Heavy Water Production Benefits of a Supporting R&D Program

1. INTRODUCTION - A.R. Bancroft, CRNL

The production of heavy water in Canada to supply CANDU nuclear power reactors began in 1970. The history of the evolution of this new Canadian industry, based on the Girdler-Sulphide (GS) process, is described in a companion report (1.1). Research and development (R&D) activities to support the production plants began while the Port Hawkesbury Heavy Water Plant (PHHWP) was being built, a year or so before the first water was produced. Although problems had not been identified by the plant owner, the Canadian General Electric Company Limited (CGE), it was considered prudent by Atomic Energy of Canada Limited (AECL) and by CGE to begin the building of a technical support capability. This followed the failure of Deuterium of Canada Limited (DCL) to bring the Glace Bay Heavy Water Plant (GBHWP) to production following the 1968 startup attempt. Also because of the DCL failure the construction of a third heavy water plant was committed to satisfy the increasing demand of an expanding nuclear power program. This plant, at the site of Ontario Hydro's Bruce Nuclear Power Development, brought AECL into the picture as plant owner and Ontario Hydro (OH) as operator. These three parties, AECL, CGE and OH, were responsible for establishing and shaping the R&D program that grew to involve a staff of more than 50 engineers and scientists by the mid-70s. Some of the achievements of this program were reported earlier (1.2).

During the design, construction and early operation of the Canadian plants information from the Dana and Savannah River Plants was made available through a United States-Canada technology exchange agreement. Although this technology was initially invaluable it proved to be inadequate to bring the Canadian plants to mature operation. Production at design rates was achieved only after the Canadian program had made significant advances. Some of this technology was generated by the designers and operators and was rapidly incorporated into the plants. Another pool of technology was evolved at the R&D sites. Throughout the entire period considerable effort has gone into the transfer of technology between sites.

There were many lessons learned during the program. One purpose of this report is to alert others considering establishing a heavy water production industry to the benefits of R&D support and to provide some guidance concerning the magnitude required to ensure success. Another purpose is to indicate the broad range of technology generated within the Canadian program that may be of value to others.

2. ORGANIZATION OF R&D EFFORT - A.R. Bancroft, CRNL

2.1 Location of GS Process Effort

As the first step in establishing a technical support team AECL assembled a working group in 1966 to assess the economics of competing processes. This drew from the staff of the Chalk River Nuclear Laboratories (CRNL) and involved individuals from six Canadian chemical and consulting companies. This group and its successors looked at the ammonia-hydrogen exchange process and showed that the amine-hydrogen exchange process was much more attractive. The advantages were sufficient to establish a permanent heavy water R&D group and begin to develop the amine-hydrogen process (2.1). It was from this base at CRNL that the GS process support team grew to involve more than twenty Canadian establishments. Table 2.1 lists the participating contractors.

Table 2.1

GS PROCESS R&D - CONTRACTORS

Contractor	Location	Typical Contribution
Canadian General Electric	Peterborough	Metallic and other materials
Canatom MHG	Montreal	Physical property evaluation
Dalhousie University	Halifax	Organic impurities in feedwater
Dilworth, Secord, Meagher	Toronto	H_2S release dispersion modelling
General Electric Company	Schenectady	Sieve tray analysis, foaming
Guelph Engineering	Cambridge	Valve development
Hatch Associates	Toronto	Heat exchange system modelling
LaSalle Hydraulics	Montreal	Heat exchanger tube vibration
Lummus Canada	Toronto	Sieve tray development
McGill University	Montreal	H_2S ignition studies
Nova Scotia Research Foundation	Dartmouth	Analytical chemistry, process chemistry, gamma scanning, effluent monitors, leak detectors
Raylo Chemicals	Edmonton	H_2S and antifoam chemistry
Sulfur Research Institute	Calgary	Thermodynamics of metal sulphides
Sulzer Canada	Toronto	Water distillation feed treatment
Union Carbide	Toronto/Tonawanda	Sieve tray development
University of Alberta	Edmonton	Vapour pressure of mercaptans
University of New Brunswick	Fredericton	Corrosion of materials

CGE was the builder and owner until 1975, when it sold the Port Hawkesbury HWP to AECL.
Canatom was designer-constructor of the rehabilitated Glace Bay HWP (1971-1976), and the LaPrade HWP (1974-1978).
Lummus was the designer-constructor of the Port Hawkesbury HWP (for CGE), Bruce A HWP (for AECL, sold to OH in 1973) and Bruce B and D HWPs (for OH).
NSRF has provided continuing R&D and other services starting in 1972.

2.2 Discipline of Effort

During the early years of commissioning and operating it became clear that the effects of the differences in process arrangement and equipment type and size between the US plants built during the 1950's and the Canadian plants were not fully understood. Since the US plants operated reliably at high capacity it was believed that detailed understanding of these differences was essential to the success of the Canadian production program. R&D effort was applied to short-term problems to satisfy the needs identified by the operators. In addition, topics were identified for which substantial gain was forecast from longer-term work. Those topics that have continued to receive attention throughout most of the decade are listed in Table 2.2. Also indicated are the sites at which most of the work was done.

Table 2.2

GS PROCESS - DISCIPLINE OF R&D EFFORT

	AECL				OH	
	CRNL	WNRE*	GBHWP PHHWP	CC*	BHWP	OHR*
1. Process Analysis and Control	x		x		x	
2. Process Chemistry	x	x	x		x	
3. Analytical Chemistry	x	x	x		x	x
4. Materials, Corrosion	x	x	x		x	x
5. Mechanical Equipment	x				x	
6. Sieve Tray Hydraulics and Mass Transfer	x		x	x	x	
7. Gamma Scanning	x			x	x	
8. Water Distillation	x			x	x	x

* WNRE - Whiteshell Nuclear Research Establishment, Pinawa, Manitoba
CC - Chemical Company Head Office, Ottawa, Ontario
OHR - Ontario Hydro Research Department, Toronto, Ontario

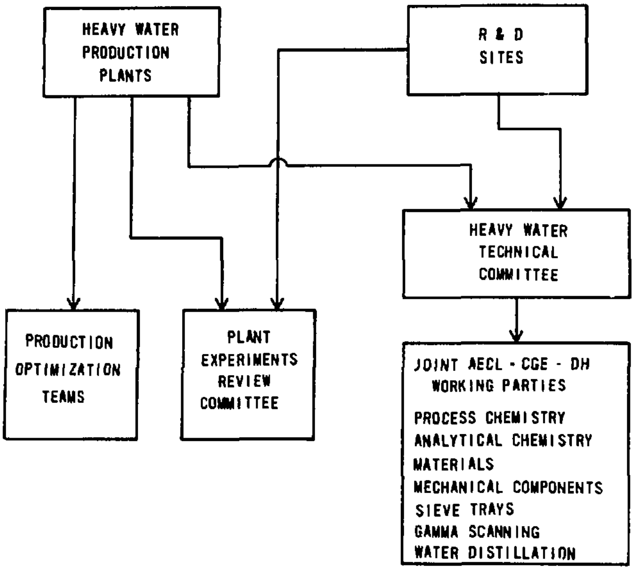
2.3 Co-ordination of Effort

There was sufficient common interest among the three companies that were involved early in the decade (AECL, CGE and OH) that they recognized the benefits that could be gained by sharing experiences. This was as true for process problem-solving as it was for operation and maintenance methods and procedures. The organization for R&D support that was evolved, and remained in effect for much of the decade, is represented in Fig. 2.3. Two committees and two groups of working parties and optimization teams were established under the control of the management of the heavy water production plants and the R&D sites. Not shown in the figure, but vital to the efficient functioning of the activities is the two-way communication at all working levels. A description of each group follows:

Heavy Water Technical Committee

This committee has the senior R&D co-ordinating role. It is composed of the technical managers from all heavy water plants and their

FIGURE 2.3
GS PROCESS R & D - COORDINATION



counterparts from the R&D sites. It meets several times each year to review the activities of the working parties and to ensure that they are consistent with plant problems and management objectives.

Working Parties

These groups are composed of the technical experts from the R&D sites and members of the plant technical departments involved with the relevant projects. The frequency of meeting varies from four times a year during periods of pressing problems to once a year when problems are few. Some of the individuals making up the working parties are also involved in the two following groups.

Production Optimization Teams

Each plant established a team that meets regularly to review plant performance, identify key problems and identify solutions using best available information. Where information is lacking the assistance of the relevant working party is requested. These teams are composed largely of the staff of the plant in question, but they have representatives from the other plants and the R&D sites.

Plant Experiments Review Committee

This committee was established by OH and AECL to conduct in-plant experiments in the Bruce HWP. It plans and co-ordinates experiments that are conducted by the plant operations staff, reviews the results and makes recommendations for plant improvements.

