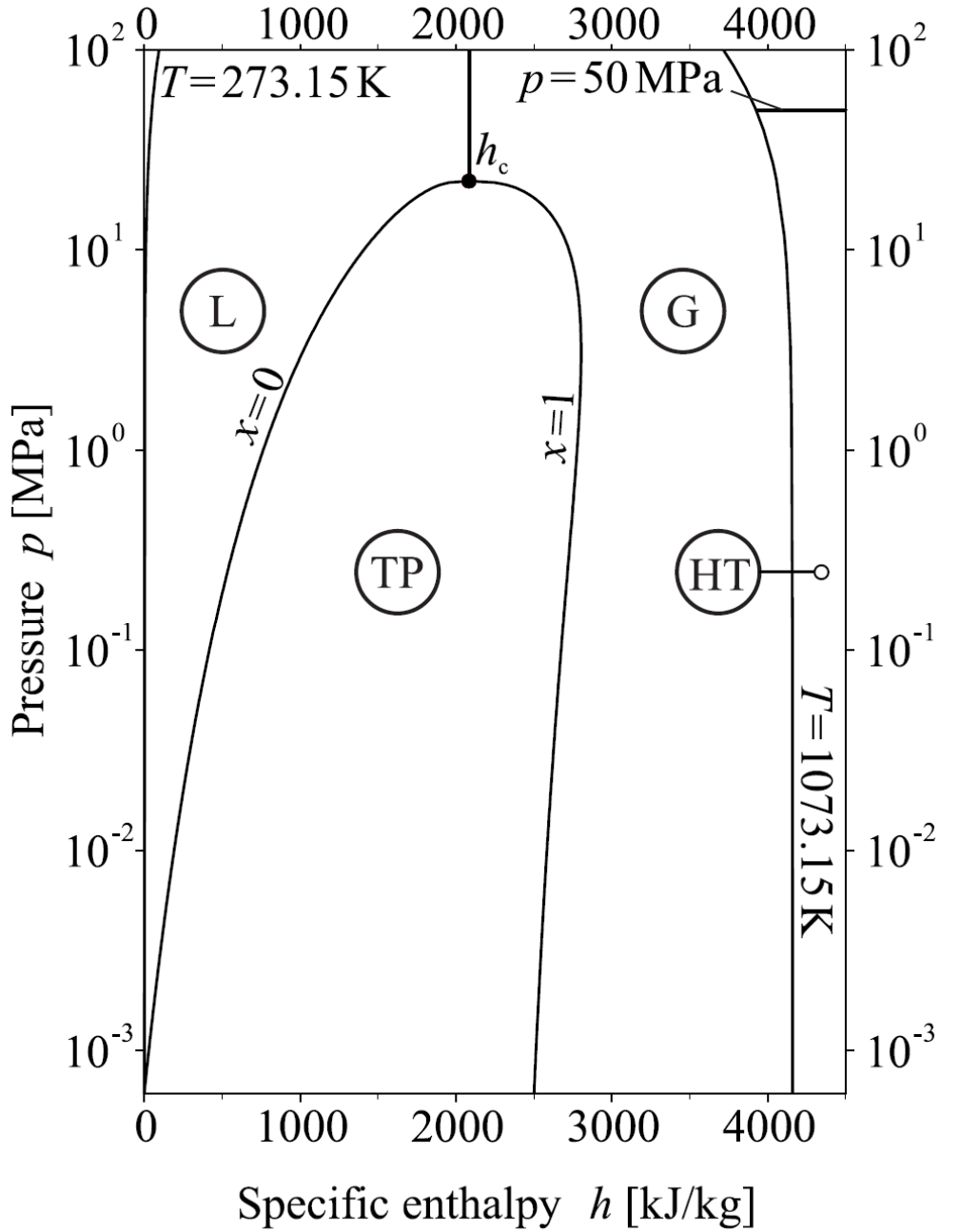
Spline Functions of (*v*,*u*) and Inverse Functions Based on IAPWS-IF97



- All thermodynamic and transport properties including derivatives and backward functions are calculated without iterations.
- Forward and backward functions are calculated with complete numerical consistency.

