CHAPTER 14

DESIGN VERIFICATION

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14.0 ABSTRACT

In this chapter we introduce the general concepts of design verification and describe how they fit into the overall design process. The incentives and benefits behind design verification are also highlighted followed by the basic methodology. As an example of thermalhydraulic design verification, recent CANDU 600 heat transport (HT) commissioning experience is discussed in some detail.

We will be dealing primarily with steady-state operating conditions, and to a lesser extent, normal operational transients. Specific design verification issues related to HT system stability and overall safety analyses will be discussed in the following two chapters respectively.

14.1 THE DESIGN VERIFICATION PROCESS

Figure 1 illustrates a rudimentary design process flow diagram. In general, a product is identified which, in the context of this course, leads to the selection of the type and megawatt size of a CANDU station. From there, a set of basic design requirements are formulated. These are based on previous designs, with additional requirements added which are unique to the particular client.

From the set of design requirements, process flow sheets are prepared, and it is at this point that the design assumptions are made. Generally, the design assumptions are conservative. In respect to thermalhydraulics, the hydraulic losses in the HT system are overestimated, and the heat transfer in the steam generator is underestimated.

A large number of systems of varying complexity interact with the HT system, and must be accounted for when analysing its overall transient behaviour.

Here again assumptions are made to simplify the overall HT system model and facilitate computer code analyses.

Figure 2 illustrates design verification incorporated into the design process. The most common aspect of design verification is the conventional commissioning process, wherein the overall design intents are verified. In other words, we verify that all the systems are doing what they were designed to do. The less evident, but equally important aspect of design verification, is the validation of design assumptions and modelling. The attempt here is to show that the fundamental theories and understanding of the thermalhydraulic phenomena are correct. While conventional commissioning shows that the systems are functioning correctly -that our design models give us the correct answers, this second feature of design verification shows that we obtained the correct answer by the right methods (i.e. we were not just lucky).

As identified in Figure 2, design verification goes hand-in-hand with the design process, and as such, should be preplanned in the early stages of the design process; not added as an afterthought. This is particularly important when it comes to specifying special instrumentation or commissioning activities. In the next section we will briefly outline the reasons why design verification is needed.

14.1.1 Why it is Needed

As a minimum, design verification is required to show that the overall design intent has been met, both from a designer-owner/operator contractual viewpoint, and from an owner-licensing viewpoint.

The station owner/operator must be assured that he is getting what he paid for. Is the station operating properly? Does the electrical output meet the warranty? Is fuel burn-up excessive? What are the D_20 losses? Quite simply, design verification answers these questions.

At the same time the licensing authority must be assured that the reactor control and safety systems are adequate, and that the risk of radiation exposure to station staff and the general public is acceptable. Design verification analyses can play an important role in supporting this assurance to the licensing authority.

In the past, we have concentrated efforts on the conventional commissioning aspects of design verification, i.e. does the system work. In the next section we will present some of the ancillary benefits which result from a full design verification program aimed at showing that the design models are correct and fundamental phenomena adequately understood.

14.1.2 What are the Ancillary Benefits

The incentives for a well planned design verification program are best dem onstrated through the benefits which can be realized, both for the design authority and the nuclear generating station owner/operator.

14.1.2.1 Benefits to the Station Owner/Operator

One of the most obvious potential benefits of the conventional commissioning aspects of design verification is early detection of design deficiencies. By correcting these through retrofits or repairs before radiation fields are established, repair costs are minimized.

In recent years there has been a drive to get more and more electricity out of a fixed size of power generation station. This drive is fostered by the increasing costs and uncertainty in world supply of conventional fuels. For nuclear stations, one way this can be achieved is by reducing margins, both operating and safety. However such reductions could lead to costly outages and have safety overtones. The alternative is to maintain margins but increase the licensable power level. This can be achieved by removing excessive design conservatism in the thermalhydraulic models based on design verification analyses.

A less direct benefit can be gained by using design verification analyses to increase operating margins and maintain the original design license power level. This will allow greater operating flexibility, particularly with regard to refuelling.

In general, the design verification analyses can be used to support safety and licensing documents, and in turn facilitate the issuance of an operating license at the desired power level.

Finally, as a result of the design verification process, subsequent units ordered by a utility will be improved.

14.1.2.2 To the Design Authority

From the design authority's viewpoint, a good verification program provides updated design criteria, guidelines and data bases for future projects. Improved overall station efficiency, operability and licensability can be achieved for new or even existing designs. By showing equipment sizes can be reduced or even eliminated, capital costs can be reduced.

Design verification is also a means for the designer to improve his product and enhance its marketability. It also leads to an improvement in the image of the design authority. He is seen as being progressive, responsibile, thorough and conscientious in his efforts to produce an efficient, reliable and safe product.

14.2 DESIGN VERIFICATION METHODOLOGY

Due to the complexity and size of typical HT systems and interacting auxillaries, thermalhydraulic design is typically handled by large computer design codes. Therefore the design verification process as outlined in Figure 2 translates into validation of the design assumptions and modeling of these design codes. This is achieved by three mechamisms or tool.

1) Experimentation designed to verify modeling. This is ideally done during the design process.
2) Designer review and scrutiny of the design codes on an ongoing basis. Comparison of results from different codes which model the same system.
3) Feedback from actual stations during commissioning and in-service operation.

The general process to be followed in any thermalhydraulic system is as follows;

a) first start by verifying that the steady-state isothermal hydraulics are correct.
b) then show that the steady-state performance with heat transfer is correct.
c) verify the steady-state predictions from transient design codes are correct (initial conditions). Steady-state analyses can be of assistance here.
d) conclude by verifying that the transient design codes predict the transient behaviour properly.

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.

We will now examine the design verification tools in more detail.