All of these groups have co-ordinating functions only. Responsibility for implementing plant trials or conducting laboratory tests rests with the line management of each site. The system has worked because individuals with appropriate authority have been assigned as members to the various groups and committees.

2.4 Other Heavy Water Processes

It was mentioned in Section 2.1 that the GS process technical support team was built on the foundation of expertise developed for the ammonia-hydrogen and amine-hydrogen exchange processes. AECL has maintained this active program in other processes for the entire period that the GS process commanded support for the operating plants. This program lead to the amine-hydrogen process reaching the stage of commercial readiness (2.1, 2.2). It has also lead to the demonstration of a series of hydrogen-water exchange processes based on the CRNL invention of a wetproof catalyst (2.3, 2.4, 2.5, 2.6). Ontario Hydro has also contributed to the monitoring and testing of new ideas (2.7, 2.8). The cross-fertilization of ideas and techniques among the several processes has yielded benefits to all of them. An analysis of the important parameters of the methods considered for heavy water production has been done recently by Rae (2.9).

3. PROBLEMS AND SOLUTIONS

3.1 Process Analysis and Control - A.I. Miller, CRNL

3.1.1 Evolution in the Canadian Heavy Water Industry

The GS process is not a difficult process to understand and can be described fairly accurately by techniques developed for two-component distillation. This approach was used to design the original GS plants in the USA in the 1950's and the details have been described (3.1.1).

The American plants had been built for strategic reasons and had design margins so large that they easily reached around double their rated capacity. Partly in consequence of this overdesign, detail of their actual functioning was obscured. In contrast, the Canadian plants were built for commercial production of heavy water at the lowest possible price. For them, some of this detail was to be important and one critical measurement, the efficiency of the sieve trays, was misinterpreted: this was not as high as construed from measurements at the American plants. In like vein, the process was presumed to be basically non-foamy, although occasional periods of foaminess had been noted at Savannah River. Design of the Canadian plants with higher gas velocities was to reveal an intrinsically foamy GS system.

In retrospect, these two elements of misinformation stand out clearly but in the early years of frustratingly poor operation of the Canadian plants, they emerged only slowly from a background of many potentially important variations in the Canadian designs. Credit for the understanding belongs to the industry as a whole, including the operators of the American Savannah River plant operated by E.I. DuPont. Fundamental studies of the system's foaminess, work on hydrates, manipulation of plant chemistry and operating conditions, measurement of local densities in the towers using attentuation of gamma rays, and much painstaking analysis of operating data by plant staffs and the industry-wide working parties all contributed to the final mastery. Also contributing to process understanding were very detailed computer simulations of the plants.

Simulation

Steady-state simulation models for heavy water separation processes had first been developed at Chalk River for the amine (aminomethane) - hydrogen process. During 1968 it became apparent that the technique of process simulation might be usefully applied to the GS plants at Port Hawkesbury (in the final stage of construction) and Bruce (under design). In 1969, work began at CRNL to develop a GS simulation. This had its first application in modelling the effects of heat of reaction in the final GS stage and led to some modifications to the Bruce design. In this period, problems with the stability of the model of the exchange tower were gradually overcome so that it was ready, though far from perfected, to be used in the redesign of the Glace Bay Heavy Water Plant for which AECL were given responsibility in 1971. In 1974 the program began to be used to study operating problems for Bruce. Today, in various forms, it is widely used to analyze both real and hypothetical operation for all the operating Canadian plants.

The technique used for the steady-state simulation of the process was based on methods evolved at McMaster University (3.1.2). Figure 3.1.1 is a typical heavy water plant simulation flowsheet and suggests the magnitude of the problem, but the reality also includes process streams of gas and liquid leaving each of the approximately 1 000 sieve trays of the actual plant. The process also is further complicated by very high levels of recycle, deuterium flows up to 60 times the product rate and mass flows thousands of times larger than the product flow. Since most of the typically 2 200 streams are defined only by the conditions of neighbouring streams, a great deal of iteration is required. The operation of each sieve tray is calculated in terms of enthalpy, mass (water and hydrogen sulphide), and deuterium balances and a typical whole-plant simulation would carry out between five and ten million of these calculations before achieving satisfactory convergence. Continuing efforts to improve the performance of the program coding have reduced computer time by about an order of magnitude.

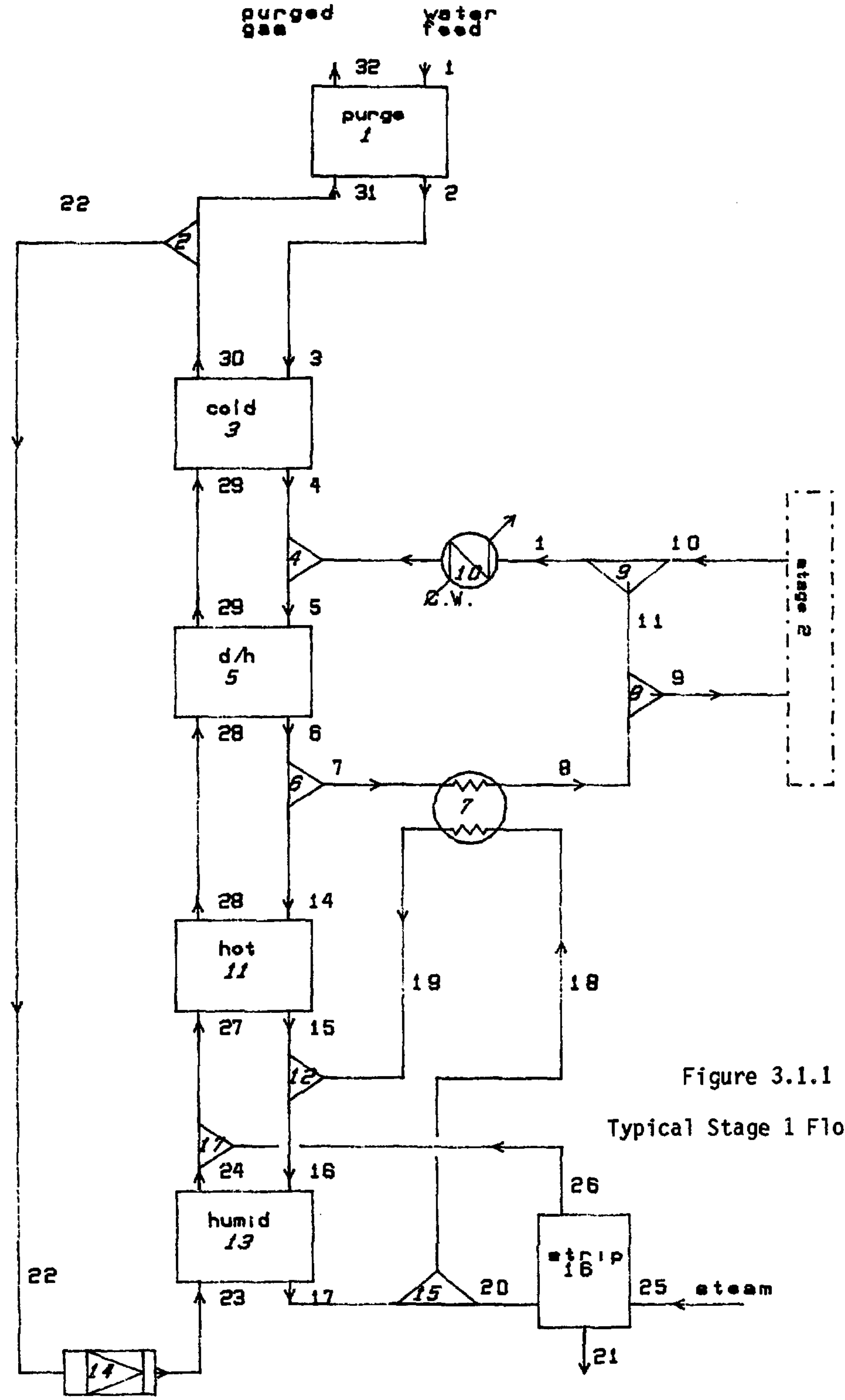


Figure 3.1.1

Typical Stage 1 Flowsheet

The American plants were able to meet their design ratings without recourse to analyses remotely approaching the complexity of the simulation models developed for the Canadian plants. Computer costs during the development and early application of the program were large - several millions of dollars. Commitment of funding on this scale is easy to justify today but at that time needed appreciable foresight to appreciate its ultimate worth.

