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FILM-30: A Heat Transfer Properties Code for Water Coolant

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FILM-30: A Heat Transfer Properties Code for Water Coolant

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Abstract

A FORTRAN computer code has been written to calculate the heat transfer properties at the wetted perimeter of a coolant channel when provided the bulk water conditions. This computer code is titled FILM-30 and the code calculates its heat transfer properties by using the following correlations: (1) Sieder-Tate: forced convection, (2) Bergles-Rohsenow: onset to nucleate boiling, (3) Bergles-Rohsenow: partially developed nucleate boiling, (4) Araki: fully developed nucleate boiling, (5) Tong-75: critical heat flux (CHF), and (6) Marshall-98: transition boiling. FILM-30 produces output files that provide the heat flux and heat transfer coefficient at the wetted perimeter as a function of temperature. To validate FILM-30, the calculated heat transfer properties were used in finite element analyses to predict internal temperatures for a water-cooled copper mockup under one-sided heating from a rastered electron beam. These predicted temperatures were compared with the measured temperatures from the author's 1994 and 1998 heat transfer experiments. There was excellent agreement between the predicted and experimentally measured temperatures, which confirmed the accuracy of FILM-30 within the experimental range of the tests. FILM-30 can accurately predict the CHF and transition boiling regimes, which is an important advantage over current heat transfer codes. Consequently, FILM-30 is ideal for predicting heat transfer properties for applications that feature high heat fluxes produced by one-sided heating.

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Preface

The experimental data presented in this report were extracted from the doctoral thesis of Dr. Marshall. Similarly, in-depth discussions on the selection process for the heat transfer correlations and the derivation of the Marshall-98 transition boiling correlation are provided in Dr. Marshall's thesis. The reader who desires these detailed discussions is encouraged to obtain a copy of Dr. Marshall's thesis by contacting either Rensselaer Polytechnic Institute or University Microfilms International, Inc.

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Executive Summary

A FORTRAN-77 computer code has been written to predict the heat transfer properties of water when an oxygen-free, high-conductivity copper (OFHC-Cu) monoblock geometry, fusion divertor channel is heated on one side. The computer code, titled FILM-30, models all regimes of the Nukiyama boiling curve, minus film boiling. Since OFHC-Cu has a melting temperature of 1083 °C, a divertor channel machined from this material will fail as a result of surface melting and internal hoop stresses before stable film boiling is established at its wetted perimeter. Accordingly, there was no need for this version of FILM-30 to model the film boiling regime.

FILM-30 was designed to have a very modular internal programming structure in order to facilitate adding new heat transfer correlations. The code's well-engineered programming structure allows it to be optimally compiled for the UNIX workstation (Hewlett-Packard and Sun) and Microsoft DOS environments. On these machines, the program executes all of its calculations within 10 seconds of CPU time. The program has an intuitive user interface and outputs three data files that clearly describe the code's heat transfer predictions. One of the data files can be directly imported into an ABAQUS input deck for finite element analysis (FEA).

The heat transfer predictions of FILM-30 were used in FEAs and the resulting FEA thermal predictions were compared with experimental data from one-sided heat transfer experiments with water coolant. Figure 1 presents the comparison for a bare channel mockup and Figure 2 presents the comparison for a swirl tape mockup. The excellent agreement between the FEA-predicted and experimentally measured temperatures demonstrates that FILM-30 correctly predicted the heat transfer properties for the water coolant. This comparison with experimental data illustrated that FILM-30's heat transfer model is applicable when: (1) the coolant channel is bare, (2) the coolant channel has a swirl tape insert, and (3) heat transfer occurs in the forced convection, partially developed nucleate boiling, fully developed nucleate boiling, critical heat flux, and transition boiling regimes.

The range of variables for the heat transfer experiments is presented in Table 1. Since this range of variable was used to validate the correct operation of FILM-30, it is implicitly implied that the heat transfer predictions of FILM-30 are valid within this range of experimental

conditions. These experimental conditions was designed to be directly applicable to fusion devices, which makes FILM-30 an excellent tool for predicting heat transfer properties for the water-cooled components of these devices.

Table 1: Range of Validity for FILM-30

Variable	Operating Range
$Y = 0$	
Inlet Temperature (°C)	70
Inlet Velocity (m/s)	1, 4, 10
Inlet Pressure (MPa)	1
Incident Heat Flux (W/cm ²)	$40 \leq \text{IHF} \leq 1800$
$Y = 2$	
Inlet Temperature (°C)	70, 150
Inlet Velocity (m/s)	1
Inlet Pressure (MPa)	1, 4
Incident Heat Flux (W/cm ²)	$60 \leq \text{IHF} \leq 2000$

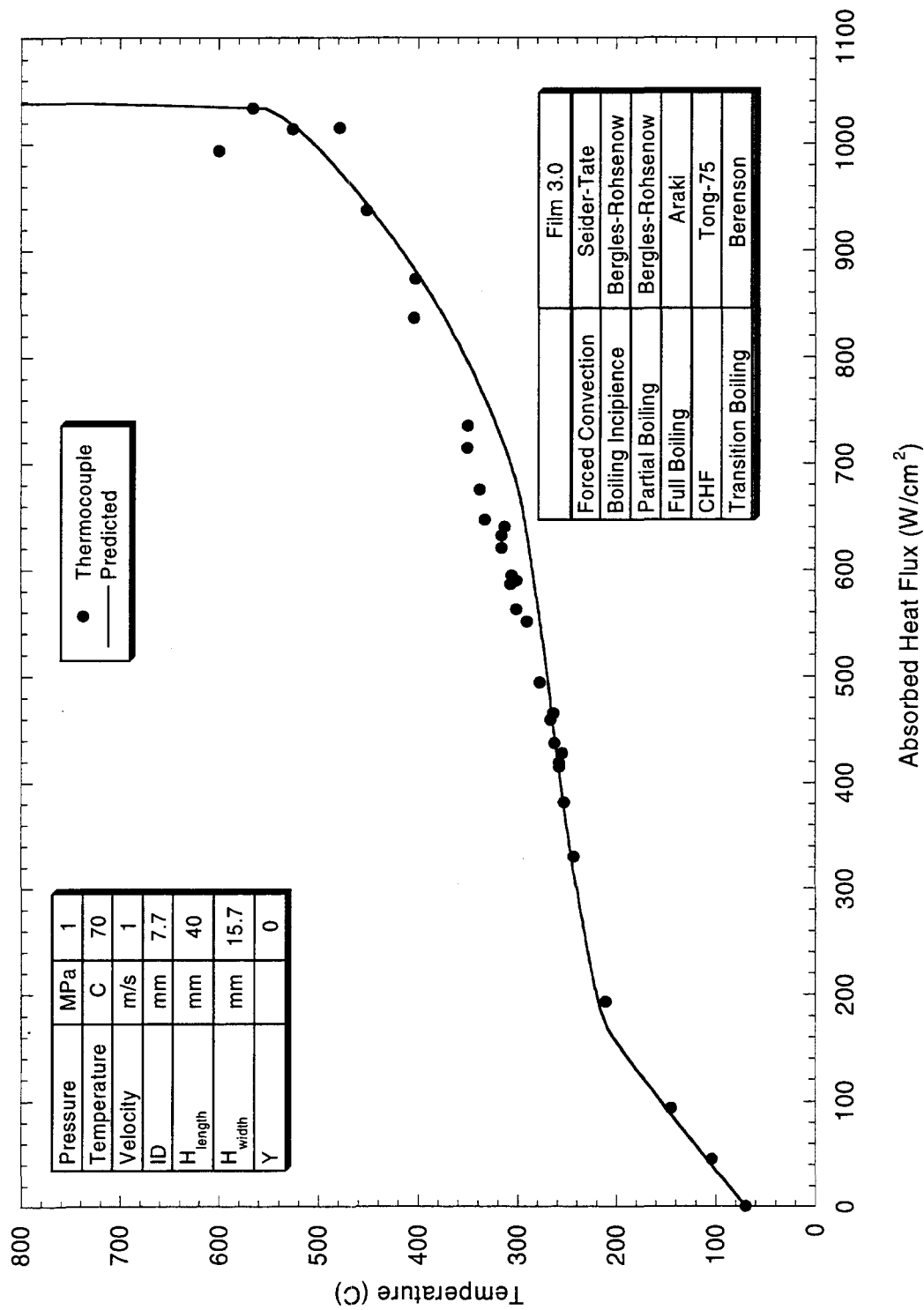


Figure 1. Experimental and predicted thermocouple temperatures for Case 1 of Marshall's experiments with bare channel mock-up.

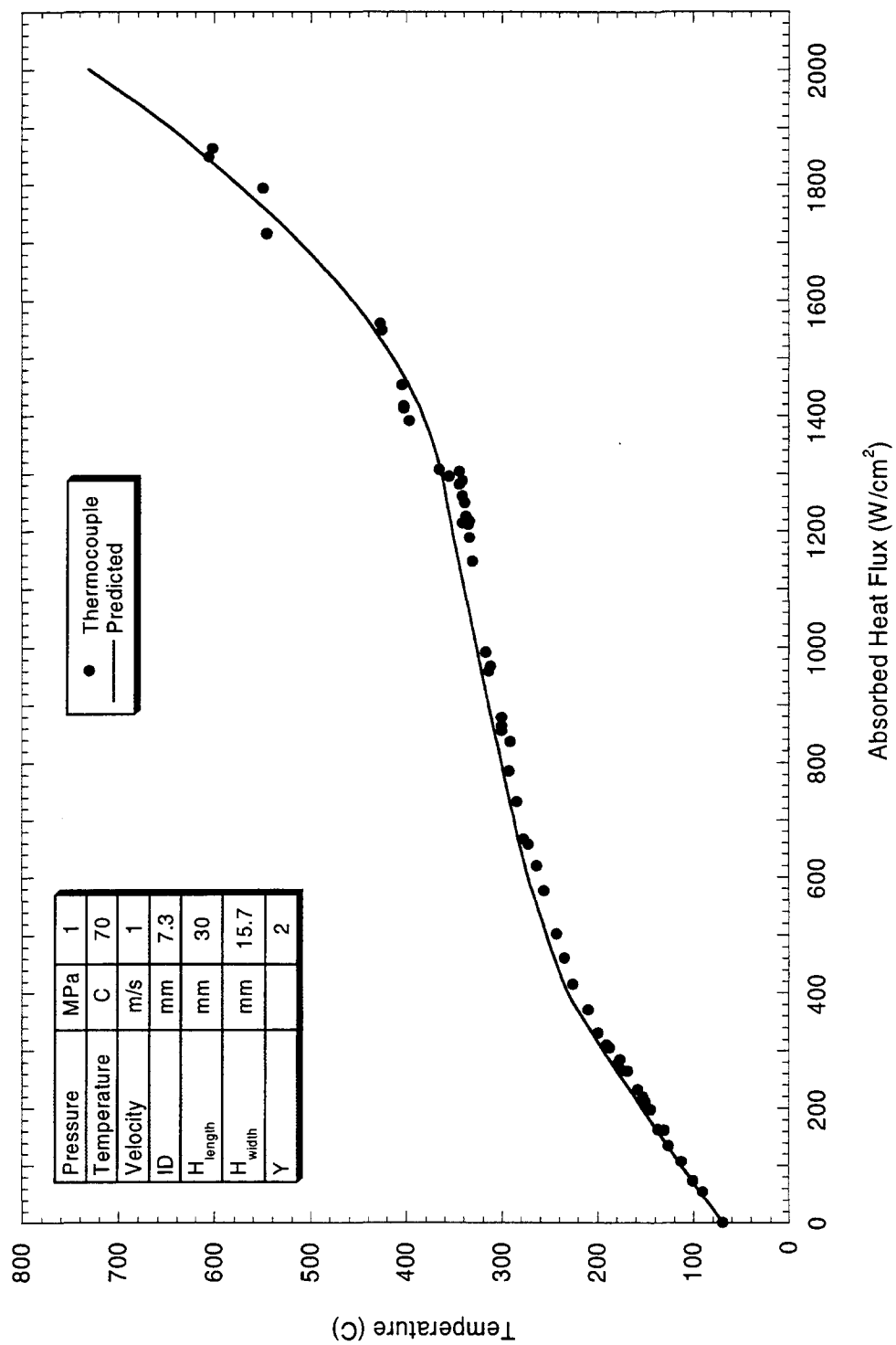


Figure 2. Experimental and predicted thermocouple temperatures for Case 1 of Marshall's experiments with swirl tape mock-up.

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Nomenclature

Acronyms

ABAQUS	finite element analysis code
CHF	critical heat flux
EBTS	Sandia's 30-kW Electron Beam Test System
FEA	finite element analysis
FEM	finite element mesh
ICHF	incident critical heat flux
IHF	incident heat flux
ITER	International Thermonuclear Experimental Reactor
MAHF	maximum achievable heat flux
OFHC-Cu	oxygen-free high-conductivity copper
PATRAN	finite element mesh modeling code
TC	thermocouple
U.S.	United States of America
WCHF	wall critical heat flux
WHF	wall heat flux

Symbols

C_p	isobaric specific heat
D	coolant channel inner diameter
f	friction factor
G	mass flux
h	heat transfer coefficient
H	enthalpy
Ja	Jakob number
k	thermal conductivity
L	length
Nu	Nusselt number
P	pressure

Pr	Prandtl number
Re	Reynolds number
T	temperature
v	velocity
Y	swirl tape twist ratio

Units

C	Celsius
cm	centimeter
K	Kelvin
kW	kilowatt
m	meter
m/s	meter per second
mm	millimeter
MPa	megaPascal
MW/m ²	megawatt per square meter
W/cm ²	watt per square centimeter

Subscripts

b	liquid bulk
bi	incipient boiling
bt	bare tube
fdb	fully developed nucleate boiling
CHF	critical heat flux
conv	forced convection
ex	exit
f	saturated liquid
fg	saturated liquid-vapor mixture
g	saturated vapor
h	hydraulic diameter
ICHF	incident critical heat flux

in	inlet
max	maximum
mod	modified
ofdb	onset to fully developed nucleate boiling
onb	onset of nucleate boiling
pb	partial boiling
sat	saturation temperature
sw	swirl tape
sub	subcooling
TB	transition boiling
tot	total
v	vapor
w	wall
WCHF	wall critical heat flux

Greek Symbols

α	void fraction
β	thermal coefficient of volumetric expansivity
δ	swirl tape thickness
ρ	density
Φ	heat flux
σ	surface tension
μ	viscosity
χ	quality

FILM-30: A Heat Transfer Properties Code for Water Coolant

1 Introduction

This report describes the FORTRAN-77 computer code written to calculate the heat transfer properties at the wetted perimeter of a coolant channel that was non-uniformly heated in the circumferential direction and used water coolant. The computer code, titled FILM-30, was written to fulfill the requirement of predicting heat transfer coefficients for a divertor coolant channel. Such a channel removes the highest heat loads in a nuclear fusion Tokamak reactor while being subjected to one-sided heating from facing the fusion plasma. Accordingly, it was important that FILM-30 predicted correct heat transfer properties for the one-sided heating and high heat flux levels anticipated for a divertor coolant channel.

FILM-30 calculates its heat transfer properties using the correlations presented in Table 1-1. With these correlations, FILM-30 calculates the Nuyikama boiling curve (see Figure 1) for the input local water conditions. The outputs from FILM-30 are data tables that provide the following information at the wetted perimeter as a function of wall temperature: heat flux and heat transfer coefficient.

Table 1-1: Correlations Used by FILM-30

Correlation	Regime of Operation
Sieder-Tate	forced convection
Bergles-Rohsenow	boiling incipience
Bergles-Rohsenow	partially developed nucleate boiling
Araki	fully developed nucleate boiling
Tong-75	critical heat flux
Marshall-98	transition boiling

In 1994 and 1998, a series of heat transfer experiments were performed that produced thermal data in all regimes of the boiling curve except that of film boiling. These experiments were performed with the parameters presented in Table 1-2. To validate that FILM-30 calculated the correct heat transfer properties, the code was run with the experimental parameters in Table 1-2 and the predicted heat transfer properties were used in a finite element analysis (FEA) code. The FEA thermal predictions exhibited excellent agreement with the experimental data in regimes of the Nuyikama curve. Accordingly, FILM-30 was demonstrated to accurately predict heat transfer properties for the range of variables in the heat transfer experiments.

Perhaps the most valuable feature of FILM-30 is its ability to accurately predict the critical heat flux (CHF) and transition boiling regimes. The use of FILM-30 in these two regimes is an improvement over other heat transfer codes. Conservatively speaking, FILM-30 is an ideal tool for predicting heat transfer properties for water-cooled applications with one-sided, high heat fluxes.

This report is organized to first discuss the heat transfer correlations that are programmed in FILM-30. The following chapter discusses the internal organization of FILM-30. Chapter 4 contains the comparison between FEA-predicted and experimentally measured thermal response curves when the predictions of FILM-30 were used in the FEA. Chapter 5 is a discussion that includes the User's Manual for FILM-30 and presents screen shots of the executing code. Known issues with the code are also presented in this chapter. Finally, Chapter 6 presents the

conclusions, including suggestions for future work. Appendices A through C present the data files output by FILM-30.

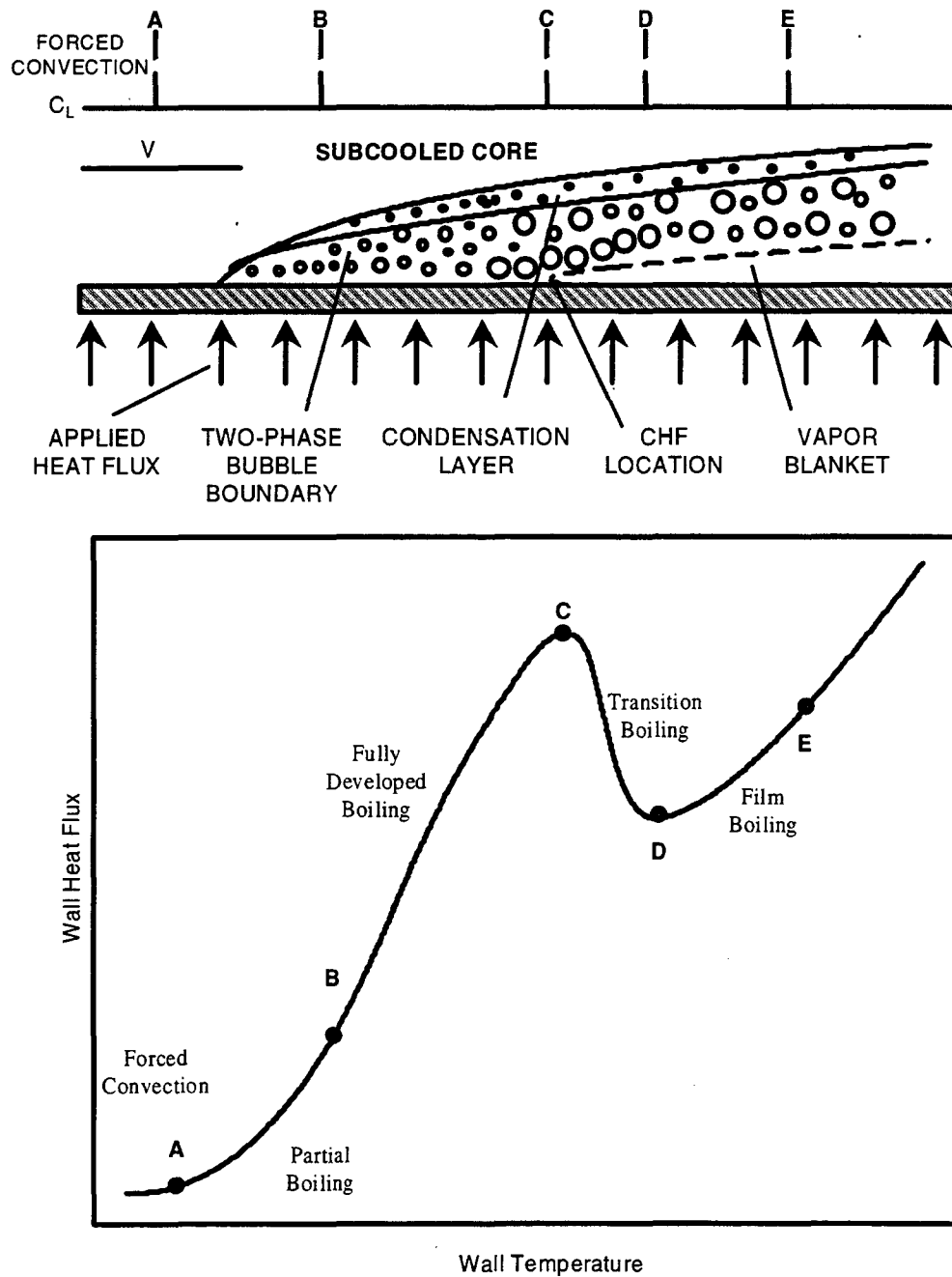


Figure 1-1: Nukiyama's Boiling Curve

Table 1-2: Experimental Parameters of Heat Transfer Experiments

Parameter	Range of Operation
<i>Mockup</i>	
Geometry	square monoblock
Material	OFHC-Cu
Twist Ratio	0 and 2
<i>Inlet Water Conditions</i>	
Temperature (°C)	70 and 150
Velocity (m/s)	1, 4, and 10
Pressure (MPa)	1 and 4
<i>Incident Heat Flux</i>	
Distribution	one-sided (one face of the mockup)
Level (W/cm ²)	40 < IHF < 2000

2 Heat Transfer Correlations of FILM-30

2.1 Introduction

This chapter presents the heat transfer correlations used in FILM-30. There are actually two sets of correlations available in FILM-30. The primary set of correlations is discussed here. These correlations predict heat transfer properties that agree very well with the author's experimental data. The secondary set of correlations was included in FILM-30 for comparison to its predecessor. This secondary set of correlations did not agree well with the author's experimental data [1], therefore it is not discussed in this report. The user can access the secondary set of correlations in FILM-30, but the default configuration uses the primary set of

correlations, which are the basis for this report.