Spline Functions of (*p*,*h*) and Inverse Functions Based on IAPWS-IF97

Range of validity:



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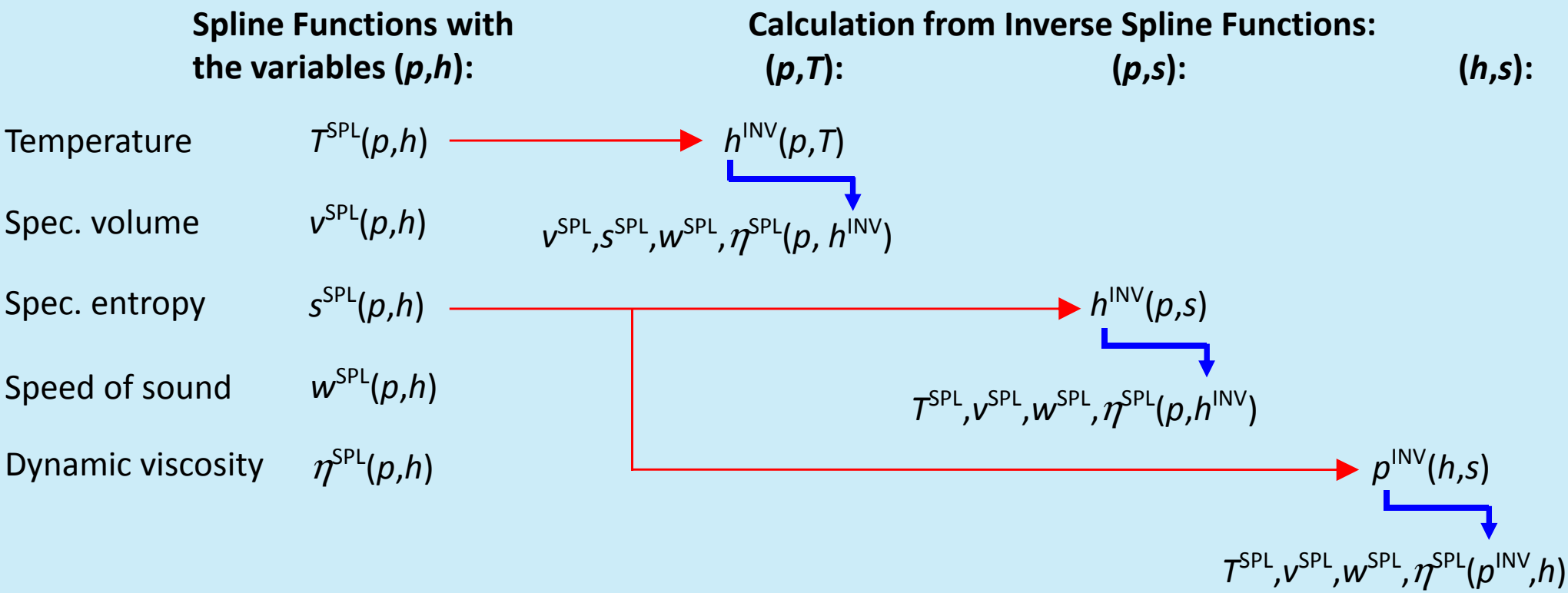
Spline Functions of (*p*,*h*) and Inverse Functions Based on IAPWS-IF97



