

# Module Interface Specification for Solar Water Heating Systems Incorporating Phase Change Material

Brooks MacLachlan

August 18, 2016

## Contents

<b>1</b>	<b>Introduction</b>	<b>4</b>
<b>2</b>	<b>Notation</b>	<b>4</b>
<b>3</b>	<b>Module Decomposition</b>	<b>4</b>
<b>4</b>	<b>MIS of Control Module</b>	<b>5</b>
4.1	Module . . . . .	5
4.2	Uses . . . . .	5
4.3	Syntax . . . . .	5
4.3.1	Exported Access Programs . . . . .	5
4.4	Semantics . . . . .	5
4.4.1	State Variables . . . . .	5
4.4.2	Environment Variables . . . . .	6
4.4.3	Access Routine Semantics . . . . .	6
<b>5</b>	<b>MIS of Input Parameters Module</b>	<b>6</b>
5.1	Module . . . . .	6
5.2	Uses . . . . .	6
5.3	Syntax . . . . .	6
5.3.1	Exported Data Types . . . . .	6
5.3.2	Exported Access Programs . . . . .	6
5.4	Semantics . . . . .	6
5.4.1	State Variables . . . . .	6
5.4.2	Access Routine Semantics . . . . .	7

<b>6</b>	<b>MIS of Input Format Module</b>	<b>7</b>
6.1	Module . . . . .	7
6.2	Uses . . . . .	7
6.3	Syntax . . . . .	8
6.4	Exported Access Programs . . . . .	8
6.5	Semantics . . . . .	8
6.5.1	State Variables . . . . .	8
6.5.2	Assumptions . . . . .	8
6.5.3	Access Routine Semantics . . . . .	9
6.5.4	Local Functions . . . . .	9
<b>7</b>	<b>MIS of Input Verification Module</b>	<b>10</b>
7.1	Module . . . . .	10
7.2	Uses . . . . .	10
7.3	Syntax . . . . .	11
7.3.1	Exported Access Programs . . . . .	11
7.4	Semantics . . . . .	11
7.4.1	Environment Variables . . . . .	11
7.4.2	Assumptions . . . . .	11
7.4.3	Access Routine Semantics . . . . .	12
<b>8</b>	<b>MIS of Temperature ODEs Module</b>	<b>13</b>
8.1	Module . . . . .	13
8.2	Uses . . . . .	13
8.3	Syntax . . . . .	14
8.3.1	Exported Access Programs . . . . .	14
8.4	Semantics . . . . .	14
8.4.1	State Variables . . . . .	14
8.4.2	Assumptions . . . . .	14
8.4.3	Access Routine Semantics . . . . .	15
<b>9</b>	<b>MIS of ODE Solver Module</b>	<b>15</b>
9.1	Module . . . . .	15
9.2	Uses . . . . .	15
9.3	Syntax . . . . .	15
9.3.1	Exported Constants . . . . .	15
9.3.2	Exported Access Programs . . . . .	16
9.4	Semantics . . . . .	16
9.4.1	State Variables . . . . .	16
9.4.2	Access Routine Semantics . . . . .	16

<b>10 MIS of Energy Module</b>	<b>16</b>
10.1 Module . . . . .	16
10.2 Uses . . . . .	16
10.3 Syntax . . . . .	17
10.3.1 External Access Programs . . . . .	17
10.4 Semantics . . . . .	17
10.4.1 State Variables . . . . .	17
10.4.2 Assumptions . . . . .	17
10.4.3 Access Routine Semantics . . . . .	18
10.4.4 Local Functions . . . . .	18
<b>11 MIS of Output Verification Module</b>	<b>19</b>
11.1 Module . . . . .	19
11.2 Uses . . . . .	19
11.3 Syntax . . . . .	19
11.3.1 Exported Access Programs . . . . .	19
11.4 Semantics . . . . .	19
11.4.1 State Variables . . . . .	19
11.4.2 Environment Variables . . . . .	19
11.4.3 Local Variables . . . . .	19
11.4.4 Assumptions . . . . .	19
11.4.5 Access Routine Semantics . . . . .	20
11.4.6 Local Functions . . . . .	20
<b>12 MIS of Plotting Module</b>	<b>21</b>
12.1 Module . . . . .	21
12.2 Uses . . . . .	21
12.3 Syntax . . . . .	21
12.3.1 Exported Access Programs . . . . .	21
12.4 Semantics . . . . .	21
12.4.1 State Variables . . . . .	21
12.4.2 Environment Variables . . . . .	21
12.4.3 Assumptions . . . . .	21
12.4.4 Access Routine Semantics . . . . .	21
<b>13 MIS of Output Module</b>	<b>22</b>
13.1 Module . . . . .	22
13.2 Uses . . . . .	22
13.3 Syntax . . . . .	22
13.3.1 Exported Constants . . . . .	22
13.3.2 Exported Access Program . . . . .	22
13.4 Semantics . . . . .	22
13.4.1 State Variables . . . . .	22