The subsections of this chapter present only the mathematical form of the various heat transfer correlations. For in-depth discussions on the correlations, the reader is directed to the thesis of Marshall [1].

2.2 Heat Transfer Correlations

2.2.1 Forced Convection

For the forced convection heat transfer coefficient predictions of FILM-30, the Sieder-Tate [2] is used. The experimental range of Sieder-Tate is shown in Table 2-1. The correlation is written as:

$$\begin{aligned} Nu &= 0.027 Re^{0.8} Pr^{1/3} \left(\frac{\mu_b}{\mu_w} \right)^{0.14} \\ Nu &= \frac{h_{fc} D_h}{k} \quad Pr = \frac{C_p \mu_b}{k} \quad Re = D_h \cdot \left(\frac{v_b \rho_b}{\mu_b} \right) \\ h_{fc} &= \left(\frac{k}{D_h} \right) \cdot \left[0.027 Re^{0.8} Pr^{1/3} \left(\frac{\mu_b}{\mu_w} \right)^{0.14} \right] \end{aligned}$$

where

- C_p = specific heat at constant pressure (J/kg-K)
- D_h = hydraulic diameter (m)
- h_{fc} = forced convection heat transfer coefficient (W/m²-K)
- k = bulk liquid thermal conductivity (W/m-K)
- ρ_b = bulk liquid density (kg/m³)
- μ_b = bulk liquid viscosity (kg/m-s)
- μ_w = wall liquid viscosity (kg/m-s)
- v_b = bulk liquid velocity (m/s)

Table 2-1: Experimental Range of Sieder-Tate Correlation

Parameter	Range of Operation
heated length divided by tube inner diameter	$L/D \leq 60$
Reynolds number	$2,000 \leq Re \leq 10,000$

2.2.2 Boiling Incipience

The heat transfer coefficient at the incipience of boiling is calculated by using the Bergles-Rohsenow [3] incipient boiling correlation. The experimental range of the incipient boiling correlation is shown in Table 2-2. The correlation is written as,

$$(T_w - T_{sat}) = 0.556 \left[\frac{\Phi_{bi}}{1082 \cdot P^{1.156}} \right]^{0.463 P^{0.0234}}$$

where P = pressure (bar)

Φ_{bi} = incipient boiling heat flux (MW/m²)

T_w = wall temperature (°C)

T_{sat} = saturation temperature (°C)

The correlation can also be expressed in terms of the heat flux as,

$$\Phi_{bi} = 1082 P^{1.156} [1.799(T_w - T_{sat})]^{2.1598} P^{-0.0234}$$

Table 2-2: Experimental range of Bergles-Rohsenow Boiling Incipience Correlation

Parameter	Range of Operation
coolant	water
Pressure (MPa)	$0.1 < P < 13.8$

2.2.3 Partially Developed Nucleate Boiling

FILM-30 uses the Bergles-Rohsenow [3] partial nucleate boiling correlation. The correlation is written as:

$$\Phi_{pb} = \Phi_{fc} \sqrt{1 + \left[\frac{\Phi_{fdb}}{\Phi_{fc}} \left(1 - \frac{\Phi_{bi}}{\Phi_{fdb}} \right) \right]^2}$$

where Φ_{bi} = heat flux at point of incipient boiling (W/m^2)

Φ_{fc} = heat flux in forced convection regime (W/m^2)

Φ_{fdb} = heat flux in fully developed nucleate boiling regime (W/m^2)

Φ_{pb} = heat flux in partially developed nucleate boiling regime (W/m^2)

2.2.4 Fully Developed Nucleate Boiling

The heat flux at the cooling channel wall in the fully developed nucleate boiling regime is calculated by FILM-30 using the Araki [4] correlation. The experimental parameters for the Araki correlation are presented in Table 2-3. This correlation is written as:

$$\Delta T_{sat} = 25.72 (\Phi_{fdb})^{0.3333} e^{\frac{P}{8.6}}$$

which in terms of the heat flux is:

$$\Phi_{fdb} = \left(\frac{\Delta T_{sat}}{25.72 e^{\frac{P}{8.6}}} \right)^3$$

where P = pressure (MPa)

Φ_{fdb} = heat flux, (MW/m^2)

ΔT_{sat} = wall superheat, $T_w - T_{sat}$ ($^{\circ}\text{C}$)

Table 2-3: Experimental Range of Araki Correlation

Parameter	Range of Operation
Tube diameter (mm)	10
Twist Ratio	0 and 3
Velocity (m/s)	$4.2 \leq v \leq 16$
Pressure (MPa)	$0.5 \leq P \leq 1.3$
Water temperature (°C)	$20 \leq T \leq 80$
Incident heat flux (MW/m ²)	$2 \leq \Phi \leq 50$

2.2.5 Critical Heat Flux

The Tong-75 [5] correlation was selected for FILM-30's predictions of the critical heat flux (CHF). The experimental range of the correlation is shown in Table 2-4 and the correlation is written as:

$$\Phi_{CHF} = 0.23 f_o G H_{fg} (1 + 0.00216 P_{ratio}^{1.8} Re^{0.5} Ja)$$

$$f_o = 8.0 Re^{-0.6} D_{ratio}^{0.32} \quad D_{ratio} = \frac{D_h}{D_o}$$

$$P_{ratio} = \frac{P}{P_{crit}} \quad Ja = -X_{sub} \frac{\rho_l}{\rho_v} \quad X_{sub} = \frac{-C_p \Delta T_{sub}}{H_{fg}}$$

where

- C_p = isobaric specific heat (J/kg-°C)
- D_o = reference inner diameter (0.0127 m)
- D_h = hydraulic diameter of cooling channel (m)
- f_o = Fanning friction factor
- G = the mass flux (kg/m²-s)
- H_{fg} = latent heat of vaporization (J/kg)
- Ja = Jakob number
- P = water pressure (MPa)

P_{crit} = critical pressure of water (22.089 MPa)

ρ_l = density of liquid bulk (kg/m^3)

ρ_v = density of vapor at the liquid bulk temperature (kg/m^3)

ΔT_{sub} = degree of subcooling, $T_{\text{sat}} - T_b$ ($^{\circ}\text{C}$)

X_{sub} = quality of subcooled liquid bulk

Table 2-4: Experimental Range of Tong-75 Correlation

Parameter	Range of Operation
Heated Length (m)	~ 4
CHF (MW/m^2)	$1 \leq \Phi_{\text{CHF}} \leq 2$

2.2.6 Transition Boiling

The Marshall-98 [1] correlation was selected for FILM-30's predictions of the heat flux in the transition boiling regime. The experimental range of the correlation is presented in Table 2-5 and the correlation is written as:

$$\Phi_{\text{TB}} = \Phi_{\text{CHF}} \cdot \left[\frac{T_w - T_s}{T_{\text{CHF}} - T_s} \right]^{-0.23}$$

where Φ_{CHF} = critical heat flux (MW/m^2)

Φ_{TB} = transition boiling heat flux (MW/m^2)

T_{CHF} = wall temperature at local CHF ($^{\circ}\text{C}$)

T_s = saturation temperature at liquid bulk pressure ($^{\circ}\text{C}$)

T_w = wall temperature ($^{\circ}\text{C}$)

Table 2-5: Experimental Range of Marshall-98 Correlation

Variable	Operating Range
Inlet Temperature ($^{\circ}\text{C}$)	70
Inlet Velocity (m/s)	1, 4, and 10
Inlet Pressure (MPa)	1
Incident Heat Flux (W/cm^2)	$40 \leq \text{IHF} \leq 1800$

2.3 Swirl Tape Inserts

When the cooling channel features a swirl tape insert, correction factors must be applied to the previously described heat transfer correlations. The following subsections discuss the correction factor derived for each of the correlations. For all cases, the experimental range for the correlation is the same as in Marshall's experiments. These ranges are presented in Table 2-7.

Prior to discussing the swirl tape correction factors, it is important to define the term «swirl tape twist ratio». The defining characteristic of a swirl tape insert is its twist ratio. The twist ratio of the tape is determined as the number of tube inner diameters per the pitch length for 180° rotation of the twisted tape. Mathematically the twist ratio can be written as:

$$Y = \frac{L}{D}$$

where Y = twist ratio

L = length for 180° turn of swirl tape (cm)

D = inner diameter of coolant channel (cm)

Table 2-6: Experimental Range of Marshall's Swirl Tape Experiments

Variable	Operating Range
Swirl Tape Material	SS-316
Twist Ratio	2
Inlet Temperature (°C)	70 and 150
Inlet Velocity (m/s)	1
Inlet Pressure (MPa)	1 and 4
Incident Heat Flux (W/cm ²)	60 ≤ IHF ≤ 2000

The following subsections present the swirl tape correction factors that were defined by Marshall. It is important to note that the correction factor is unit-less. Thus, the units that were defined in Section 2.2 for the heat transfer correlations remain unchanged. For brevity, the units are not repeated in this section.

2.3.1 Forced Convection

For the swirl tape insert, the Sieder-Tate correlation is modified as follows:

$$h_{sw} = h_{bt} \cdot 1.42 \left[(2.26 \cdot Y^{-0.248}) \right]$$

$$h_{sw} = \left[\left(\frac{k}{D} \right) 0.027 \text{Re}^{0.8} \text{Pr}^{1/3} \left(\frac{\mu_b}{\mu_w} \right)^{0.14} \right] \cdot [1.42 (2.26 \cdot Y^{-0.248})]$$

where h_{sw} = swirl tape heat transfer coefficient (W/cm^2)
 h_{bt} = bare tube heat transfer coefficient (W/cm^2)
 Y = swirl tape twist ratio

2.3.2 Boiling Incipience

No modification is required for the Bergles-Rohsenow boiling incipience correlation to correctly work with a swirl tape insert.

2.3.3 Partially Developed Nucleate Boiling

No modification is required for the Bergles-Rohsenow partially developed nucleate boiling correlation to correctly work with a swirl tape insert.

2.3.4 Fully Developed Nucleate Boiling

No modification is required for the Araki correlation to correctly work with a swirl tape insert.

2.3.5 Critical Heat Flux

For the swirl tape insert, the Tong-75 correlation is modified as follows:

$$f_{sw} = f_0 \cdot 0.95 [2.75 \cdot (Y)^{-0.406}]$$

$$f_0 = 8.0 \text{Re}_{sw}^{-0.6} D_{ratio,sw}^{0.32}$$

$$D_{ratio,sw} = \frac{D_{sw}}{D_0}$$

$$D_{sw} = 4 \cdot \left(\frac{\frac{\pi D^2}{4} - \delta D}{\frac{\pi D}{2} - \delta + D} \right)$$

$$\text{Re}_{sw} = \frac{G D_{sw}}{\mu}$$

The modified Tong-CHF correlation for swirl tape tubes is thus defined as:

$$\Phi_{crit} = 0.23 f_{sw} G H_{fg} (1 + 0.00216 P_{ratio}^{1.8} \text{Re}_{sw}^{0.5} \text{Ja})$$

where D_0 = reference inner diameter (0.0127 m)

D_{sw} = swirl tape tube modified-diameter (m)

f_{sw} = swirl tape tube modified friction factor

Re_{sw} = swirl tape tube modified Reynolds number

Y = swirl tape twist ratio

2.3.6 Transition Boiling

No modification is required for the Marshall-98 correlation to correctly work with a swirl tape insert.

3 Program Philosophy

3.1 Introduction

The programming of FILM-30 was accomplished under three directives:

- use heat transfer correlations that were proven to be correct with one-sided, high heat flux heating conditions
- maintain the legacy of Sandia's former heat transfer prediction code, which was deemed necessary for comparison purposes
- use a highly modular format to facilitate updates to the code

The previous chapter discussed the heat transfer correlations that are used in FILM-30.

The predecessor to FILM-30 will henceforth be referenced as FILM. Both FILM-30 and FILM use Sieder-Tate and Tong-75 for respective modeling of the forced convection and local CHF. However, there are no other similarities between the two codes.

In addition to the issue of internal structure, FILM-30 and FILM differ in their respective approach to modeling heat transfer properties. FILM models the forced convection regime through its use of the Sieder-Tate correlation. The code does not calculate the incipience of boiling since the code uses Koski's method of modeling the partial nucleate boiling regime, which does not require the incipience of boiling. For the fully developed nucleate boiling regime, FILM uses the Thom correlation. FILM uses Tong-75 for the local CHF and the Groenveld-Stewart and Berenson correlations for the respective transition and film boiling regimes. In his doctoral thesis, Marshall illustrated that these two correlations do a very poor job of matching the post-CHF data from his experiments.

The remainder of this chapter provides a detailed discussion on the modeling approach and internal organization of FILM-30. These two components of the code's design are the principal reasons for FILM-30 being the superior analysis tool when compared to FILM.

3.2 Internal Organization

Since heat transfer research in the fusion discipline is an ongoing activity, it was considered paramount that FILM-30 allowed new correlations to be easily incorporated. This design objective implied that the core of the code did not require any modifications when new subroutines were added. To fulfill the aforementioned requirement, FILM-30 was given a highly modular format. In addition, great care was taken to ensure that the code was extremely consistent in its use of subroutines, functions, and programming protocol. Examples of the stringent programming protocol are:

- programming code that perform any type of calculation are written as double-precision floating point functions
- all other programming code are written as independent subroutines, with each subroutine having only one assigned task
- to insure their proper definition throughout the code, variables are passed to subroutines exclusively through the use of ordered and named COMMON statements
- variables are passed to functions via the parameter list
- each function and subroutine has a header section that lists the input variable(s), the output variable(s), the engineering units used, and the literature reference for

the correlation or procedure used within the function or subroutine.

3.2.1 Engineering Units

In the interest of minimizing calculation errors, an exclusive set of engineering units was used. Variables in the main body of the program have the units shown in Table 3-1. Some of the heat transfer correlations programmed in FILM-30 required input variables with engineering units other than the ones in Table 3-1. In these cases, the FORTRAN function that contains the correlation makes the necessary change in units to allow the correlation to correctly calculate its value. However, this change in engineering units remains internal to that particular function. When the function returns its calculated value to the main program, that value is in the engineering units of Table 3-1.

Table 3-1: Engineering Units of FILM-30

Variable	Engineering Units
Velocity	m/s
Temperature	°C
Pressure	MPa
Heat transfer coefficient	W/cm ² -K
Diameter	m
Heat flux	W/cm ²

3.2.2 Output Files

Figure 3-1 outlines the organization of FILM-30. In the figure, subroutines for the program are represented by boxes and the number printed in each box indicates that subroutine's position in the program's sequence of operation. The first subroutine called in Figure 3-1 is

OPENUNITS. This subroutine prepares the four data files that are generated by FILM-30. The data files are: errmsg.dat, filmp.dat, hfilm.dat, and hplot.dat. All of the files are in ASCII format so that they are readable by most text editors.

Errmsg.dat reports any run-time error messages that the program generates. If there were no errors encountered, the program automatically erases this file when the calculations are completed. By default, the program sends a message to the user's computer screen informing him/her if the calculations were successfully completed. If the program does not issue this message, then the user should open and read errmsg.dat. In errmsg.dat, the program writes,

1. the type of error encountered
2. the subroutine that produced the error
3. any suggested corrections.

If the error resulted because the user requested a correlation that is not currently supported, FILM-30 references the default set of correlations for its calculations. This default set is comprised of the correlations that were presented in Chapter 2. Upon completion of the calculations, the program directs the user to errmsg.dat in order to view the correlations that were actually used.

Filmp.dat (Appendix B) is an output file that is designed to be directly imported into an ABAQUS input deck as the film property table, *FILMP. The finite element analysis (FEA) program ABAQUS is discussed in Marshall's thesis. When writing filmp.dat, FILM-30 uses the ABAQUS comment characters, '**', to inform the user about the generated film property table. This information includes the temperature-based transition points on the boiling curve, i.e., the onsets of nucleate boiling, fully developed nucleate boiling, and local CHF. Filmp.dat also reports the inlet water conditions that were used to calculate the corresponding boiling curve. Since it is specifically formatted for ABAQUS conventions and can be directly imported into an ABAQUS input deck, filmp.dat provides an excellent and essentially error-free path for using the predictions of FILM-30 in the FEAs performed with ABAQUS.