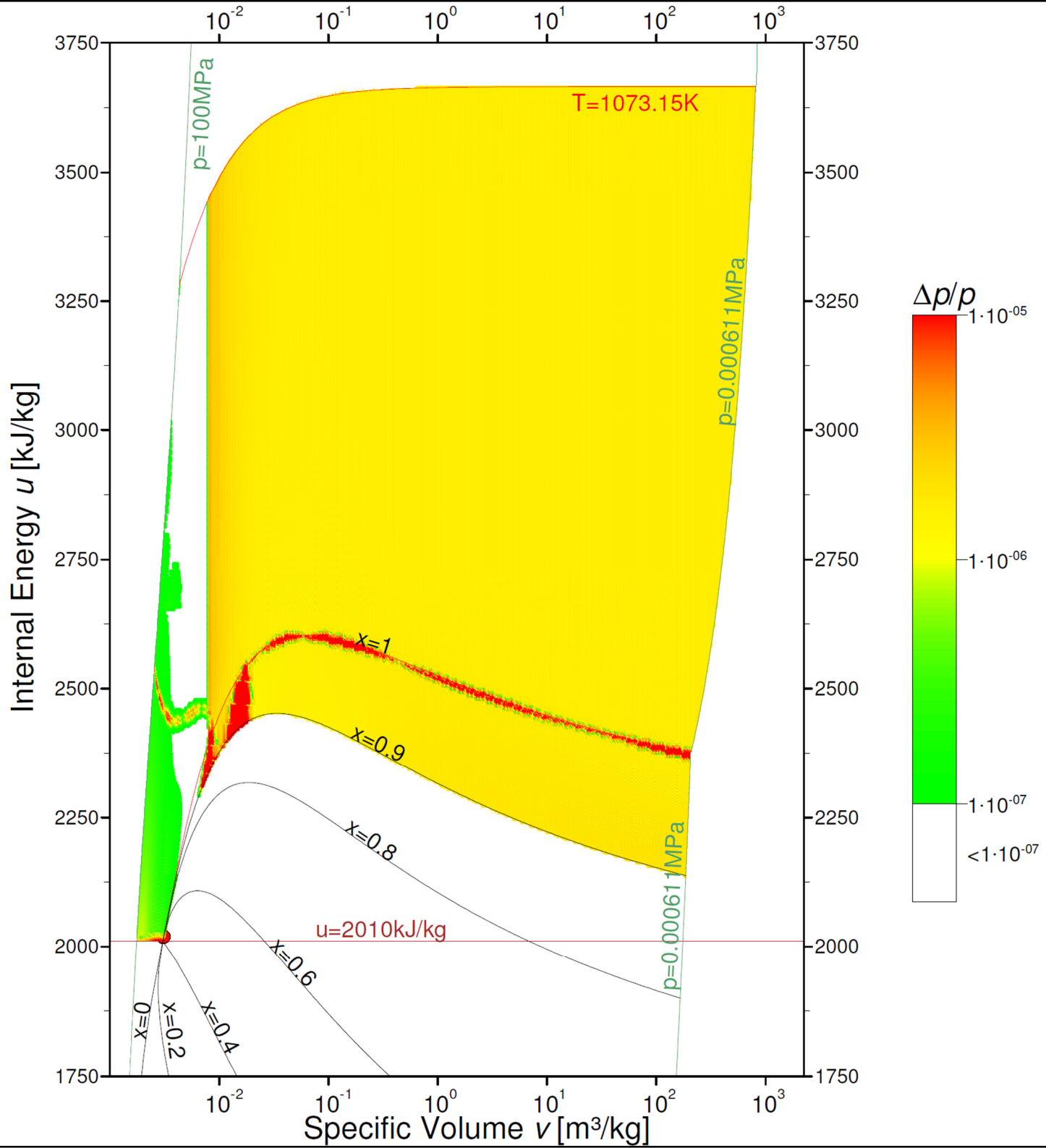
- All thermodynamic and transport properties including derivatives and backward functions are calculated without iterations.
- Forward and backward functions are calculated with complete numerical consistency.

Spline Functions for the Metastable-Vapor Region Based on IAPWS-IF97

- **Range of validity:**
  - From the dew curve to the 5% equilibrium moisture line (determined from the equilibrium *h*' and *h*" values).
  - In order to avoid discontinuities at the dew curve, the range of validity of these spline functions has been extended to the entire vapor region.
- **Max. deviations except for the vicinity of the dew curve:**
  At the dew curve for pressures $p < 10$ MPa, increased deviations due to the limited consistency between the IAPWS-IF97 supplementary equation for the metastable-vapor region and the IAPWS-IF97 basic equation for region 2 cannot be avoided.

SBTL function	***p*(*v*,*u*)**	***T*(*v*,*u*)**	***s*(*v*,*u*)**	***w*(*v*,*u*)**	$\eta(v,u)$
Max. dev.	$\lvert\Delta p/p\rvert<10^{-5}$	$\lvert\Delta T\rvert<1$ mK	$\lvert\Delta s\rvert<10^{-6}$ kJ kg^{-1} K^{-1}	$\lvert\Delta w/w\rvert<10^{-5}$	$\lvert\Delta\eta/\eta\rvert<10^{-5}$

SBTL function	***T*(*p*,*h*)**	***v*(*p*,*h*)**	***s*(*p*,*h*)**	***w*(*p*,*h*)**	$\eta(p,h)$
Max. dev.	$\lvert\Delta T\rvert<1$ mK	$\lvert\Delta v/v\rvert<10^{-5}$	$\lvert\Delta s\rvert<10^{-6}$ kJ kg^{-1} K^{-1}	$\lvert\Delta w/w\rvert<10^{-5}$	$\lvert\Delta\eta/\eta\rvert<10^{-5}$