13.4.2 Environment Variables . . . . .	22
13.4.3 Access Routine Semantics . . . . .	22

## 14 Appendix 23

# 1 Introduction

The following document details the Module Interface Specifications for the implemented modules in a program simulating a Solar Water Heating System with Phase Change Material. It is intended to ease navigation through the program for design and maintenance purposes.

Complementary documents include the System Requirement Specifications and Module Guide.

# 2 Notation

The following table summarizes the primitive data types used by SWHS.

Data Type	Notation	Description
character	char	a single symbol or digit
integer	$\mathbb{Z}$	a number without a fractional component in $(-\infty, \infty)$
natural number	$\mathbb{N}$	a number without a fractional component in $[1, \infty)$
real	$\mathbb{R}$	any number in $(-\infty, \infty)$

SWHS also uses some derived data types: arrays, strings, and structures. Arrays are lists filled with elements of the same data type. Strings are arrays of characters. Structures contain pairs of keys and values, where keys are unique variable names used to identify their corresponding value, and values can be of any data type. In addition, SWHS uses functions, which are defined by the data types of their inputs and outputs. Functions are described by showing their input data types separated by multiplication symbols on the left side of an arrow, and their output data type on the right side.

# 3 Module Decomposition

The following table is taken directly from the Module Guide document for this project.

Level 1	Level 2
Hardware-Hiding Module	
Behaviour-Hiding Module	Input Format Module Input Parameters Module Input Verification Module Output Format Module Output Verification Module Temperature ODEs Module Energy Equations Module Control Module
Software Decision Module	Sequence Data Structure Module ODE Solver Module Plotting Module

Table 1: Module Hierarchy

## 4 MIS of Control Module

### 4.1 Module

main

### 4.2 Uses

parameters (5), load\_params (6), verify\_params (7), temperature (8), ODE Solvers Module (9), energy (10), verify\_output (11), plot (12), output (13)

### 4.3 Syntax

#### 4.3.1 Exported Access Programs

Name	In	Out	Exceptions
main	string	-	-

### 4.4 Semantics

#### 4.4.1 State Variables

*time*: array of reals

*tempW*: array of reals

*tempP*: array of reals

*latHeat*: array of reals

*eW*: array of reals  
*eP*: array of reals  
*eTot*: array of reals

#### 4.4.2 Environment Variables

*win*: 2D array of pixels displayed on the screen

#### 4.4.3 Access Routine Semantics

main(*s*): transition: *time, tempW, tempP, latHeat, eW, eP, eTot, win* := *results*[0],  
*results*[1], *results*[2], *results*[3], *eW1*||*eW2*||*eW3*, *eP1*||*eP2*||*eP3*,  
 $(\forall i \in [0..|post(eW)| - 1]) (post(eW[i]) + post(eP[i]))$ , Prints infor-  
 mation about the melting of PCM.  
 exception: none

## 5 MIS of Input Parameters Module

### 5.1 Module

parameters

### 5.2 Uses

N/A

### 5.3 Syntax

#### 5.3.1 Exported Data Types

parameters := structure

#### 5.3.2 Exported Access Programs

N/A

### 5.4 Semantics

#### 5.4.1 State Variables

*params.L*: real  
*params.diam*: real  
*params.Vp*: real  
*params.Ap*: real  
*params.rho\_p*: real

*params.Tmelt*: real  
*params.C\_ps*: real  
*params.C\_pl*: real  
*params.Hf*: real  
*params.Ac*: real  
*params.Tc*: real  
*params.rho\_w*: real  
*params.C\_w*: real  
*params.hc*: real  
*params.hp*: real  
*params.Tinit*: real  
*params.tstep*: real  
*params.tfinal*: real  
*params.AbsTol*: real  
*params.RelTol*: real  
*params.ConsTol*: real  
*params.Vt*: real  
*params.Mw*: real  
*params.tau\_w*: real  
*params.eta*: real  
*params.Mp*: real  
*params.tau\_ps*: real  
*params.tau\_pl*: real  
*params.Epmelt\_init*: real  
*params.Ep\_melt3*: real  
*params.Mw\_noPCM*: real  
*params.tau\_w\_no\_PCM*: real

