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On Assuring Quality in Thermalhydraulic System Simulation

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ABSTRACT

A simple philosophical basis for quality assurance is given and supported by a concrete example. A simple overview of the main characteristics of the CANDU nuclear reactor heat transport system generates the main parameters as targets for verification. Primarily through plant commissioning, the simulation code is systematically locked-on to actual plant performance in the key areas of heat transport system flow and steam generator heat transfer performance. Subsequent model extrapolation into high power, oscillatory two-phase flow was confirmed by plant experience. This lends great credibility to the simulation model and supports the philosophy of the approach to QA advanced in the paper.

A PHILOSOPHY

A recurring theme in simulation is, "How do we assure quality in the product?". This paper advances the philosophy that true QA has its roots, not in codes and standards or specifications or detailed rules for developing and verifying computer codes, but in the individuals who do the developing and verifying. To be sure, we do require codes and standards, etc. But these are not sufficient to assure quality since rules have to be interpreted and implemented by those all important individuals.

Now, what makes the individual so valuable to the success of any project is his* ability to recognize patterns, to put the details of a project into perspective, to reflect, to develop a feeling of the big picture, to recognize the major factors, etc. The professional who is concerned with ensuring quality will naturally ask, sooner or later, "To what is my system most sensitive to? What are the biggest uncertainties?"

To answer these questions, the professional invariably ends up performing a very useful exercise: the back of the envelope calculation. He must do this because his alternative is to use simulation codes, the very thing he is trying to verify. In addition, it is necessary to use as simple a calculation as possible so that errors and limitations of the calculation are as obvious as possible. And so, our concerned simulationist acquires a feeling of what parameter is both a sensitive one and an uncertain one. This becomes his main focus of attention. Only after he has resolved that item could he then focus on the next critical item with some peace of mind. This is continued until there remain no errors or uncertainties of any consequence to the problem at hand.

Unfortunately, life is never so linear or settled. Thus the simulationist must frequently step back for reassessment, always starting at the big picture and working down to the details. One cannot fine tune before the rough tuning is done. To illustrate the above procedure, consider the issue of verification of the thermal-hydraulic simulation of the heat transport system of the CANDU nuclear reactor.

* Until someone invents an acceptable genderless third person singular pronoun, I will use "him" in the generic sense.

CANDU T/H - AN OVERVIEW

Before entertaining the questions laid down in the previous section, the system in question is briefly described.

CANDU 600 Heat Transport System (reference 1)

Figure 1 gives an overview of the CANDU Nuclear Power System. The pressure tube forms the pressure boundary of the Heat Transport System (HTS) in the core; the heavy water coolant passes through and around the bundles of natural uranium fuel located within the pressure tube. The portions of the fuel channel assemblies external to the calandria are known as the end fittings; the end fittings are connected to the feeder pipes (feeders) which feed coolant into and out of the fuel channels. The CANDU 600 reactor has 380 fuel channels arranged in a square lattice within the calandria. The Heat Transport System (HTS) is arranged into two circuits, one on each side of the vertical centre line of the reactor core, with 190 fuel channels in each circuit. Each circuit contains 2 pumps, 2 steam generators, 2 inlet headers and 2 outlet headers in a "figure-of- eight" arrangement. Feeders connect the inlet and outlet of the fuel channels to the inlet and outlet headers respectively.

The flow through the fuel channels is bidirectional (i.e. opposite directions in adjacent channels). The feeders are sized such that the coolant flow to each channel is approximately proportional to channel power. The enthalpy increase of the coolant is therefore approximately the same for each fuel channel assembly. The operating pressure of the CANDU 600 reactor (outlet header) is 10 MPa. In order to increase unit efficiency, boiling in the core at high power is utilized, leading to an outlet header quality of up to approximately 4% at full power. Other typical Heat Transport System parameters are given in Figure 1.

Why Verify?

The HTS is, in the simplest sense, merely a sytem which transports fluid for the purposes of heat transfer. However, the design of the HTS covers many aspects including chemistry, mechanics, safety analysis (for LOCA's, etc.) and process design and analysis. This example will be limited to the verification of process (thermalhydraulic) design and analysis work.

Since process design and analysis is largely based on computer simulations, verification of process design work and analysis is centered around the verification of the methodology, models and base data used by the relevant computer codes. We turn our attention, therefore, on a typical model to determine the source of errors.

The Inherent Approximation (reference 2)

The fundamental relationships governing thermalhydraulic analysis are:
1) Conservation laws: mass, energy, momentum,
2) Constitutive laws: state equations.

The basic step of establishing mathematical statements to reflect reality is, in itself, an approximation.

All component (fluid, pipes, heat exchangers, valves, pumps) equations are derivable from these fundamental relationships. The state of the art is such that empirical relations are heavily relied on to compensate for the lack of understanding of the fundamental terms in the basic equations. For example, stress tensors are invariably reduced, ignored, or replaced by friction factors. Multiphase flow equations are invariably combined into mixture equations. This is the second level of approximation.

The third level of approximation is created because the solutions to the various approximate forms of equations that have been derived are usually not directly achievable. Discrete approximations are made to continuous systems and numerical solution techniques, guaranteed to work only for linear systems, are used (the fourth level of approximation). The final solution is thus four-fold removed from reality. Small wonder that the simplified component models used in systems analysis do not always produce perfect results.