The reader should realize that the poor performance of the GS plants could be diagnosed by quite simple methods. However, the effect of the plant's tray deficiencies appeared not only as poor extraction but also as much enhanced sensitivity to process parameters. Small perturbations from ideal operation became very important. This was where the detailed simulation first showed its utility: because of its fundamental rigour, the simulation pointed to a number of ways in which plant operation could be improved and what settings should be aimed for and how precisely they should be maintained.

Simulation alone would be academic and sterile. Its utility stems entirely from availability of plant data. The willingness of all of the Canadian plants to vary normal operation to provide data was essential to development of effective models. As important was the instrumentation to monitor plant behaviour. AECL and Ontario Hydro collaborated to retrofit one BHWP tower with extra temperature, deuterium concentration and pressure drop monitoring devices and the redesign of Glace Bay included a similar tower. In addition, operating data for all three plants have been fed into computerized data bases on the CRNL computers. For Port Hawkesbury and Glace Bay data are collected by on-line minicomputers and provide a particularly extensive and invaluable resource for study of normal and abnormal operation. But even with all these resources, simulation would have remained marginally useful if it had not been given life by plant technical and operating staffs. Their knowledge of what actually seemed to happen and what did or did not make sense was and will remain vital to the understanding of analysts using simulation both at plant sites and at CRNL.

Simulation has developed most effectively where several specialists worked together. It is a tool for skilled users and can easily be misinterpreted in inexperienced hands. In particular, isolated individuals have found it difficult to discern when the program was no longer describing a plant realistically.

The GS process R&D program required a comprehensive set of physical properties for the hydrogen sulphide-water system and for pure water at various isotopic concentrations of deuterium. When GS process studies commenced at CRNL in 1969, the properties used initially were those reported by Burgess (3.1.3) but it soon became evident that these were not as accurate as desired, especially with respect to enthalpies. AECL then undertook an extensive review of all available information in 1970-72 and produced a new compilation (3.1.4) which became the recommended standard for the Canadian heavy water industry. This review by AECL drew attention to several areas where information was suspect or not available and as a result several research contracts were placed with Canadian universities and research organizations to determine new data.

When new information became available the original AECL publication was extensively revised, particularly with respect to solubility and P-V-T data for pure H_2S gas and H_2S-H_2O vapour mixtures. This information was published in 1977 as report AECL-5702 (3.1.5), which remains the definitive source of GS process physical property data.

3.1.2 Applications

3.1.2.1 Plant Operating Performance Analysis

The GS plants operate as one large whole rather than as a sequence of processing stages. Hence it is often difficult to characterize the behaviour of a part of the plant in isolation. Steady-state simulation can give a complete view of the plant by fitting measurements of operation throughout the process into a complete modelling. Then the operation of constituent parts can be assessed and the contribution of their actual or any projected form of operation can be expressed as influences on whole-plant operation.

3.1.2.2 Process Optimization and Control

GS Product Concentration

As one example of performance analysis, the effect of the concentration of the product from the GS process (a complex result of direct and indirect temperature influences) could be described. The simulations justified large reductions in product concentration through measures to augment the finishing capacity of the plants' water distillation finishing units. Extraction gains range from 1 to 2% for Bruce and Port Hawkesbury to exceeding 10% for Glace Bay.

While it seems reasonable to ask whether the effect of product concentration could have been deduced from plant experience, the reality was that such data were extremely misleading through being confused by numerous other variations in plant behaviour that could only be properly unified by the simulation. The actual plant data were, of course, essential to prove and tune the model.

Cold Tower Temperatures

By assuming isothermal behaviour in the major tower sections of a GS plant, simple calculation methods can achieve good approximations to the ideal performance of all but the stage with the highest concentration (i.e. exceeding about 1% heavy water). However, there are small temperature gradients in all stages and the heightened sensitivity caused by low tray efficiency gives these far more importance than expected from the experience of the American plants. For Glace Bay's cold towers, a temperature rise of one kelvin lowers extraction by 2.4%. But the formation of solid hydrogen sulphide hydrate sets a lower boundary to cold tower temperature and, with this very real boundary, the simulation model can 1) take the sparse array of plant temperatures and produce a complete temperature profile, 2) show the optimum location of the minimum temperature, and 3) provide an essential interpretive tool for probing the lowest attainable value for the minimum temperature.

Plant trials on the heavily instrumented tower at the Bruce plant and their interpretation by simulation led to cold tower temperature reductions of two kelvins (or a 3% gain in extraction) for routine operation for the whole plant. An example of the importance of correct location of the minimum temperature is given in Fig. 3.1.3.

Heat Optimization

The steep temperature profiles (about 100 kelvins over 12 to 15 trays) of the heat transfer sections of the main towers are also amenable to simulation techniques, and usefully so. With the mass transfer trays, measured information on deuterium concentrations is very sparse and only large blocks of trays can be assessed. In contrast, on the heat transfer trays, temperature information is generally more abundant. In the heavily instrumented towers, it is so dense that interpretation of performance data is only limited by apparent variations in temperature across individual trays.

GS plants use large quantities of steam - typically a unit mass of heavy water needs 12 000 times that mass of steam. Rising energy costs have encouraged development of specialized simulations to optimize energy usage. Quite early in the application of simulation, lower than design dehumidifier return temperatures were shown to save 2-4% of steam consumption. Today we are developing a whole-plant heat optimization model for the Port Hawkesbury heavy water plant that will accommodate the performance of individual exchanger banks for each of the three stage-one towers in the complex heat recovery network. One useful development has been presentation of key parameters from the simulation results as graphic output on a computer-drawn flowsheet schematic.

This should remind the reader that simulations are not omniscient black boxes but powerful tools to present the essentials of complex plant operation. Properly used, they indeed provide numerical guidance but they also allow deep insight into plant working.

Other Applications

The same process of plant tests combined with simulation have led to numerous other gains in plant performance by showing how small flow changes and temperature alterations influence extraction. This has been

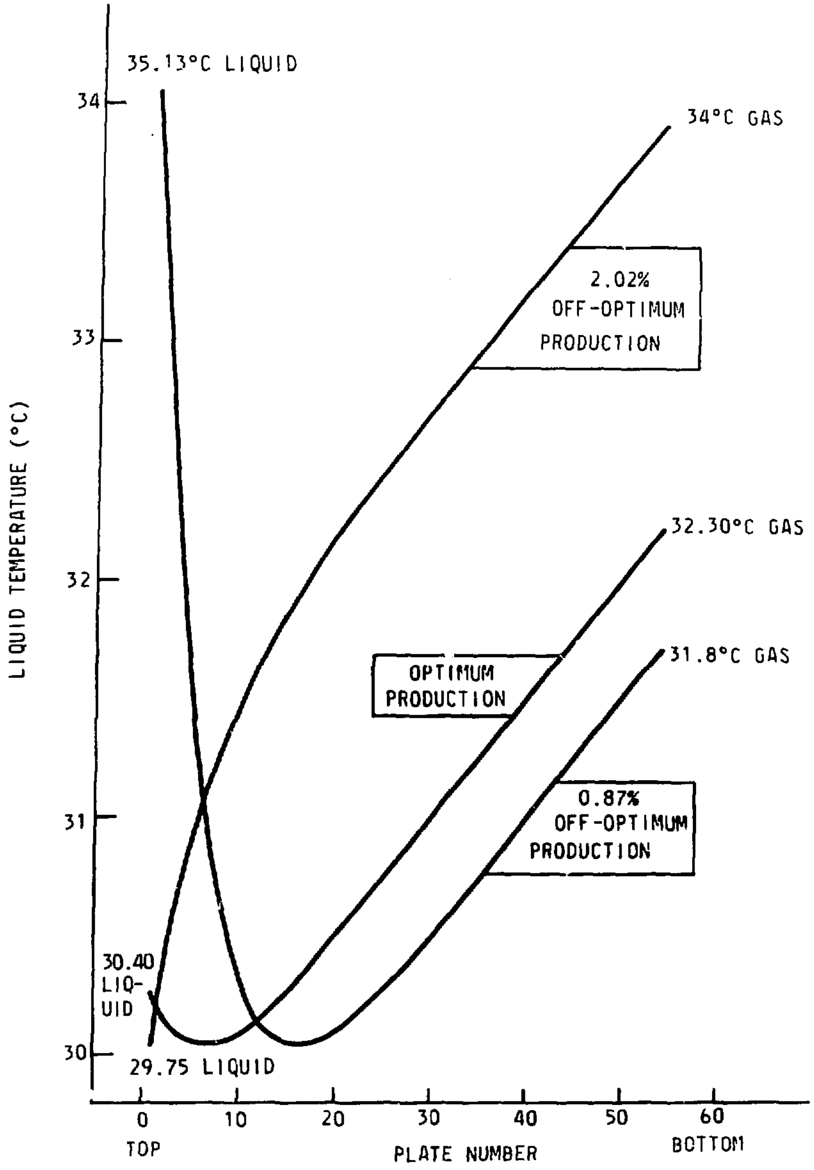


Figure 3.1.3

Typical Cold Tower Temperature Profiles

especially important to Glace Bay, where the presence of very large flows between stages makes process optimization difficult and complex.