14.2.1 Experimental Programs

Some of the design assumptions made during the early design phase can be verified through testing. The results are then factored into the final design process. In such cases, the cost of the experimental program must be weighed against the penalty being paid for the uncertainty in the design assumption, keeping in mind that the experimental results may impact on more than one system and on subsequent reactors.

A good example is the hydraulics of the fuel channel. The flow path through a fuel channel cannot be accurately modeled by standard correlations, and would result in a large uncertainty in the fuel channel pressure drop. Expensive design margins would have to be added to account for this uncertainty. Therefore extensive experimental investigation has been devoted to developing models for the pressure losses in fuel channel end fittings, liner tubes, shield plugs and fuel bundles.

Other examples include critical heat flux correlations, pipe erosion-corrosion based velocity limits, pump flow characteristics, steam generator heat transfer correlations, valve hydraulic losses and two-phase pressure drops in fuel bundles and pipe fittings.

14.2.2 Designer Review and Scrutiny

The second tool for code verification is constant re-evaluation and scrutiny of the methodologies and assumptions used in the design codes. The designer should always be looking for new approaches to a problem and fresh ideas. He should always be asking "is this the best way?", "is the answer reasonable?".

At the same time, the results from different codes applied to the same problem should be compared. If there is a significant difference then at least one of the codes is wrong.

14.2.3 Commissioning and In-Service Station Feedback

The third and most valuable tool for design verification is feedback from station commissioning and in-service performance. Certain assumptions made during design cannot be investigated using laboratory tests. Either the real phenomenon cannot be properly duplicated in a laboratory environment, or the experimental program would be prohibitively expensive. In these instances we must rely on commissioning and in-service feedback.

Here, the general methodology is to tune out the uncertainties in the codes so that the predictions match stations data. Using the commissioning data, and guided by good engineering judgement and standard engineering practices, excessive conservatisms can be removed from the code modelling.

However, this is not as easy as it appears. There may not be adequate instrumentation to verify a particular assumption. Or the instrumentation is not accurate enough or located poorly. Such problems can be avoided by planning a design verification program during the initial design process. Of course there is a practical limitation to the amount of instrumentation which can be added to a reactor for design verification. Care must be taken to identify the most important areas which need verification, usually those with the greatest economic benefit, and select the minimum amount of instrumentation needed to provide the necessary data.

A design verification program, particularly involving transient behaviour, can be very intensive and put a burden on the normal functions of the station control computer. Ideally a separate mini-computer should be dedicated for data gathering and analyses which would not interfere with the station control computer. This would greatly enhance the flexibility of design verification during commissioning, and provide an excellent tool for operating staff to assess station performance on an ongoing basis.

14.3 THE KEY AREAS OF THERMALHYDRAULIC DESIGN VERIFICATION

Thermalhydraulic design verification can be divided into three separate areas as follows:

a) steady-state isothermal hydraulics;

b) steady-state heat transfer; and

c) transient thermalhydraulic behaviour of systems for normal operating transients.

Using the CANDU HT system as an example, verification of steady-state isothermal hydraulics translates into showing that the gross core flow and channel flow distribution are such that there is adequate fuel cooling. Verification of steady-state heat transfer translates into showing that the sufficient heat is being transferred to the steam turbine cycle and that the temperature-enthalpy distribution within the HT system is correct. When there is no boiling in the reactor core the thermal and hydraulic aspects of verification do not influence each other significantly. However, as in CANDU 600 designs, boiling serves to closely couple the hydraulics and heat transfer through the two phase pressure drop multiplier. Boiling increses the hydraulic resistance of the HT system which in turn lowers the flow rate. Lower flow rates will mean more boiling in the core.

The steady-state thermalhydraulics of CANDU HT systems are modeled using the computer design code NUCIRC. This code exhibits a large amount of detail, including all the feeders, fuel channels, reactor external circuit piping, main pumps and steam generators. Correlations are included for the frictional and form losses of all piping, pipe fittings and equipment. The time averaged power map, and hence heat input distribution within the core, is also modeled. The various heat transfer regimes and recirculation within the steam generator are also a feature of NUCIRC modeling. However, the secondary side of the station and the HT systems auxillaries are not modeled.

The transient behaviour of the HT system is modeled by the computer design code SOPHT. Though SOPHT only models one, or at the most a few fuel channels and feeders, it boasts the capability of simulating all the auxillary systems including key features of the secondary side turbine cycle. As such it is used to study and verify the design of the HT system control systems and the behaviour of the HT system and auxillaries under transient conditions such as reactor start-up, cool-down, trip etc.

Due to the complexity of the CANDU HT system and auxillary systems, we rely heavily on these two design codes. As a result, design verification is very much interwoven with verification of the NUCIRC and SOPHT computer codes. It is particularly important to recognize this since the codes are used to extend our realm of experience to cover scenarios which cannot be tested in a laboratory or during commissioning, and to more fully understand the impact of one system on another.

14.3.1 Steady-State Thermalhydraulics

Uncertainty in the steady-state hydraulics arises from many sources. Generally large equipment such as steam generators have an upper limit set for the pressure drop at normal operating conditions. The suppliers of such equipment will tend to ensure a design pressure drop comfortably below this value. The inside diameters of pipes and tubing are subject to manufacturing tolerances. While these are small in terms of the diameter, they can be significant with respect to hydraulic resistances which are inversely proportional to the fifth power of diameter. Hydraulic loss coefficients for standard components are typically no better than ±5% to ∓10%. Nonstandard components should be tested or else much higher uncertainties must be accepted. The main HT pumps have a manufacturing tolerance applied. This will introduce uncertainty into the driving head for the system. Finally certain overall system modeling errors arise.