Simple Steady State Equations (reference 2)

Performing an energy balance around the reactor, the energy out of the reactor equals the energy going in plus the reactor energy generation. Thus:

$$M\,h_o = M\,h_i + Q \text{ or } Q = M(h_o - h_i), \tag{1}$$

where M = coolant mass flowrate (kg/s);
h_o = core exit enthalpy (kJ/kg);
h_i = core inlet enthalpy (kJ/kg);
Q = reactor power transferred to the coolant (kJ/s or kW).

Neglecting minor factors such as pump heat, piping heat losses, pump gland seal leakage and miscellaneous heat losses via auxiliary systems, the power transferred to the steam generator is Q kW. The heat transfer at any point in the steam generator is given by Newton's law of cooling:

$$dQ = U\,(T_p - T_s)\,dA \tag{2}$$

where U = overall heat transfer coefficient (kW/m^2 °C),
A = heat transfer area (m^2),
T_p = primary (D_2O) side temperature (°C),
T_s = secondary side (H_2O) temperature (°C).

U is a function of flow, temperature, the amount of boiling (quality), the physical layout, heat exchanger tube material and the degree of crudding or fouling in the steam generator. Thus the total heat transfer is

$$Q = \int_Q dQ = \int_A U(T_p - T_s)\,dA \tag{3}$$

However the D_2O and H_2O temperatures are not constant throughout the steam generator. A schematic representation of the variation is shown in Figure 2.

Using the 600 MW CANDU as an example, demineralized feedwater (H_2O) enters the preheating section of the steam generator at roughly 175°C and gains heat from the exiting D_2O (~265°C at ~5 MPa) and the H_2O begins to boil. The temperature then remains essentially constant as the H_2O travels through the boiler (left to right in Figure 2). The D_2O (primary fluid) enters the boiler section of the steam generator at roughly 310°C at 10 MPa with 4% quality (i.e., 4% by weight of steam). The heat transfer to the secondary side condenses the steam and the temperature subsequently drops as the D_2O travels through the steam generator tubes (right to left in Figure 2).

For the purposes of discussion, we will simplify equation 3 by assuming a temperature distribution as shown in Figure 3. Thus we have ignored the preheating section (where the H_2O temperature is less than saturation) and have assumed that no boiling occurs on the primary side. Further we assume that U is constant. These are crude

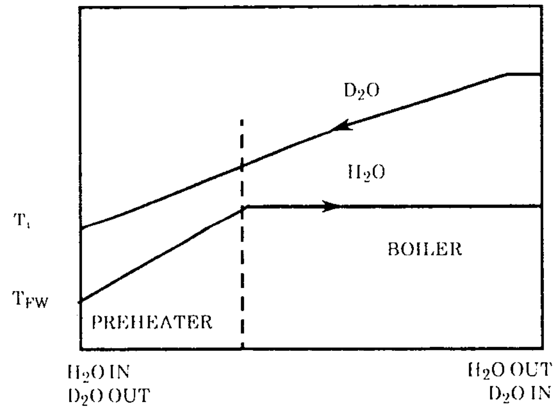

Figure 2 Steam Generator Temperature Distribution

approximations but adequate for discussion purposes. Thus, equation 3 becomes:

$$Q = UA\left|\frac{T_o + T_i}{2} - T_s\right| \tag{4}$$

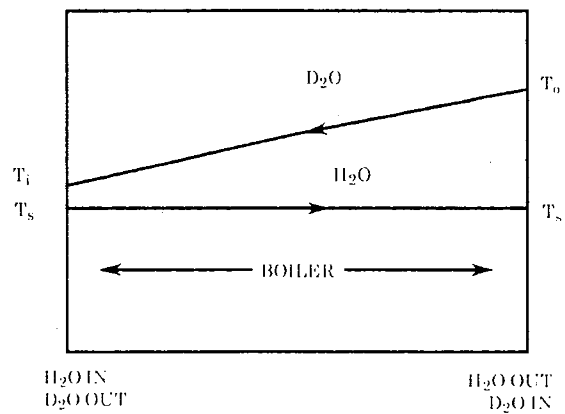

Figure 3 Simplified Steam Generator Temperature Distribution

This can be related to enthalpy by noting that

$$h \simeq C_pT + \text{CONSTANT}, \tag{5}$$

where C_p is the heat capacity of water, Equation 4 then becomes:

$$Q = \frac{UA}{C_p}\left|\frac{h_o + h_i}{2} - h_s\right| \tag{6}$$

if we assume the same properties for H_2O and D_2O.

