NUCLEAR REACTOR PROCESS SYSTEMS:

THERMAL HYDRAULIC ANALYSIS

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February 1998

for the Thailand Initiative

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FOREWORD

This is a course about the simulation of nuclear reactor process systems for analysis purposes. Simulation is neither experimentation in the traditional sense of the word, nor theoretical. But clearly, our science and engineering as we now know it would not exist without simulation. Can you conceive of sending a man to the moon without simulation? Or building a nuclear power plant without simulation?

I propose (not originally of course) that there has emerged since the 60's, a new aspect of the scientific method: Simulation, which is orthogonal to experimentation and to theory. This new element alters the manner in which we go about our business. Prior to the advent of simulation tools, theories were posed and experiments were performed, often with severe limitations. Theoretical studies are limited by analytical constraints and experiments are limited by the bounds of cost, hazard, and measurement techniques. With simulation, however, analytical work is extended by numerical calculations and experiments are augmented by simulations. Often a simulation is superior to experiments. Some parameters are now more accurately simulated than they can be measured. Full scale simulations are feasible whereas full scale experiments are usually too risky or too costly to do. Not only is the nature of the scientific method changed, but the extent and scope of the method is vastly enhanced.

The nuclear industry is a typical industry that involves a great deal of fluid processes. It is atypical, however, because one of the process systems, the Heat Transport System (HTS), is of critical importance to the safety of the nuclear station. Sustained loss of cooling of the fuel is a catastrophic event. It has to be shown, a priori, that such events are of negligible probability and that the design is adequate to handle all probable events. Adequate design margin must be demonstrated. To compound the difficulty of the task, there is often insufficient evidence (thankfully) to base arguments on statistics. Consider also that current designs are pushed to their safe limits in order to extract the maximum power at the minimum cost. A nuclear station can typically cost $\$10^{10}$ (US). A 1% increase in output power can save $\$2\text{x}10^{8}$ (US) over the life of the station. The key task of design and analysis of the HTS is, then, is to demonstrate safety, performance, reliability and maintainability prior to the actual construction of the facility. Without simulation, this clearly would not be possible.

Typically, the simulation support involves the setting up of a large code such as RELAP and RETRAN (or their Canadian equivalents CATHENA and SOPHT). Large data sets are required as input and copious tables of numbers are the result of the many runs that are required. It can take months to acquire the primary data for such codes in the environment of an engineering design office, although the use of project-wide data bases and CAD/CAE systems have reduced the cycle time somewhat. Manual analysis of the numerical output from a single run can often take days. Clearly, the actual computation time for the computer runs is small compared to the elapsed time of the total engineering task at hand. The bottleneck is not usually the computer; it is the engineer/scientist. It is stark testimony to the achievements of the last 20 years that a very wide scope of problems can be routinely handled by industrial codes. A new era of simulation is upon us! There is a distinct qualitative difference in such simulation tools over the calculations of the past.

For all the bravado of faster and more detailed plant renderings, we would be well advised to step back and look at simulation as an element in a larger project. Much is usually made of the enhancement of a simulator by the discovery of a faster algorithm. Obtaining a speedup of a factor of 2 is a notable event worthy of praise. But is it needed? Where is the bottleneck in your project? For the nuclear industry, the elapsed time for project completion, from project concept to in-service, is not significantly affected by simulation run time. Rather, the engineering phase is governed by concept generation, data preparation, model definition, coding, debugging, code verification, analysis, and design. A slow running code that is easy to use, modify or develop, even though it is not the last word in accuracy or speed, is a clear winner over the exotic, temperamental, accurate and speedy A-stable, implicit, all singing-all dancing code.

But, alas, the real world demands compromises, a balance must be sought. Some enhancements over a naive explicit number cruncher are essential for stiff systems (for instance) and well worth the price in coding. The key thing to note, however, is that the parameter to optimize is not speed of computation, or stability or robustness per se. We need to optimize the overall project, not the code. In this regard, the optimum code is one that gets the job done with the minimum of fuss and muss. Keep in mind, however, that some careful planning in code design can lead to big payoffs down the line. For instance, effort spent in modularizing a code or generalizing it so that the code serves more than one project is often well spent. The art of simulation is knowing when to stop modularizing or generalizing and when to get down to work.

ACKNOWLEDGEMENTS

This work was funded by McMaster University and the Natural Sciences and Engineering Research Council of Canada. The author is indebted to Atomic Energy of Canada Ltd. and to Ontario Hydro since this work is inextricably linked to past involvements with these companies. Special thanks go to my students, John Hoskins and Brian Hand, for water property development, and to Raymond Sollychin for his central role in the development of the rate method for the equation of state. A general thanks to all my students over the years; their freshness is a constant delight.