What is the cost of this uncertainty? Quite simply, computed power is directly proportional to computed flow. Since we design on the conservative side, the uncertainties will tend to reduce design flows, where in fact actual core flows will be higher. Design verification can remove these systematic conservatisms. A 1% underestimation in flow results in a ~1% reduction in power out of a typical CANDU reactor. This translates into a decrease in yearly revenue of roughly 1$M. Over the 30 year design life this is a significant economic penalty.

As introduced earlier, heat transfer is directly coupled to system hydraulics thorugh boiling and two-phase pressure drop multipliers. Uncertainty in heat transfer correlations and the mechanisms of heat transfer within a steam generator necessitate oversizing (adding extra heat transfer surface area). Capital costs could be reduced if this uncertainty could be minimized. Better heat transfer also translates into less boiling and hence, greater flow. On the other hand if heat transfer is over-estimated, the actual station will exhibit greater boiling and lower flow. Derating would result.

Another source of uncertainty is in pressure control, both in the steam generator steam drum (secondary side) and the ROH. A high steam drum pressure raises the HT system quality and decreases core flow. A low steam drum pressure has the opposite effect. A high ROH pressure will also depress the quality and raise core flow. These uncertainties must be accounted for in the design of operating margins.

Another area of uncertainty is in the measurement of the reactor power, both the magnitude and distribution throughout the core. This is done generally by two methods. The first uses the channel flows predicted by the design code NUCIRC and measured inlet and outlet feeder temperatures (thermal power). The second method uses a number of local measurements of flux. These are input to a computer code which generates flux shapes and relative channel powers. The absolute magnitude of the channel powers are uniformly adjusted to give the same total secondary side thermal power. The uncertainty in these calculations directly affects the operating margins. One other measurement of power is possible. This is the gross electrical power. All three powers should be consistent with the design. Indeed, each of the measurements can be used in tracking down errors in the others, thereby showing that uncertainties are as low or lower than claimed in design. This type of design verification is being actively carried out successfully at one of our CANDU 600 stations. Channel power mapping using flux measurements has been found to be very useful in assessing potential flow distribution problems.

14.3.2 Normal Operational Transients

Transient behaviour is important because flow, temperature and pressure swings can be damaging to system components. As for steady-state analyses, uncertainty in the models used in transient analyses directly affects the size of design margins.

The pressurizer behaviour is of prime importance to the total plant behaviour and hence should receive close attention. Temperature and pressure data are required on the condensation processes and on insurge and outsurge. The mechanisms of phase change under these conditions are not well understood.

In the steam generator, modeling of swell, shrink, recirculation and heat transfer with the tube bundle partially uncovered needs improvement. For the bleed condenser, verification of U-tube behaviour and condensation is needed.

Valve sizing is important. Capacities should be certified prior to installation. Ideally the valves should also be instrumented for position so that during commissioning and normal operation, the valve performance can be evaluated. In-situ stroking times can also be assessed and fed back into the transient design analyses codes. An oversized valve is no better than an undersized valve in general. Oversizing may require that during operation the valve be throttled to the point of cavitation. This can result in erosion of the seat or wedge, improper closure and leaks. An undersized valve will simply not pass sufficient flow. The design intent of the associated system may be jepordized.

Also, the relationship between the quality and void fraction is important for determining swell and shrink, and plays a large role in HT system stability behaviour. While our transient codes for CANDU 600 were able to predict a potentially unstable region of operation, they lacked sufficient detail to give a definitive answer. As a result, an expensive preventative plant modification was required.

Finally, the errors introduced into codes by the node-link discretization need a more thorough investigation. The discrete modeling of a continuous system affects the propagation of flow and pressure disturbances, the pressure distribution, and the quality distribution. Furthermore, since the transient codes typically model many interacting systems, the amount of detail must be traded off against computation costs.

14.4 AN EXAMPLE - CANDU 600 HT SYSTEM EXPERIENCE

AECL has had the opportunity to actively participate in design verification commissioning on 2 domestic and 2 overseas CANDU 600 reactors over the past 2 to 3 years. The most direct and extensive involvement has been on a domestic nuclear generating station and, to the authors' knowledge, it represents the most intensive effort at thermalhydraulic design verification during commissioning in CANDU history.

The incentive for this effort came from HT system stability concerns which will be discussed in the next chapter. The main purpose of the program was to tune the NUCIRC and SOPHT design codes to the station performance, assess the stability at the station start-of-life, then assess the stability at the station end-of-life based on projected operating performance from NUCIRC and SOPHT.

The transient portion of this program will be addressed in the next chapter, and only highlighted here. The main focus will be on steady-state performance and NUCIRC. Finally, while this design verification program was the most ambitious one to date for CANDU, it still represents a "bare bones" effort compared to an ideal program. This is because it was implemented after the station was designed and almost completely constructed. Therefore we will be desciribng what was done, and how and what should be done the next time.

14.4.1 Methodology

Figure 3 illustrates the design verification program for the CANDU 600 HT system. The methodology follows that described in 14.2. The program was divided into 5 stages as follows;

Stage 1: Establish the steady state hydraulics for the HT system at various
0% FP temperatures with no heat addition in the reactor core and no heat removal in the steam generators. Ultrasonic flow measurements are to

be taken at cold operating conditions to provide a means of verifying the flow distribution within the core. Key areas of investigation and verification include the core and steam generator hydraulic resistances and the manufacturer's pump curve.

Stage 2: Investigate primarily the temperature distribution in the HT system.
0% FP The key area of analysis is in the steam generator heat transfer
75% FP methodology and correlations. Some attention is to be given to thermal hydraulic interactions and pressure distributions as power is increased to 75% FP. This stage of tuning does not deal with two-phase flow and primary side boiling heat transfer.

Stage 3: Stage 3 is an extension of Stage 2 but involves transient and steady
75% FP state testing up to the onset of void (OOV) in the ROH. The intent here
- 00V is to approach the potentially unstable region (void in the headers) slowly and carefully. Pre-prediction of transient test results is suggested to reduce the chance of a reactor trip during the test.