#### 5.4.2 Access Routine Semantics

N/A

## 6 MIS of Input Format Module

### 6.1 Module

load\_params

### 6.2 Uses

parameters (5)

## 6.3 Syntax

## 6.4 Exported Access Programs

Name	In	Out	Exceptions
load_params	string	parameters	-

## 6.5 Semantics

### 6.5.1 State Variables

*params*: parameters

*param*: array of reals

### 6.5.2 Assumptions

The input string corresponds to an existing filename in the current directory. The input file is formatted correctly.



### 6.5.3 Access Routine Semantics

load\_params(*s*): transition: *params.L*, *params.diam*, *params.Vp*, *params.Ap*,  
*params.rho\_p*, *params.Tmelt*, *params.C\_ps*, *params.C\_pl*,  
*params.Hf*, *params.Ac*, *params.Tc*, *params.rho\_w*,  
*params.C\_w*, *params.hc*, *params.hp*, *params.Tinit*,  
*params.tstep*, *params.tfinal*, *params.AbsTol*,  
*params.RelTol*, *params.ConsTol*, *params.Vt*, *params.Mw*,  
*params.tau\_w*, *params.eta*, *params.Mp*, *params.tau\_ps*,  
*params.tau\_pl*, *params.Epmelt\_init*, *params.Ep\_melt3*,  
*params.Mw\_noPCM*, *params.tau\_w\_noPCM* :=  
*param*[0], *param*[1], *param*[2], *param*[3], *param*[4],  
*param*[5], *param*[6], *param*[7], *param*[8], *param*[9],  
*param*[10], *param*[11], *param*[12], *param*[13], *param*[14],  
*param*[15], *param*[16], *param*[17], *param*[18], *param*[19],  
*param*[20], calcVt(post(*params.L*), post(*params.diam*)),  
calcMw(post(*params.Vp*), post(*params.rho\_w*),  
post(*params.Vt*)), calcTauw(post(*params.Mw*),  
post(*params.C\_w*), post(*params.hc*),  
post(*params.Ac*)), calcEta(post(*params.hp*),  
post(*params.Ap*), post(*params.hc*), post(*params.Ac*)),  
calcMp(post(*params.rho\_p*), post(*params.Vp*)),  
calcTaups(post(*params.Mp*), post(*params.C\_ps*),  
post(*params.hp*), post(*params.Ap*)),  
calcTaupl(post(*params.Mp*), post(*params.C\_pl*),  
post(*params.hp*), post(*params.Ap*)),  
calcEpmeltinit(post(*params.C\_ps*), post(*params.Mp*),  
post(*params.Tmelt*), post(*params.Tinit*)),  
calcEpmelt3(post(*params.Hf*), post(*params.Mp*)),  
calcMwnoPCM(post(*params.rho\_w*), post(*params.Vt*)),  
calcTauwnoPCM(post(*params.Mw\_noPCM*),  
post(*params.C\_w*), post(*params.hc*), post(*params.Ac*)),  
where *param* is the array of parameters obtained from the  
input file *s*

exception: none

### 6.5.4 Local Functions

calcVt:  $\text{real} \times \text{real} \rightarrow \text{real}$

$$\text{calcVt}(L, \text{diam}) \equiv \pi \times L \times \left(\frac{\text{diam}}{2}\right)^2$$

calcMw:  $\text{real} \times \text{real} \times \text{real} \rightarrow \text{real}$

$$\text{calcMw}(Vp, \text{rho}_w, Vt) \equiv \text{rho}_w \times (Vt - Vp)$$

calcTauw:  $\text{real} \times \text{real} \times \text{real} \times \text{real} \rightarrow \text{real}$   
 $\text{calcTauw}(Mw, C\_w, hc, Ac) \equiv \frac{Mw \times C\_w}{Ac \times hc}$

calcEta:  $\text{real} \times \text{real} \times \text{real} \times \text{real} \rightarrow \text{real}$   
 $\text{calcEta}(hp, Ap, hc, Ac) \equiv \frac{hp \times Ap}{hc \times Ac}$

calcMp:  $\text{real} \times \text{real} \rightarrow \text{real}$   
 $\text{calcMp}(\rho_p, Vp) \equiv \rho_p \times Vp$