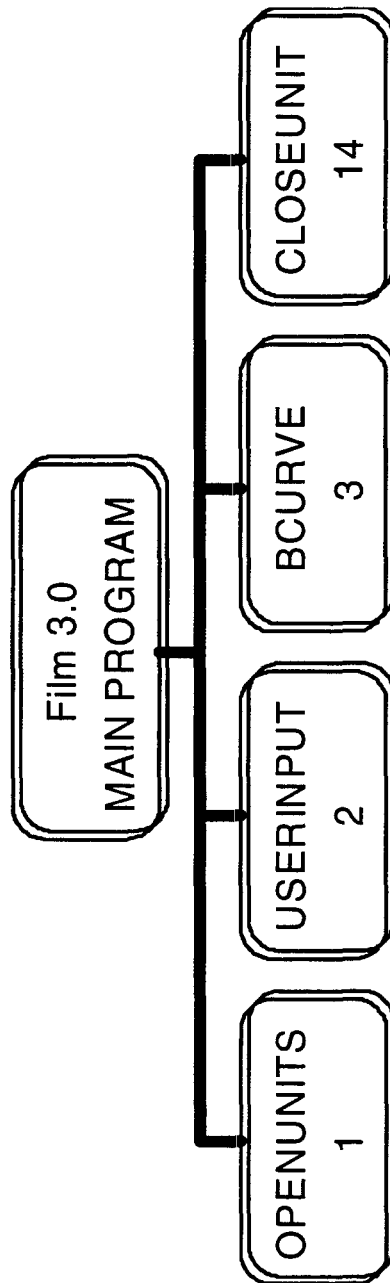


Figure 3-1a: Schematic of FILM-30's organization

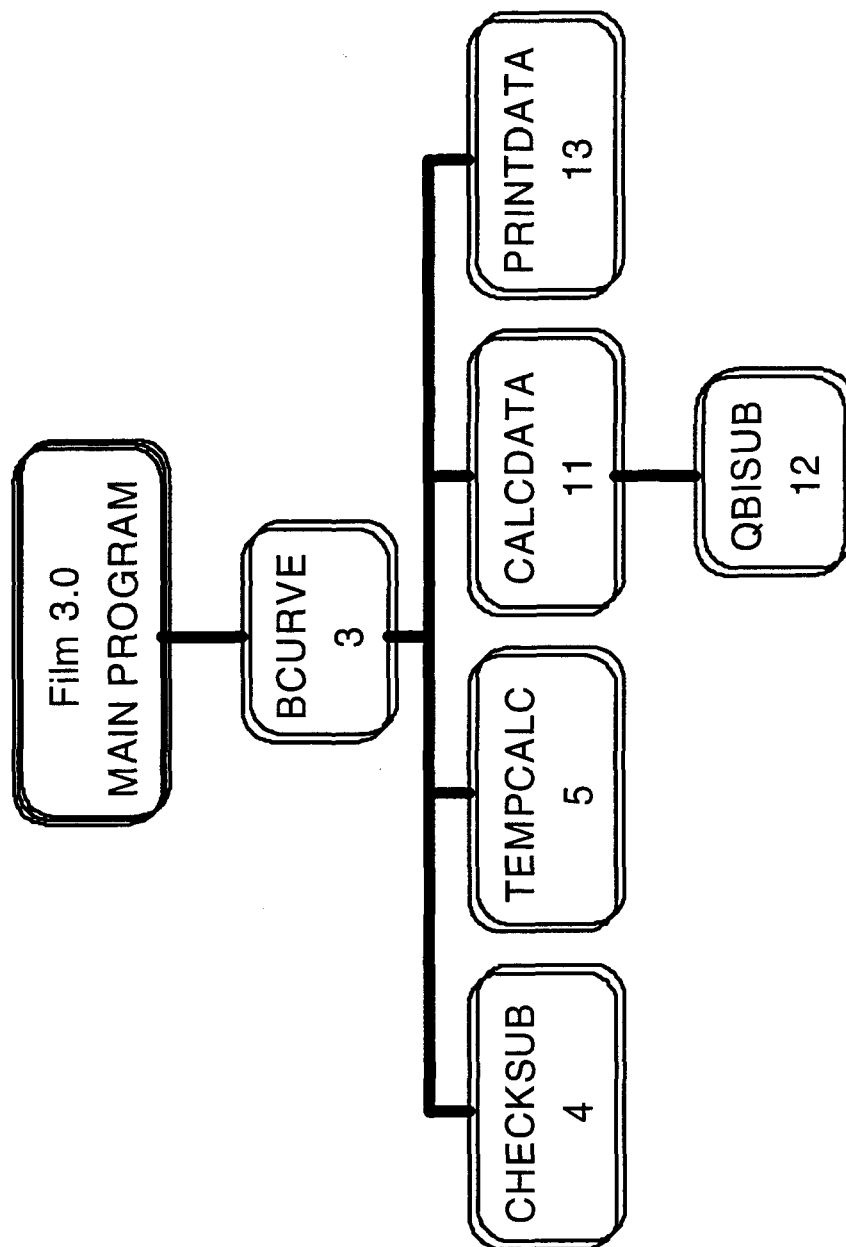


Figure 3-1b: Schematic of FILM-30's organization (continued)

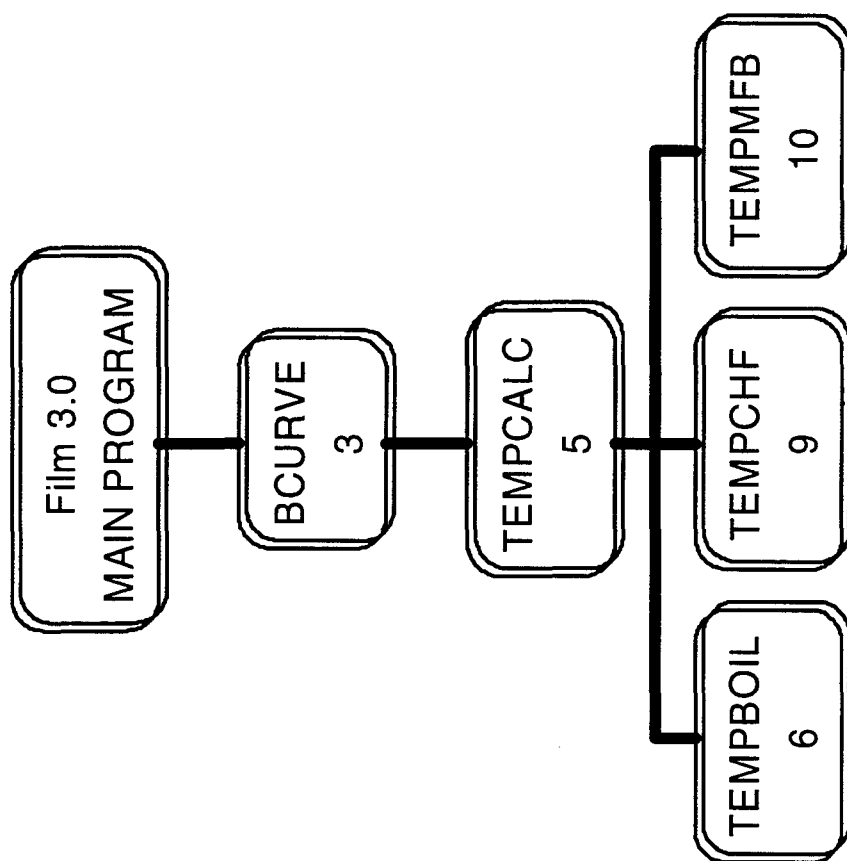


Figure 3-1c: Schematic of FILM-30's organization (continued)

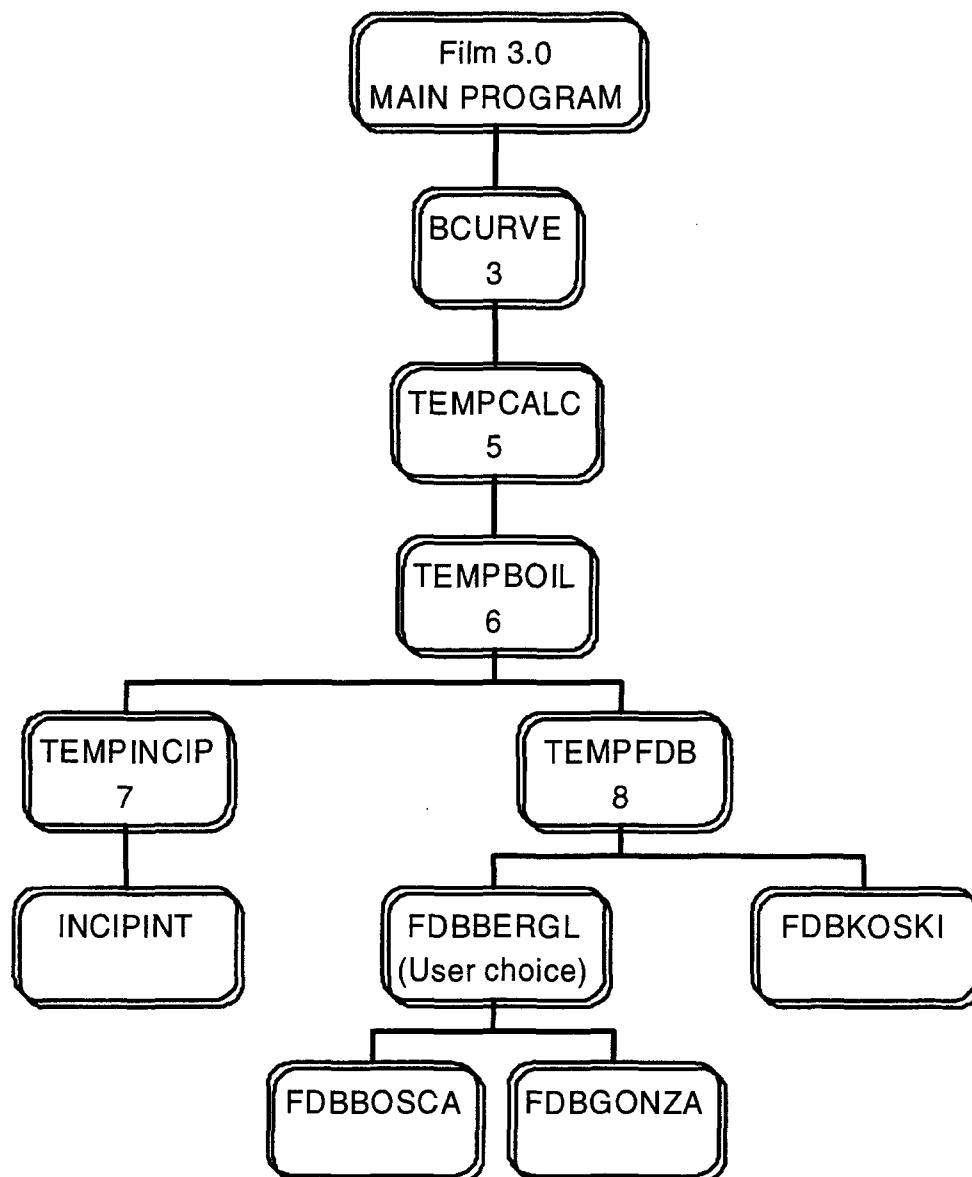


Figure 3-1d: Schematic of FILM-30's organization (continued)

Hfilm.dat (Appendix A) contains detailed information on the heat transfer properties calculated by FILM-30. The heat transfer coefficient, correlation used to calculate the coefficient, and regime of the boiling curve associated with the coefficient is provided for every wall temperature listed in Hfilm.dat. Since it is often desired to plot the heat transfer coefficient and wall heat flux (WHF) as a function of wall temperature, a separate file called hplot.dat (Appendix C) is written that contains only these data. With its space delimited columns of data, hplot.dat is easily imported into most plotting programs.

3.2.3 Subroutines

The inlet water conditions and correlations selection are input into FILM-30 via the **USERINPUT** subroutine, see Figure 3-1. The subroutine has a scrolling menu (Appendix A) that presents the available options to the user and accepts the appropriate selection. There are defaults for each of the correlation selection options. As presented in Chapter 2. Table 3-2 shows the correlations currently available in FILM-30.

Subroutine **BOILCURVE** is subsequently called and its first subroutine, **CHECKSUB**, compares the input data from the user against the program's list of available correlations. If **CHECKSUB** determines that the user has requested a correlation that is currently unavailable, it selects the default correlation and notifies the user at his/her computer screen.

Subroutine **TEMPCALC** calculates the transition temperatures for the various regimes of the boiling curve. These temperatures are those associated with

- boiling incipience
- onset of fully developed nucleate boiling
- critical heat flux

Boiling incipience is determined with subroutines **TEMPINCIP** and **INCIPINT**, where **INCIPINT** uses the Bergles-Rohsenow correlation. **TEMPINCIP** is a decision junction that easily allows other boiling incipience correlations to be added.

Table 3-2: Correlation Options for FILM-30

Boiling Curve Regime	Available Correlations	Default
Forced Convection	1. Dittus 2. Sieder-Tate	Sieder-Tate
Boiling Incipience	Bergles-Rohsenow	Bergles-Rohsenow
Partial Nucleate Boiling	1. Bergles-Rohsenow 2. Koski	Bergles-Rohsenow
Fully Developed Nucleate Boiling	1. Araki 2. Thom	Araki
Critical Heat Flux	Tong-75	Tong-75
Transition Boiling	1. Marshall-98 2. Groeneveld-Stewart	Marshall-98
Minimum Film Boiling Temperature	1. Groeneveld-Stewart 2. Groeneveld-Marshall	<u>not required with Marshall-98</u>
Film Boiling	Groeneveld-Berenson	<u>not required with Marshall-98</u>

TEMPFDB calculates the onset to fully developed nucleate boiling using the Bergles-Rohsenow method. There are two methods of applying the Bergles-Rohsenow correlation, one derived by Dr. Jean Boscary and the other by Dr. Jorge Gonzalez. Numerically, the two methods produce very similar results. The option of choosing between the correlations was provided to assist users who were more comfortable with one of the correlations.

The wall temperature at the local CHF point is calculated by **TEMPCHF**. The user-selected CHF correlation is used to calculate the local CHF. This heat flux is subsequently used with the user-selected correlation for the fully developed nucleate boiling regime to calculate the corresponding wall temperature.

As explained in his thesis, Marshall's modeling of the boiling curve is for an oxygen-free, high-conductivity copper (OFHC-Cu) mockup. This mockup fails due to surface melting and internal hoop stresses prior to the onset of stable film boiling so Marshall did not include the film boiling regime in his post-CHF modeling. Thus, when the user selects the Marshall-98

correlation for the transition boiling regime, the minimum film boiling temperature and film boiling regime are not used in the calculations of FILM-30. Instead, the program uses Marshall-98 to a maximum wall temperature of 1000 °C. This 1000 °C limit is the approximate melting temperature of OFHC-Cu. This 1000 °C limit was used as the temperature limit for FILM-30's calculations although it is well understood that the mockup will fail before the wetted perimeter temperature reaches such a value.

Once the transition temperatures are calculated, it is possible to define heat transfer coefficients for the entire boiling curve. In Figure 3-1, subroutine **CALCDATA** performs this task. A detailed discussion on **CALCDATA** is provided below. Prior to that presentation, the remaining subroutines in Figure 3-1 are discussed.

The two remaining subroutines in Figure 3-1 are **PRINTDATA** and **CLOSEUNIT**. **PRINTDATA** writes the calculated heat transfer coefficients, wall temperatures and WHFs to the aforementioned four data files. **CLOSEUNIT** closes the data files so that the user may view them. **CLOSEUNIT** also checks the processing error flag to determine if there were any errors during the calculations. If the error flag is not set, the file errmsg.dat is erased.

3.2.4 Functions

FILM-30 contains 14 FORTRAN subroutines. These subroutines are primarily decision junctions, with the actual calculations being performed in FORTRAN functions. Accordingly, it is necessary to discuss the functions that were programmed in FILM-30. The reader is reminded that the first level functions are called by the subroutines presented in Figure 3-1. Figure 3-2 shows that the subroutine **BCURVE** has only one function call. This function, **TEMPSAT**, calculates the saturation temperature, T_{sat} , at the pressure input by the user. Since



Figure 3-2: Function call of **BCURVE** subroutine

T_{sat} is used by nearly all of the correlations, it has to be calculated first, thus the reason for it

being called by the master subroutine, **BCURVE**.

Figure 3-3 outlines the function organization for the **TEMPINCIP** subroutine. There is a simple protocol to all of the function organization charts. Functions with the letter “H” as the first letter in their name are procedures that output the heat transfer coefficient. Likewise, functions with the letter “T” as the first letter in their name are procedures that output temperatures. In addition, boxes on the far right of function organization charts are typically procedures that predict water properties for the given inlet conditions. Exceptions to the rule are functions who subordinate functions that have been previously described.

In Figure 3-3, the subroutine **INCIPINT** calculates the temperature where the heat flux from the user-selected forced convection correlation equals the heat flux from the user-selected onset to nucleate boiling correlation. At the time of this writing, there was only one onset to nucleate boiling correlation, **ONSTBERGL**, thus the single path for the subroutine **ONSTBOIL**.

Figure 3-2 shows one function that calculates a water property, that is, the saturation temperature at a given pressure, while Figure 3-3 shows four functions that calculate water properties, namely thermal conductivity, Prandtl number, specific volume, and viscosity. Table 3-3 lists the water properties required by the functions presented in Figures 3-2 and 3-3. All of the thermal-hydraulic