A final primary heat transport system relation is needed to complete this approximate picture. The primary side flow is determined by a balance between the pressure head generated by the primary pumps and the circuit head losses due to friction.

$$\Delta P_{pump} = A_o + A_1M + A_2(M)^2 + \ldots = \Delta P_{circuit} = K(M)^2 \tag{7}$$

where K can be a complex function of material properties and pipe geometric details. Typical shapes for Equation 7 are shown in Figure

4. The intersection of the two curves is the operating point, equation 7.

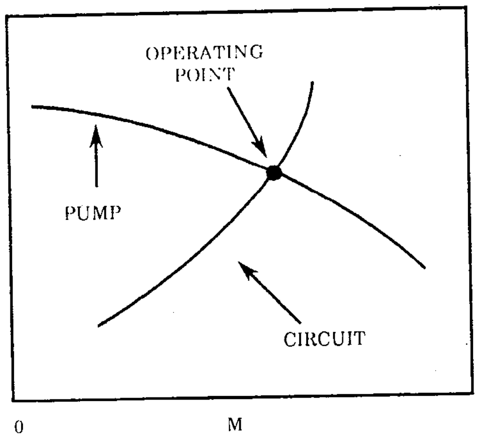

Figure 4 Circuit Losses and Pump Head vs. Flow

The primary heat transport approximate conditions are set, then, by the simultaneous solution of the energy balance at the core, the energy balance at the steam generator and the momentum balance around the circuit.

Equations 1 and 6 can be rearranged (eliminating h_o) to give:

$$h_i = Q/M\left[\frac{C_pM}{UA} - \frac{1}{2}\right] + h_s . \tag{8}$$

Thus we see that since all parameters, Q, M, C_p, A, U, etc., are positive quantities, the reactor inlet enthalpy (and hence the inlet temperature will rise up as flow rises, will rise as secondary side temperature and enthalpy rise and may go up or down as power changes.

The reactor outlet enthalpy, h_o, is directly related to h_i by equation 1. Thus:

$$h_o = Q/M + h_i = Q/M\left[\frac{C_pM}{UA} + \frac{1}{2}\right] + h_s . \tag{9}$$

The average enthalpy in the core and the steam generator is:

$$\bar{h} = \frac{h_o + h_i}{2} = (Q/M)\left(\frac{C_pM}{UA}\right) + h_s = \frac{QC_p}{UA} + h_s . \tag{10}$$

This result is worth remarking since it shows that $\bar{h}$ is not a direct function of flow. Given h_s, C_p/UA as fixed for a given secondary side temperature and steam generator geometry, $\bar{h}$ is a simple linear function of the reactor power, Q. Figure 5 illustrates this point and also shows the spread or variation in h about $\bar{h}$ given by:

$$h_o - \bar{h} = Q/M\left(\frac{C_pM}{UA} + \frac{1}{2}\right) + h_s - \frac{Q}{M}\frac{C_pM}{UA} - h_s = Q/M \tag{11}$$

Similarly,

$$h - h_i = Q/M . \tag{12}$$

From equation 12 we see that the primary side enthalpy floats on top of the secondary side with just enough Δh to transfer Q kW of power. Also, given a rough estimate of flow for the calculation of U (not a strong function of flow since M is large and turbulent - most of the resistance to heat transfer is due to conduction through the tubes

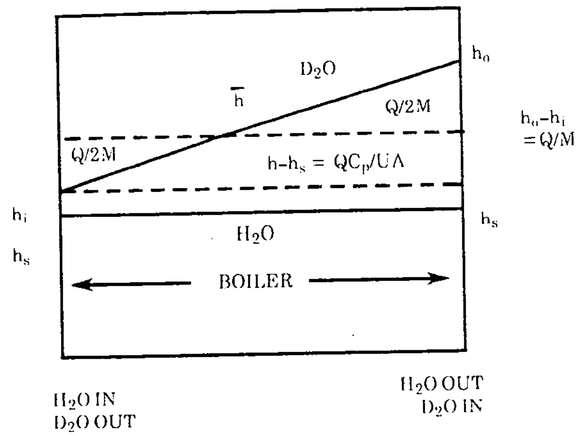

Figure 5 Enthalpy Variations

and crud layer) we can calculate h and estimate the spread in h ($\bar{h}$ ± Q/2M). This gives a good first estimate of the temperatures and enthalpies and indicates whether boiling will occur in the primary circuit or not. With this enthalpy, temperature and hence density estimate, the circuit losses can be calculated and compared to the available pump head at that flow. The flow estimate can be updated and the whole procedure repeated until convergence is reached. A sample calculation follows.

<u>Sample Heat Balance for CANDU 600</u>

Parameters:

$Q = 2000$ MW (th) $= 2 \times 10^6$ kW (th) (given)

$M = 8000$ kg/s (guessed)

$T_s = 265$°C (given)

$C_p = 4.25$ kJ/kg

$h_s = 1125$ kJ/kg

$U = 21.25$ kJ/s°C m^2

$A = 320$ m^2

$\frac{UA}{C_pM} = 2$ (guessed)

$P_{ROH} = 10$ MPa (given)

Thus from equation 8

$$h_i = 250[\tfrac{1}{2} - \tfrac{1}{2}] + h_s = h_s = 1125 \text{ kJ/kg}. \tag{13}$$

and

$$h_o = h_i + Q/M = h_i + 250 = 1375 \text{ kJ/kg}. \tag{14}$$

The saturation enthalpy at the outlet header is roughly 1370 kJ/kg. Hence our prediction of the primary outlet conditions is that the D_2O should just come to saturation. In fact, the detailed design calculations give the outlet quality at 4% with an enthalpy of ~ 1415 kJ/kg.