Stage 4: Both thermal and hydraulic analyses is to be conducted between the OOV

00V- and 100% FP. Hydraulic analysis is to center on two-phase pressure
100% FP drop multipliers. Pre-predictions of transient test results are also recommended, as in Stage 3.

Stage 5: Based on the analysis and code tuning of Stages 1 to 4, the reactor performance is to be evaluated at various points during its operating life by making appropriate code input adjustments. The purpose is to verify the design intent over the entire reactor life.

The five stages were carefully thought out and attempted to encompass all the possible outcomes. They were intended as a guideline, and did not necessarily have to be adhered to.

14.4.2 Instrumentation and Procedures

Figure 4 illustrates the type and quantity of measurements taken on the CANDU 600 HT system and auxillary systems. They include:

	Description	No. of Measurements
1.	Channel: - flows at cold operating conditions	- 380
	- flows at normal operating temperatures	- 12
	- outlet feeder temperatures	- 380
	- powers normalized to secondary side thermal power	- 38
2.	ROH: - pressures	- 4
	- temperatures	- 4
3.	RIH: - pressures	- 4
	- temperatures	- 4
4.	RIH-ROH: - ΔP (3 per header pair)	- 12
	- ΔT (3 per header pair)	- 12
5.	Pump: - ΔP	- 4
	- suction P	- 4
	- speed	- 4
6.	Pressurizer: - level	- 1
	- temperature	- 1
	- pressure	- 1
7.	Degasser Condensor: - pressure	- 1
	- temperature	- 1
	- level	- 1
8.	$D_2 0$ Storage Tank level	- 1
9.	Feed Pump: - suction pressure	- 2
	- discharge pressure	- 2
	- flow	- 1
	- discharge temperature	- 2
10.	Bleed flows	- 2
11.	Feedwater: - flow	- 4
	- temperature	- 4
12.	Steam flow	- 4
13.	Steam generator: - drum pressure	- 4
	- level	- 4
	- blowdown	- 4
14.	Reheater: - flow	- 1
	- temperature	- 1
15.	Gross electrical output	- 1
16.	ROH-ROH (Interconnect) ΔP	- 4

Of these 16 groups only the last one was added to the existing station instrumentation. Special permission from the AECB had to be obtained to tie-in safety system signals to the station control computer. Figure 5 illustrates the data acquisition scheme. A data logger was added to the station data acquisition equipment for the transient tests, since the station control computer could not record some of the key signals fast enough. A special program was written to dump the majority of steady-state data from the control computer to a paper tape (~500 data points). Graphical and numerical trends were used to supplement the data logger and paper tape.

Special procedures were written for gathering data. Although they were designed to minimize the burden put on commissioning staff during the tests, the mixture of data acquisition methods (data logger, station computer paper tape, graphical trend, numerical trends) still resulted in difficulties. This is where a dedicated data acquisition system separate from the station control computer would be very useful. It could be operated without interferring with normal station control activities. Recent technological advances in the electronic data processing field make such a system feasible at a reasonable cost. The system could be designed with a large data storage capacity, and be directly linked to AECL computers. This would allow rapid analyses and review by the designer and a quick feedback path to commissioning staff. Certainly much more input during the early design stage related to instrumentation and data aquisition is needed for future station design verification.

14.4.3 General Processing of Data and Analyses Procedures

Figure 6 illustrates the general scheme for processing data and analysis procedures at AECL. The bulk of the steady-state data from the paper tape was transmitted to AECL via modem link. The data file was transferred to permanent magnetic tape storage, and a local copy was kept active on the computer system. The local file was processed through two data reduction programs which averaged and condensed the data into a digestible format. The resulting output files were stored on permanent magnetic tape and hard copies also made. Data logger and station computer graphical and numerical trend hard copies were also mailed to AECL and kept with the hard copies of the paper tape data. The overall result was a comprehensive data base for various operating configurations of the HT system and auxillaries. From this data base, a data sub-set could be extracted for a particular operating condition and compared to code predictions, used in code tuning, design analyses or as representative input boundary conditions for code predictions.

The general analyses involved tuning the codes to match the station data. The methodology was described in 14.4.1. It is important to note the guidelines which were followed through the tuning process;

a) changes could be made to the code only when they could be supported by sound engineering practices, i.e. no arbitrary changes, and

b) changes could be made only when commissioning data clearly indicated that a change was necessary, and that the result would maintain design conservatism.

Problems were also encountered in rationalizing a complete data sub-set. This was because some of the measurements were not ideal, and a significant amount of engineering judgement had to be exercised in rejecting or accepting a set of measurements. In fact, some very interesting and previously overlooked problems with standard methods for measuring basic quantities like pressure or temperature were highlighted.

For example, a static pressure measurement is relatively straightforward in a pipe exhibiting fully developed flow. However this situation is rare on the CANDU HT system external circuit. Secondary flows, turbulence and flow separation can cause significant errors in the static pressure measurements. There is a large potential for these types of errors on the ROH and RIH headers for example. Temperature measurement on the ROH headers could also be a potential problem. Channel temperature rises vary typically by $\pm 6\%$ in the single phase region. Thus the RIH-ROH ΔT measurements could be out by as much as $\pm 6\%$ if the feeder exit flows in the header do not properly mix. Heat conduction losses and radiation heat transfer effects on "stand-off" temperature measurement should also not be overlooked.

Certainly some rethinking as to future instrumentation for CANDU has been suggested, particularly if we intend to try to extract as much power as possible out of a constructed station.

14.4.4 Main Benefits of the CANDU 600 PHT System Design Verification

The primary benefit of the CANDU 600 PHT system design verification program was in finding that the start-of-life core gross flow was much higher than the design value. Instead of having to do a lot of "hand-waving" to the AECB about why the core flows were up from design and what the impact was, we were able to provide solid technical support for the increases in flows based on the design verification program, and factor this work directly into the licensing procedure and improve the overall licensing submission.