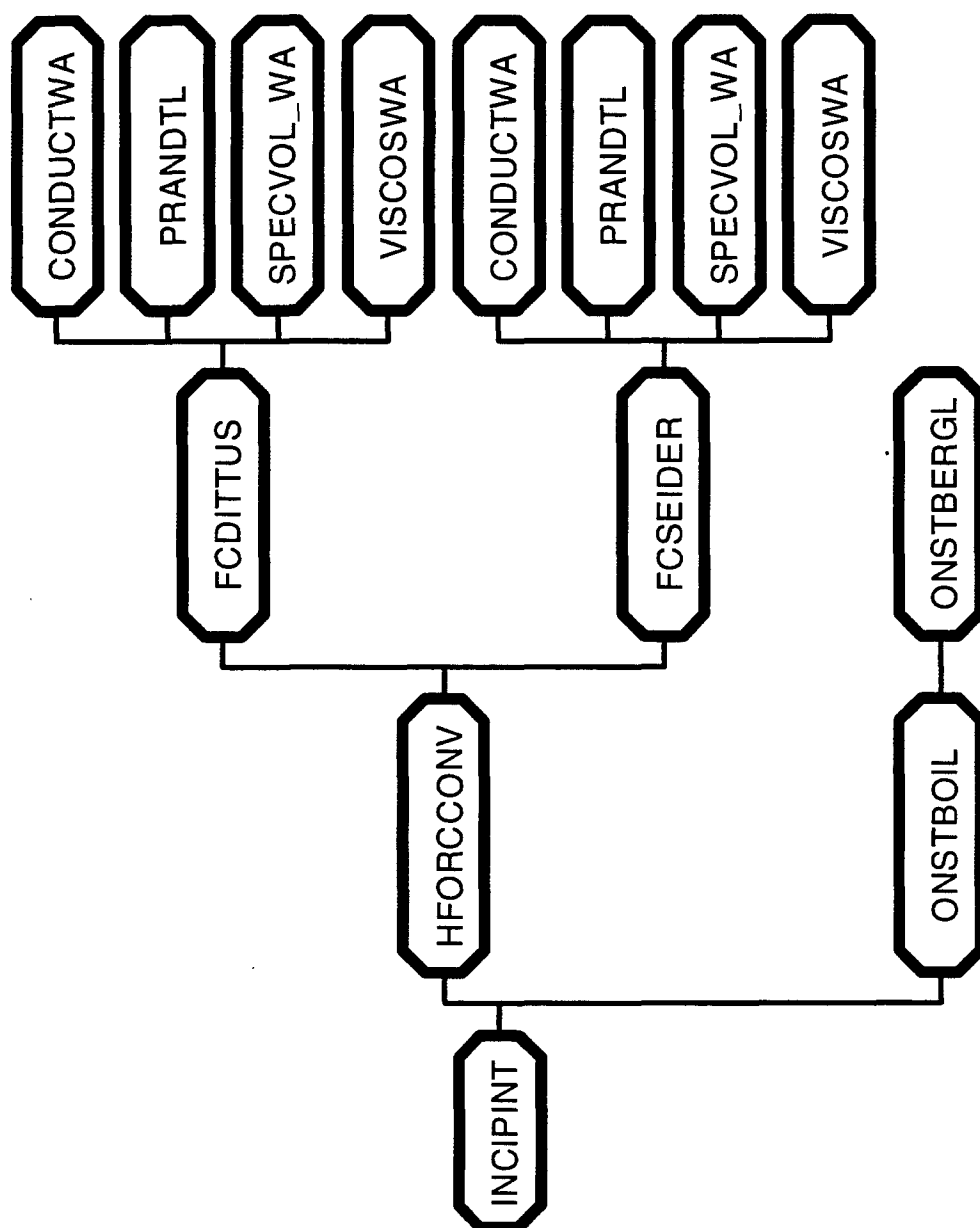


Figure 3-3: Function calls of **TEMPINCIP** subroutine

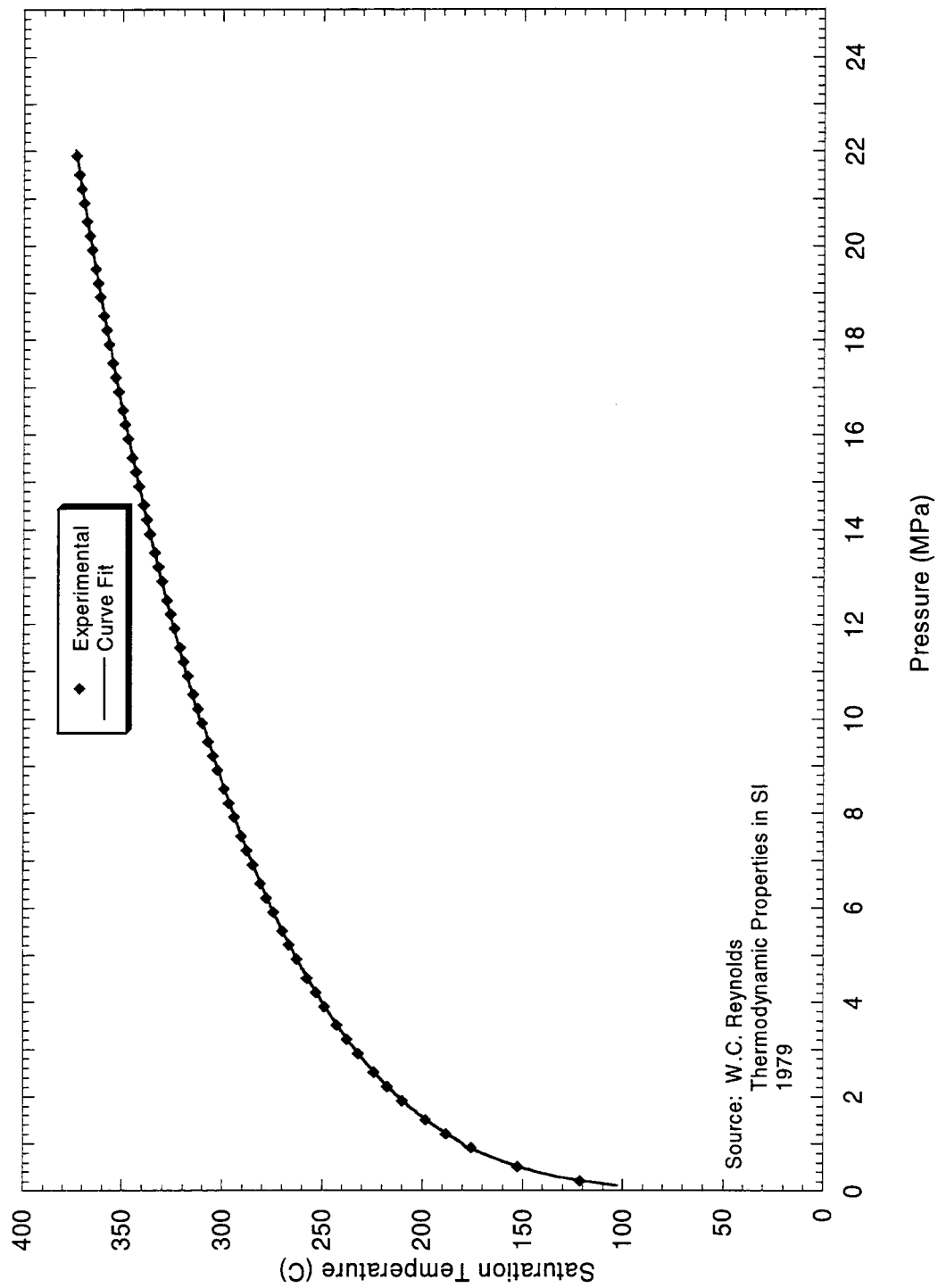


Figure 3-4 : Curve fit of the saturation temperature of water used for FILM-30

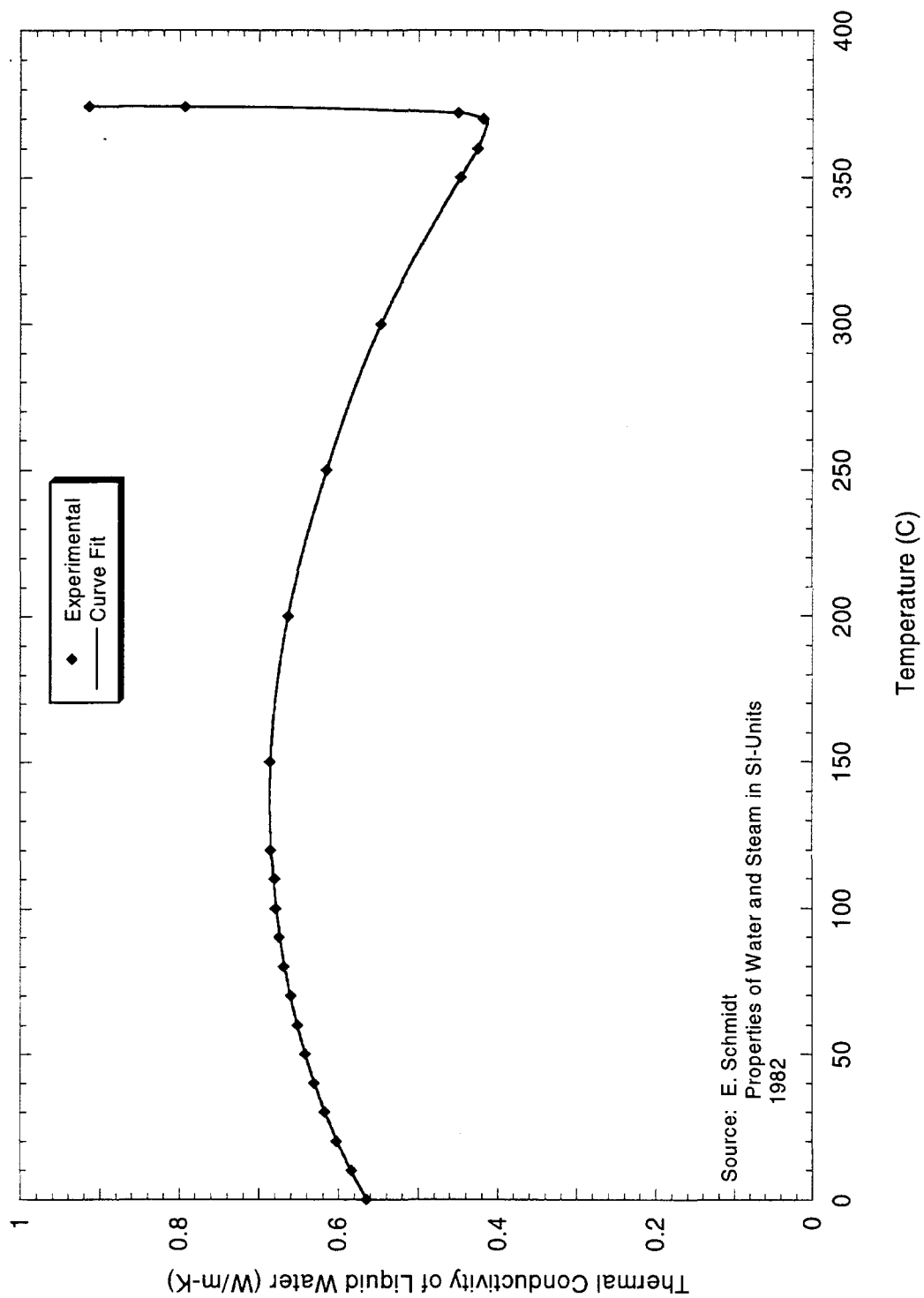


Figure 3-5: Curve fit of the thermal conductivity of water used for FILM-30

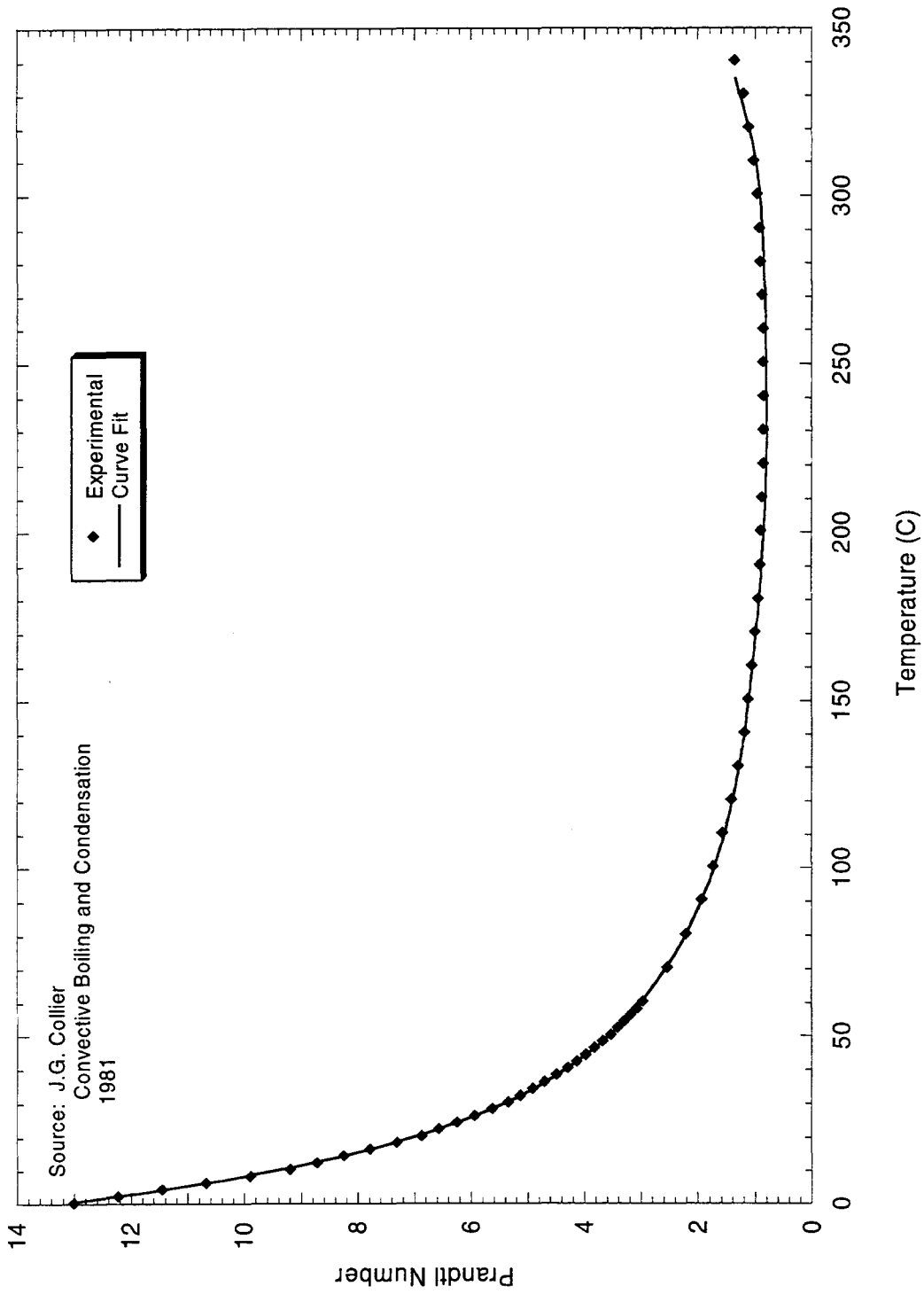


Figure 3-6: Curve fit of the Prandtl number for water used for FILM-30

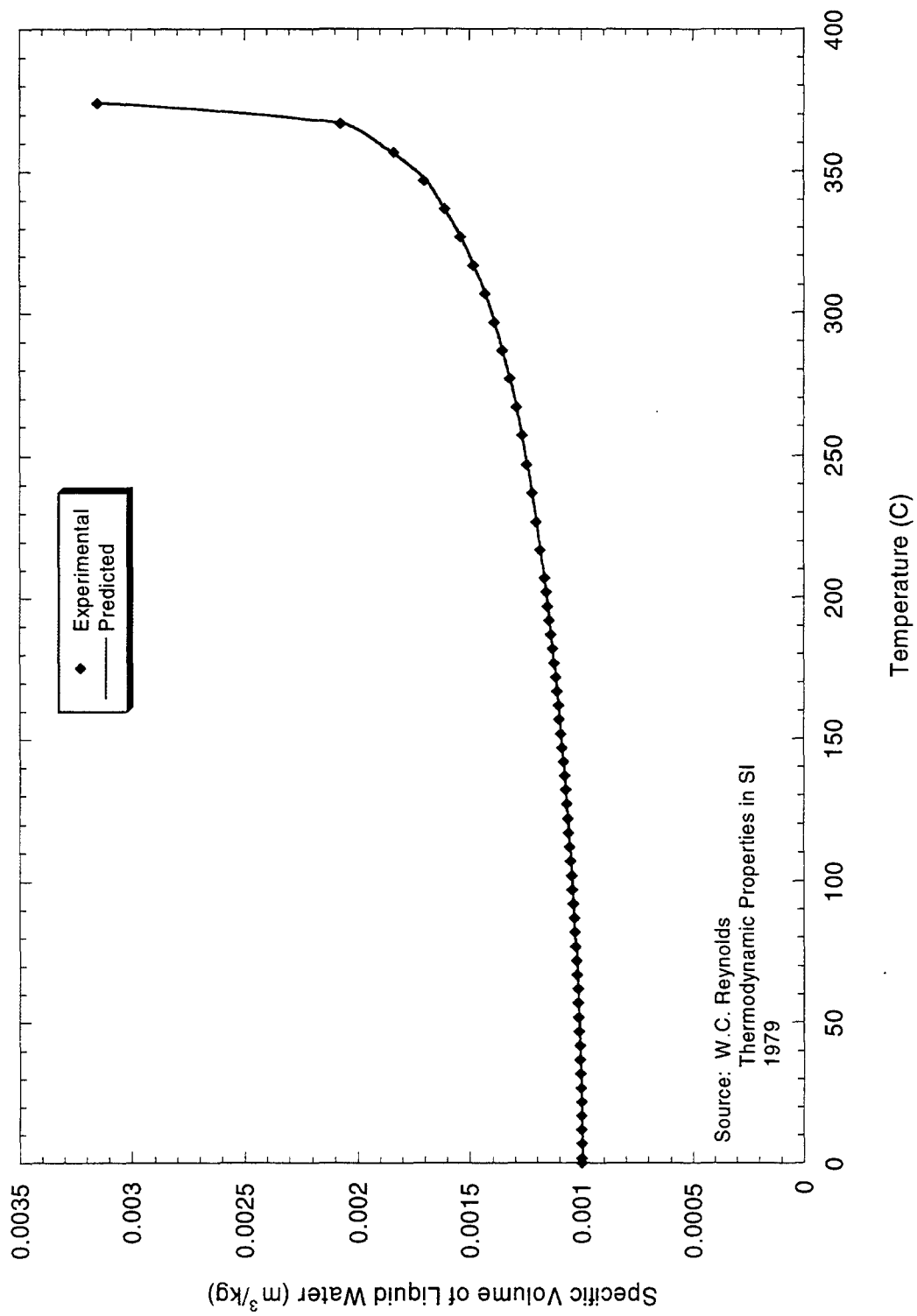


Figure 3-7: Curve fit of the specific volume of water used for FILM-30

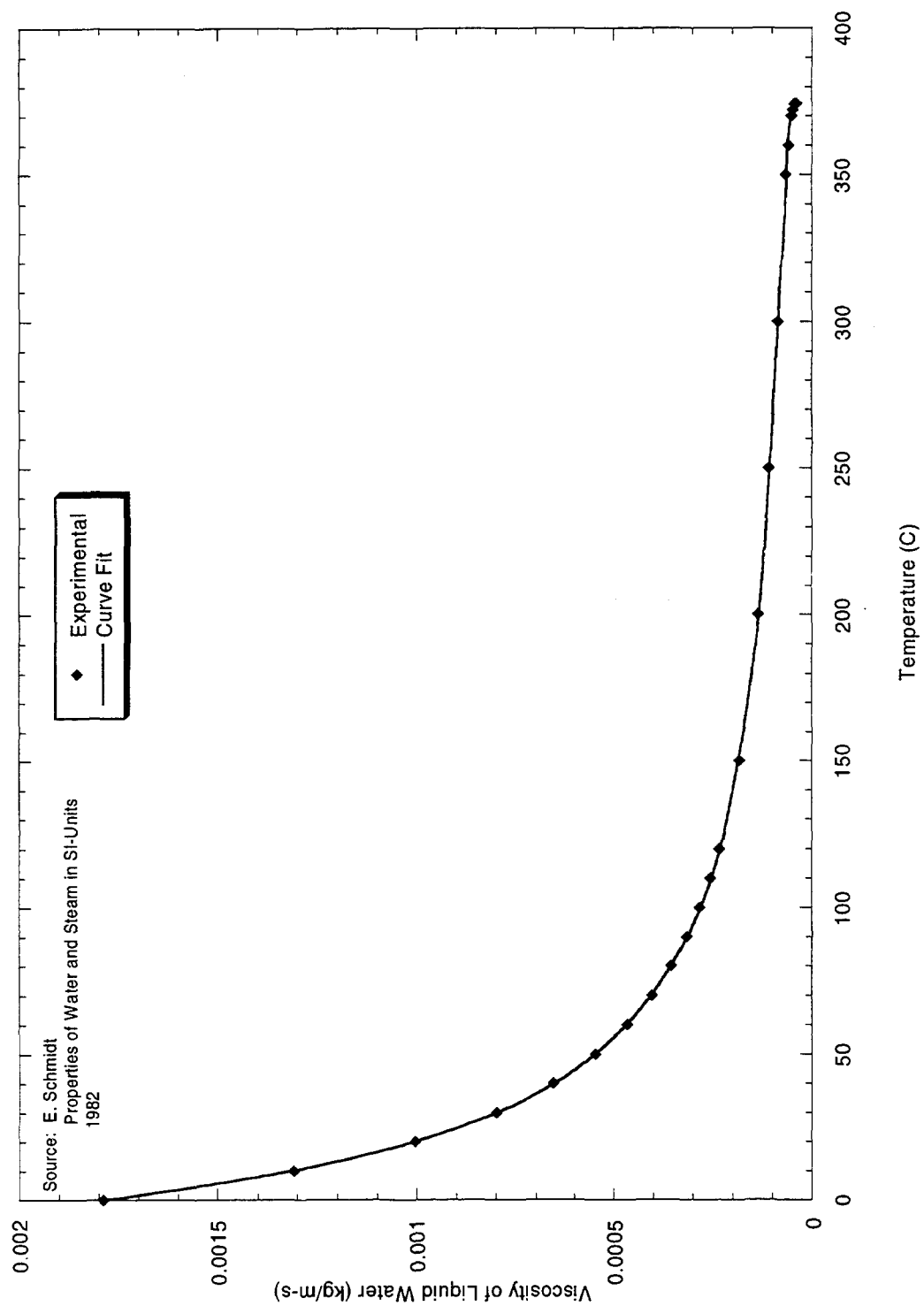


Figure 3-8: Curve fit of the viscosity of water used for FILM-30

properties listed in Table 3-3 are for water in its liquid state.

The accuracy of the correlations used by FILM-30 greatly depends upon accurate values of the water properties. For consistency, a standard procedure was followed when developing correlations for the various water properties. First a reliable and published steam table for the desired water property was acquired. The experimental data from the steam table was input into an electronic spreadsheet. Data in the spreadsheet was thoroughly compared with that from the printed steam table to insure there were no input errors. Various curve fits were subsequently applied to the electronic data. Predicted values from the curve fits were compared with the experimental data to determine the level of agreement. Predicted values had to agree with the entire set of experimental data with a 0.1% error to meet the acceptance criteria for the curve fit.

In applying curve fits to the steam table data, it was often necessary to divide the data into several regions since one curve fit could not accurately predict the entire data set. By demanding such accuracy from the curve fits, greater accuracy was obtained from the correlations that used the steam table properties.

Figures 3-4 through 3-8 present the experimental data and resulting curve fit for the five water properties of saturation temperature, thermal conductivity, Prandtl number, specific volume, and viscosity. The literature reference for the experimental data is shown in each of the figures. Sources for the steam properties data were Schmidt [6] Reynolds [7] and Collier [8]. The figures illustrate that the water properties are predicted with a very high degree of accuracy.

Table 3-3: Water Property Functions in Figures 3-2 and 3-3

Function	Water Property
CONDUCTWA	Thermal conductivity of liquid water
PRANDTL	Prandtl number for liquid water
TEMPSAT	Saturation temperature of water
VISCOSWA	Viscosity of liquid water

Since the function **ONSTBERGL** in Figure 3-2 performs its calculations based only on the inlet conditions, it does not reference any subordinate functions. Function **ONSTBERGL** is a good example of the organization of FILM-30. When a subroutine calls a function, that function will either perform its calculations based on the inlet conditions and temperature variables that were previously calculated or the function will reference other functions.

The temperature variables that every function can access are the transition temperatures. These variable are the inlet bulk temperature, T_b , saturation temperature, T_{sat} , onset to nucleate boiling temperature, T_{onb} , onset to fully developed nucleate boiling temperature, T_{fdb} , and local CHF temperature, T_{CHF} . This set of temperature variables is assigned to a named COMMON statement so that every function and subroutine has access to it.

The temperature at the incipience of boiling, T_{bi} , is determined by finding the temperature where the forced convection heat flux, Φ_{fc} , equals the heat flux at the incipience of boiling, Φ_{bi} . This point of convergence is calculated to the third decimal place, that is, the two heat fluxes must agree within 0.005 W/cm^2 , before the subroutine **TEMPINCIP** concludes that convergence has been achieved.

Figure 3-9 shows the function and subroutine calls of subroutine **TEMPFDB**. As indicated by its name, **TEMPFDB** calculates T_{fdb} . To calculate T_{fdb} , the Bergles-Rohsenow correlation requires the knowledge of T_{onb} . Marshall reported two methods of calculating T_{onb} , Boscary's method and Gonzales' method. Both methods use the Bergles-Rohsenow onset to nucleate boiling correlation, but they differ in their formation of the equation. Boscary's version is

$$\Phi_{ofdb} = \sqrt{\Phi_{conv}^2 + (\Phi_{fdb} - \Phi_{bi})^2}$$

where Φ_{ofdb} = heat flux at the onset to fully developed nucleate boiling

Φ_{fdb} = heat flux in the fully developed nucleate boiling regime

while Gonzalez's method is

$$\Phi_{ofdb} = \frac{\Phi_{conv}^2 + \Phi_{bi}^2}{2 \cdot \Phi_{bi}}$$

The author programmed both versions of the equation for Φ_{ofdb} and they yield very similar results. However, the option for allowing the user to decide which method is desired was added. These are the two functions **FDBBOSCA** and **FDBGONZA** in Figure 3-9.