calcTaups:  $\text{real} \times \text{real} \times \text{real} \times \text{real} \rightarrow \text{real}$   
 $\text{calcTaups}(Mp, C\_ps, hp, Ap) \equiv \frac{Mp \times C\_ps}{hp \times Ap}$

calcTaupl:  $\text{real} \times \text{real} \times \text{real} \times \text{real} \rightarrow \text{real}$   
 $\text{calcTaupl}(Mp, C\_pl, hp, Ap) \equiv \frac{Mp \times C\_pl}{hp \times Ap}$

calcEpmeltinit:  $\text{real} \times \text{real} \times \text{real} \times \text{real} \rightarrow \text{real}$   
 $\text{calcEpmeltinit}(C\_ps, Mp, T_{melt}, T_{init}) \equiv C\_ps \times Mp \times (T_{melt} - T_{init})$

calcEpmelt3:  $\text{real} \times \text{real} \rightarrow \text{real}$   
 $\text{calcEpmelt3}(Hf, Mp) \equiv Hf \times Mp$

calcMwnoPCM:  $\text{real} \times \text{real} \rightarrow \text{real}$   
 $\text{calcMwnoPCM}(\rho_w, Vt) \equiv \rho_w \times Vt$

calcTauwnoPCM:  $\text{real} \times \text{real} \times \text{real} \times \text{real} \rightarrow \text{real}$   
 $\text{calcTauwnoPCM}(Mw\_noPCM, C\_w, hc, Ac) \equiv \frac{Mw\_noPCM \times C\_w}{hc \times Ac}$

## 7 MIS of Input Verification Module

### 7.1 Module

verify\_params

### 7.2 Uses

parameters (5)

## 7.3 Syntax

### 7.3.1 Exported Access Programs

Name	In	Out	Exceptions
verify_valid	parameters	-	badLength, badDiam, badPCMVolume, badPCMAndTankVol, badPCMArea, badPCMDensity, badMeltTemp, badCoilAndInitTemp, badCoilTemp, badPCMHeatCapSolid, badPCMHeatCapLiquid, badHeatFusion, badCoilArea, badWaterDensity, badWaterHeatCap, badCoilCoeff, badPCMCoeff, badInitTemp, badFinalTime, badInitAndMeltTemp
verify_recommended	parameters	-	-

## 7.4 Semantics

### 7.4.1 Environment Variables

*win*: 2D array of pixels displayed on the screen.

### 7.4.2 Assumptions

All of the fields of the input parameters structure have been assigned a value.

### 7.4.3 Access Routine Semantics

`verify_valid(params):`    transition:    *win*: (error is thrown  $\Rightarrow$  Prints error message)  
                                  exceptions:    *exc* := ( $params.L \leq 0 \Rightarrow \text{badLength} \mid params.diam \leq 0 \Rightarrow \text{badDiam} \mid params.Vp \leq 0 \Rightarrow \text{badPCMVolume} \mid params.Vp \geq params.Vt \Rightarrow \text{badPCMAndTankVol} \mid params.Ap \leq 0 \Rightarrow \text{badPCMArea} \mid params.rho_p \leq 0 \Rightarrow \text{badPCMDensity} \mid params.Tmelt} \leq 0 \vee params.Tmelt \geq params.Tc \Rightarrow \text{badMeltTemp} \mid params.Tc \leq params.Tinit \Rightarrow \text{badCoilAndInitTemp} \mid params.Tc \geq 100 \vee params.Tc \leq 0 \Rightarrow \text{badCoilTemp} \mid params.C_{ps} \leq 0 \Rightarrow \text{badPCMHeatCapSolid} \mid params.C_{pl} \leq 0 \Rightarrow \text{badPCMHeatCapLiquid} \mid params.Hf} \leq 0 \Rightarrow \text{badHeatFusion} \mid params.Ac} \leq 0 \Rightarrow \text{badCoilArea} \mid params.rho_w \leq 0 \Rightarrow \text{badWaterDensity} \mid params.C_w} \leq 0 \Rightarrow \text{badWaterHeatCap} \mid params.hc} \leq 0 \Rightarrow \text{badCoilCoeff} \mid params.hp} \leq 0 \Rightarrow \text{badPCMCoeff} \mid params.Tinit} \leq 0 \vee params.Tinit \geq 100 \Rightarrow \text{badInitTemp} \mid params.tfinal} \leq 0 \Rightarrow \text{badFinalTime} \mid params.Tinit} \geq params.Tmelt \Rightarrow \text{badInitAndMeltTemp}$ ) See Appendix (14) for the complete list of exceptions and associated error messages.