GLOSSARY OF ABBREVIATIONS AND ACRONYMS

AECB	Atomic Energy Control Board (Canadian nuclear regulatory agency)
AECL	Atomic Energy of Canada Limited (CANDU design company)
AESOP	Atomic Energy Simulation of Optimization (computer code)
ASDV	Atmospheric Steam Discharge Valve
ASSERT	Advanced Solution of Subchannel Equations in Reactor Thermal hydraulics (computer code)
ASTM	American Society for Testing Materials
BLC	Boiler Level Control
BLW	Boiling Light Water
BOILER	Computer code for boiler (steam generator) design
BOSS	BOiler Secondary Side (computer code)
BPC	Boiler Pressure Controller
CAD/CAE	Computer Aided Drafting / Computer Aided Engineering
COBRA	?? (thermalhydraulic computer code)
CANDU	CANadian Deuterium Uranium (reactor type)
CATHENA	Canadian Thermalhydraulic ??? (computer code)
CCP	Critical Channel Power
CHF	Critical Heat Flux
CPR	Critical Power Ratio
CRL	Chalk River Laboratories (part of AECL)
CSA	Canadian Standards Association
CSDV	Condenser Steam Discharge Valve
CSNI	Canadian Standards for the Nuclear Industry
DCC	Digital Control Computer
DF-ET	Drift Flux-Equal Temperature (thermalhydraulic model)
DF-UT	Drift Flux-Unequal Temperature (thermalhydraulic model)
DNB	Departure from Nucleate Boiling
DRIP	Distributed Resistance in Porous Media (computer code)
ECC	Emergency Core Cooling
ECI	Emergency Core Injection
EVET	Equal Velocity Equal Temperature (thermalhydraulic model)
EVUT	Equal Velocity-Unequal Temperature (thermalhydraulic model)
EWS	Emergency Water Supply
FIREBIRD	??(computer code)
FLASH	??(computer code)
FBR	Feed, Bleed and Relief
FP	Full Power
HEM	Homogeneous Equilibrium Model
HTS	Heat Transport System
HUT	Hold-Up Tank
HX	Heat eXchanger
HYDNA	Hydraulic Network Analysis (computer code)
I&C	Instrumentation and Control
IBIF	Intermittent Buoyancy Induced Flow
LOCA	Loss of Coolant Accident
LOC/LOECC	Loss of Coolant with Coincident Loss of Emergency Core Cooling
LOP	Loss of Pumping

LOR	Loss of Regulation
milli-k	Unit of reactivity for reactor physics
NPSH	Net Positive Suction Head
NUCIRC	Nuclear Circuits (computer code)
OH	Ontario Hydro (electrical utility company, Ontario, Canada)
PGSA	Pickering Generating Station A
PHTS	Primary Heat Transport System
PHW	Pressurized Heavy Water
PHWR	Pressurized Heavy Water Reactor
POWDERPUFFS-V	(reactor physics computer code)
PRESCON2	Pressure Containment (computer code)
QA	Quality Assurance
RAMA	Reactor Analysis Implicit Algorithm (computer code)
R&M	Reliability and Maintainability
RELAP	(thermalhydraulic computer code)
RETRAN	(thermalhydraulic computer code)
RB	Reactor Building
rem	röentgen or rad equivalent mammal or man??
RIH	Reactor Inlet Header
ROH	Reactor Outlet Header
RTD	Resistance Temperature Detectors
SDM	Safety Design Matrices
SOPHT	Simulation of Primary Heat Transport (computer code)
SRV	Safety Relief Valve
THIRST	Thermal-Hydraulics in Recirculating STeam Generators (computer code)
TMI	Three Mile Island
TOFFEA	Two Fluid Flow Equation Analysis (computer code)
TUEC	Total Unit Energy Cost
UVUEUP	Unequal Velocity, Unequal Energy, Unequal Pressure (thermalhydraulic model)
UVUT	Unequal Velocity Unequal Temperature (thermalhydraulic model)
VB	Vacuum Building
VC	Vacuum Chamber
WRE	Whiteshell Research Establishment (part of AECL)

NOMENCLATURE

A	area
A	arbitrary vector
C	concentration
C_p	heat capacity at constant pressure
C_v	heat capacity at constant volume
e	specific internal energy
E	internal heat source or sink
f	friction factor
f	long range or body force
g_c	gravitational constant
g	acceleration due to gravity
h	specific enthalpy
h_N	heat transfer coefficient
H	total enthalpy in volume, V
I	unity tensor
k	head loss coefficient
L	length
M	mass in volume, V
M	momentum interchange vector
n	unit vector normal to the surface
P	pressure
q	heat flux
Q	lumped heat source or sink
s	surface bounding volume, V
S	surface sink or source
t	time
T	temperature
U	total internal energy in volume, V
V	arbitrary fluid volume
v	velocity vector
W	mass flow
x	quality (weight fraction)

Greek

α	void fraction
γ	phase volume fraction
Γ	local sink or source
ψ	field variable
ρ	density
$\boldsymbol{\sigma}$	stress tensor
θ	angle with respect to horizontal
$\boldsymbol{\tau}$	shear stress tensor

Operators

$\frac{\partial}{\partial t}$	partial time derivative
$\frac{d}{dt}$	total time derivative
$\frac{D}{Dt}$	substantial time derivative
∇	Del operator
$\iiint_V (\ )dV$	volume integral
$\iint_S (\ )ds$	surface integral
$<(\ )> = \frac{1}{A}\iint_S (\ )ds$	cross sectional average

Subscripts

f	liquid (fluid) phase
g	vapour (gaseous) phase
i	summation index for nodes
j	summation index for links
k	1, 2 (1 = liquid, 2 = vapour)
S	surface
SAT	saturated
IN	ingoing
OUT	outgoing