The strength of the simulation is always in its ability to describe the plant entirely. From this one can see a) the effect of a local variation on the whole plant and b) local conditions at places in the plant not directly instrumented.

3.1.2.3 Equipment Modification

Very precise descriptions of the actual operation of plants over the full range of operating conditions is useful if one wants to look at possible changes to the plant. As discussed elsewhere in this paper, numerous changes to tray detail have been implemented and recommended. Both trays and plant understanding are needed. The plant simulation first shows the current situation for either deuterium or heat transfer; knowledge of tray design shows how one or other of these might be improved; simulation predicts the effect on operation and finally measures what has been achieved.

This technique has been applied to single malfunctioning trays as well as to whole towers.

3.1.2.4 New Designs

Many fundamental changes to the flowsheets of existing plants have been suggested but the difficulty of implementing these without new tower penetrations has usually been a major factor inhibiting implementation.

However, the understanding of the minutiae of the GS process that the simulations have built up should lead to new plant designs that contain sophisticated improvements and will perform as expected. Partially this sophistication was applied to the design of the suspended LaPrade plant (as in an asymmetric distribution of mass transfer trays between cold and hot towers - calculated to augment production by 0.7%) but the full power of the simulations would also fully exploit the capacity of trays to provide both heat and deuterium transfer exchange. The ability to analyse this is intrinsic to the advanced hot feed designs evolved at Chalk River. Because they depend on deuterium transfer where large variation in temperature exists from tray to tray, evolution of these designs is only possible with detailed simulation. They have the ability to produce 5 to 10% more heavy water per unit of tower volume and per unit of steam.

3.2 Process Chemistry - D.A. Spagnolo, CRNL

The chemistry of the GS process is dominated by the presence of hydrogen sulphide at 2 MPa and the recycle flow arrangement through the two temperature regions of the towers. Under cold tower conditions the system operates close to the liquefaction pressure of H_2S resulting in inherent foaminess (3.2.1). Foaming can be further enhanced by the presence of certain trace impurities entering with the feedwater. These same impurities, if present at the same concentration, would have a negligible effect if the process were operated significantly further from the H_2S liquefaction conditions.

Impurities can also accumulate to high concentration because of the concentrating action of the process, and this leads to foaming and fouling problems. These impurities may originate in the feedwater or H_2S supply gas or may be the decomposition products of antifoam agents and sealing oils that are used in mechanical rotating seals. They may be too volatile to flow down through the hot tower or the effluent stripper, and not sufficiently volatile to be purged as a gas from the system and so concentrate in the process.

All of the plants have had problems in the area of process chemistry although the severity of specific problems has varied from plant to plant, depending on feedwater characteristics, flowsheet details, materials of construction and chemicals used. An industry-wide Process Chemistry Working Party has met throughout much of the decade as the forum for focusing experience, problems and solutions.

3.2.1 Antifoams

Foaming has been a major problem in the heavy water industry, dating back to the early operation of the USA plants where the need to control foaming with adequate water treatment and with an antifoam agent was first identified. The use of antifoams is essential to maintain plant stability while operating at high throughputs. First sign of instability is usually an increase in column pressure drop which signifies an increase in liquid holdup on the trays caused by downcomer backup of the foam. If not corrected, this leads to instabilities involving severe dumping of the liquid on the trays and loss of heavy water production.

A conventional silicone-based antifoam was initially used in Canada, based on USA plant experience. This antifoam consisted of a water-insoluble silicone oil, surface-active silica particles and organic emulsifiers. The cost was several million dollars per year. Moreover, its use resulted in process problems which appeared only after several years of operation. Emulsifiers, present in the antifoam, hydrolyzed under hot tower conditions to form fatty acids which, because of their volatility, accumulated in the process. When combined with the hydrocarbon sealing oil that leaked into the process the fatty acids formed grease-like semi-solids which fouled heat exchangers and caused blocking and foaming problems on the trays.

Two lower cost conventional hydrocarbon-based antifoams were assessed in plant trials at BHWP. The first trial ended when the hydrocarbon oil in the antifoam accumulated in the third stage, causing severe instabilities. The second trial with a heavier hydrocarbon oil appeared effective during summer operation but was not capable of controlling instabilities during the more foamy winter periods. Both antifoams had the disadvantage of containing emulsifiers capable of breaking down under hot tower conditions to form fatty acids.

An antifoam development program (3.2.2) was started at CRNL in 1977 to find new and more suitable antifoams for the GS process. Early in the program certain nonionic surfactants were identified as effective antifoams under cold tower conditions, even though some of these surfactants behaved as foamers at ambient conditions. Antifoam action was attributed to their limited solubility in aqueous H_2S solutions.

Candidate antifoams are first screened for their chemical stability, volatility and antifoam effectiveness under GS process conditions in the laboratory. Those that pass this initial screening undergo extensive pilot plant testing at various flow, temperature and pressure conditions and over a wide range of antifoam dosage rates. Also, influence on deuterium mass transfer, tray-to-tray entrainment and froth characteristics on the tray and in the downcomer are studied in a 0.3 m diameter sieve tray column in the pilot plant.

Antifoam candidates that pass the extensive laboratory and pilot plant screening are further assessed during sequence of trials of increasing duration at a production plant. During these trials, the influence of the antifoam on froth height, tray efficiency, out-of-column entrainment, plant production and accumulation of antifoam or reaction products are measured and related to plant performance. Four such nonionic surfactants have progressed to the stage of having undergone production plant trials; two are presently in regular plant use. Table 3.2.1 summarizes the status of these antifoams.

The silicone-based nonionic surfactant (Antifoam B) has been in use at BHWP and PHHWP since 1978. Its benefits over the conventional type of antifoam (A) are higher D_2O production because of fewer foam-related process problems, and a factor of four reduction in antifoam consumption resulting in an antifoam material saving of $700 000 per year for both plants combined.

GBHWP did not respond so favourably to the use of Antifoam B, although performance was still better than with the conventional one. Dosage rates were higher and operating stability poorer. Further laboratory and pilot plant work revealed that at the more severe conditions of the effluent stripper at GBHWP, the antifoam decomposed to form products that were foaming agents under GS cold tower conditions.

This led to plant trials at GBHWP in 1980 of two new hydrocarbon nonionic surfactants (Antifoams C and D). The trial with Antifoam D was the most successful. Dosage rates were reduced by a factor of almost two with improved plant stability by eliminating the foam-causing decomposition

Table 3.2.1

Antifoam Usage

Antifoam	Type	Relative Dosage	Relative Usage Cost	Plant Usage
A	conventional silicone based antifoam	1.	1	originally used at plants
B	silicone based non-ionic surfactant	0.25	0.20	presently used at PHHWP & BHWP
C	hydrocarbon based nonionic surfactant	0.25	0.06	has undergone plant trial at GBHWP
D	hydrocarbon based nonionic surfactant	0.5	0.12	presently used at GBHWP
E	hydrocarbon based nonionic surfactant	0.5	0.12	presently undergoing plant trials at BHWP

products of Antifoam B. The antifoam was also four times cheaper than the silicone-based surfactant, resulting in an antifoam material saving at GBHWP of approximately $500 000 per year. Moreover, improvement in stability and overall plant performance resulted in a production gain of approximately 7%. BHWP is presently undergoing a plant trial with another hydrocarbon-based surfactant (Antifoam E) which is generically similar to Antifoam D.

Work continues on developing better and cheaper antifoams for heavy water plants with possibly more emphasis on improving mass transfer performance.

3.2.2 Behaviour of Impurities

Studies of the mechanisms for concentrating or eliminating impurities from the process system were initially undertaken to predict the behaviour of oil in the process. Oil is used in the mechanical seals for rotary pumps and blowers to prevent leakage of hydrogen sulphide gas to the atmosphere. Oil accumulation in the process by in-leakage can lead to plant instability.

A model was developed at CRNL to describe the behaviour of impurities, which is largely determined by the relative volatility with respect to hydrogen sulphide.

$$\alpha = K \text{ impurity}/K\ H_2S$$

where K = vapour - liquid equilibrium constant (y/x).

The model predicts that impurities with K-values close to the L/G ratio in the tower concentrate between hot and cold towers. This buildup leads to instability if the impurities are foamers at the process conditions.