A less obvious, but equally important benefit was the establishment of a high degree of confidence in the predictive capabilities of the two key design codes, NUCIRC and SOPHT.

14.4.5 Impact on Design and Design Codes

1. Resulted in identification of new, and verification or modification of existing design assumptions for future reactors.
2. Improved the code modeling for steady-state and transient operating conditions. Some examples of items 1 and 2 are:
   a) fuel crudding allowances are likely not needed;
   b) steam generator tube fouling allowance may not be necessary;
   c) the assumption of constant header-to-header pressure drop should be carefully re-evaluated;
   d) better estimates of fitting losses;
   e) verification of steam generator heat transfer modeling.
3. Identified areas in code modelling which need improvement. Some examples are given below.

14.3.5.1 Example 1: Hydraulic Modeling of Orifice Plates

The design of CANDU reactors requires that all the fuel channels be thermalhydraulically matched to certain proprietary design criteria. These criteria are used to generate the size of the feeder pipes which connect the fuel channels to the main flow distribution headers, and it is generally found that for approximately 1/2 of the fuel channels (the outer half), additional hydraulic resistance must be added to the inlet feeder pipes. The extra hydraulic resistance cannot be introduced by reducing pipe sizes because the resultant fluid velocities would exceed pipe erosion-corrosion based design targets. Therefore orifices are used to add additional hydraulic resistance.

The design codes calculate the overall pressure drop across the orifice based on ASME (or SPINK), both of which give virtually identical results. Note that we are talking about the orifice overall pressure drop, which is the ΔP typically used for flow metering (maximum) minus the recoverable pressure drop downstream of the orifice vena contracta.

Through analysis of ultrasonic flow measurements taken on all feeders during cold commissioning and comparison to NUCIRC code predictions, we identified a systematic bias in flow between the inner region non-orificed channels and the outer region orificed channels. The implication was that the orifices had approximately 10% less hydraulic resistance than suggested by ASME.

This sort of error is important in terms of feeder sizing and flow distribution. Therefore an experimental program was launched to measure the hydraulic resistance of 40 mm (1.5") orifices typically used in CANDU (diameter ratios of 0.6 to 0.9). The test program has in fact verified that for the orifices tested, overall pressure drops are significantly lower than suggested by ASME. Indeed, while ASME indicates a very small dependence on Reynolds number, we have found a very strong effect. At the Reynolds numbers typical in feeders during cold commissioning, the orifice pressure drops are approximately 15% lower than ASME (close to what we had estimated from the design verification analyses). At typical 100% FP Reynolds numbers, the orifice pressure drops are approximately 25% to 30% lower than ASME!

These findings also impact on any design where the orifice is a major contributor to the piping system pressure drop. We plan to do further testing in other pipe sizes to verify these findings, which without the design verification program, may never have been uncovered.

14.4.5.2 Example 2: Header/Manifold Hydraulic Modeling

The flow in CANDU is supplied to and extracted from the channel feeders via headers, typically 13" to 20" in inside diameter. The feeders are connected to the bottom half of the headers and are spaced in planes approximately 4 feeder diameters apart. Each plane can contain 5 or 6 feeders.

In the hydraulic modeling of the headers, past practice has been to treat them as constant pressure reservoirs. However, as in the case of the orifice example, we have been able to show through analyses of ultrasonic channel flow measurements that there appears to an error in flow prediction dependent on the location of the feeder connection to the header.

This prompted a review of header modeling which subsequently lead to initiation of an experimental program. We have conducted preliminary scoping runs on a 1/4 scale acrylic model of a typical inlet header and outlet header. The data suggests that, in fact, the hydraulic resistance of the connections between the feeder and header are very sensitive to the feeder to header flow ratio, which in turn relates to feeder location on the header. More testing aimed at improving header modeling in CANDU design codes is planned.

14.5 CLOSURE

As designers we should recognize the short and long term benefits of a well organized and executed design verification program. Certainly this has been demonstrated by the recent CANDU 600 design verification/commissioning experiences. It should also be evident that more attention to design verification is needed, particularly with regards to design code validation.