Internal Energy u [kJ/kg]
Specific Volume v [m³/kg]
T=1073.15K
p=100MPa
p=0.000611MPa
x=1
x=0.9
x=0.8
x=0.6
x=0.4
x=0.2
x=0
u=2010kJ/kg
Δp/p
1·10-05
1·10-06
1·10-07
<1·10-07

Spline Functions for the Metastable-Vapor Region Based on IAPWS-IF97

➢ Max. deviations:

Table 18: Deviations in pressure $p(v,u)$, temperature $T(v,u)$, specific entropy $s(v,u)$, speed of sound $w(v,u)$, and dynamic viscosity $\eta(v,u)$ from the supplementary equation for the metastable-vapor region and the basic equation for region 2 of IAPWS-IF97

Spline function	Permissible deviation	Maximum deviation in the metastable-vapor region and in region 2 of IAPWS-IF97 outside the range $\lvert T - T_s(p)\rvert$ defined in the next column	Range $\lvert T - T_s(p)\rvert$ along the dew curve for $p < 10$ MPa		RMS deviation in the metastable-vapor region and in region 2 of IAPWS-IF97
			$\lvert T - T_s(p)\rvert$	Maximum deviation	
$p(v,u)$	$\lvert\Delta p\rvert_{perm} = 0.001\ \%$	$\lvert\Delta p\rvert_{max} = 0.00097\ \%$	7 K	$\lvert\Delta p\rvert_{max,\,dew} = 0.016\ \%$	$(\Delta p)_{RMS} = 0.00034\ \%$
$T(v,u)$	$\lvert\Delta T\rvert_{perm} = 1$ mK	$\lvert\Delta T\rvert_{max} = 0.60$ mK	10 K	$\lvert\Delta T\rvert_{max,\,dew} = 25.2$ mK	$(\Delta T)_{RMS} = 1.1$ mK
$s(v,u)$	$\lvert\Delta s\rvert_{perm} = 1\cdot10^{-6}$ kJ/(kg K)	$\lvert\Delta s\rvert_{max} = 0.45\cdot10^{-6}$ kJ/(kg K)	12 K	$\lvert\Delta s\rvert_{max,\,dew} = 0.81\cdot10^{-4}$ kJ/(kg K)	$(\Delta s)_{RMS} = 0.83\cdot10^{-6}$ kJ/(kg K)
$w(v,u)$	$\lvert\Delta w\rvert_{perm} = 0.001\ \%$	$\lvert\Delta w\rvert_{max} = 0.00088\ \%$	10 K	$\lvert\Delta w\rvert_{max,\,dew} = 0.05\ \%$	$(\Delta w)_{RMS} = 0.0017\ \%$
$\eta(v,u)$	$\lvert\Delta\eta\rvert_{perm} = 0.001\ \%$	$\lvert\Delta\eta\rvert_{max} = 0.00096\ \%$	6 K	$\lvert\Delta\eta\rvert_{max,\,dew} = 0.0082\ \%$	$(\Delta\eta)_{RMS} = 0.00031\ \%$

Spline Functions for the Metastable-Vapor Region Based on IAPWS-IF97

- **Computing-time comparisons:**

Computing Time Ratio (*CTR*) $$CTR = \frac{\text{Computing time of the calculation from IAPWS - IF97}}{\text{Computing time of the calculation from the SBTL function}}$$