When applied to the fatty acids produced from the breakdown of emulsifiers in the conventional antifoam the model predicts accumulation in the higher stages. It also shows that with the existing flowsheet the only mechanism to remove the fatty acid is via the oil coalescer downstream of the third stage tower, but since the flow through this coalescer is only a small fraction of the total third stage contents it is incapable of removing fatty acids at sufficient rates. Analysis of the oil removed by the coalescer at BHWP and GBHWP gave fatty acid concentrations of approximately 45 g/kg and 130 g/kg, respectively, confirming the behavioural prediction of the model.

3.2.3 Sulphur Formation and Control

Sulphur is an in-process impurity that causes production incapability. It accumulates as a solid mainly in two areas: 1) heat exchangers and piping of the dehumidifier circuit and 2) overhead gas coolers and knock-out drums of the purge and stripper system.

Sulphur is formed mainly by the oxidation of hydrogen sulphide by the oxygen that remains dissolved in the feedwater after the degassing operation.

$$H_2S + \tfrac{1}{2}O_2 \longrightarrow H_2O + S$$

A second source of sulphur can be the decomposition of hydrogen sulphide.

$$H_2S \rightleftharpoons H_2 + S$$

Decomposition is favoured in the effluent stripper where the temperature is highest and the hydrogen concentration is low.

There are a number of solutions to this problem:

1) improved degassing of the feedwater,
2) design of equipment to accommodate sulphur accumulation, and
3) chemical techniques to control the formation rate of sulphur.

The second solution, extensively used at the Savannah River Plant (SRP) in the USA, is currently favoured although it eases rather than solves the problem.

Two promising chemical techniques have been assessed in the laboratory. They are 1) the addition of sodium sulphite with catalyst to the feedwater to scavenge residual oxygen, and 2) the addition of hydrogen to the gas systems to reverse the hydrogen-sulphide decomposition reaction.

3.3 Analytical Chemistry - W.J. Holtslander, CRNL

Analytical chemistry serves an important function in the operation of the heavy water production process. Analysis of the deuterium concentration in process water provides the information necessary for the fundamental control of the process flows. Proper control of these gas and liquid flows govern the deuterium extraction rate. The hydraulic behaviour of the water-H_2S mixture in the process towers is sensitive to trace amounts of impurities so that knowledge of the purity of these streams is important.

The deuterium molar concentration in water must be measured over a wide range from 118 parts per million to 99.8 percent. To cover this range methods based on mass spectrometry, infrared spectroscopy, density and refractometry have been developed. Both methods and instrumentation were extensively investigated to provide reliable systems for plant operations. Industry-wide standards with accurately known deuterium concentrations were prepared at CRNL and used for interlaboratory comparisons between the plants and CRNL. Deuterium concentrations in the hydrogen sulphide gas was also required for measuring sieve tray efficiencies. Methods of doing this difficult analysis for both wet and dry gas were successfully developed. This analysis method has allowed the key work on tray efficiency to proceed.

The toxicity of hydrogen sulphide meant careful monitoring of its presence in air was essential. Work at CRNL was carried out to evaluate commercial monitors for this critical application and to define a reliable system that has been applied in both plants and laboratories.

The major emphasis on process analytical chemistry stemmed from the severe foaming problems encountered in the early operations of the Port Hawkesbury and Bruce plants. It was believed the foaming was caused, at least in part, by impurities being added to the process through either the feedwater, the H_2S make-up, or both.

To co-ordinate this analytical chemistry effort a group of chemists from the three heavy water plants, the Nova Scotia Research Foundation, the Chalk River and the Whiteshell laboratories and the General Electric Research and Development Centre in Schenectady, N.Y., was formed. Subsequently chemists from Ontario Hydro Research and the Savannah River heavy water plant participated occasionally. The group meets twice a year on a continuing basis.

A major sampling and analysis program was set up between Bruce HWP and CRNL to provide information on the impurities in the major process streams throughout the plant. Samples were taken once a week and shipped to CRNL for analysis. This program provided a baseline of impurity levels and their movement throughout the plant during both stable and unstable operation. The data generated by this program was deposited in a computer-based data system from which it could be retrieved in graphical or tabular form.

This, and similar programs at the Glace Bay and Port Hawkesbury plants, identified many problems in obtaining reliable analytical results from plant samples. One of the major problems was obtaining representative samples of the process streams and preserving these samples until they reached the laboratory for analysis. This was particularly severe for the determination of impurities with a volatility intermediate between that of water and the H_2S. Samples could not be taken in open sampling bottles because an unknown fraction of the volatile impurities would be lost, making the subsequent analytical results meaningless. This problem was solved by sampling into stainless steel cylinders at process pressures. Special precautions were then taken to analyse the entire sample.

The second major problem was that established chemical analysis methods did not always apply to samples containing H_2S, water and various sulphur impurities. For example there are many methods available in the open literature for the determination of trace sulphur containing compounds in air, but there are very few methods published for the determination of trace quantities of these impurities in essentially pure H_2S. As a result, special methods were developed by chemists at the plants and in the research laboratories and assembled in a manual of standard analytical methods for the heavy water industry. Table 3.3.1 lists the contents of this manual.

Since many of the analytical methods had been specifically developed for GS process samples the accuracy and precision were not established. For comparison of data from one plant to another it was necessary to establish the accuracy and precision through formal interlaboratory comparison using standard samples. Standard published ASTM procedures for carrying out interlaboratory comparisons were followed.

Many of the methods for analysing special samples require the use of sophisticated analytical instrumentation (3.3.1, 3.3.2, 3.3.3). Other analyses, required for normal day-to-day operation of the plant, are done in the plant laboratories. Originally all of the special samples were sent to the research laboratories, but because of sample preserving problems most of the plant laboratories were eventually equipped with some special equipment. Typical instrumentation in the plant laboratories includes mass spectrometers (exclusively for deuterium analysis), infrared and atomic absorption spectrometers, gas and liquid chromatographs, as well as conventional laboratory equipment. Some special analyses are still done in the research laboratories.

Some examples of the applications of analytical chemistry to process problems follow. One early problem was the deposition of a scale

Table 3.3.1

Standard Chemical Analysis Methods for the GS Process

Acidity (water)
Alkalinity of water and waste water
Aluminum (water)
Aluminum sulfate
Ammonia (water)
Atomic absorption-atomic emission spectrometry for
  metals - Al,Ca,Cr,Cu,Fe,Mg,Mn,Si,Na
Calcium (water)
Carbon dioxide (water, gas)
Carbonate (water)
Chemical oxygen demand (water)
Chloride (water)
Coagulant aid
Colour (water)
Conductivity (water)
Dew point
Deuterium oxide (water)
Foam test
GS process gas impurities (H_2S)
Gas sampling cylinders
Hydrazine (water)
Hydrogen sulphide (water)
Methanol (water)
Moisture (solids, gases)
Nitrate (water)
Oil (water)
Organics (water)
Oxygen (water)
pH (water)
Phenolic compounds (water)
Phosphorous (water)
Silicon (water)
Siloxanes (water)
Specific gravity
Sulphate (water)
Sulphide (water)
Sulphite (water)
Sulphur (water)
Total organic carbon (water)
Turbidity (water)
Total solids (water)
UV254 absorbance (water)
Water (oil)

on surfaces such as tower trays and heat exchanger tubes. A detailed analysis of sample deposits from more than 60 plant locations were characterized in terms of composition, structure and morphology. This work was done at the Whiteshell Nuclear Research Establishment (WNRE) using highly specialized applications of electron microscopy, emission spectrography, x-ray diffraction, thermogravimetry and combustion analysis. This study showed iron sulphides were the major constituents of the deposits where H_2S and water were present and iron oxides where H_2S was not present with the water. Pyrite was the most prevalent iron sulphide. Elemental sulphur was also found (3.3.4, 3.3.5, 3.3.6).

Detailed analysis of the feedwater was done to identify impurities that may have contributed to foaming and unstable operation. The impurity levels were very low, particularly for organic compounds, so that a preconcentration step was required to bring the impurity concentrations up to detectable levels. These very low concentrations in the feedwater were important because of the unique ability of the heavy water process to concentrate some impurities within the plant. The preconcentration was done by passing a large volume of water through a carbon bed. The impurities were then extracted from the carbon with different solvents and the solvents analysed. This program was co-ordinated, and the analysis done by the Nova Scotia Research Foundation. This resulted in a compilation that contained 172 different compounds classified by organic groups. Some of these species were shown to contribute to the water foaminess but the removal of no single compound or group of compounds would have eliminated the foaming problem. The practical solution was the addition of antifoams to the feedwater (see Section 3.2). Methods were developed for analysis of antifoam in the process to monitor its decomposition and movement throughout the plant. Some antifoam agents decomposed in the process and required the development of new methods of analysis for both the antifoam and the decomposition products.