verify\_recommended(*params*): transition: *win*: (Warning is thrown  $\Rightarrow$  Prints warning message)

exceptions: *exc* := (*params.L* < 0.1  $\vee$  *params.L* > 50  $\Rightarrow$  warnLength | *params.diam*/*params.L* < 0.002  $\vee$  *params.diam*/*params.L* > 200  $\Rightarrow$  warnDiam | *params.Vp* < *params.Vt*  $\times 10^{-6}$   $\Rightarrow$  warnPCMVol | *params.Vp* > *params.Ap*  $\vee$  *params.Ap* > (2/0.001)  $\times$  *params.Vp*  $\Rightarrow$  warnVolArea | *params.rho\_p*  $\leq$  500  $\vee$  *params.rho\_p*  $\geq$  20000  $\Rightarrow$  warnPCMDensity | *params.C\_ps*  $\leq$  100  $\vee$  *params.C\_ps*  $\geq$  4000  $\Rightarrow$  warnPCMHeatCapSolid | *params.C\_pl*  $\leq$  100  $\vee$  *params.C\_pl*  $\geq$  5000  $\Rightarrow$  warnPCMHeatCapLiquid | *params.Ac* >  $\pi \times (\textit{params.diam}/2)^2$   $\Rightarrow$  warnCoilArea | *params.rho\_w*  $\leq$  950  $\vee$  *params.rho\_w* > 1000  $\Rightarrow$  warnWaterDensity | *params.C\_w*  $\leq$  4170  $\vee$  *params.C\_w*  $\geq$  4210  $\Rightarrow$  warnWaterHeatCap | *params.hc*  $\leq$  10  $\vee$  *params.hc*  $\geq$  10000  $\Rightarrow$  warnCoilCoeff | *params.hp*  $\leq$  10  $\vee$  *params.hp*  $\geq$  10000  $\Rightarrow$  warnPCMCoeff | *params.tfinal*  $\leq$  0  $\vee$  *params.tfinal*  $\geq$  86400  $\Rightarrow$  warnFinalTime) None of these exceptions terminate the program. See Appendix (14) for the complete list of exceptions and associated warning messages.

## 8 MIS of Temperature ODEs Module

### 8.1 Module

temperature

### 8.2 Uses

parameters (5)

## 8.3 Syntax

### 8.3.1 Exported Access Programs

Name	In	Out	Exceptions
temperature1	array of reals, array of reals, array of reals, parameters	array of functions	-
temperature2	array of reals, array of reals, array of reals, array of reals, parameters	array of functions	-
temperature3	array of reals, array of reals, array of reals, parameters	array of functions	-
event1	array of reals, array of reals, array of reals, parameters	function	-
event2	array of reals, array of reals, array of reals, array of reals, parameters	function	-

## 8.4 Semantics

### 8.4.1 State Variables

$t$ : array of reals

$Tw1$ : array of reals

$Tw2$ : array of reals

$Tw3$ : array of reals

$Tp1$ : array of reals

$Tp2$ : array of reals

$Tp3$ : array of reals

$Qp2$ : array of reals

### 8.4.2 Assumptions

All of the fields of the input parameters structure have been assigned a value. The values have been properly constrained.

### 8.4.3 Access Routine Semantics

temperature1( $t, Tw1, Tp1, params$ ):	output:	$out := \{dT_w : real \times real \times real \rightarrow real, dT_p : real \times real \times real \rightarrow real\}$
	exception:	none
temperature2( $t, Tw2, Tp2, Qp2, params$ ):	output:	$out := \{dT_w : real \times real \times real \times real \rightarrow real, dT_p : real \times real \times real \times real \rightarrow real, dQ_p : real \times real \times real \times real \rightarrow real\}$
	exception:	none
temperature3( $t, Tw3, Tp3, params$ ):	output:	$out := \{dT_w : real \times real \times real \rightarrow real, dT_p : real \times real \times real \rightarrow real\}$
	exception:	none
event1( $t, Tw1, Tp1, params$ ):	output:	$out := Ev : real \times real \times real \rightarrow real$
	exception:	none
event2( $t, Tw2, Tp2, Qp2, params$ ):	output:	$out := Ev : real \times real \times real \times real \rightarrow real$
	exception:	none