From equation 8

$$\frac{\partial M}{\partial h_i} = \frac{Q}{2\left(h_i - h_s - \frac{QC_p}{UA}\right)^2} = \frac{Q}{2(Q/2M)^2} \cdot 2 = \frac{2M^2}{Q} . \tag{15}$$

and

$$\frac{\partial(M/M_o)}{\partial(h_i/h_{io})} = 9.0 . \tag{16}$$

Thus if we had chosen h_i to start our iterative calculation, and our guess was in error by 25% the flow will subsequently be in error by 9.0 x 25% or 225%. Thus huge swings in estimated flow will accompany the search for the right h_i.

If, instead, we guess at flow and are out by 25%, the h_i calculated will be out by only 2.8%. Convergence will, thus, be much better behaved.

The proper iterative procedure, then, would take full advantage of these sensitivities. The key parameters are fixed or guessed: Q is usually given, M is guessed from, say, a single phase circuit loss calculation at any reasonable enthalpy, U is calculated based on empirical correlations, A is usually given and T_s is usually given. The enthalpies can then be readily calculated. Depending on the nature of the correlations used for U, the iteration may involve an inner loop on U and h to converge on a self-consistent heat transfer given the flow. The flow, then, is updated based on the circuit loss calculation until convergence is reached.

CODE LOCK-ON PROCEDURE (references 2,3,4)

Since the codes are used for station design and safety analysis, it is required to show that these codes predict performance in, at least, a conservative manner. To satisfy this requirement, a commissioning program was performed to compare station performance to code prediction and to adjust the models in a prescribed manner to lock the codes onto the station.

Briefly, the procedure was to:

1) Measure the HT flow under 0% F.P. conditions and compare to code predictions. Adjust codes to suit (frictional correlations and pump curve).
2) Measure the HT thermal performance (mainly, temperature as a function of power) and compare to code predictions. Adjust codes to suit (heat transfer correlations). The power maps from reactor physics are used here and may also be adjusted.
3) Predict the onset of voiding and compare to plant data. Discrepancies would require a code retuning or modified code modelling.
4) Perform dynamic predictions and tests. Adjust the void-quality relation, if necessary, or retune/remodel the code as required.

The logic of this process is of course to start with the simplest case first, then work to the most complicated case, adding a new degree of freedom at each stage. Further details of the procedure are given in Tables 1 and 2 (reference 2). A list of some tuneable parameters is given in Table 3 (reference 2) listed in the order that they would likely be employed in the code lock-on procedure.

COMMISSIONING EXPERIENCE

The first three parts of the procedure were summarized in reference 4. The fourth part was reported previously (reference 5).

In summary, part one showed that the single phase pressure drops and pump heads matched well with code predictions. Only minor adjustments were made to some local entrance and exit losses, etc. All adjustments were within engineering tolerances and measurement error.

Part two revealed modelling differences between NUCIRC* and SOPHT** steam generator models. Updating the NUCIRC steam generator model to include more detailed and realistic heat transfer coefficients gave agreement with site data and SOPHT predictions provided the SOPHT node structure was sufficiently detailed. The major impact of modelling variations was in the prediction of the onset of void. Pretest estimate for the onset of void was 98% F.P. The plant tests gave an onset of void at approximately 100% FP. The details of the steady state NUCIRC code tuning process is an interesting study in its own right. It is hoped that this will be reported upon at later date. The "best estimate" SOPHT prediction of the dynamic tests with no interconnect are within the spectrum of the prepredictions. The SOPHT results shown in Figure 6 include minor modelling enhancements, mainly in the use of more detail in the feeder modelling. Excellent agreement between SOPHT and the plant data was achieved (reference 5).

This "best estimate" post-test model was used to reaffirm the pre-test design analysis and associated analyses such as plant aging, transient performance, etc. The post-test activity was largely perfunctory since the test outcome fell within the range of the predictions upon which the design modification was based.

* NUCIRC is a steady state design code for the HTS.
** SOPHT (references 6-7) is a steady state and transient systems design code for the HTS.

CONCLUSION

In the foregoing example, it was shown that the systematic identification and resolution of the main sensitivities and uncertainties in thermalhydraulic simulation results in a substantially verified computer code. This approach stems from and capitalizes on the characteristics of humans as the prime movers in true QA. Thus, we conclude that the philosophy advanced by this paper is supported: the true source of QA is from within the individual.

ACKNOWLEDGEMENTS

Work of this scope could only have been accomplished by a dedicated team with the support of many people distributed throughout the various organizations of New Brunswick Power Commission, Hydro Quebec, Ontario Hydro and Atomic Energy of Canada Limited. This report is an overview of their work and reflects their achievements. Any errors or omissions remain the responsibility of the author.