Special analyses are required for pilot plant operation at CRNL. One is a method to measure the deuterium concentration in H_2S to determine sieve tray efficiencies.

In addition a number of on-line analysers have been developed. These include analysers for monitoring plant effluent streams for trace concentrations (ppb) of H_2S in water (see Fig. 3.3.1), oil in the feedwater to the finishing unit and deuterium concentration in the plant product from the finishing unit. The H_2S-in-water analyser development is an example of the solution to a plant problem conceived by plant people and developed by a contractor to the heavy water industry (3.3.7). A second commercial H_2S-in-water analyser was modified and further developed in a co-operative program between CRNL and GBHWP (3.3.8). Both types of analysers have been found to be suitable to several applications at heavy water plants.

Further application of on-line analysers is continuing. A deuterium-in-water analyser originally developed as a heavy water leak

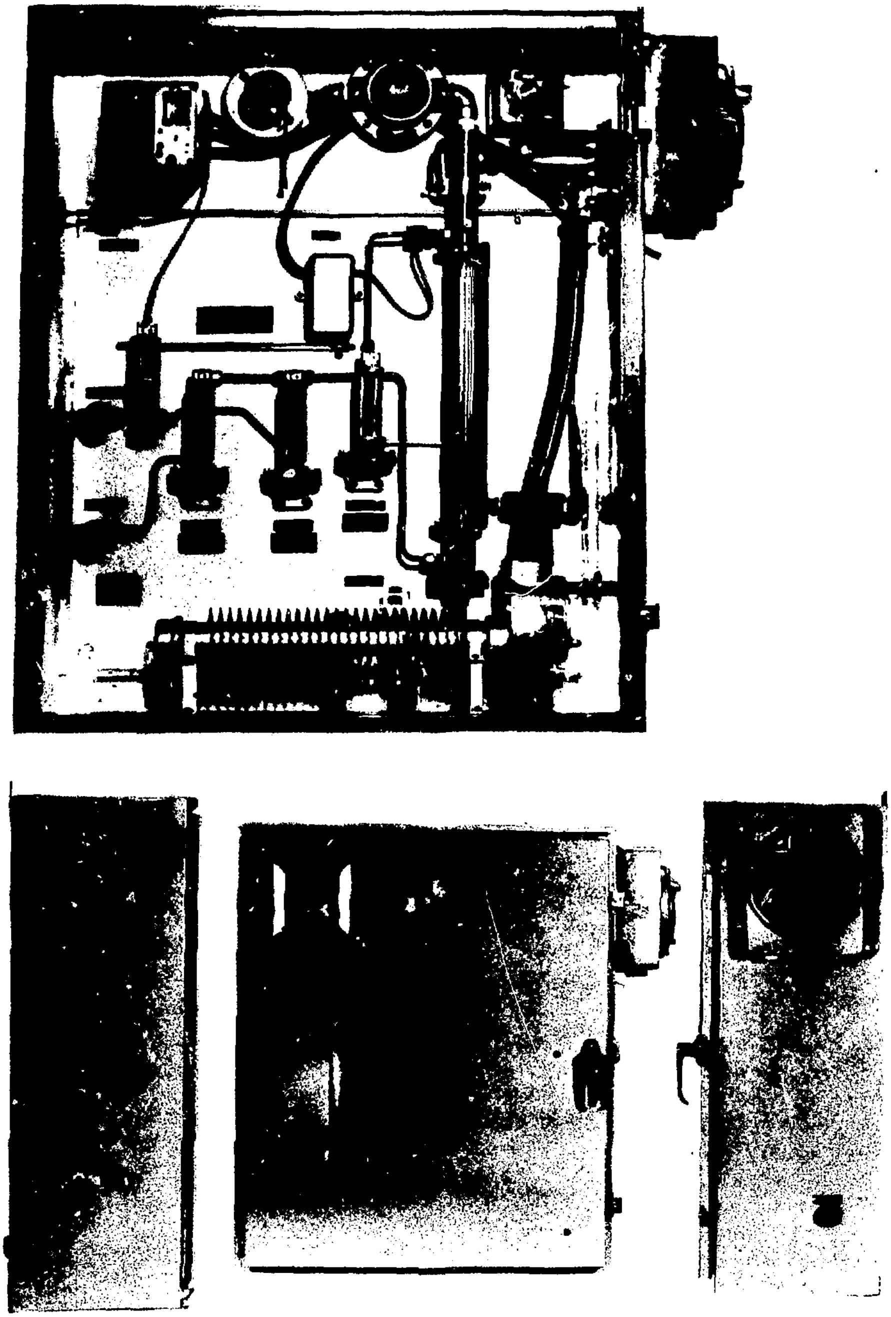


Figure 3.3.1: On-Line H_2S-in-Water Effluent Analyser Manufactured by Nova Scotia Research Foundation Corporation

detector in CANDU (CANadian Deuterium Uranium) reactor systems is being adapted to monitor the difference in concentrations of the feed and effluent streams at GBHWP. This will provide an on-line indicator of plant extraction.

3.4 Materials, Corrosion and Iron Transport - G.F. Taylor, and R.S. Pathania, CRNL

3.4.1 Introduction and History

The selection of materials for the Canadian heavy water plants (3.4.1, 3.4.2) was, at first, based on experience at the US plants and the research and development carried out in their support (3.4.3). Initially materials research in Canada focused on extending the application of some materials, e.g. raising the velocity limit on carbon steel and testing elastomers that had not been previously available. As more plants were built and more laboratories became involved in materials research a GS Materials Working Party was created to aid information flow. In particular, it was necessary to get 1) the experience of each operating plant into the others, 2) the experience of the operating plants into the design and operation of the new ones and into the laboratory programs and 3) the information from the laboratory programs back into the plants.

To this end the materials engineers from the plants, the design companies and the laboratories have met two or three times a year since 1971. By rotating the meeting place among the plant and laboratory sites the working party members were able to examine for themselves the facilities and work in progress at each place. During the ten years of operation of the GS Materials Working Party a few problems have arisen which required a more intensive and co-ordinated effort from plants and laboratories. In each case a smaller task force was formed and charged with finding solutions to an individual problem. Examples are the Iron Transport Task Force and the Impeller Task Force.

The information generated by ten years of effort by the materials engineers and scientists currently resides in numerous journal publications, conference proceedings, internal laboratory reports, plant inspection reports and minutes of meetings. An attempt has been made to consolidate the plant experience in an industry-wide summary and the laboratory personnel are committed to a similar summary of their work. Together these documents will form the base of materials selection decisions for both new and operating plants. In the rest of this section a short summary is provided.

3.4.2 Applications

3.4.2.1 Carbon Steel

In a GS heavy water plant the major use of carbon steel is for towers, piping and heat exchanger shells, though the shells are frequently clad or lined with stainless steel. Typically ASTM A516 and A333 are specified for plate and pipes, respectively.

The simple concept of carbon steel quickly forming a protective and chemically stable film of iron sulphide and thereafter corroding at a very low rate was supported by the early operation of Port Hawkesbury HWP and laboratory testing. The laboratory measurements suggested that the film could withstand higher liquid flowrates than the seven feet per second to which the plants had been designed. A few failures occurred in the plants downstream of control valves and other locations of high turbulence, indicating that there is indeed a limit to the mechanical stability of the film, and new designs continued to acknowledge the seven feet per second limit as a generally useful criterion. In 1973 carbon steel piping in liquid service at Bruce HWP was found to be corroding rapidly at locations which were not considered particularly turbulent. In addition considerable deposition of iron sulphide was found on stainless steel trays and heat exchanger tubes. The iron had been released from corroding carbon steel. Neither the corrosion nor the deposition diminished significantly with time, contrary to the accepted theory and contrary to the observation at Port Hawkesbury. Shutdowns for cleaning and line replacement reduced the production of heavy water. A large intersite program, involving staff at the laboratories and the plant, was begun to increase our understanding of the corrosion and deposition processes. Three years of effort involving at its peak twelve scientists and engineers resulted in a good understanding of the processes (3.4.4, 3.4.5, 3.4.6) and a technique to minimize iron transport (3.4.7). It was found that the initial corrosion product on steel, mackinawite (FeS_{1-x}), is not protective but transforms to troilite and then pyrrhotite and pyrite. Only the latter two are protective. Process conditions including dissolved iron concentration, liquid velocity, pH and temperature were found to influence the rate of transformation. A pre-conditioning treatment to passivate the carbon steel surfaces of a heavy water plant was developed in the laboratory, tested in the plant and applied successfully to two new units of Bruce HWP.