FIGURE 1 : SIMPLIFIED DESIGN PROCESS FLOW DIAGRAM

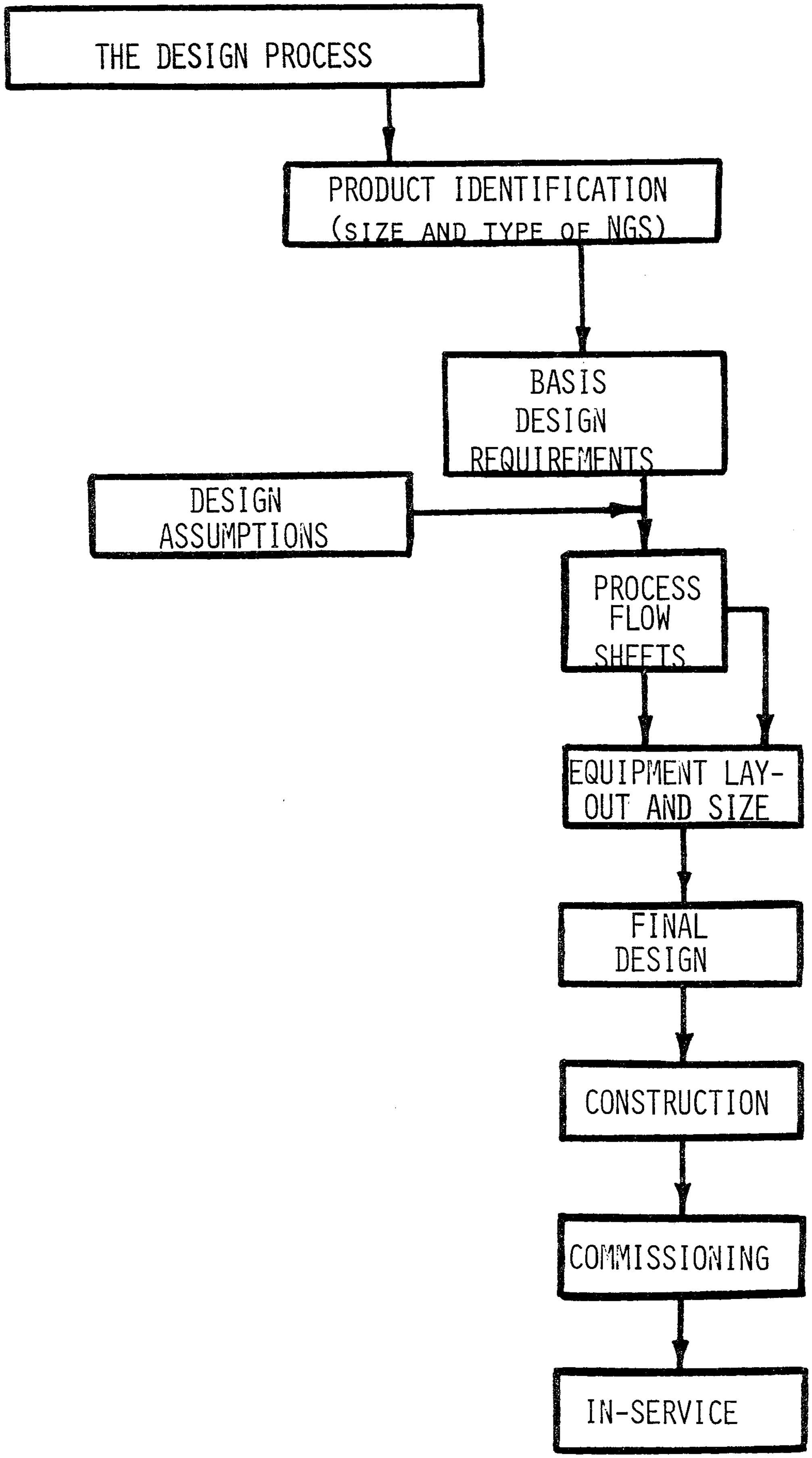


FIGURE 2 : SIMPLIFIED DESIGN