The temperature at the onset to fully developed nucleate boiling, T_{ofdb} , is determined by finding the temperature where Φ_{ofdb} equals Φ_{fdb} . Convergence is assumed when the two heat fluxes agree within 0.002 W/cm^2 .

Figure 3-9 is a further example of the programming nomenclature of FILM-30. The functions **HFORCONV** and **HNBBOIL** respectively calculate heat transfer coefficients in the forced convection and fully developed nucleate boiling regimes. Since the Dittus-Boelter and Sieder-Tate correlations are for the forced convection regime, their function name begins with “FC”. Similarly, the fully developed nucleate boiling regime correlations of Araki and Thom begin with the letters “NB” for nucleate boiling.

An outline of the organization of the functions used by the **TEMPFCHF** subroutine is shown in Figure 3-10. As seen in the figure, **TEMPCHF** requires the knowledge of several water properties. The required water properties and the functions that calculate them are presented in Table 3-4.

Table 3-4: Water Property Functions in Figure 3-10

Function	Water Property
ENTHALPY_F	Enthalpy of liquid water
ENTHALPY_FG	Latent heat of vaporization
CPF	Isobaric specific heat of water
SPECVOL_VA	Specific volume of water vapor

Figures 3-11 through 3-14 present the experimental data for the water properties shown in Table 3-4 and the curve fits that FILM-30 use to predict the data. As was previously discussed, the curve fits were required to agree with the experimental data within 0.1%.

Although the primary set of correlations, which are the subject of this report, does not use T_{mfb} , that segment of coding was included in FILM-30 to maintain the legacy of FILM. An

outline of the function calls for calculating T_{mfb} is shown in Figure 3-15.

After the transition temperatures are calculated, FILM-30 calculates the boiling curve for the inlet conditions input by the user. Subroutine **CALCDATA**, Figure 3-16, performs these calculations and its procedure is relatively straightforward. The first operation is equating the wall temperature, T_w , to the bulk temperature, T_b , since this is the wall's initial temperature. The forced convection correlation is used to calculate the heat transfer coefficient and corresponding WHF for this T_w and the values stored in an array. T_w is subsequently incremented and the code calculates new heat transfer properties, depending on T_w 's value in relation to the transition temperatures.

The amount that T_w is incremented is dependent upon the boiling curve regime. Table 3-5 shows the values of incrementation used for the various regimes of the boiling curve. The degree of incrementation varies in order to best define the boiling curve. For temperature in the forced convection regime, the heat transfer coefficient does not change rapidly so a larger increment of T_w is permissible. When T_w is in the partial boiling regime, the degree of incrementation decreases because this regime is so narrow. When T_w enters the fully developed nucleate boiling regime, the degree of incrementation increases since the temperature response is very linear in this regime. Lastly, T_w is moderately incremented in the transition boiling regime since it is important to capture the shape of the heat transfer coefficient response.

Table 3-5: Incrementation of T_w During FILM-30 Calculations

Boiling Curve Regime	T_w Increment (°C)
Forced Convection	1
Partial Nucleate Boiling	0.25
Fully Developed Nucleate Boiling	1
Transition Boiling	1

In Figure 3-16, functions and subroutines that begin with the letter “H” calculate heat transfer coefficients. Similarly, routines that begin with the letter “Q” calculate heat fluxes. The

second and third letters in the routine's name identify the boiling curve regime for its operation. The forced convection regime is identified by 'FORCCONV', the transition boiling by 'TB', the film boiling by 'FB', the fully developed nucleate boiling by 'NB', and the partial nucleate boiling by 'PB'. The function **QBISUB** calculates the subcooled incipience of boiling by finding the interception between the partial boiling and forced convection correlations.

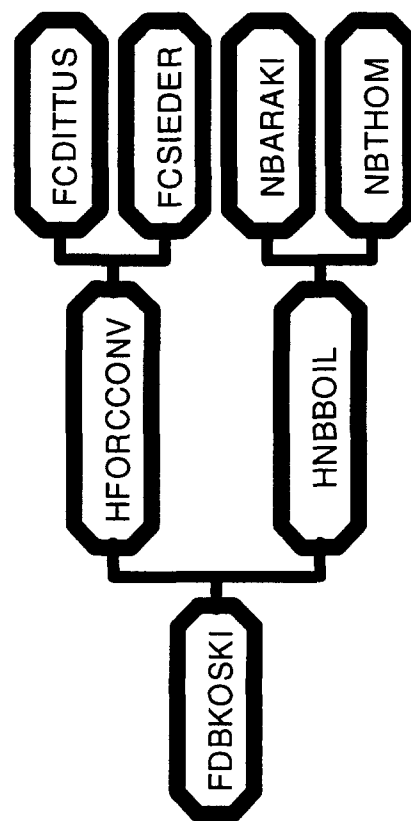
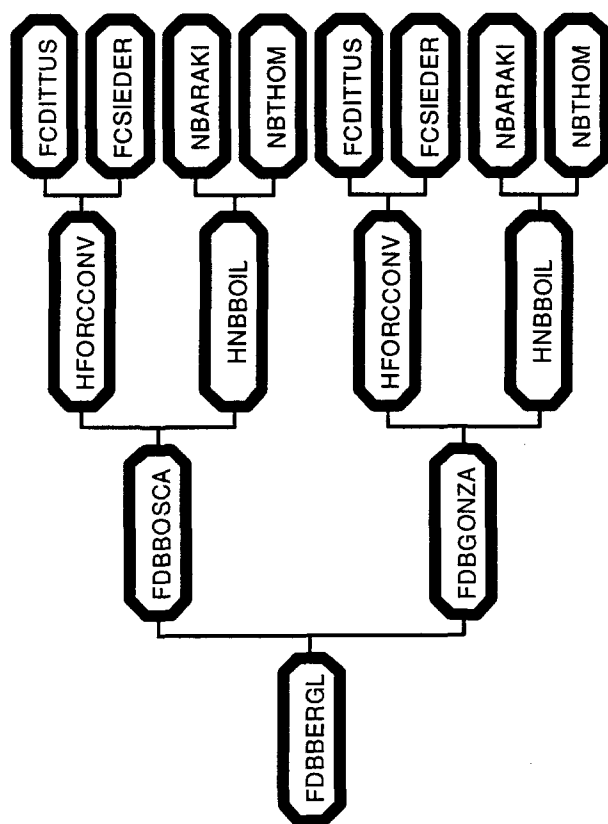


Figure 3-9: Function calls of **TEMPFDB** subroutine

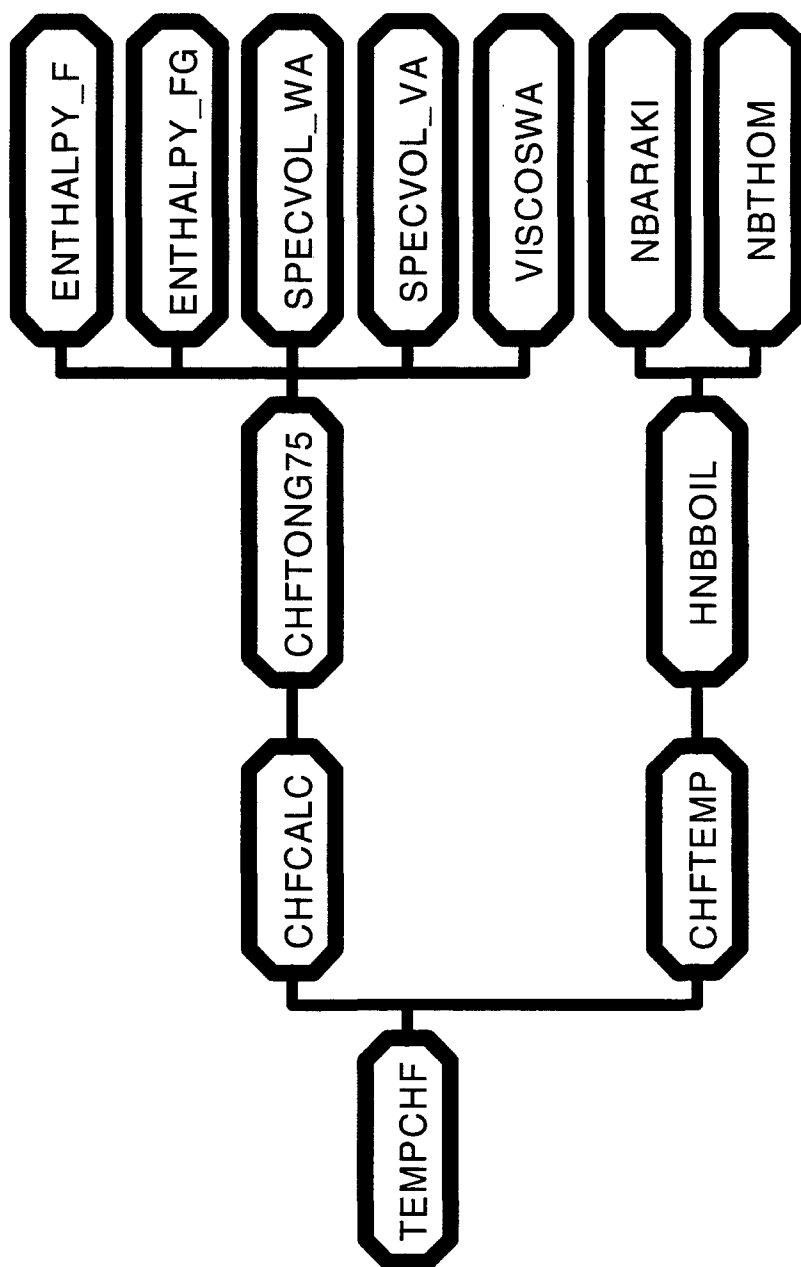


Figure 3-10: Function calls of **TEMPCHF** subroutine

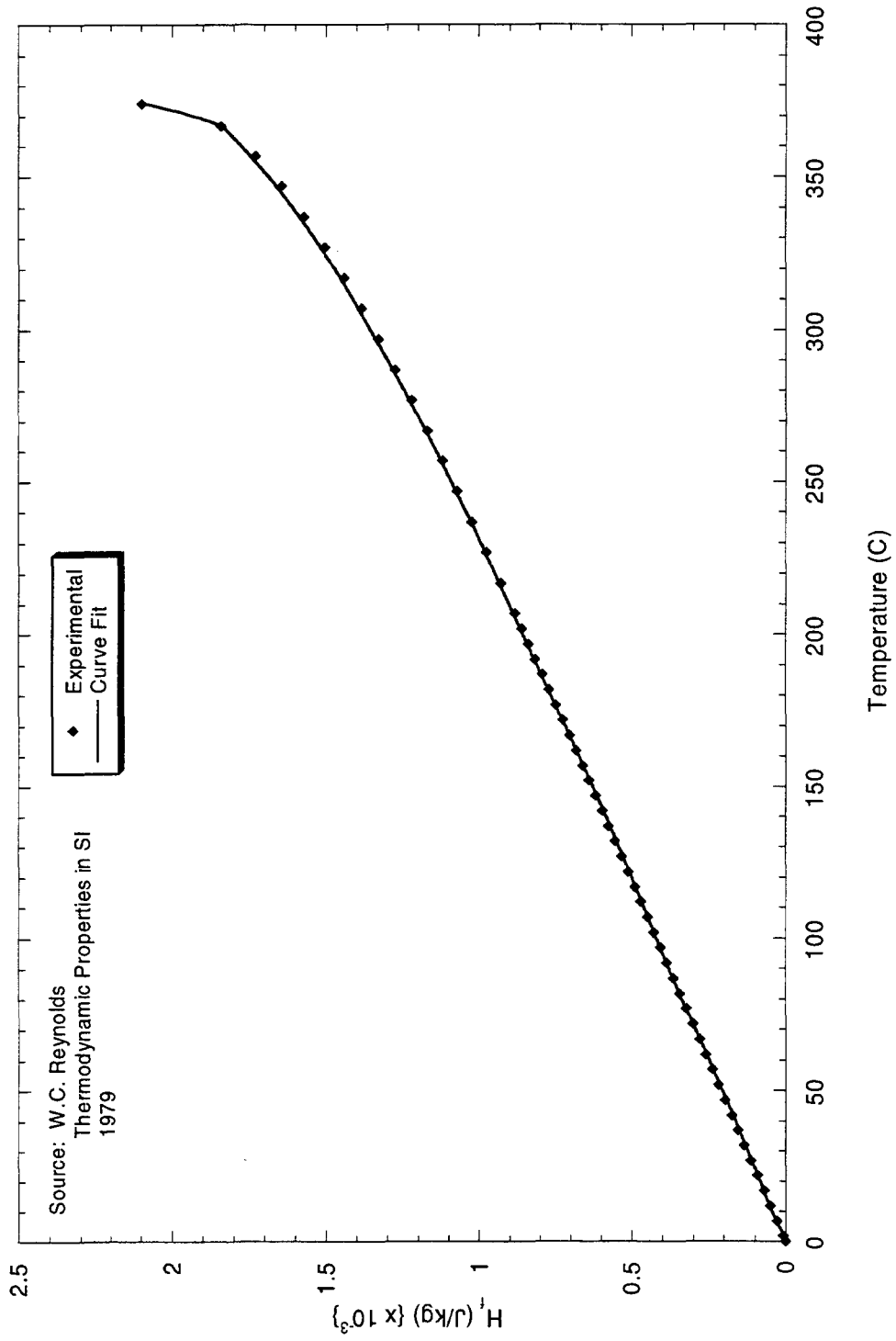


Figure 3-11: Curve fit of the enthalpy of liquid water used for FILM-30

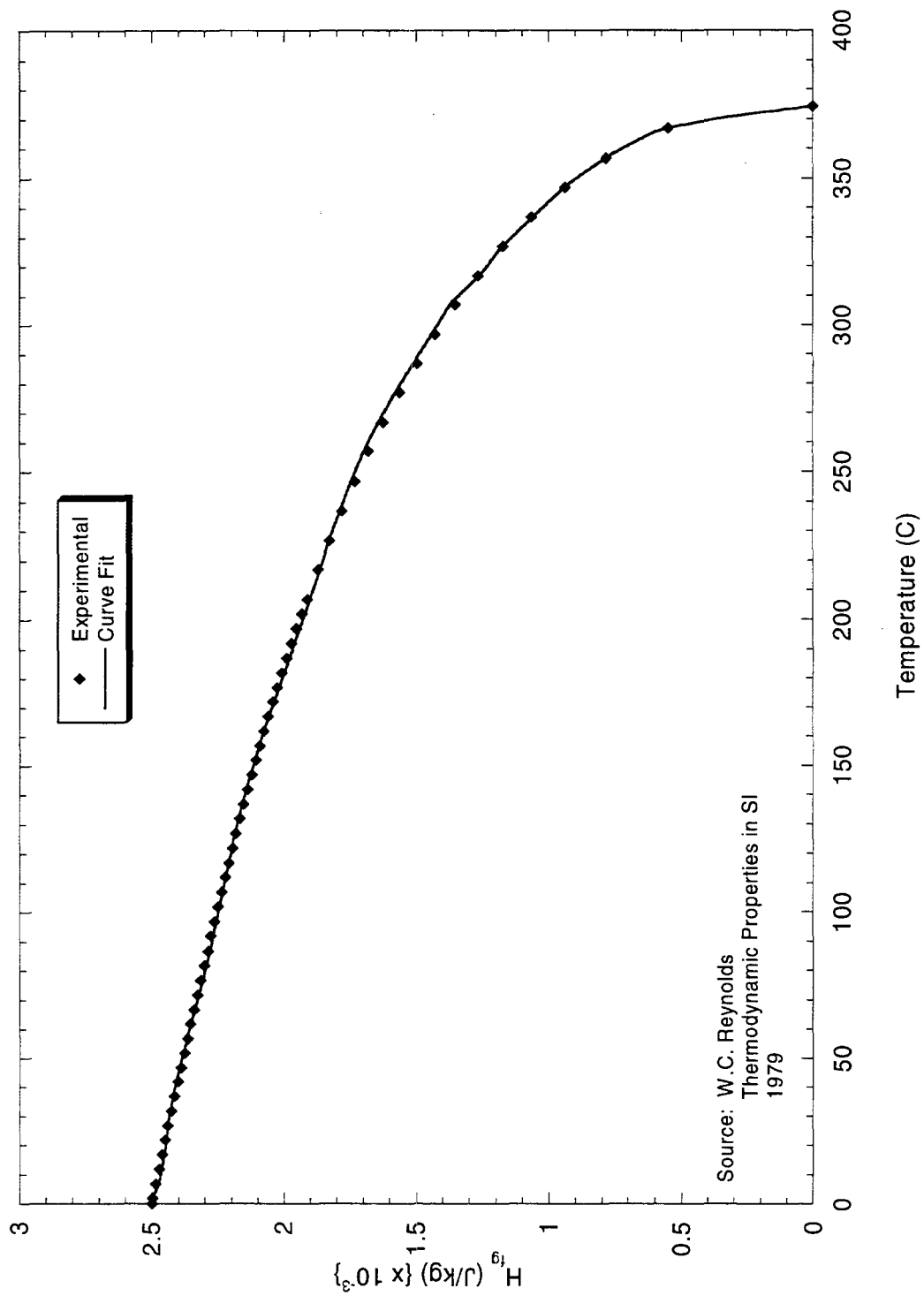


Figure 3-12: Curve fit of the latent heat of vaporization of water used for FILM-30