## 9 MIS of ODE Solver Module

### 9.1 Module

ODE Solver Module

### 9.2 Uses

N/A

### 9.3 Syntax

#### 9.3.1 Exported Constants

$MaxStep$ : natural number

$N$ : natural number

### 9.3.2 Exported Access Programs

Name	In	Out	Exceptions
solve	function, array of reals, array of reals, function, real, real	array of reals ( $N$ of them)	ODE_BAD_INPUT, ODE_MAXSTEP, ODE_ACCURACY

## 9.4 Semantics

### 9.4.1 State Variables

*results*: array of reals ( $N$  of them)

### 9.4.2 Access Routine Semantics

$\text{solve}(f, \text{domain}, \text{ics}, \text{events}, \text{abstol}, \text{reltol})$  output:  $\text{out} := \text{results}$ , where *results* holds the solution to the ODE system generated by the solver.

exceptions:  $\text{exc} := (\text{Invalid input parameters} \Rightarrow \text{ODE\_BAD\_INPUT} \mid \text{MaxStep steps taken and no solution found} \Rightarrow \text{ODE\_MAXSTEP} \mid \text{reltol and abstol not satisfied for a step} \Rightarrow \text{ODE\_ACCURACY})$

## 10 MIS of Energy Module

### 10.1 Module

energy

### 10.2 Uses

parameters (5)



## 10.3 Syntax

### 10.3.1 External Access Programs

Name	In	Out	Exceptions
energy1Wat	array of reals, parameters	array of reals	-
energy1PCM	array of reals, parameters	array of reals	-
energy2Wat	array of reals, parameters	array of reals	-
energy2PCM	array of reals, parameters	array of reals	-
energy3Wat	array of reals, parameters	array of reals	-
energy3PCM	array of reals, parameters	array of reals	-

## 10.4 Semantics

### 10.4.1 State Variables

*eW1*: array of reals

*eP1*: array of reals

*eW2*: array of reals

*eP2*: array of reals

*eW3*: array of reals

*eP3*: array of reals

### 10.4.2 Assumptions

All of the fields of the input parameters structure have been assigned a value. The values have been properly constrained.

### 10.4.3 Access Routine Semantics

energy1Wat( $Tw1, params$ ):	transition:	$(\forall i \in [0.. Tw1  - 1]) (eW1[i] := \text{watEnergy}(Tw1[i], params))$
	output:	$out := eW1$
	exception:	none
energy1PCM( $Tp1, params$ ):	transition:	$(\forall i \in [0.. Tp1  - 1]) (eP1[i] := \text{pcmEnergy1}(Tp1[i], params))$
	output:	$out := eP1$
	exception:	none
energy2Wat( $Tw2, params$ ):	transition:	$(\forall i \in [0.. Tw2  - 1]) (eW2[i] := \text{watEnergy}(Tw2[i], params))$
	output:	$out := eW2$
	exception:	none
energy2PCM( $Qp2, params$ ):	transition:	$(\forall i \in [0.. Qp2  - 1]) (eP2[i] := \text{pcmEnergy2}(Qp2[i], params))$
	output:	$out := eP2$
	exception:	none
energy3Wat( $Tw3, params$ ):	transition:	$(\forall i \in [0.. Tw3  - 1]) (eW3[i] := \text{watEnergy}(Tw3[i], params))$
	output:	$out := eW3$
	exception:	none
energy3PCM( $Tp3, params$ ):	transition:	$(\forall i \in [0.. Tp3  - 1]) (eP3[i] := \text{pcmEnergy3}(Tp3[i], params))$
	output:	$out := eP3$
	exception:	none

### 10.4.4 Local Functions

watEnergy:  $\text{real} \times \text{parameters} \rightarrow \text{real}$

$\text{watEnergy}(Tw, params) \equiv params.C\_w \times params.Mw \times (Tw - params.Tinit)$

pcmEnergy1:  $\text{real} \times \text{parameters} \rightarrow \text{real}$

$\text{pcmEnergy1}(Tp, params) \equiv params.C\_ps \times params.Mp \times (Tp - params.Tinit)$

pcmEnergy2:  $\text{real} \times \text{parameters} \rightarrow \text{real}$

$\text{pcmEnergy2}(Qp, params) \equiv params.Epmelt\_init + Qp$

pcmEnergy3:  $\text{real} \times \text{parameters} \rightarrow \text{real}$

$$\text{pcmEnergy3}(Tp, \text{params}) \equiv \text{params.Epmelt\_init} + \text{params.Ep\_melt3} + \text{params.C\_pl} \times \text{params.Mp} \times (Tp - \text{params.Tmelt})$$