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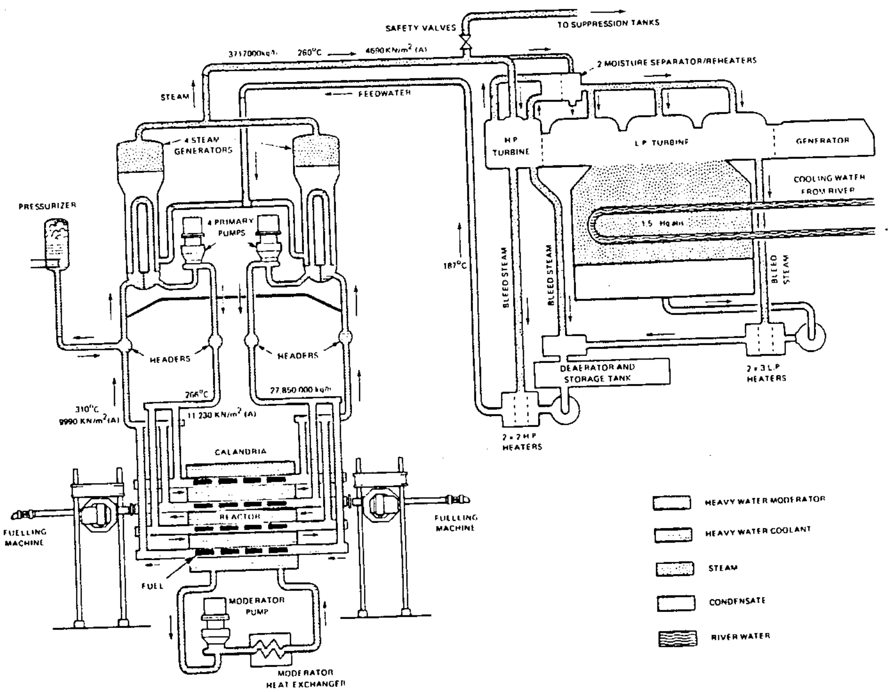


FIGURE 1 CANDU NUCLEAR POWER SYSTEM

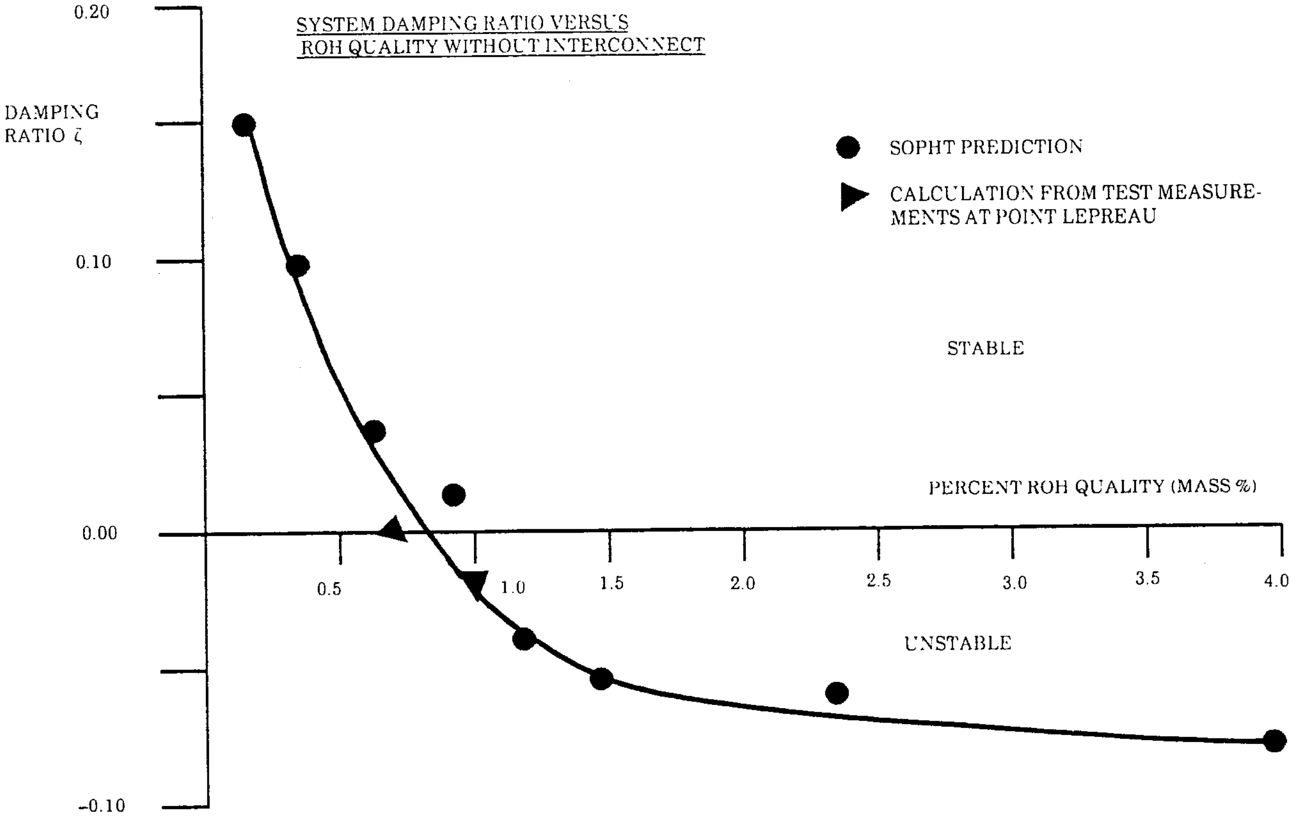


Figure 6 Reactor Outlet Header Quality Achieved during Tests and System Damping Ratio Comparison Between Prediction and Test Results

WJG-05b

ON ASSURING QUALITY IN THERMALHYDRAULIC SYSTEM SIMULATION

WHO	:	Atomic Energy of Canada Ltd. New Brunswick Electric Power Commission Hydro Quebec Ontario Hydro
WHAT	:	Quality Assurance, heat transfer and fluid flow
WHEN	:	1980 - 1983
WHERE	:	Nuclear Reactor – CANDU 600 Heat Transport System
HOW	:	Commissioning tests / laboratory tests / computer simulation / closed form solutions.
WHY	:	To achieve accurate computer simulation by locking code into a specific station.