Hydrogen Blistering

Atomic hydrogen formed by the corrosion reaction can diffuse through the steel. If the hydrogen atoms encounter significant voids or inclusions the rate of diffusion through the steel is slowed allowing hydrogen atoms to join and form molecular hydrogen gas pockets. The pressure of hydrogen is sometimes sufficient to deform the steel forming blisters. As blisters grow ductile tearing and step-wise cracking can ultimately damage the integrity of the vessel.

Hydrogen blistering has been controlled by chemical specification of the steel as well as ultrasonic testing of plate. At BHWP this was quite successful for Plant A. Very little hydrogen blistering was found in the enriching units. Areas of high corrosion such as absorber tower trim sections and rundown tanks suffered some hydrogen blistering which led to the replacement of these vessel sections. In other locations hydrogen damage was controlled by drilling into the isolated blisters to relieve the gas pressure. In 1977 work started at Ontario Hydro Research to improve the selection or protection of carbon steel to resist hydrogen damage.

BHWP B was built with steel to the same specification as BHWP A but hydrogen damage has been much more extensive. The absorber and purge towers in both E3 and E4 were replaced in 1980 due to hydrogen blistering following fairly short exposure to H_2S. (E3 four months, E4 one year). Hydrogen damage has been found in other towers and vessels so further replacement or repair may be required.

Because of the research program ongoing from 1977, new tighter specifications, tests and inspection techniques are available for the selection of replacement steels. These purchase specifications were used for the replacement steel for the absorber and purge tower in BHWP B. The revised specification would be applicable to any new heavy water plant construction.

3.4.2.2 Stainless Steel and Nickel Alloys

In a GS plant stainless steels are used for piping, heat exchanger tubes and liners, impellers, valve stems, etc. Nickel-base alloys are used in applications such as bellows, springs and diaphragms. Although the experience with stainless steel and nickel alloys in H_2S service has generally been satisfactory, occasional failures have occurred due to localized corrosion, e.g. stress corrosion cracking (SCC) and pitting corrosion. The factors responsible for localized corrosion of stainless steel and nickel alloys in H_2S-saturated water have been identified through research programs and failure investigations in various laboratories.

Stress Corrosion Cracking

Both intergranular and transgranular stress corrosion cracking of stainless steels have been observed in H_2S-saturated water. Intergranular SCC may occur in sensitized stainless steels and nickel alloys when they are exposed to sulphur-oxy acids (e.g. polythionic acids, sulphurous acid) formed by interaction of sulphides, moisture and oxygen. Stainless steels may be sensitized (a condition characterized by precipitation of chromium carbide along the grain boundaries and depletion of chromium adjacent to the grain boundaries) during welding or heat treatment. A study showed that stressed types 304 and 316 stainless steels, heated at 650-760°C for one hour and exposed to a solution containing H_2S and air failed by intergranular SCC. However, types 304L, 316L and 321 stainless steels were resistant to SCC under the same conditions. Similar behaviour was observed in a solution containing polythionic acids. Types 304L and 316L stainless steels are resistant to sensitization because of their low (<0.03 wt%) carbon contents. Type 321 (and type 347) contain carbide stabilizers which minimize the formation of intergranular chromium carbides. Nickel alloys such as Inconel-625 are also resistant to sensitization.

The startup of BHWP B was delayed for two years due to a series of materials failures. The major problem was failure of the expansion joints in the large diameter blower suction lines which suffered from stress corrosion cracking. The initial failure in October '78 and the subsequent failure in Febuary '79 of a rebuilt joint were both due to cracking at the transition zone where Inconel bellows were welded to carbon steel piping. These expansion joints were replaced by all-Inconel joints which also suffered from cracking. The major cause in this case was sensitization of the alloy due to improper heat treatment. To avoid further problems all the expansion joints in BHWP B have been replaced with expansion loops in the large diameter carbon steel lines.

The following steps can help to control intergranular SCC in H_2S environments.

a) For welded applications low carbon or stabilized stainless steels should be used. The welds should be solution-annealed or stress-relieved to minimize residual stresses.

b) The residual H_2S in stainless steel equipment should be neutralized before exposure to air.

Transgranular stress corrosion cracking has been observed in the presence of H_2S, chlorides and air at ambient temperatures and pressures. For example, stressed types 304 and 316 stainless steels exposed to H_2S-saturated water containing 500 mg Cl^-/kg H_2O and oxygen suffered transgranular SCC in 1 600 and 6 000 h, respectively. However, no cracking was observed in a solution containing 500 mg Cl^-/kg H_2O and oxygen but no H_2S. Nickel alloys such as Inconel-625 and Hastelloy C-276 were immune to this type of cracking. Tests also showed that cold-worked type 316 stainless steel was highly susceptible to transgranular SCC.

To avoid transgranular SCC in H_2S environments it is necessary to use annealed austenitic stainless steels and to avoid ingress of air.

Pitting corrosion of stainless steels is most severe in environments containing H_2S, chlorides and oxygen. In the absence of oxygen the rate of pitting corrosion is fairly low. Molybdenum-bearing stainless steels (e.g. type 316) have better resistance to pitting corrosion than type 304 stainless steel. Inconel-625 and Hastelloy C-276 have excellent resistance to pitting corrosion in H_2S environments. These alloys are used in critical applications, e.g. diaphragms and bellows.

3.5 Mechanical Equipment - D.G. Dalrymple, CRNL

3.5.1 Introduction

Equipment design and maintenance philosophies in the nuclear and chemical process industries are similar in some respects, but generally quite different. The major difference is that the design life of major nuclear power plant equipment such as heat exchangers is thirty years; that of chemical process plant equipment is shorter, typically ten years. This results from the relative ease of replacing chemical process plant equipment. Much of the advanced design and maintenance technology developed in support of nuclear power plants results from applied research and development undertaken because of regulatory requirements, plant maintenance environments, materials of construction, and economic considerations unique to the nuclear industry (3.5.1, 3.5.2). What often results are advances in technology that have wider applicability, since incentives such as increased reliability and reduced downtime also apply in other process industry plants. The purpose of this section is to present a few examples illustrating how nuclear equipment technology has been used in the design and maintenance of heavy water production plants.

In many respects the mechanical equipment problems encountered by the Canadian heavy water production industry are quite compatible with the technology developed by AECL in support of the CANDU nuclear power reactor. This has led to extensive interaction between the two groups in many areas and over many years. The high degree of technical compatibility has generally yielded high return for the R&D effort expended. There has been continuing contact between plant and laboratory staff on mechanical equipment topics that has led to the formation of the industry-wide task forces, covering the topics of valves, inspection and reliability. There is also important liaison on materials of construction through the GS Materials Working Party (see Section 3.4). The goal of R&D activities on these topics is to improve equipment performance, reliability and maintainability.

3.5.2 Applications

3.5.2.1 Heat Exchanger Vibration

The main causes of heat exchanger tube failure are vibration and/or corrosion. Excessive flow-induced vibration may cause tube failure by fretting wear or fatigue. Some degree of flow-induced vibration is inevitable in shell and tube heat exchangers; however, rational design procedures to assure adequate reliability throughout the design life have only recently been developed (3.5.3). These are not generally available, and specifications such as the Tubular Exchanger Manufacturers Association provide little assurance of design life.

There are three relevant flow-induced vibration excitation mechanisms: 1) fluid-elastic instability, 2) periodic wake shedding, and 3) random excitation due to flow turbulence. The objectives of rational vibration design are: 1) avoid fluid-elastic instability, 2) limit tube response due to wake shedding resonance to 2% (rms) of tube diameter, and 3) ensure that fretting wear rates at tube supports, due to impact resulting from tube vibration, are consistent with design life specified.

Such design procedures were not available for initial design of heat exchangers in Canadian heavy water plants. Involvement of CRNL in evaluating and resolving problems encountered in operating plants contributed significantly to development of design procedures. Figure 3.5.1 illustrates five examples in which vibration analysis led to an understanding of problems encountered in process heat exchangers (3.5.4).

To avoid such problems in the future, AECL's heat exchanger vibration design technology has been transferred to Canadian manufacturers of such equipment. In addition, all new heat exchange equipment is subjected to an independent vibration analysis audit at the design stage.

3.5.2.2 Tower and Stack Vibration

A GS process heavy water plant is characterized by high structures such as flare stacks and sieve tray towers which are subject to wind-induced vibration. While vibration response of such structures is incorporated in design, the validity of such analyses depends on the knowledge of such parameters as structural damping, wind-induced dynamic forces, flexural rigidity, and inter-structure coupling. Full-scale vibration experiments by AECL at Glace Bay HWP were undertaken to confirm the design data, and a dynamic model of the inter-connected tower structures was developed. This technology is now incorporated in the design of Canadian heavy water plant structures and provides a degree of confidence in the design consistent with the environmental hazard of hydrogen sulphide.