## 11 MIS of Output Verification Module

### 11.1 Module

verify\_output

### 11.2 Uses

parameters (5)

### 11.3 Syntax

#### 11.3.1 Exported Access Programs

Name	In	Out	Exceptions
verify_output	array of reals, array of reals, array of reals, array of reals, array of reals, parameters	-	-

### 11.4 Semantics

#### 11.4.1 State Variables

*expEPCM*: array of reals

*expEWat*: array of reals

*errorWater*: real

*errorPCM*: real

#### 11.4.2 Environment Variables

*win*: 2D array of pixels displayed on the screen

#### 11.4.3 Local Variables

#### 11.4.4 Assumptions

All of the fields of the input parameters structure have been assigned a value. The values have been properly constrained. The input arrays are not empty.

### 11.4.5 Access Routine Semantics

$\text{verify\_output}(t, Tw, Tp, Ew, Ep, \text{params})$ : transition:  $\text{expEPCM}, \text{expEWat}, \text{errorWater}, \text{errorPCM}$ ,  
 $\text{win} := (\forall i \in [1..|t| - 1])$   
 $(\text{expectedEp}(\text{traprule}(\text{delta}(t[i - 1], t[i]), Tw[i], Tp[i], Tw[i - 1], Tp[i - 1]), \text{params})),$   
 $(\forall i \in [1..|t| - 1]) (\text{expectedEw}(\text{expectedEc}(\text{traprule}(\text{delta}(t[i - 1], t[i]), \text{params.Tc}, Tw[i], \text{params.Tc}, Tw[i - 1]), \text{params}), \text{post}(\text{expEPCM}))),$   
 $\text{error}(\text{sum}(\text{post}(\text{expEWat})), Ew[|Ew| - 1]),$   
 $\text{error}(\text{sum}(\text{post}(\text{expEPCM})), Ep[|Ep| - 1]), (\text{errorWater} > \text{ConsTol} \vee \text{errorPCM} > \text{ConsTol} \Rightarrow \text{Prints warning message(s)})$   
 exception:  $(\text{errorWater} > \text{ConsTol} \Rightarrow \text{warnWaterError} \mid \text{errorPCM} > \text{ConsTol} \Rightarrow \text{warnPCMErrors})$   
 These exceptions do not terminate the program.

### 11.4.6 Local Functions

$\text{delta}: \text{real} \times \text{real} \rightarrow \text{real}$

$\text{delta}(t1, t2) \equiv t2 - t1$

$\text{traprule}: \text{real} \times \text{real} \times \text{real} \times \text{real} \times \text{real} \rightarrow \text{real}$

$\text{traprule}(t, A1, B1, A2, B2) \equiv t \times (A1 - B1 + A2 - B2)/2$

$\text{expectedEc}: \text{real} \times \text{parameters} \rightarrow \text{real}$

$\text{expectedEc}(c, \text{params}) \equiv \text{params.hc} \times \text{params.Ac} \times c$

$\text{expectedEp}: \text{real} \times \text{parameters} \rightarrow \text{real}$

$\text{expectedEp}(p, \text{params}) \equiv \text{params.hp} \times \text{params.Ap} \times p$

$\text{expectedEw}: \text{real} \times \text{real} \rightarrow \text{real}$

$\text{expectedEw}(Ec, Ep) \equiv Ec - Ep$

sum: array of reals  $\rightarrow$  real  
 $\text{sum}(a) \equiv \sum_{i=0}^{|a|-1} a[i]$

error: real  $\times$  real  $\rightarrow$  real  
 $\text{error}(\text{exp}, \text{act}) \equiv \frac{|\text{exp}-\text{act}|}{\text{act}} \times 100$

## 12 MIS of Plotting Module

### 12.1 Module

plot

### 12.2 Uses

N/A

### 12.3 Syntax

#### 12.3.1 Exported Access Programs

Name	In	Out	Exceptions
plot	array of reals, array of reals, array of reals, array of reals, array of reals, string	-	-

### 12.4 Semantics

#### 12.4.1 State Variables

*plotFilename*: string

#### 12.4.2 Environment Variables

*directory*: The current directory of files from which the program is run.