MAJOR POINTS

1. True Q.A. has its roots in the individual

2. Why verify

3. H.T.S. is complicated in detail, but the main characteristics are simple. We will look at these overview equations.

4. Manipulation of simple equations to yield the essence of the system behaviour.

5. The above leads to the strategy for assuring Q.A. (stagewise process).

6. Results of implementing this strategy.

THE ROOTS OF QUALITY ASSURANCE

1. We have codes and standards, procedures, guidelines, rules, specifications, etc. These are necessary but not sufficient.

2. The above focuses on a product at particular stages and is **static.**

3. But Q.A. is a **process**, not a physical thing. It is **dynamic**. The essence of Q.A. is the flow of the design / procurement / commissioning / . . . activity.

4. This flow is directed by the individual.

5. Thus the key to true Q.A. is the **individual**.

HOW DOES THE INDIVIDUAL PERFORM THIS KEY ROLE?

1. Ask the right questions
    - major factors?
    - sensitivities?
    - uncertainties?

2. Answer questions by analysis
    - B.O.E.
    - which computer tool?
    - K.I.S.S.

3. Conceive plan to reduce vulnerability.

4. Carry-out plan.

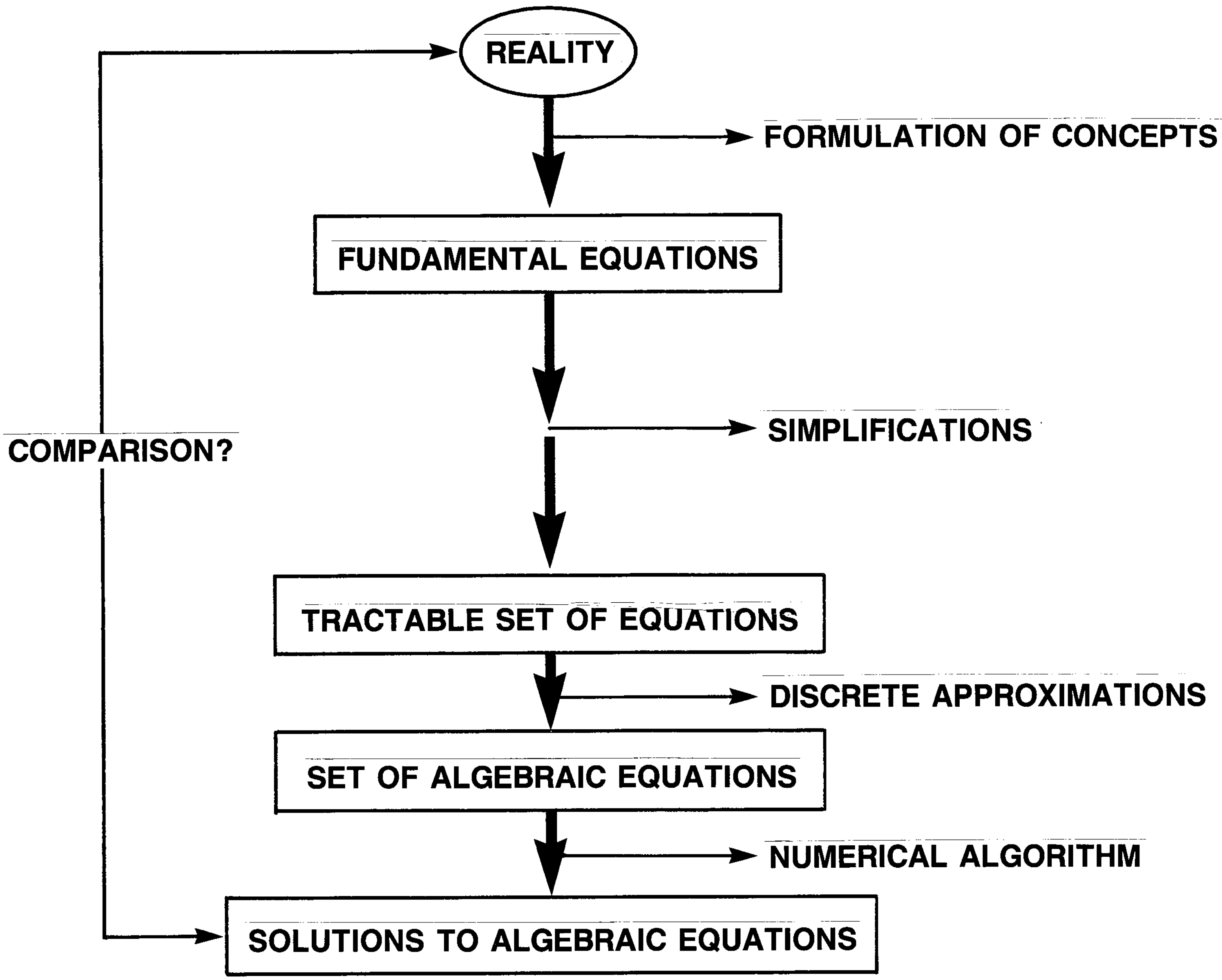
5. Iterate until no critical items remain.