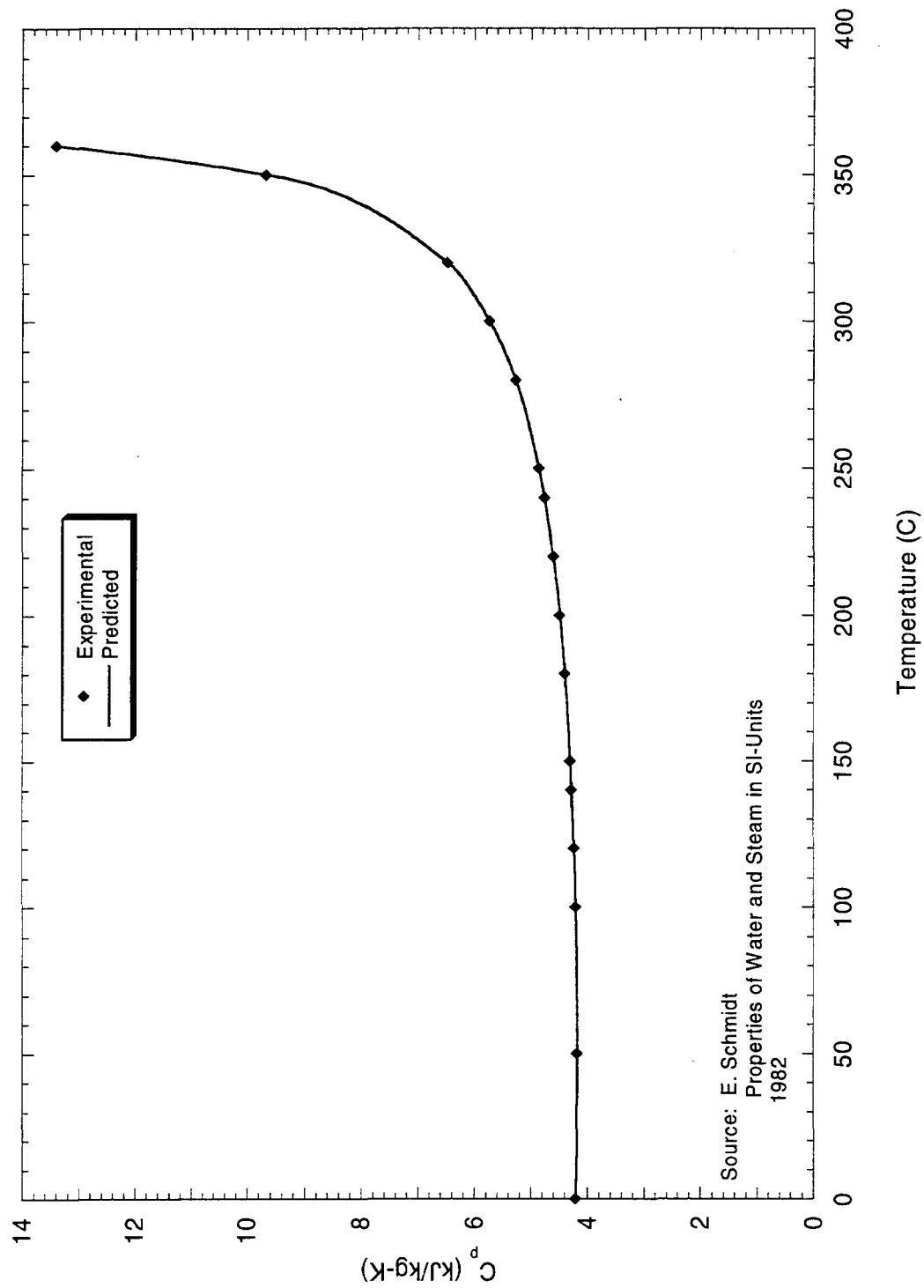


Figure 3-13: Curve fit of the isobaric specific heat of water used for FILM-30

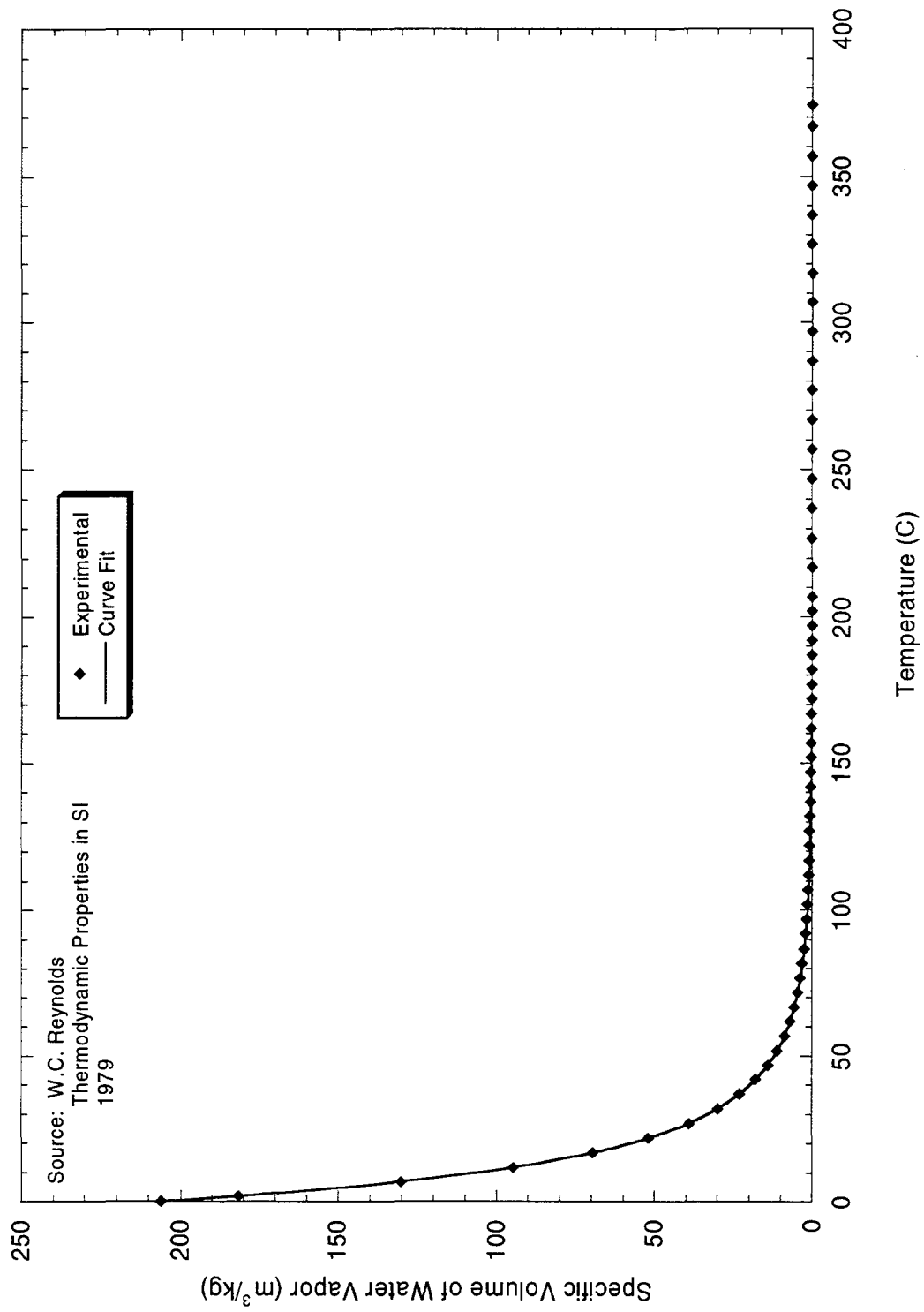


Figure 3-14: Curve fit of the specific volume of water vapor used for FILM-30

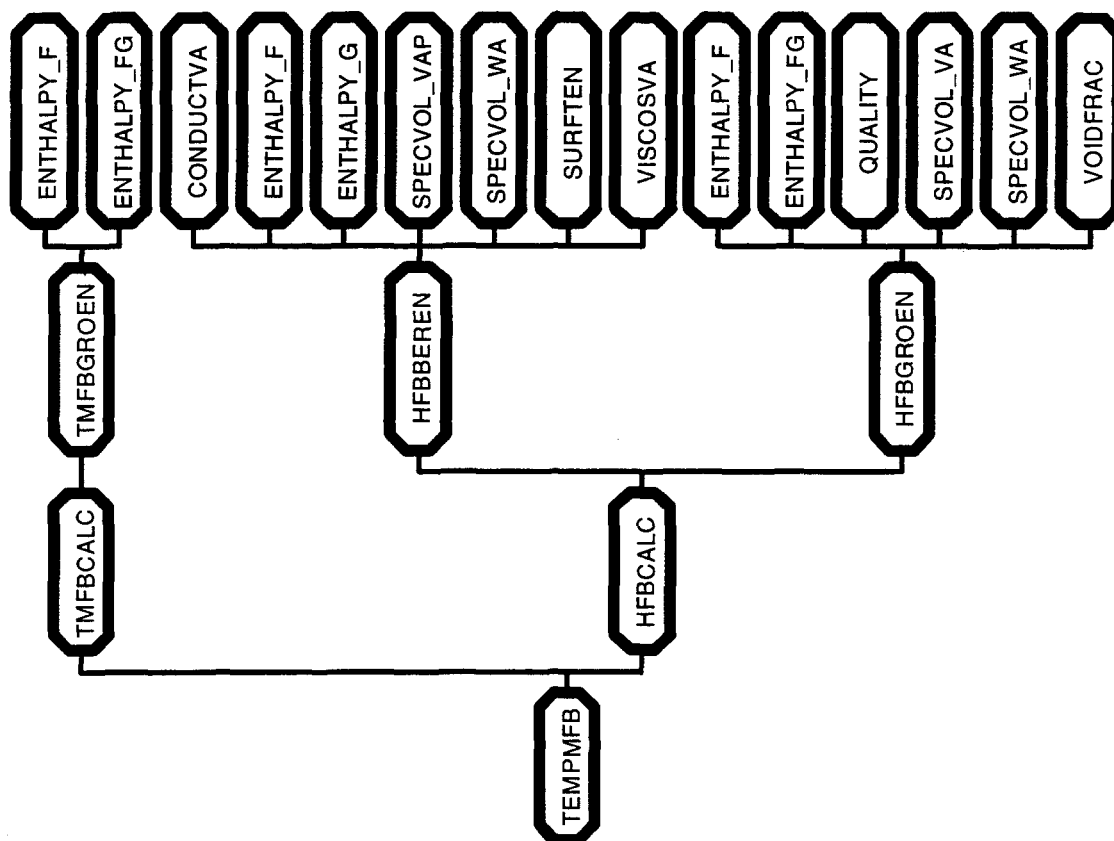


Figure 3-15: Function calls of TEMPMFB subroutine

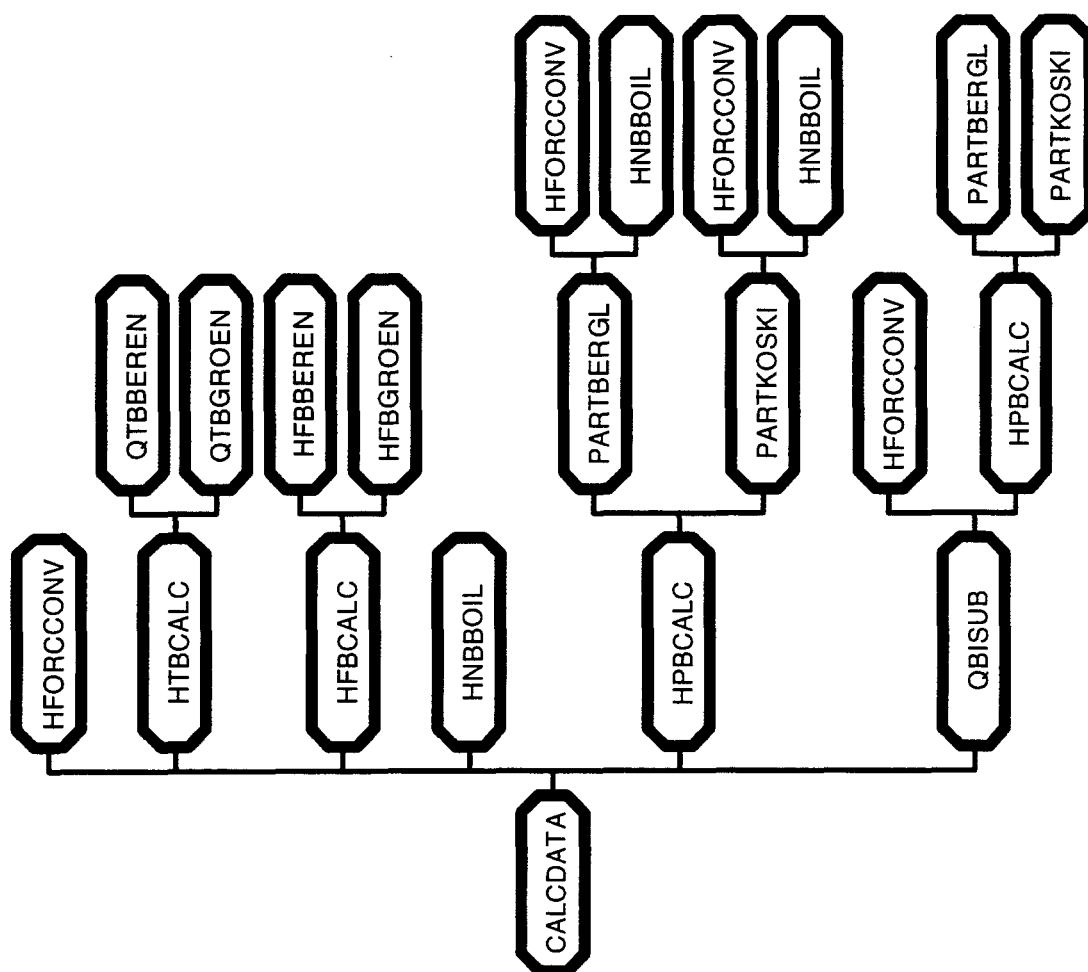


Figure 3-16: Function calls of CALCDATA subroutine

4 Comparison with Experimental Data

4.1 Introduction

A very thorough discussion on the finite element model and analyses that were configured and performed for comparison with experimental data can be found in Marshall's thesis. An equivalent discussion is presented for two mockups, experimental facility, test procedures, and measured data. These topics are not presented here, but the reader is encouraged to refer to the thesis if such information is desired.

The following two subsections present some of the plots from Marshall's thesis that illustrate the excellent agreement between the FEA predicted and experimentally measured thermocouple temperatures for these cases. The FEA predicted thermocouple temperatures were produced from FEAs that used the heat transfer properties calculated by FILM-30.

4.2 Bare Channel Mockup

Figures 4-1, 4-3, and 4-5 show the comparison between Marshall's FEA predicted and experimentally measured thermocouple temperatures. Figures 4-2, 4-4, and 4-6 present the FILM-30 boiling curves for each of the comparison plots.

4.3 Swirl Tape Mockup

Figures 4-7 and 4-9 show the comparison between Marshall's FEA predicted and experimentally measured thermocouple temperatures. Figures 4-8 and 4-10 present the FILM-30 boiling curves for each of the comparison plots.

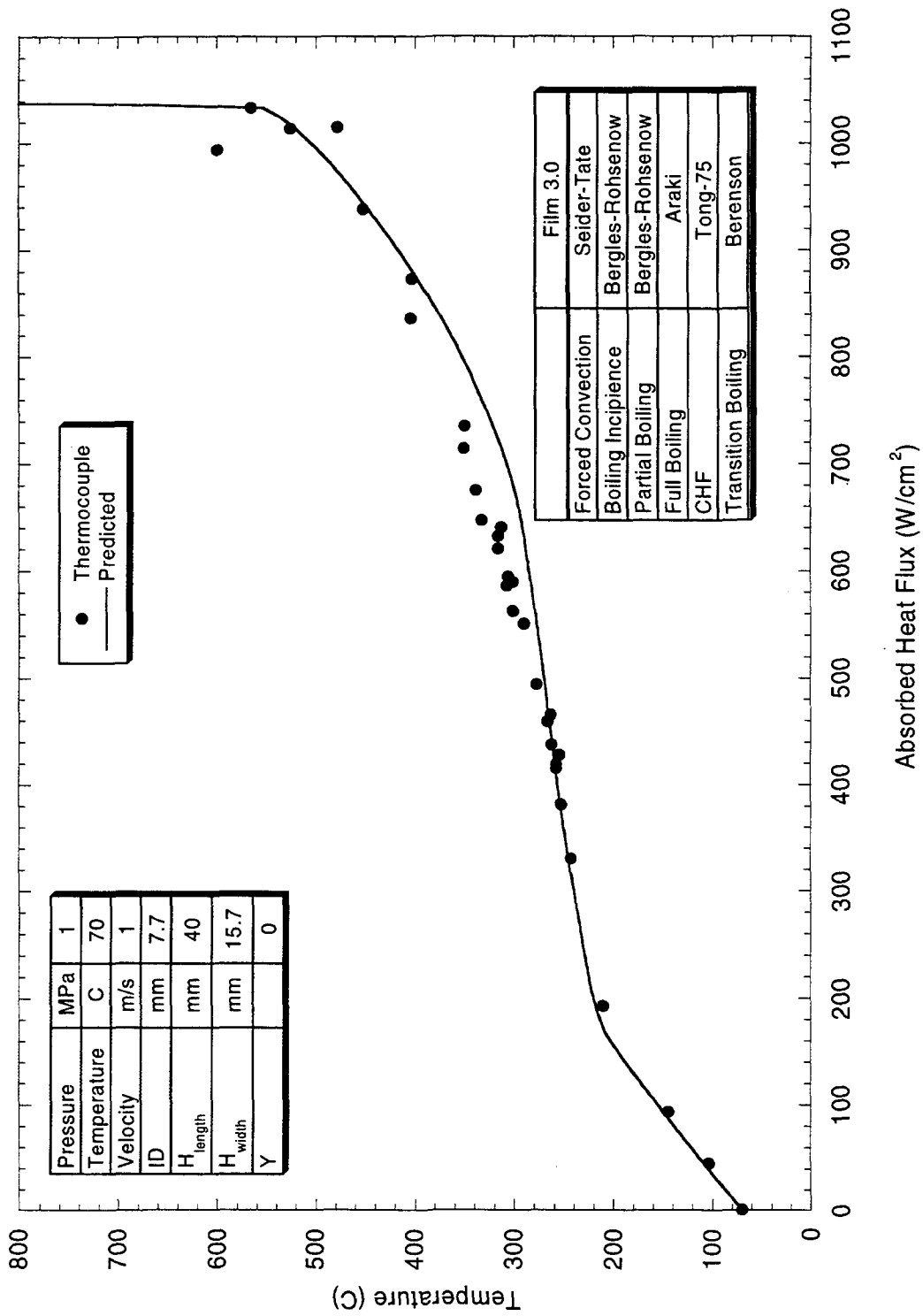


Figure 4-1: Experimental and predicted thermocouple temperatures for Case 1 experiments with bare channel mockup

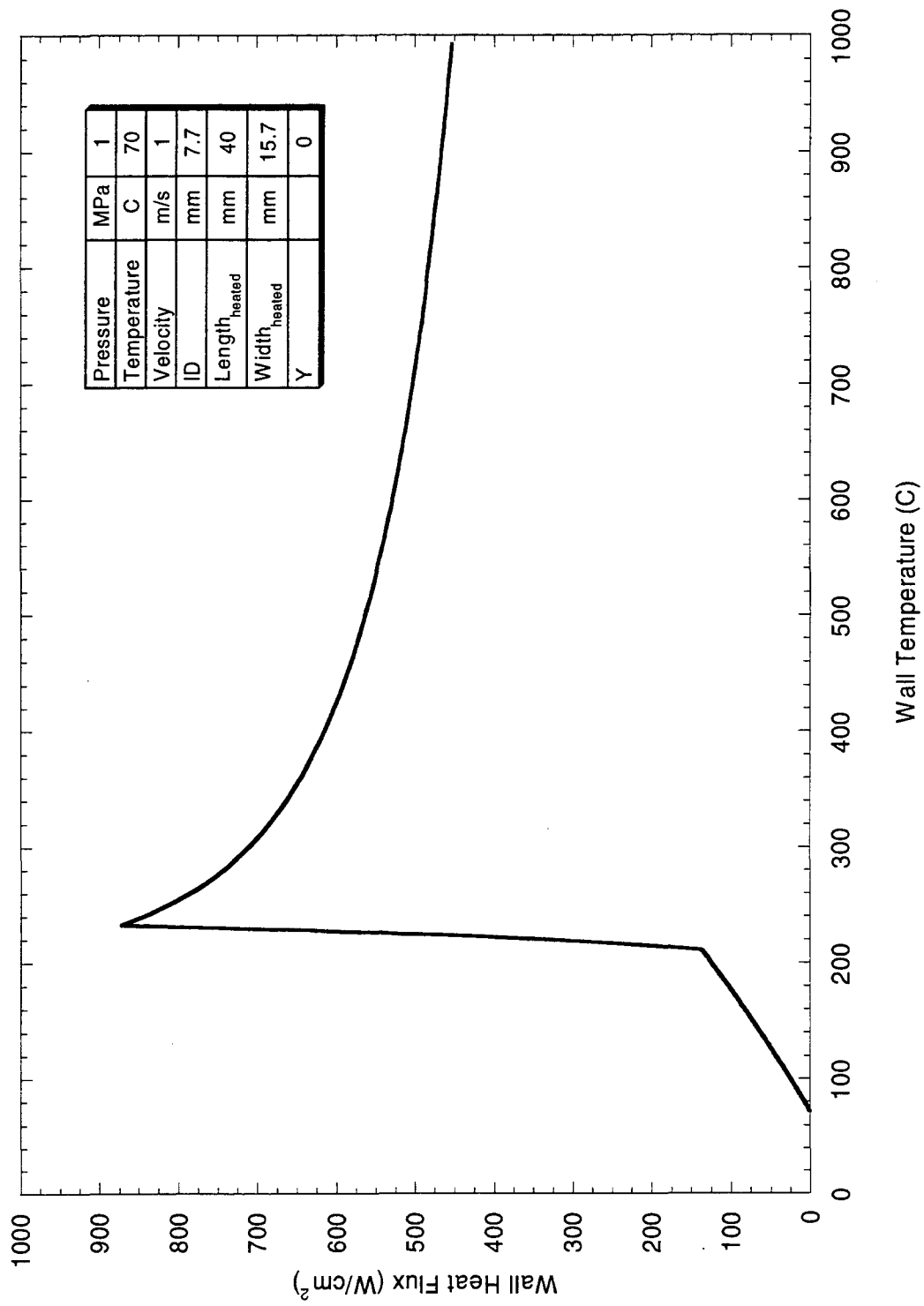


Figure 4-2: Boiling curve calculated by FILM-30 for Case 1 experiments with bare channel mockup