#### 12.4.3 Assumptions

The input arrays are all of the same size.

#### 12.4.4 Access Routine Semantics

`plot(t, Tw, Tp, Ew, Ep, filename):` transition: *directory*: writes a .png file named *plotFilename* containing the graphs of the simulation results.  
exception: none

## 13 MIS of Output Module

### 13.1 Module

output

### 13.2 Uses

parameters (5)

### 13.3 Syntax

#### 13.3.1 Exported Constants

*max\_width*: integer

#### 13.3.2 Exported Access Program

Name	In	Out	Exceptions
output	string, array of reals, array of reals, array of reals, array of reals, array of reals, parameters	-	-

### 13.4 Semantics

#### 13.4.1 State Variables

*outFilename*: string

#### 13.4.2 Environment Variables

*directory*: The current directory of files from which the program is run.

### 13.4.3 Access Routine Semantics

`output(params, t, Tw, Tp, Ew, Ep, ETot, filename):` transition: *directory:* writes a .txt file named *outFilename* containing the input parameters, calculated parameters, and results of the simulation.

exception: none

## 14 Appendix

Table 2: Possible Exceptions

Message ID	Error Message
badLength	Error: Tank length must be $> 0$
badDiam	Error: Tank diameter must be $> 0$
badPCMVolume	Error: PCM volume must be $> 0$
badPCMAndTankVol	Error: PCM volume must be $<$ tank volume
badPCMArea	Error: PCM area must be $> 0$
badPCMDensity	Error: $\rho_p$ must be $> 0$
badMeltTemp	Error: $T_{melt}$ must be $> 0$ and $< T_c$
badCoilAndInitTemp	Error: $T_c$ must be $> T_{init}$
badCoilTemp	Error: $T_c$ must be $> 0$ and $< 100$
badPCMHeatCapSolid	Error: $C_{ps}$ must be $> 0$
badPCMHeatCapLiquid	Error: $C_{pl}$ must be $> 0$
badHeatFusion	Error: $H_f$ must be $> 0$
badCoilArea	Error: $A_c$ must be $> 0$
badWaterDensity	Error: $\rho_w$ must be $> 0$
badWaterHeatCap	Error: $C_w$ must be $> 0$
badCoilCoeff	Error: $h_c$ must be $> 0$
badPCMCoeff	Error: $h_p$ must be $> 0$
badInitTemp	Error: $T_{init}$ must be $> 0$ and $< 100$
badFinalTime	Error: $t_{final}$ must be $> 0$
badInitAndMeltTemp	Error: $T_{init}$ must be $< T_{melt}$

ODE_ACCURACY	<i>reltol</i> and <i>abstol</i> were not satisfied by the ODE solver for a given solution step.
ODE_BAD_INPUT	Invalid input to ODE solver
ODE_MAXSTEP	ODE solver took <i>MaxStep</i> steps and did not find solution
warnLength	Warning: It is recommended that $0.1 \leq L \leq 50$
warnDiam	Warning: It is recommended that $0.002 \leq D/L \leq 200$
warnPCMVOL	Warning: It is recommended that $V_p$ be $\geq 0.0001\%$ of $V_t$
warnVolArea	Warning: It is recommended that $V_p \leq A_p \leq (2/0.001) * V_p$
warnPCMDensity	Warning: It is recommended that $500 < \rho_p < 20000$
warnPCMHeatCapSolid	Warning: It is recommended that $100 < C_{ps} < 4000$
warnPCMHeatCapLiquid	Warning: It is recommended that $100 < C_{pl} < 5000$
warnCoilArea	Warning: It is recommended that $A_c \leq \pi * (D/2) \wedge 2$
warnWaterDensity	Warning: It is recommended that $950 < \rho_w \leq 1000$
warnWaterHeatCap	Warning: It is recommended that $4170 < C_w < 4210$
warnCoilCoeff	Warning: It is recommended that $10 < h_c < 10000$
warnPCMCoeff	Warning: It is recommended that $10 < h_p < 10000$
warnFinalTime	Warning: It is recommended that $0 < t_{final} < 86400$
warnWaterError	Warning: There is greater than $x\%$ relative error between the energy in the water output and the expected output based on the law of conservation of energy. (Where $x$ is the value of <i>ConsTol</i> )
warnPCMError	Warning: There is greater than $x\%$ relative error between the energy in the PCM output and the expected output based on the law of conservation of energy. (Where $x$ is the value of <i>ConsTol</i> )

---