6. Requires constant reflection, reassessment.

7. Overall strategy is to rough-in the main factors and do the fine tuning later.

WHY VERIFY?

SOURCES OF ERRORS



MAIN CHARACTERISTICS

1. **Energy balance for reactor:**

$$Mh_o = Mh_i + Q \rightarrow Q = M(h_o - h_i)$$

2. **Energy balance for steam generator:**

$$dQ = u(T_p - T_s)\, dA \rightarrow Q = \frac{UA}{C_p}\left[\frac{h_o + h_i}{2} - h_s\right]$$

3. **Momentum equation:**

$$P_{pump} = A_o + A_1 M + A_2 M^2 + \ldots = \triangle P_{circuit} = K(M)^2$$

4. **Manipulation gives:**

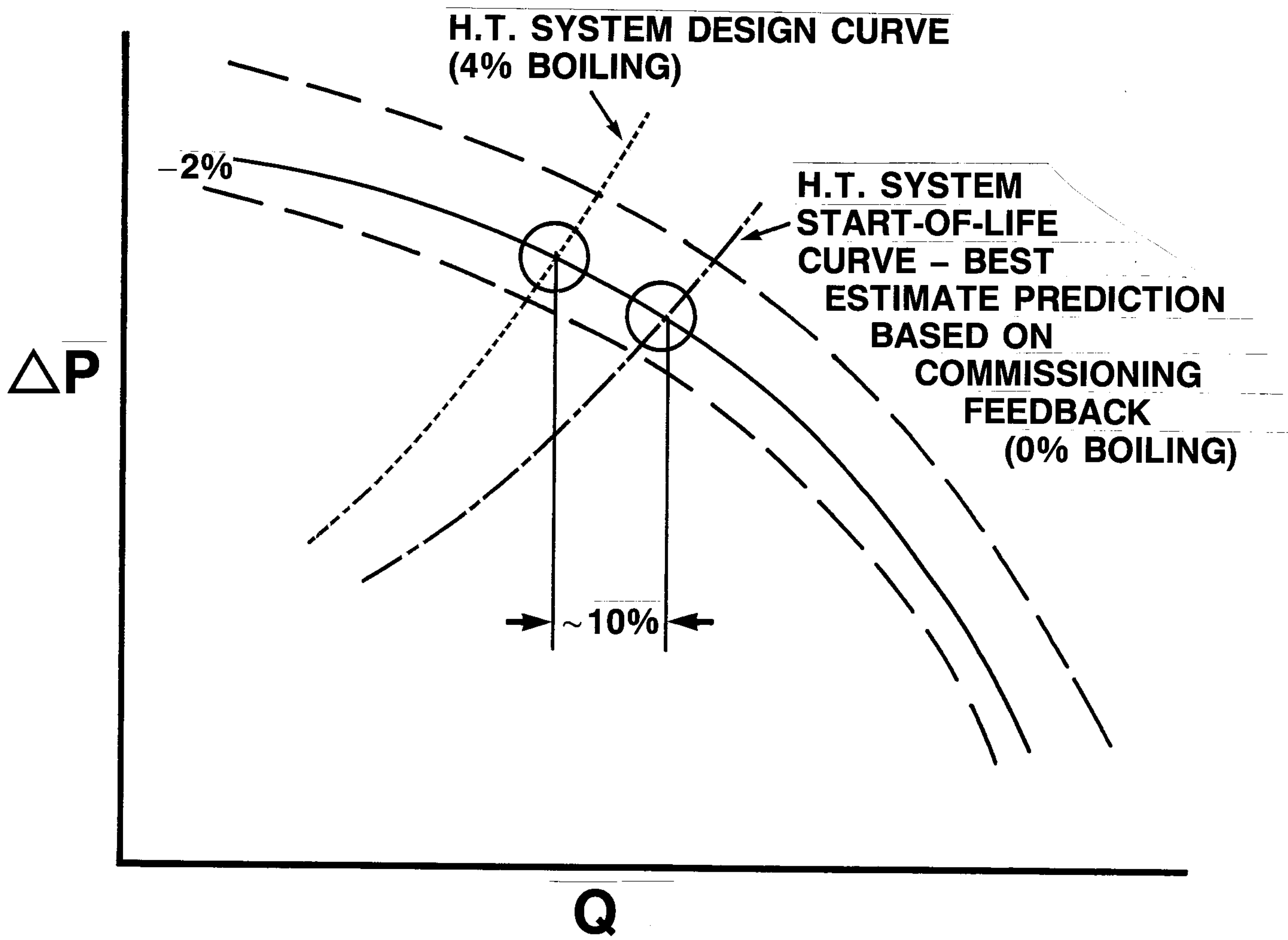
$$h_i = Q\left[\frac{C_p M}{UA} - \tfrac{1}{2}\right] + h_s$$