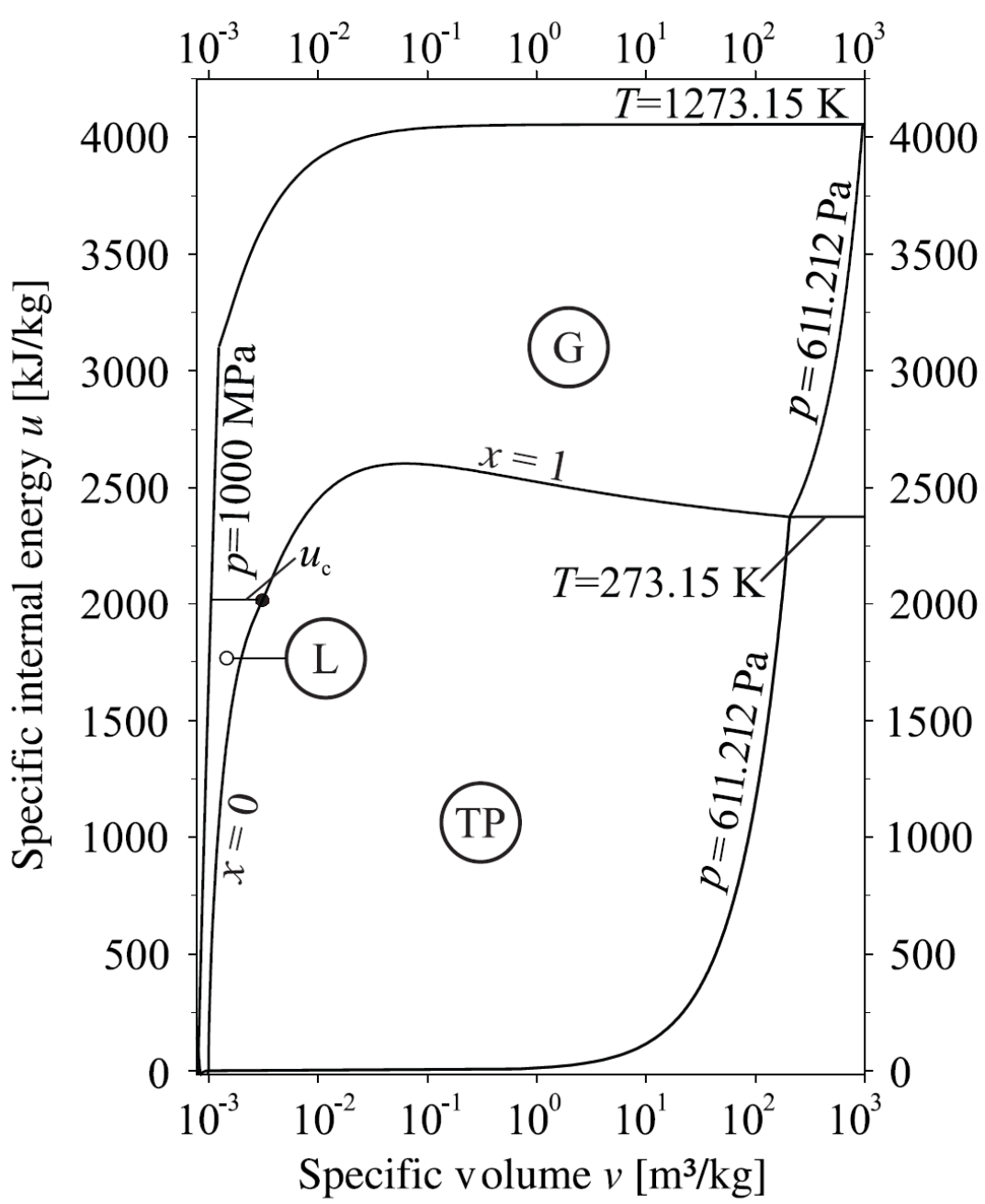
- **Computing time for region determination is included in these values.**
- **Starting values from backward eq. $T_2^{\mathrm{BWE}}(p,h)$ are used for property functions of (*p*,*h*).**

SBTL function	*p*(*v*,*u*)	*T*(*v*,*u*)	*s*(*v*,*u*)	*w*(*v*,*u*)	η(*v*,*u*)
CTR	88.3	86.4	89.5	87.0	90.0

SBTL function	*T*(*p*,*h*)	*v*(*p*,*h*)	*s*(*p*,*h*)	*w*(*p*,*h*)	η(*p*,*h*)
CTR	16.0	16.0	12.1	15.7	19.0

Spline Functions of (*v*,*u*) Based on IAPWS-95

- **Range of validity:**



Regions:

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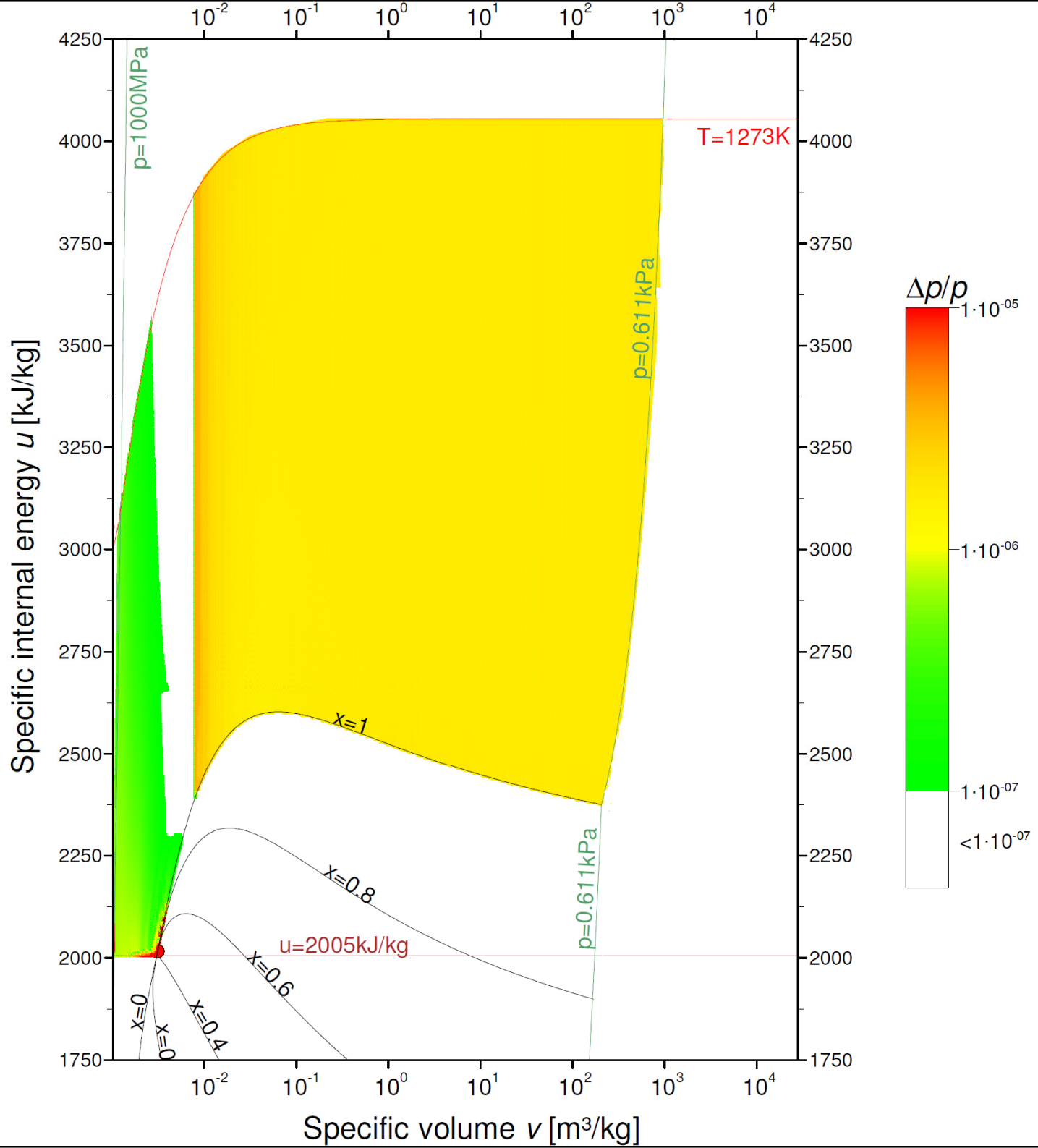

Specific internal energy u [kJ/kg]
Specific volume v [m³/kg]
p=1000MPa
T=1273K
p=0.611kPa
p=0.611kPa
x=1
x=0.8
x=0.6
x=0.4
x=0
x=0
u=2005kJ/kg
Δp/p
1·10-05
1·10-06
1·10-07
<1·10-07

Spline Functions of (*v*,*u*) Based on IAPWS-95

➢ Max. deviations:

SBTL function		Max. deviation (L)	Max. deviation (G)
$p(v,u)$	$p \le 2.5$ MPa	$\lvert\Delta p / p\rvert < 0.092\ \%$	$\lvert\Delta p / p\rvert < 0.001\ \%$
	$p > 2.5$ MPa	$\lvert\Delta p\rvert < 2.8$ kPa	
$T(v,u)$		$\lvert\Delta T\rvert < 1$mK	$\lvert\Delta T\rvert < 1$mK
$s(v,u)$		$\lvert\Delta s\rvert < 10^{-6}$ kJ kg^{-1} K^{-1}	$\lvert\Delta s\rvert < 10^{-6}$ kJ kg^{-1} K^{-1}
$w(v,u)$		$\lvert\Delta w / w\rvert < 0.001\ \%$	$\lvert\Delta w / w\rvert < 0.001\ \%$
$\eta(v,u)$		$\lvert\Delta \eta / \eta\rvert < 0.001\ \%$	$\lvert\Delta \eta / \eta\rvert < 0.001\ \%$

➢ Computing-time comparisons:

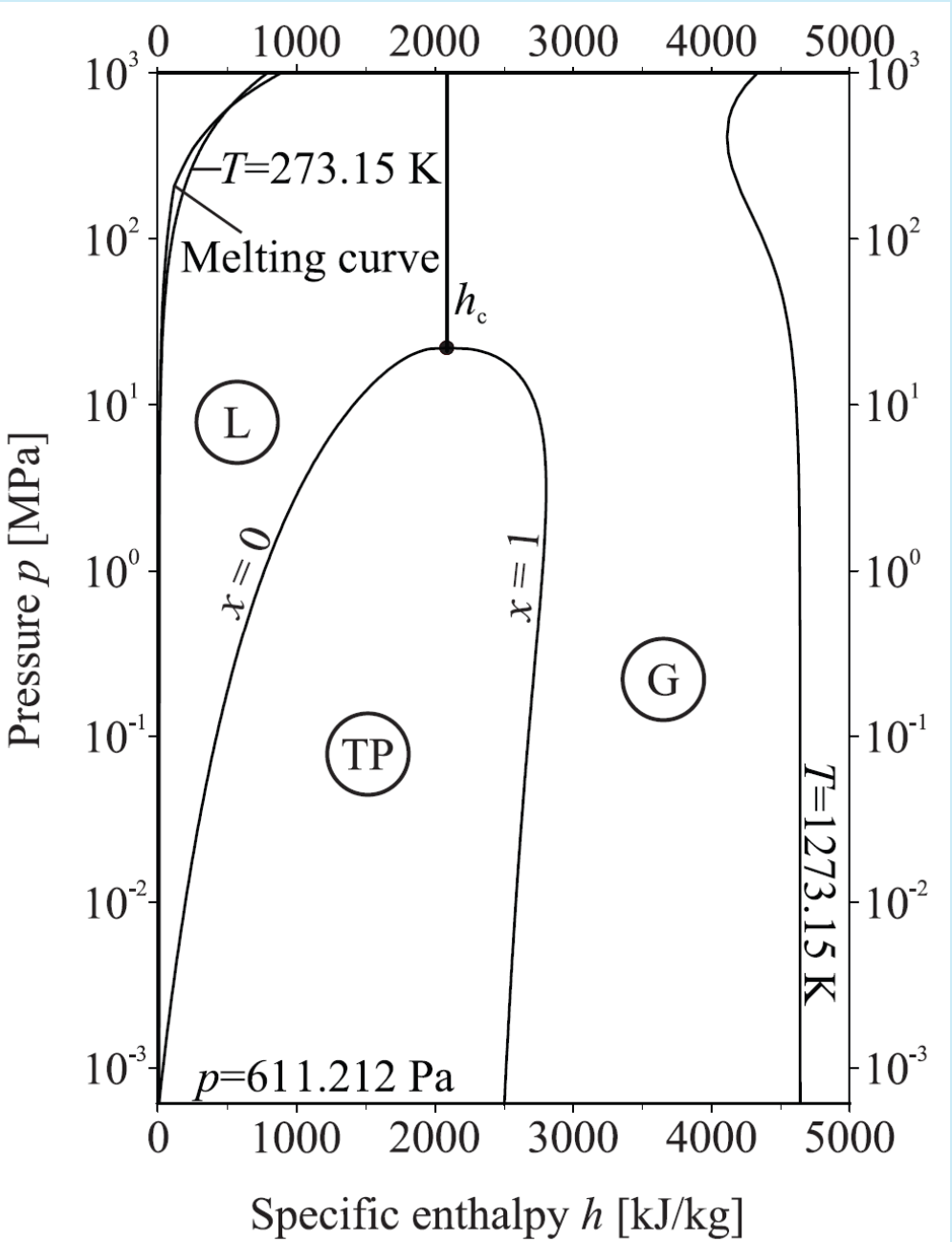
Computing Time Ratio $CTR = \dfrac{\textit{Computing time of IAPWS-95}}{\textit{Computing time of SBTL function}}$