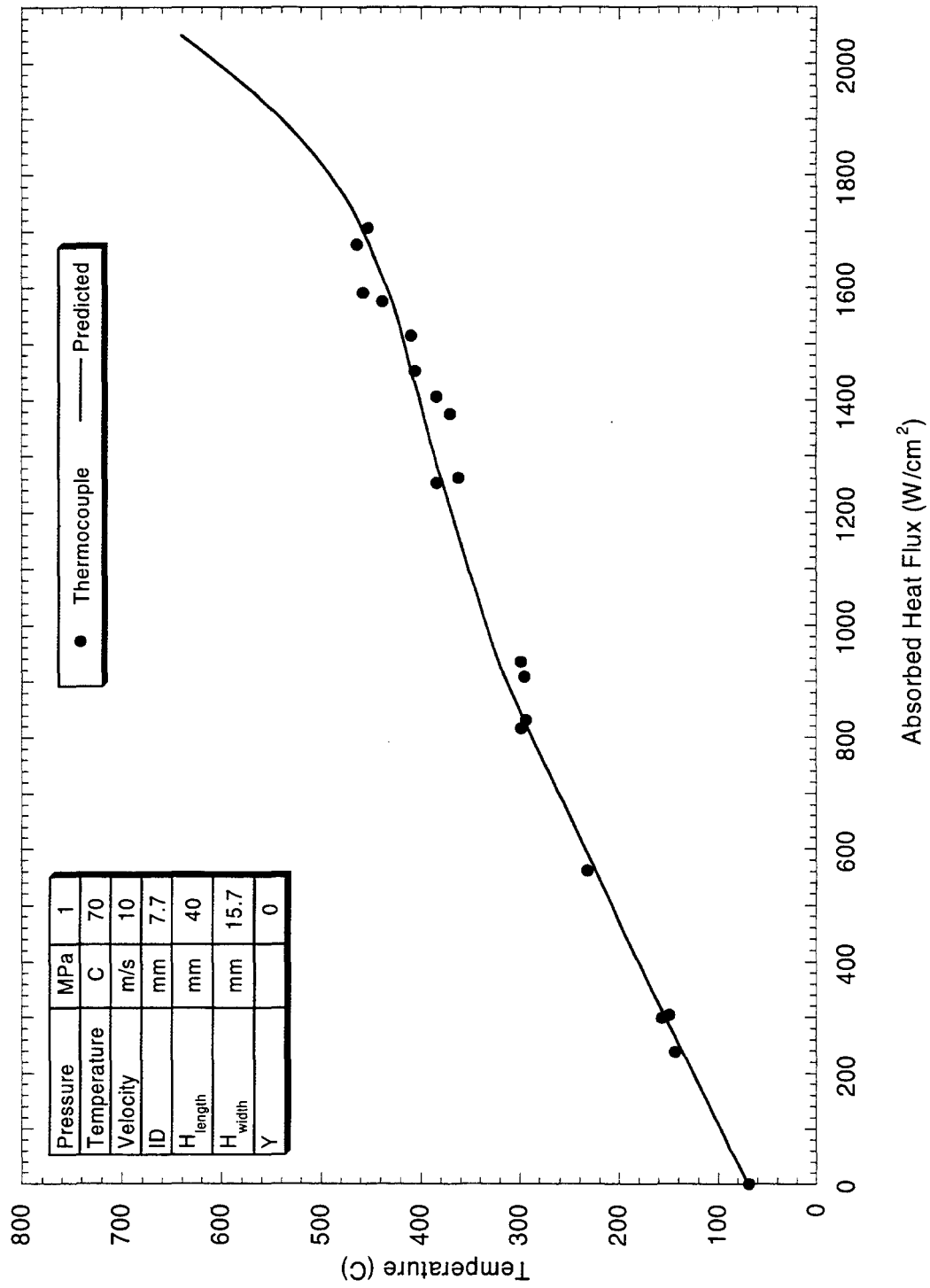


Figure 4-3: Experimental and predicted temperatures for Case 2 experiments with bare channel mockup

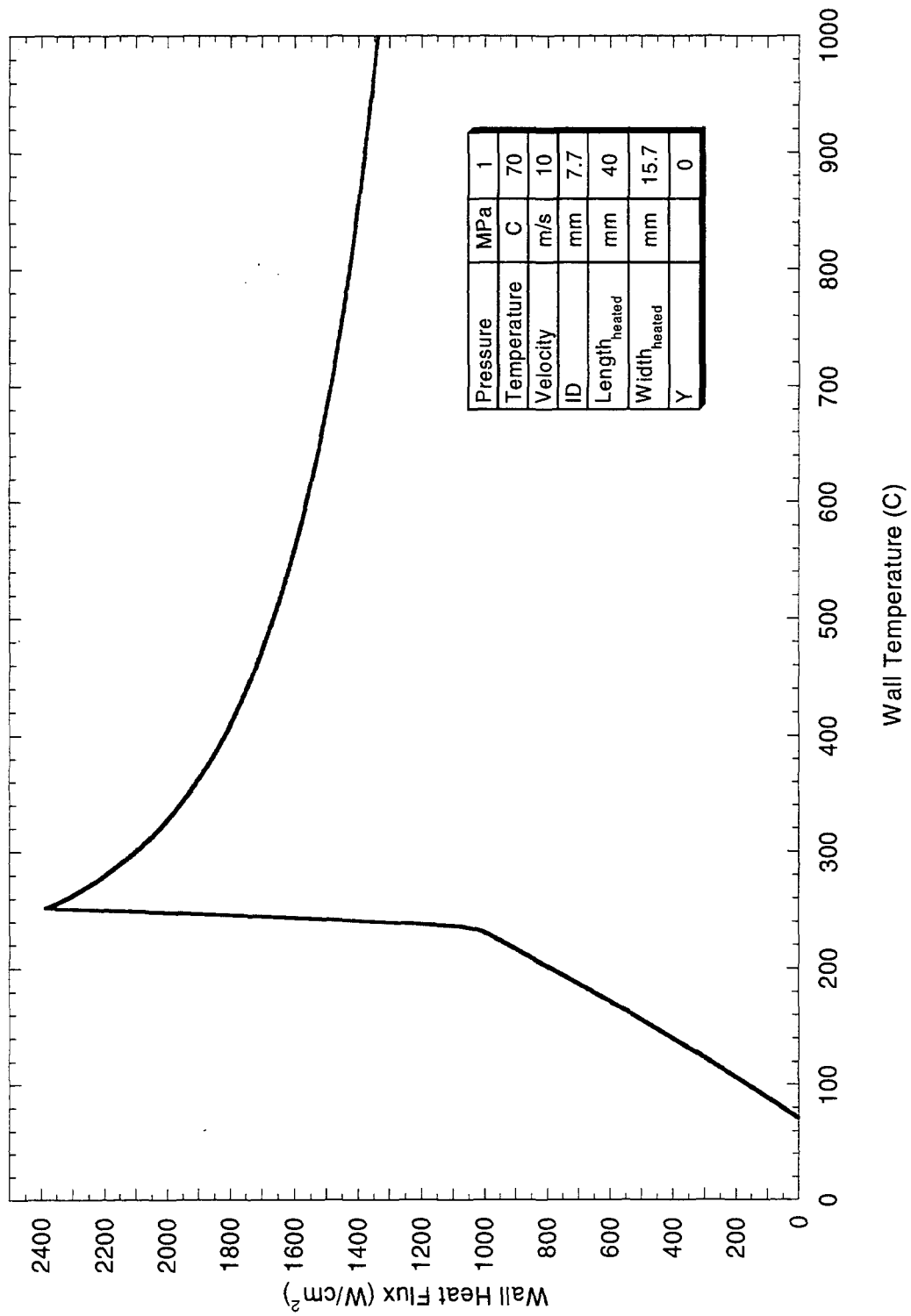


Figure 4-4: Boiling curve calculated by FILM-30 for Case 2 experiments with bare channel mockup

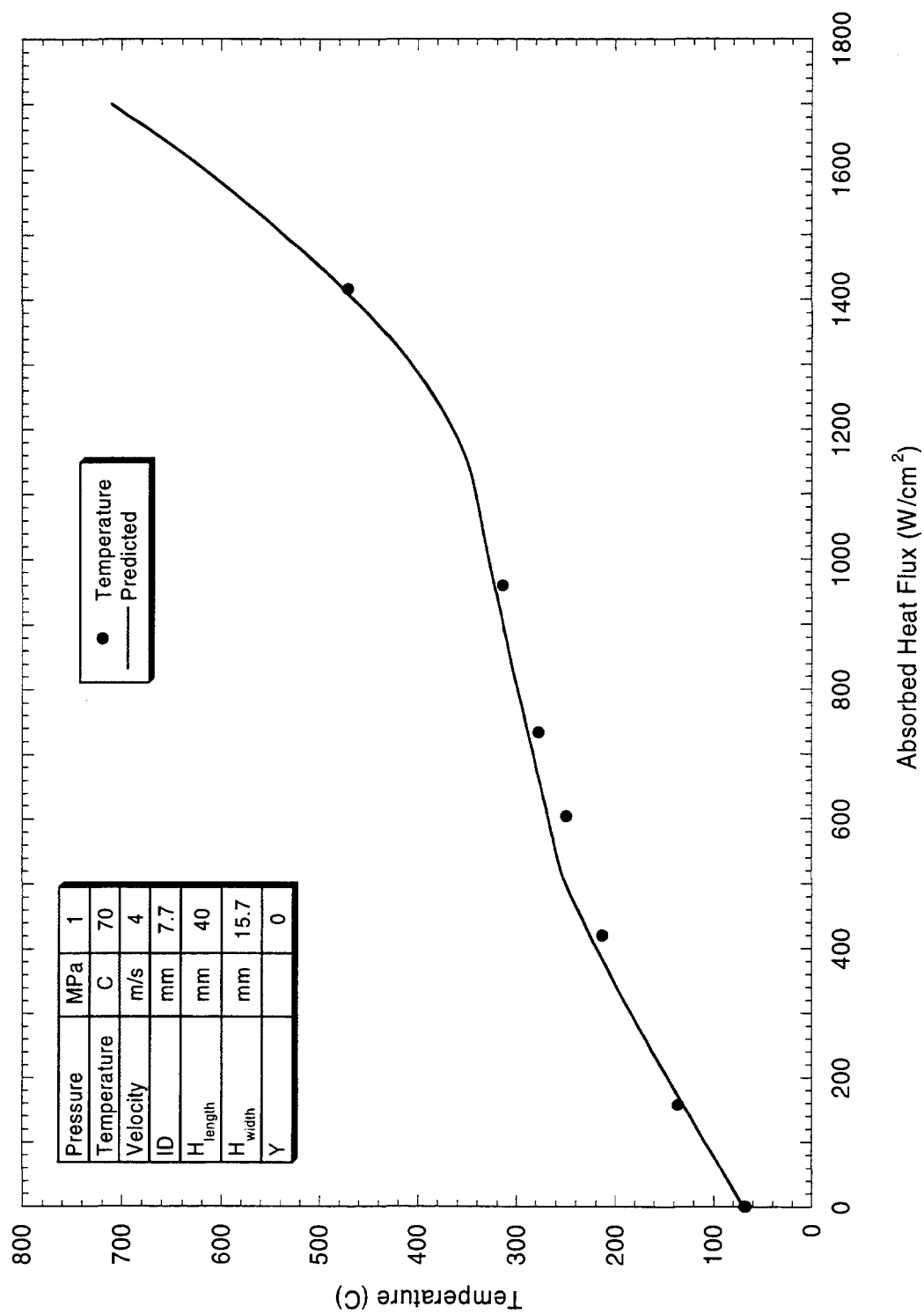


Figure 4-5: Experimental and predicted thermocouple temperatures for Case 3 experiments with bare channel mockup

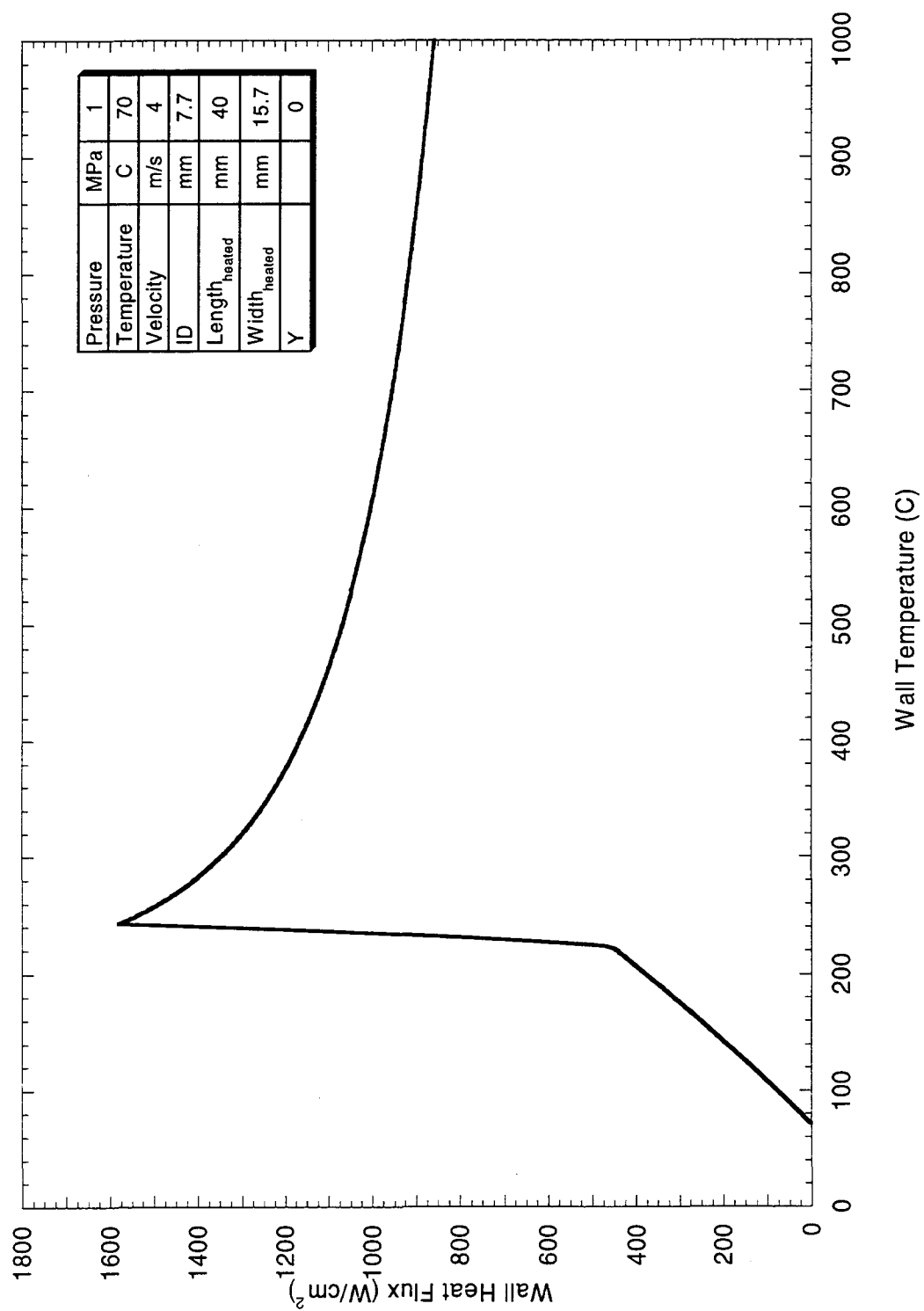


Figure 4-6: Boiling curve calculated by FILM-30 for Case 3 experiments with bare channel mockup

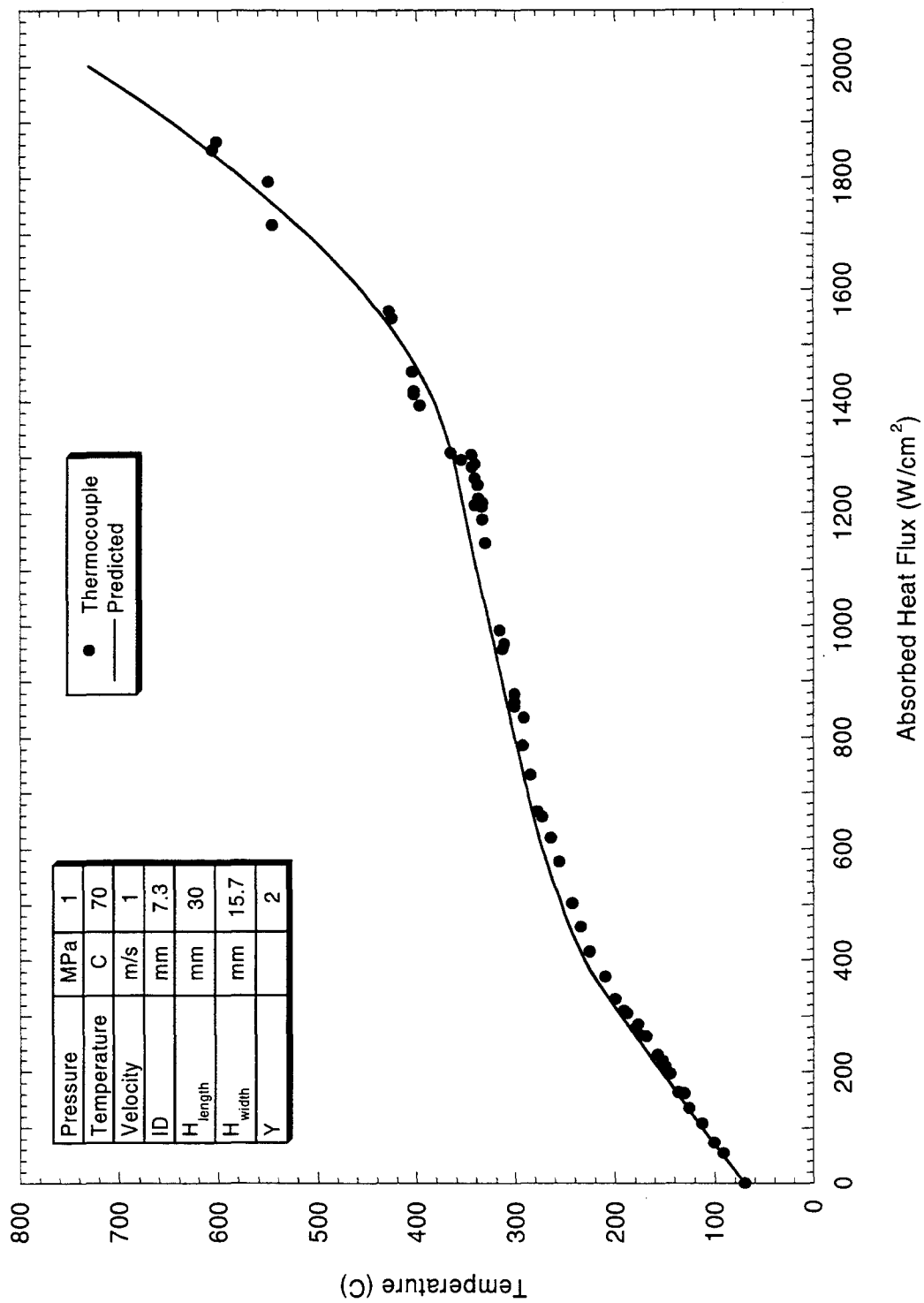


Figure 4-7: Experimental and predicted thermocouple temperatures for Case 1 experiments with a swirl tape mockup