$$h_o = Q\left[\frac{C_p M}{UA} + \tfrac{1}{2}\right] + h_s$$

$$h = \frac{QC_p}{UA} + h_s$$

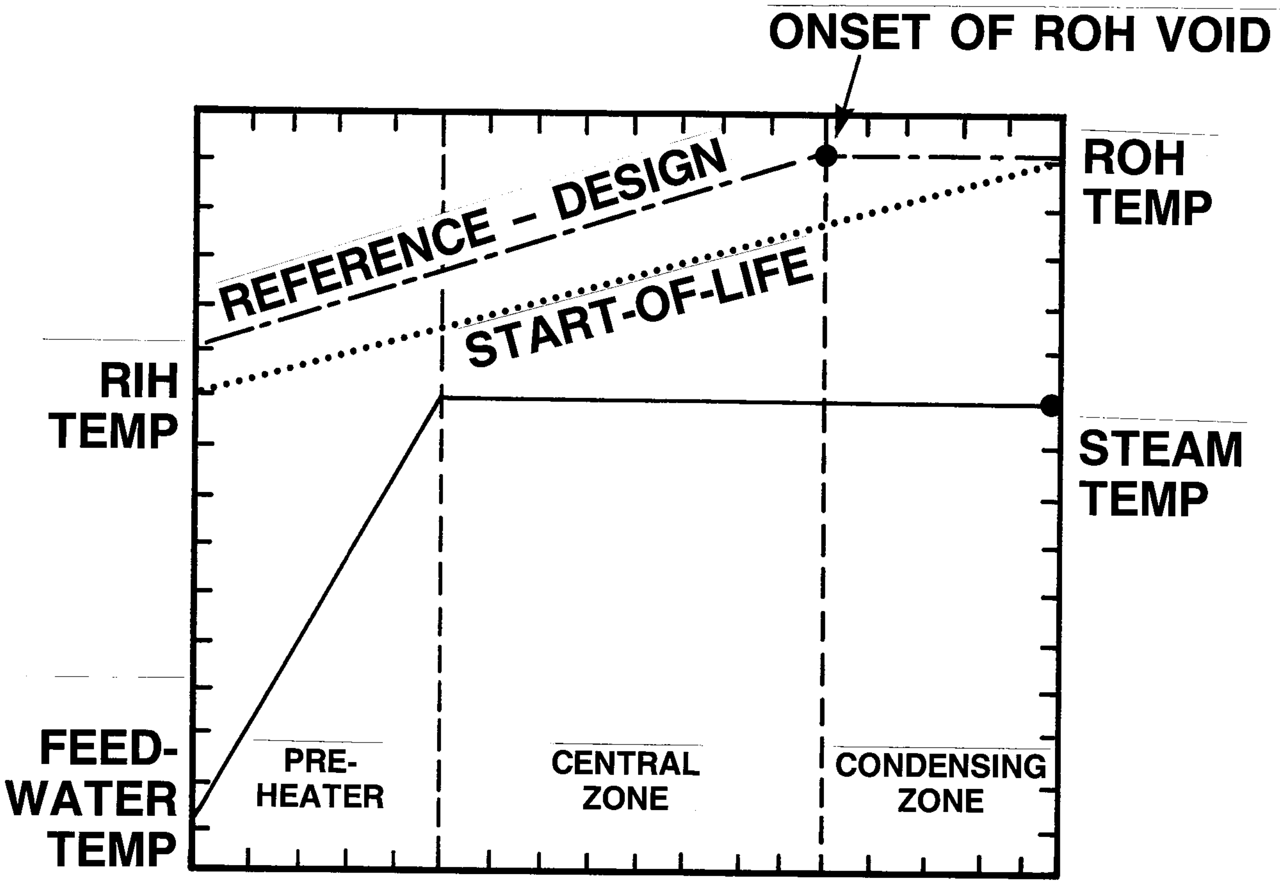
SYSTEM OPERATING POINT

------ DESIGN —·— ACTUAL



DESIGN PUMP CURVE AND
MANUFACTURING TOLERANCES

STEAM GENERATOR THERMAL PERFORMANCE



...... – flow up
– good heat transfer

STRATEGY FOR CODE LOCK-ON VIA COMMISSIONING

STAGE 1: H.T. Flow – 0% full power, cold and hot
- adjust pump curve and frictional losses

STAGE 2: H.T. thermal performance
- T as function of power
- adjust H.T. coefficient

STAGE 3: Predict onset of boiling

STAGE 4: Dynamic predictions and tests.

CONCLUSIONS

1. The systematic identification and resolution of main sensitivities and uncertainties resulted in a substantially verified computer code.

2. The approach taken did not stem from codified procedures, but from the care and concern of a small group of individuals who exert constant pressure on their area of work to improve, to maintain quality, over and above that required by even strict regulations.

3. The onus is on the designer (code writer, etc.), not the Q.A. team, to insure quality.

4. The best activity of Q.A. personnel, therefore, is in promoting the right attitude in the individual who is carrying out the work.