PROCESS FLOW DIAGRAM WITH VERIFICATION

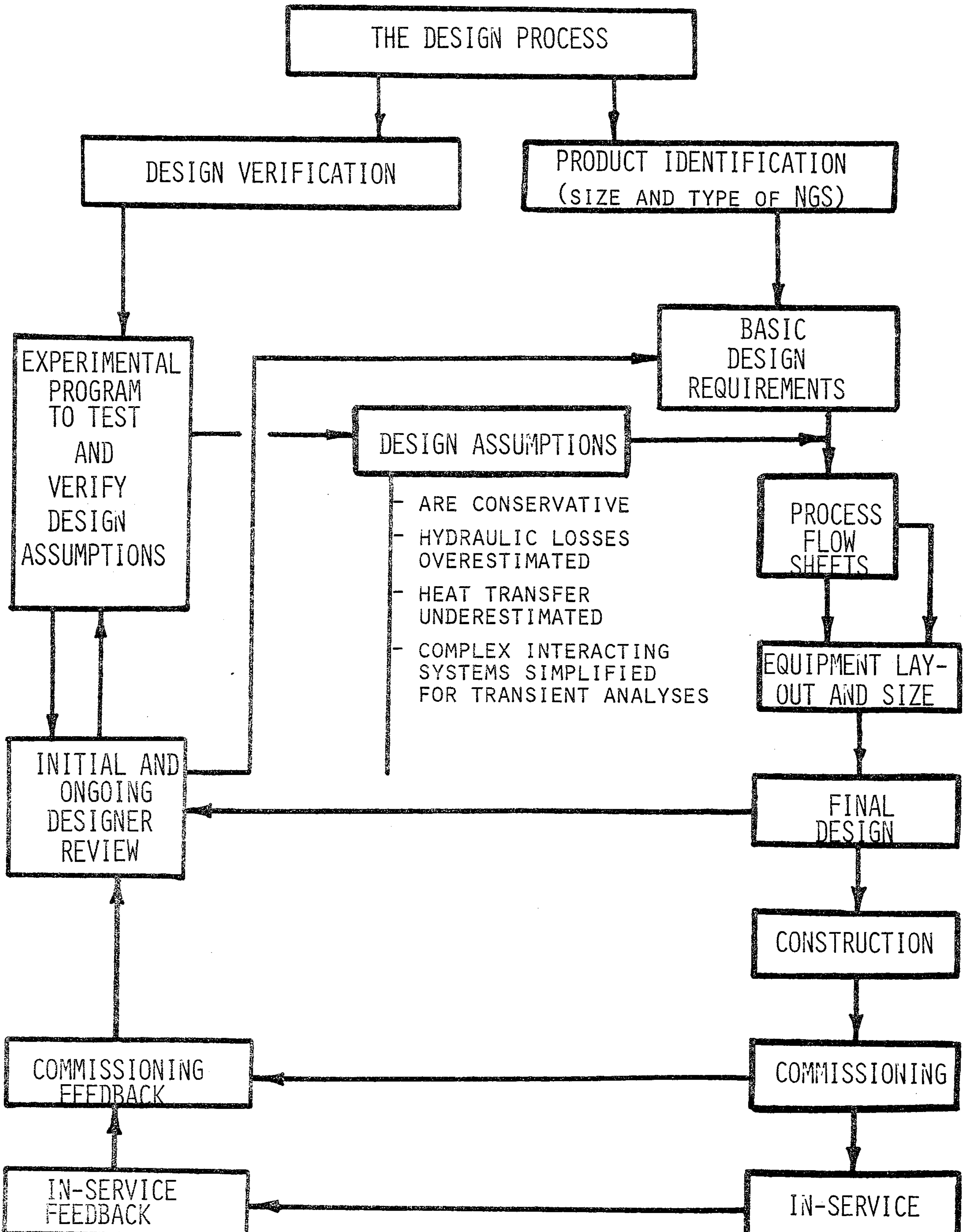
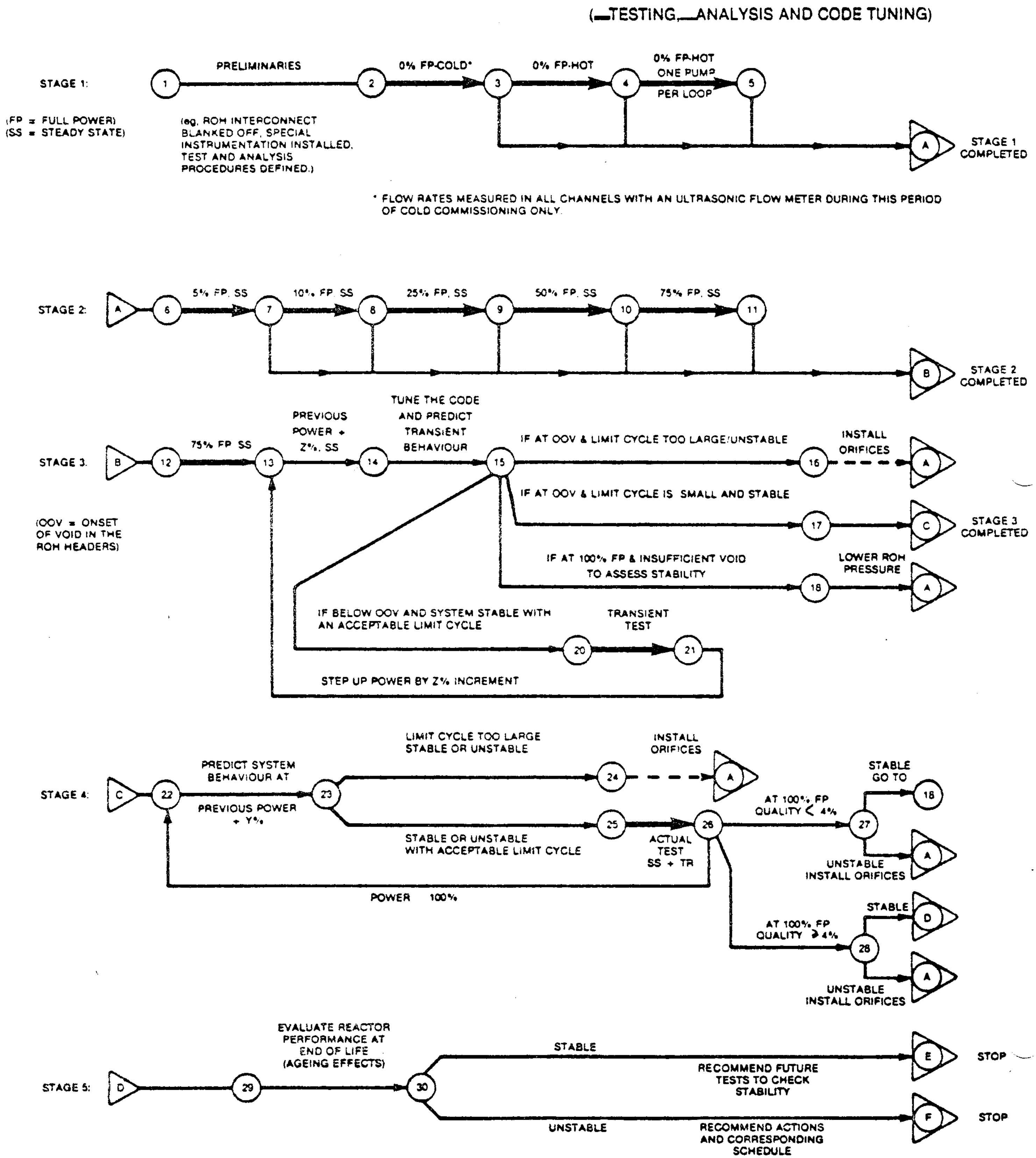