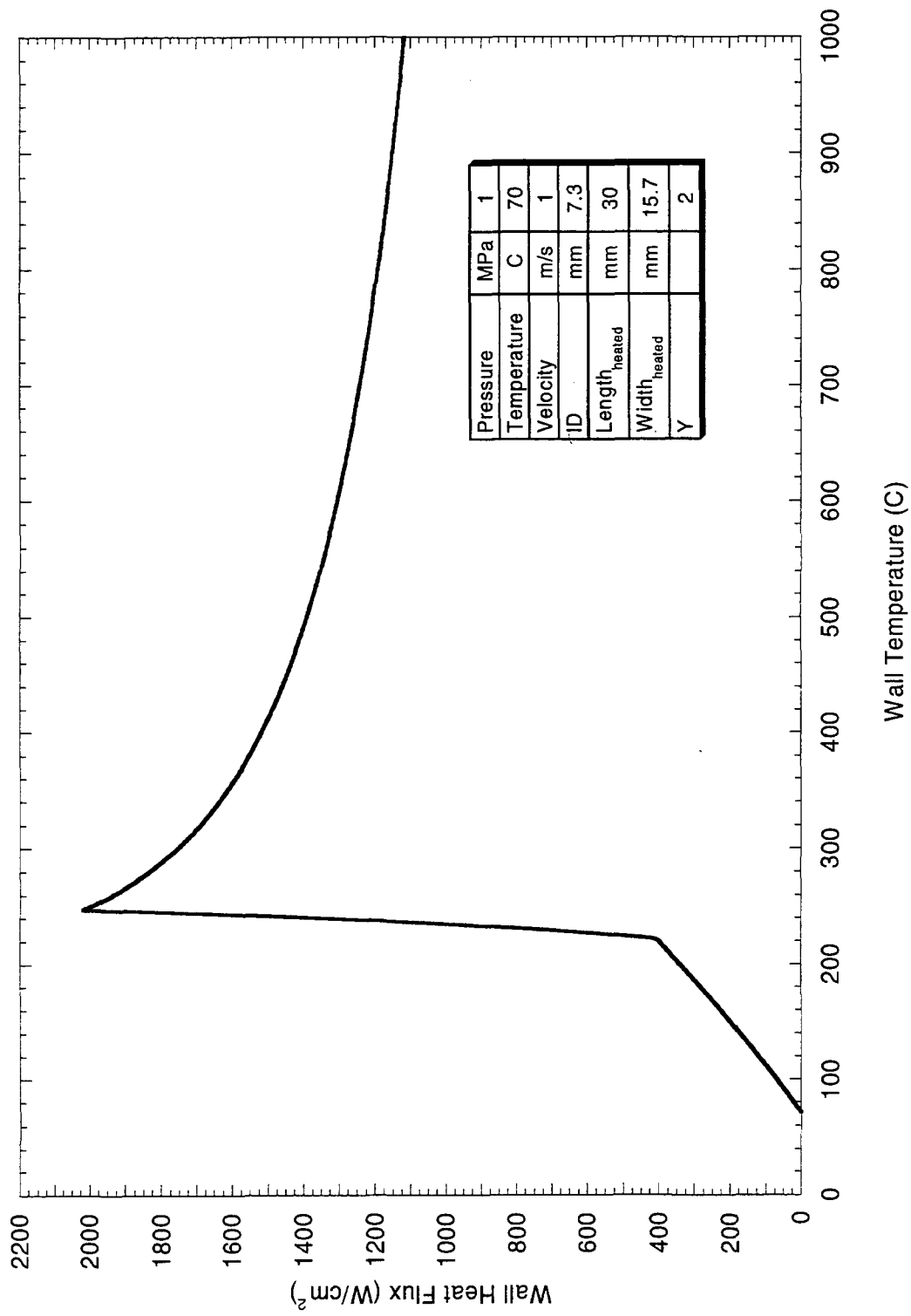


Figure 4-8: Boiling curve calculated by FILM-30 for Case 1 experiments with a swirl tape mockup

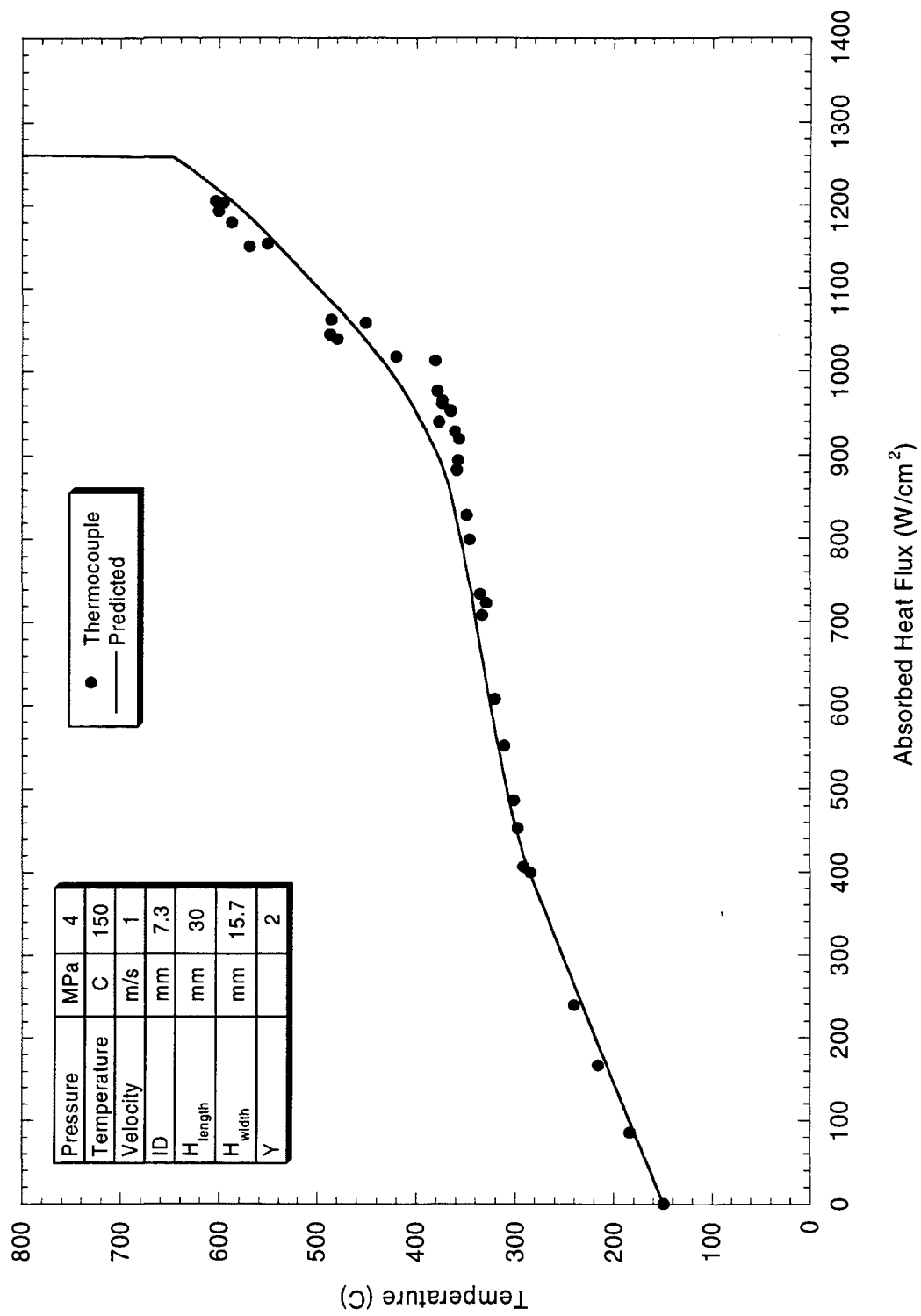


Figure 4-9: Experimental and predicted thermocouple temperatures for Case 2 experiments with a swirl tube mockup

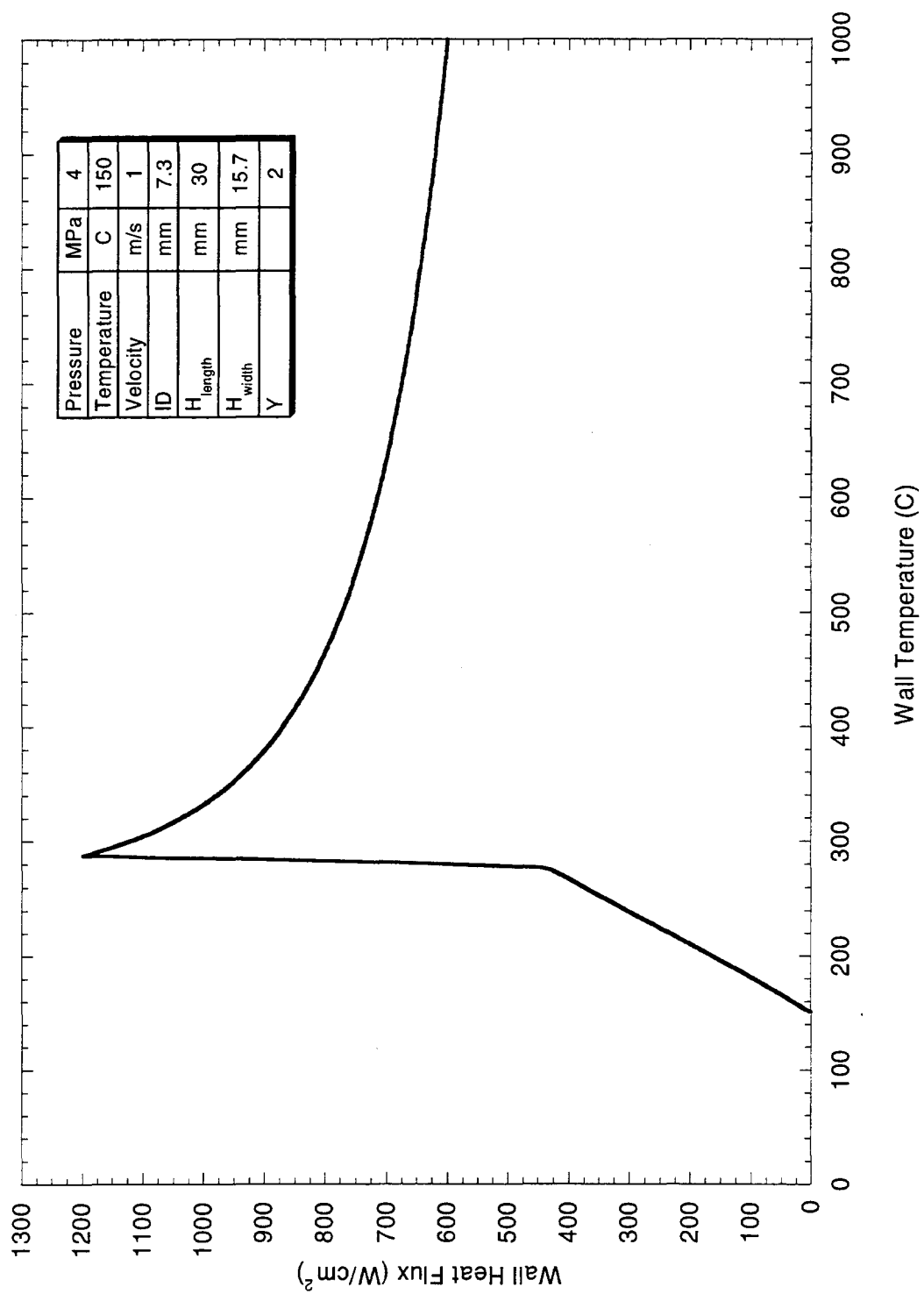


Figure 4-10: Boiling curve calculated by FILM-30 for Case 2 experiments with a swirl tape mockup

5 Discussion

5.1 Introduction

This chapter is divided into four sections:

- User's Manual
- FILM-30 Executable
- Programming Limitations
- Proposed Revisions

Collectively these sections provide instructions on how to obtain and use FILM-30 within its range of operation. The last section discussed proposed revisions to FILM-30.

5.2 FILM-30 Executable

The source code for FILM-30 is the intellectual property of Sandia National Laboratories and the U.S. Department of Energy. This source code has been successfully compiled to execute on Hewlett Packard and Sun workstations. While access to the source code is restricted, copies of the executable will be freely distributed. To obtain a copy of the executable, one needs only to contact the Fusion Technology Department, Organization 6428, of Sandia National Laboratories.

5.3 User's Manual

FILM-30 was written to provide the user with an intuitive interface for executing the code. This section presents the command prompts and screen outputs that are presented to the user when executing FILM-30. In the presentation that follows, the command prompt of the user's computer system is indicated by '**>>>**', the user's input is printed in **bold**, and FILM's screen output is printed in *italics*. Comments are written between French brackets, { }.



>>> Film30

{Note: UNIX is case sensitive}

/=====

/ Film 3.0 - Sandia National Laboratories, 1998 /

/=====

1. Inlet Pressure (MPa): 4.00
2. Inlet Temperature (C): 150.00
3. Inlet Velocity (m/s): 10.00
4. Inner Diameter (mm): 10.00
5. Twist Ratio : 0.0

Which Option to change (0 = NONE)?

⚙ ≥ 1 {EXAMPLE, change inlet pressure; do NOT use decimal point}

Enter the NEW Inlet Pressure

⚙ ≥ 3

/=====

/ Film 3.0 - Sandia National Laboratories, 1998 /

/=====

1. Inlet Pressure (MPa): 3.00
2. Inlet Temperature (C): 150.00
3. Inlet Velocity (m/s): 10.00
4. Inner Diameter (mm): 10.00
5. Twist Ratio : 0.0

Which Option to change (0 = NONE)?

⚙ ≥ 0 {finish input of inlet water conditions}

/=====

/ Film 3.0 - Sandia National Laboratories, 1998 /

/=====

Boiling Curve Options

1. *POST-CHF Regime* : *Y*
2. *Forced Convection* : *Sieder-Tate*
3. *Incipience of Boiling* : *Bergles-Rohsenow*
4. *Partial Boiling* : *Bergles-Rohsenow*
5. *Partial Boiling Method* : *Boscary (CEA)*
6. *Nucleate Boiling* : *Araki*
7. *Critical Heat Flux* : *Tong-75*
8. *Transition Boiling* : *Marshall-98*

Which Option to change (0 = NONE)?

➤ >> 6 {EXAMPLE, change nucleate boiling correlation}

Select the Nucleate Boiling Correlation

1. *Araki*
2. *Thom*

➤ >> 2

/=====

/ Film 3.0 - Sandia National Laboratories, 1998 /

/=====

Boiling Curve Options

1. *POST-CHF Regime* : *Y*
2. *Forced Convection* : *Sieder-Tate*
3. *Incipience of Boiling* : *Bergles-Rohsenow*
4. *Partial Boiling* : *Bergles-Rohsenow*
5. *Partial Boiling Method* : *Boscary (CEA)*
6. *Nucleate Boiling* : *Thom*
7. *Critical Heat Flux* : *Tong-75*
8. *Transition Boiling* : *Marshall-98*

Which Option to change (0 = NONE)?

➤ >> 0 {finish selection of heat transfer correlations}

program successfully completed

NOTES

1. The UNIX operating system is case sensitive so "film30" is not equivalent to "Film30". To execute FILM-30, the user must type "Film30".
2. When entering floating point values for the inlet conditions and coolant channel properties (e.g. "1.55" for the "Inlet Pressure"), you may enter "1.0" or simply "1" and FILM-30 will correctly read the value.
3. When entering the inlet conditions and coolant channel properties, you have two options:

- a. You can enter the values on one line, separating each value by a comma and pressing the RETURN key when all of the values have been entered.
 - b. You can enter each value and press the RETURN key. With this method, you will have to press the RETURN key for the total number of variables in order to proceed. That is, for the inlet conditions, FILM-30 will expect RETURN key inputs since there are three requested variables. FILM-30 will know when it has received the correct number of entries. If you do not enter all of the requested variables, FILM-30 will not re-prompt you, it will simply wait for your entry.
4. When entering selecting a correlation from the presented list (e.g. "2" for the 'Sieder-Tate' correlation), you **MUST** enter an integer number (i.e., "2" and not "2.") or FILM-30 will cancel its execution as a result of your input error.
5. The 'Post-CHF Regime' question allows the user to calculate heat transfer properties if the local CHF was never achieved. In this situation, the process of heat transfer remains in the fully developed nucleate boiling regime and FILM-30 uses this correlation until a maximum wall temperature of 1000 °C is reached in its calculations.

5.4 Programming Limitations

FILM-30 was written to be the most versatile and complete heat transfer property code available for one-sided heat with water cooling and a copper mockup. While the code does achieve this goal, there are a few caveats to the current release version. This section discusses those caveats.

FILM-30 was designed to predict the heat transfer properties of water when an OFHC-CU mockup is used. The selection of OFHC-Cu as the mockup material has several important implications. OFHC-Cu has a melting temperature of approximately 1083 °C. With this melting temperature, an OFHC-Cu mockup will fail as a result of surface melting and internal hoop stresses before stable film boiling is initiated. Consequently, FILM-30 does not model the film

boiling regime. In addition, FILM-30 performs its heat transfer property calculations to a maximum wall temperature of 1000 °C. An OFHC-Cu mockup will not reach a wall temperature of 1000 °C (the maximum wall temperature is conjectured to be near 750 °C) so the 1000 °C was considered to be more than sufficient for OFHC-Cu.

All heat transfer experiments were performed with a swirl tape insert that had a thickness of 1 mm. Accordingly, FILM-30 was programmed with this thickness for the swirl tape insert. With the current release version, the user can change the twist ratio of the swirl tape insert, but not the thickness of the swirl tape insert.

Finally, FILM-30 uses its calculated transition temperatures to determine when the wall temperature has entered another regime of the boiling curve. An unusual situation has been noted when a swirl tape insert is used with FILM-30. If the inlet subcooling is very high (i.e., $T_{\text{sub}} \gg 120 \text{ }^{\circ}\text{C}$) AND the water velocity is high (i.e., $v_{\text{in}} \geq 10 \text{ m/s}$) AND a small twist ratio is used ($Y \leq 2.5$), the swirl tape insert will cause the forced convection regime to be extended in such a fashion that the local CHF will be incurred prior to the onset of fully developed nucleate boiling. Since the programming logic of FILM-30 depends upon the entire boiling curve being traversed during the heat transfer process, the omission of the fully developed nucleate boiling regime produces a runtime error in FILM-30.

5.5 Recommended Revisions

The list of recommended revisions for FILM-30 can be divided into the categories of desired and projected. The desired category is a list of items that would increase the general applicability of FILM-30, but can only be accomplished through experimentation. The projected category is a list of programming changes that are planned for the near future.

Desired Revisions

1. Inclusion of the film boiling regime for materials other than OFHC-Cu.

Projected Revisions

1. Allowing the user to specify the swirl tape thickness
2. Allowing the user to specify the maximum wall temperature
3. Porting the source code to a JavaScript applet that can be run over the Internet
4. Porting the source code to the Microsoft Windows environment
5. Producing a graphical user interface
6. Allowing realtime viewing of the generated boiling curve

With Points 1 and 2 of the projected revisions, the user will be cautioned that changing the swirl tape thickness from 1 mm and the twist ratio from 2 will cause FILM-30 to be operated outside of Marshall's range of experimental data, for which FILM-30 has been validated.

To help manage the revisions of FILM-30, the following plan will be followed:

1. The Fusion Technology Department and Sandia National Laboratory will retain the name "FILM-3" for all of their versions of FILM-30.
2. Sandia-based revisions to FILM-30 will have the following convention:
 - a. Minor revisions will add a small case letter to the current version. That is, if the current version is FILM-30 and a new correlation is added, the new version will be named "FILM-30a".
 - b. Any revisions that detail a change to the original programming structure, regardless of how minor or large will result in an increment in the program number. That is, if the current version is "FILM-30a" and an internal function or subroutine is renamed, the new program version will be named "FILM-31a".
3. The program author, Marshall, will retain the name "FILM-" for his revisions of the code.

6 Conclusions

A FORTRAN computer code has been written to predict the heat transfer properties of water when an OFHC-Cu mockup is heated on one side. The computer code is named FILM-30 and it models all regimes of the Nukiyama boiling curve, minus film boiling. With a material melting temperature of 1000 °C, an OFHC-Cu mockup will fail prior to the onset of stable film boiling, thus the code's omission of the film boiling regime.

FILM-30 was designed to have a very modular internal programming structure in order to facilitate adding new heat transfer correlations, as they are developed. The code's well engineered programming structure allows it to be optimally compiled for the Hewlett Packard and Sun UNIX environments, which translates to the program running within five seconds of CPU time. The program has an intuitive user interface and outputs three data files that clearly describe the code's heat transfer predictions. One of the data files can be directly imported into an ABAQUS input deck for FEA analyses.

The heat transfer predictions of FILM-30 were used in FEAs and the resulting FEA thermal predictions were compared with experimental data from one-sided heat transfer experiments with water that were performed at Sandia. The excellent agreement between the FEA predicted and experimentally measured temperatures confirmed that FILM-30 correctly predicted the heat transfer properties of the water coolant. This comparison with experimental data illustrated that FILM-30 is applicable when the coolant channel is bare, when it has a swirl tape insert, and when heat transfer occurs in the forced convection, partially developed nucleate boiling, fully developed nucleate boiling, critical heat flux, and transition boiling regimes.

The range of variables for the heat transfer experiments are presented in Table 6-1. Since this range of variables was used to validate the correct operation of FILM-30, it is implicitly implied that the heat transfer predictions of FILM-30 are valid within this range of experimental conditions. This range of experimental conditions is directly applicable to fusion devices, which makes FILM-30 an excellent heat transfer prediction tool for nuclear fusion thermal hydraulics.

Table 6-1: Range of Validity for FILM-30

Variable	Operating Range
$Y = 0$	
Inlet Temperature (°C)	70
Inlet Velocity (m/s)	1, 4, 10
Inlet Pressure (MPa)	1
Incident Heat Flux (W/cm ²)	$40 \leq \text{IHF} \leq 1800$
$Y = 2$	
Inlet Temperature (°C)	70, 150
Inlet Velocity (m/s)	1
Inlet Pressure (MPa)	1, 4
Incident Heat Flux (W/cm ²)	$60 \leq \text{IHF} \leq 2000$

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-
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