- Property functions of IAPWS-95 computed from REFPROP (internal functions)
- Region determination not included

	Region	
SBTL function	**L**	**G**
***p*(*v*,*u*)**	243	434
***T*(*v*,*u*)**	251	410

Spline Functions of (*p*,*h*) Based on IAPWS-95

- **Range of validity:**



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Spline Functions of (*p*,*h*) Based on IAPWS-95

- **Max. deviations:**

SBTL function	Max. deviation
$T(p,h)$	$\lvert\Delta T\rvert < 1\,\mathrm{mK}$
$v(p,h)$	$\lvert\Delta v / v\rvert < 10^{-5}$
$s(p,h)$	$\lvert\Delta s\rvert < 10^{-6}\ \mathrm{kJ\ kg^{-1}\ K^{-1}}$
$w(p,h)$	$\lvert\Delta w / w\rvert < 10^{-5}$
$\eta(p,h)$	$\lvert\Delta \eta / \eta\rvert < 10^{-5}$

- **Computing-time comparisons:**

Computing Time Ratio $CTR = \dfrac{\textit{Computing time of IAPWS-95}}{\textit{Computing time of SBTL function}}$

- Property functions of IAPWS-95 computed from REFPROP (internal functions)
- Region determination not included

	Region	
SBTL function	**L**	**G**
***T*(*p*,*h*)**	≈ 15000	6760
***v*(*p*,*h*)**	≈ 14500	6900

Application of the SBTL Method in computationally intensive process simulations

- **Computational Fluid Dynamics (CFD):**
  - Software: TRACE – German Aerospace Agency (DLR)
  - Benefits of SBTL method:
    - Overall computing times are reduced by factors of 6 to 10 in comparison to simulations with IAPWS-IF97 implementation
    - Only 1.4 times slower than simulations with ideal gas model

- **Stationary Heat-Cycle Simulations:**
  - Software:
    - EBSILON Professional – STEAG Energy Services
    - KRAWAL – SIEMENS
  - Benefits of SBTL method:
    - Overall computing times are reduced with regard to simulations with IAPWS-IF97 and backward equations
    - Differences in the results of the process simulations are negligible, i.e., less than 0.02 %

- **Non-Stationary Heat-Cycle Simulations:**
  - RELAP-7 – Idaho National Laboratory
    nuclear reactor system safety analysis code
  - DYNAPLANT – SIEMENS
    simulation of non-stationary processes in power plants

Summary

- **The Task Group "CFD Steam Property Formulation" has developed the Spline-Based Table Look-up Method and proposes a new Guideline:**

  "IAPWS Guideline on the Fast Calculation of Steam and Water Properties with the Spline-Based Table Look-Up Method (SBTL)"

- **Spline functions for the metastable vapor region based on IAPWS-IF97 have been developed:**
  - Spline functions of (v,u) and (p,h)
  - Property functions of underlying standards are reproduced with an accuracy of 10-100 ppm, depending on the function
  - Computing speed:
    - (v,u) functions on average 80 times faster
    - (p,h) functions on average 15 times faster

- **Spline functions based on IAPWS-95 have been developed:**
  - Spline functions of (v,u) and (p,h)
  - Property functions of underlying standards are reproduced with an accuracy of 10-100 ppm, depending on the function
  - Computing speed:
    - (v,u) functions on average 250/400 (liquid/vapor) times faster
    - (p,h) functions on average 14,000/6,000 times faster

Summary

- **SBTL is currently applied in:**
  - TRACE by DLR
  - KRAWAL & DYNAPLANT by SIEMENS
  - EBSILON by STEAG
  - RELAP-7 by Idaho National Laboratory (INL)
- **Planned project:** ANSYS CFX/Fluent

The SBTL Method serves as a supplement to existing IAPWS standards and enables fast and accurate property calculations in computationally intensive process simulations.

The DRAFT Guideline has been send to the members of TPWS and IRS on February, 21st 2015.
No comments from the Working Groups were received.

⇨ **The Guideline is ready for adoption.**

Thank you for your attention.