FIGURE 3 : COMMISSIONING DESIGN VERIFICATION METHODOLOGY FOR THE CANDU HEAT TRANSPORT SYSTEM



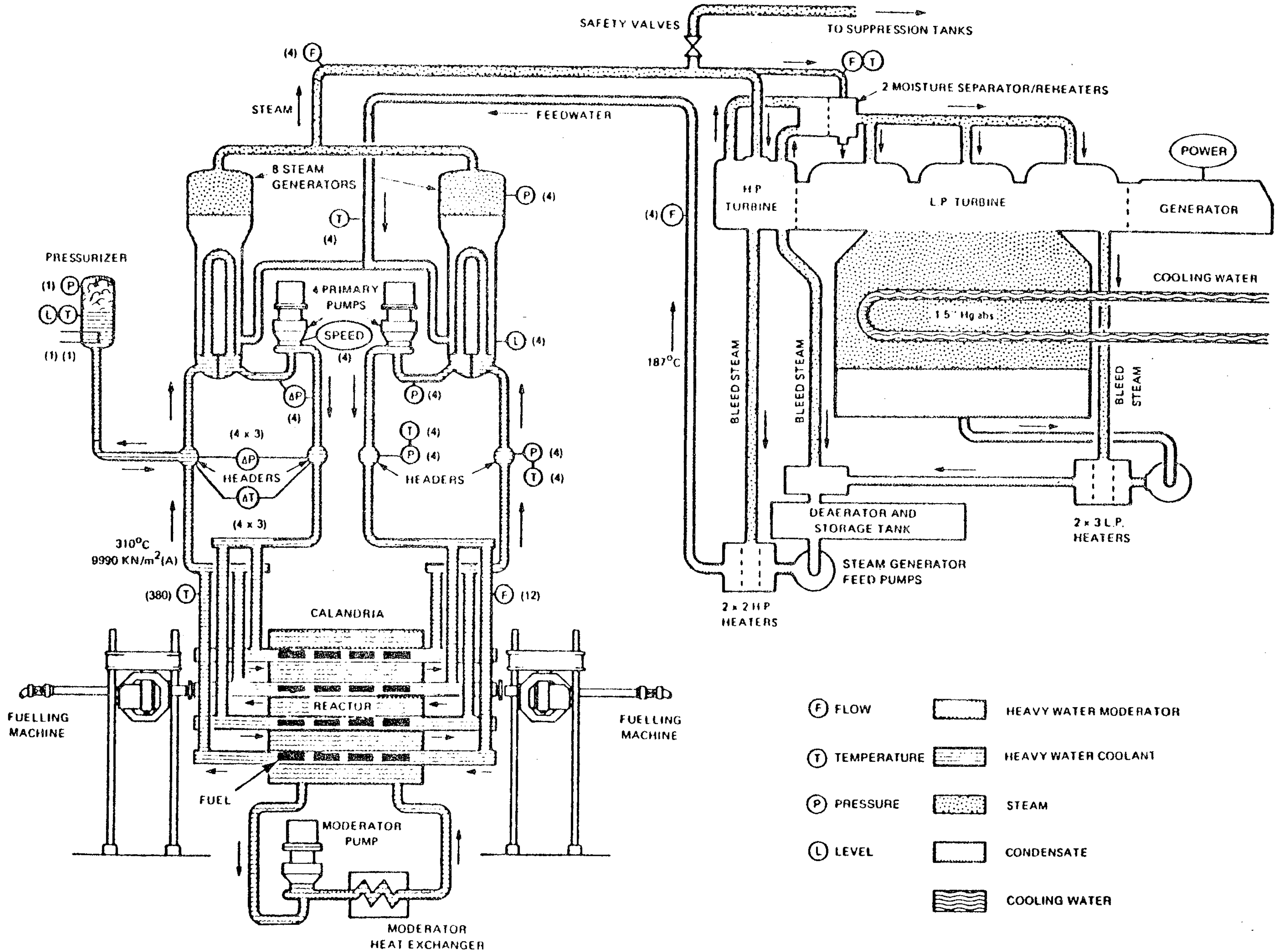


FIGURE 4 : COMMISSIONING DESIGN VERIFICATION MEASUREMENTS FOR A CANDU HTS

FIGURE 5 : EXAMPLE OF A DATA TRANSMITTAL SCHEME FROM A CANDU 600 TO AECL

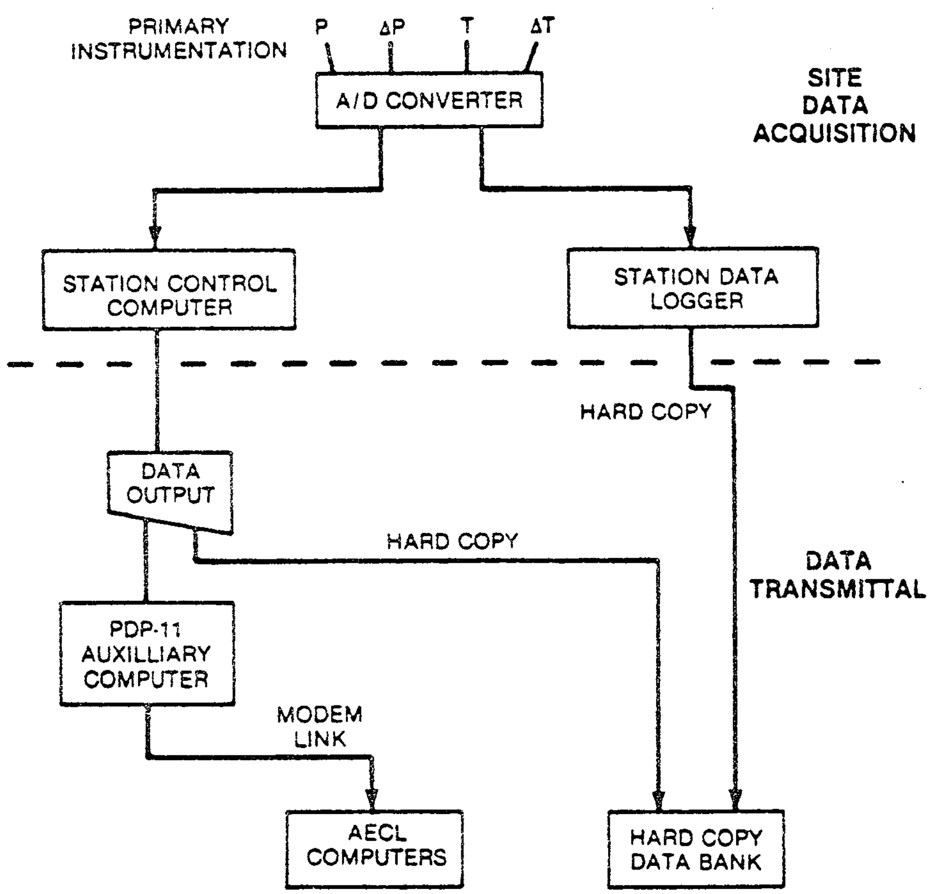


FIGURE 6 : EXAMPLE OF DATA PROCESSING AT AECL