3.5.2.3 Heat Exchanger Tubesheet Packings

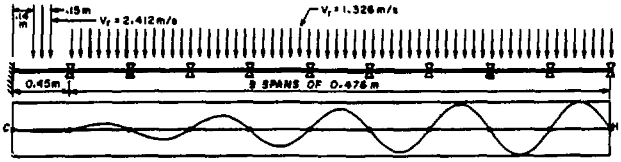
Most heat exchangers in Canadian heavy water plants have floating tubesheets. Considerable difficulty was initially encountered with packing dissolution leading to excessive maintenance. Prior AECL experience with valve packings contributed to one proprietary grade of woven teflon packing being accepted as the industry standard for several years. Subsequent price increases led to a series of six-week laboratory tests on eight similar products to qualify other proprietary grades as generic equivalents. Hard packings generally performed better than soft packings, and packings without spring-loaded gland followers were found to leak profusely after the first thermal cycle (when cold). These tests led to a considerably increased understanding of floating tubesheet packings. In addition, three proprietary grades were identified as being equal in performance, and superior to the other materials tested. Somewhat surprisingly, the three materials recommended on the basis of these tests were superior to the previously preferred material and were about one-third the price.

3.5.2.4 Pump and Compressor Shaft Seals

High priority had to be given to the design and construction of shaft seals used in liquid and gaseous hydrogen sulphide systems. Little directly relevant information as to the performance and reliability of pump and compressor seal assemblies was available at the outset of the Canadian heavy water industry. A number of seal assemblies were therefore tested under simulated service conditions at CRNL (3.5.5). These tests generally

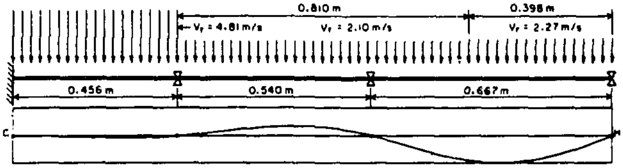
Case DPBC-1: PROBLEM: Outer tube fretting at baffles; SOLUTION: Plug tubes for now and redesign system; FLUIDELASTIC INSTABILITY: No; $V_r/V_{rc}=0.77<1$; 1st mode, 103 Hz.

$d = 12.7$ mm
$p/d = 1.5$
$m/\ell = 0.61$ kg/m
$EI = 133$ N·m^2
$\rho = 971$ kg/m^3
$c = 5.07$ kg·s^{-1}·m^{-1}



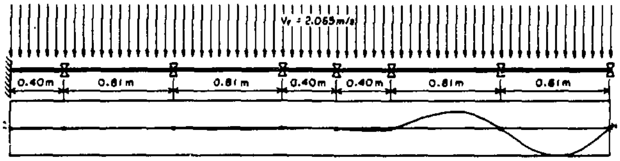
Case PASC-2: PROBLEM: Excessive vibration at 100% flow; SOLUTION: Operate below 60% flow; FLUIDELASTIC INSTABILITY: Yes; $V_r/V_{rc}=1.74>1$; 3rd mode, 209 Hz.

$d = 12.6$ mm
$p/d = 1.26$
$m/\ell = 0.61$ kg/m
$EI = 130$ N·m^2
$\rho = 998$ kg/m^3
$c = 5.04$ kg·s^{-1}·m^{-1}



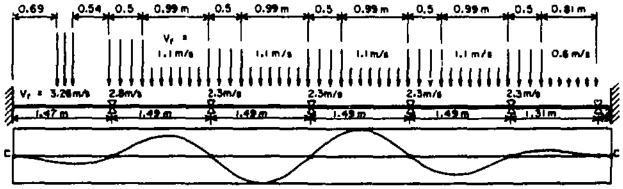
Case PAMX-1: PROBLEM: Tube fatigue & fretting near outlet; SOLUTION: Install lacing rod supports; FLUIDELASTIC INSTABILITY: Yes; $V_r/V_{rc}=2.04>1$; 1st mode, 37.1 Hz.

$d = 12.7$ mm
$p/d = 1.5$
$m/\ell = 0.67$ kg/m
$EI = 127$ N·m^2
$\rho = 997$ kg/m^3
$c = 5.07$ kg·s^{-1}·m^{-1}



Case GBCX-1: PROBLEM: Tube fatigue at tubesheet near inlet, fretting; SOLUTION: Modify inlet now, redesign tube bundle; FLUIDELASTIC INSTABILITY: Yes; $V_r/V_{rc}=1.71$; 1st mode, 18.2 Hz.

$d = 19.1$ mm
$p/d = 1.25$
$m/\ell = 1.20$ kg/m
$EI = 665$ N·m^2
$\rho = 996$ kg/m^3
$c = 7.63$ kg·s^{-1}·m^{-1}



Case PHRC-1: PROBLEM: Tube fretting at supports; SOLUTION: Add supports, modify inlet; FLUIDELASTIC INSTABILITY: at inlet; $V_r/V_{rc}=1.37>1$; 15th mode, 177 Hz.

$d = 19.1$ mm
$p/d = 1.33$
$m/\ell = 1.25$ kg/m
$EI = 716$ N·m^2
$\rho = 993$ kg/m^3
$c = 7.63$ kg·s^{-1}·m^{-1}

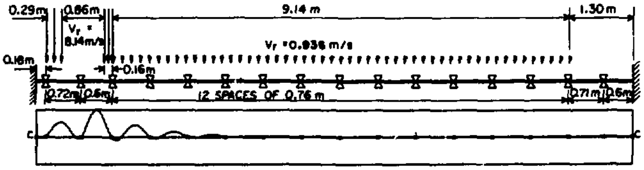


Figure 3.5.1

Five Analyses of Liquid-Liquid Cross-Flow Heat Exchanger Failures

Note of Explanation: V_r/V_{rc} = actual/critical reference gap velocity ratio for the most significant vibration mode in each case ($V_r/V_{rc} \geq 1.0$ indicates fluidelastic instability). The corresponding frequency is specified and the normalized vibration amplitude distribution plotted below for each case. Parameters d, p, M/L, EI represent tube diameter, pitch, mass per unit length and flexural rigidity; ρ, c represent shell-side fluid mass density and viscous damping coefficient. As implied by the data illustrated the first mode is usually, but not always the significant one for heat exchanger vibration design.

indicated acceptable rates of seal face wear could only be achieved at low balance ratio, and that leakage rates would remain acceptably low under these conditions. This early learning experience (based on many years of pump seal research and development dedicated to achieving a five-year life for the seals of the main coolant pumps in CANDU reactors) has contributed significantly to plant productivity, and relatively few pump and compressor shaft seal problems have been encountered.

3.6 Sieve Tray Hydraulics and Mass Transfer - K.T. Chuang, H.J. Neuburg, and D.A. Spagnolo, CRNL

3.6.1 Industry Needs

Sieve tray design for Canadian heavy water plants was originally based on technology derived from systems other than GS, and on the operating experience of existing US heavy water plants. GS plants in the USA at Dana and Savannah River have towers up to 3.5 m in diameter, and Canadian plant design had to be scaled up for sieve trays up to 8.5 m in diameter. In the early stages of operation, Canadian heavy water plants were plagued by cold tower tray instability. It was also soon apparent that mass transfer tray efficiency was lower than the design values, which were based on measurements performed at the Dana plant (3.6.1). As a result throughput and extraction were far below design levels.

An R&D program was required to improve sieve tray performance at the heavy water plants. The objective was to develop reliable correlations which could be used to design and predict the performance of GS process sieve trays. This program represented a large cooperative effort between personnel from CRNL, Ontario Hydro, Nova Scotia Research Foundation, heavy water plants, tray vendors and Canadian universities. Due to the open exchange among these groups, unnecessary duplication of effort was avoided and an extensive range of studies from the behaviour of single bubbles to tests with plant scale trays was possible. Periodic meetings of the Tray Mass Transfer Working Party, where most of these groups actively participate, are held to discuss the R&D results and tray-related problems and activities at the plants. Future programs that satisfy the needs of the heavy water industry are also defined.

3.6.2 Test Program

Tray hydraulic parameters have been investigated in air/water test rigs up to 6.1 m in diameter, and also in a pilot plant at CRNL containing 0.3 m diameter trays operating at GS process conditions (see Fig. 3.6.1). At BHWP and GBHWP first stage towers have been selected to study tray behaviour, and have been fitted with extra instrumentation. Tray efficiency measurements were made at the pilot plant for a wide range of operating conditions and tray variables. A single-hole bubble column and a wetted wall column were also used to learn about the fundamentals of the GS exchange process.

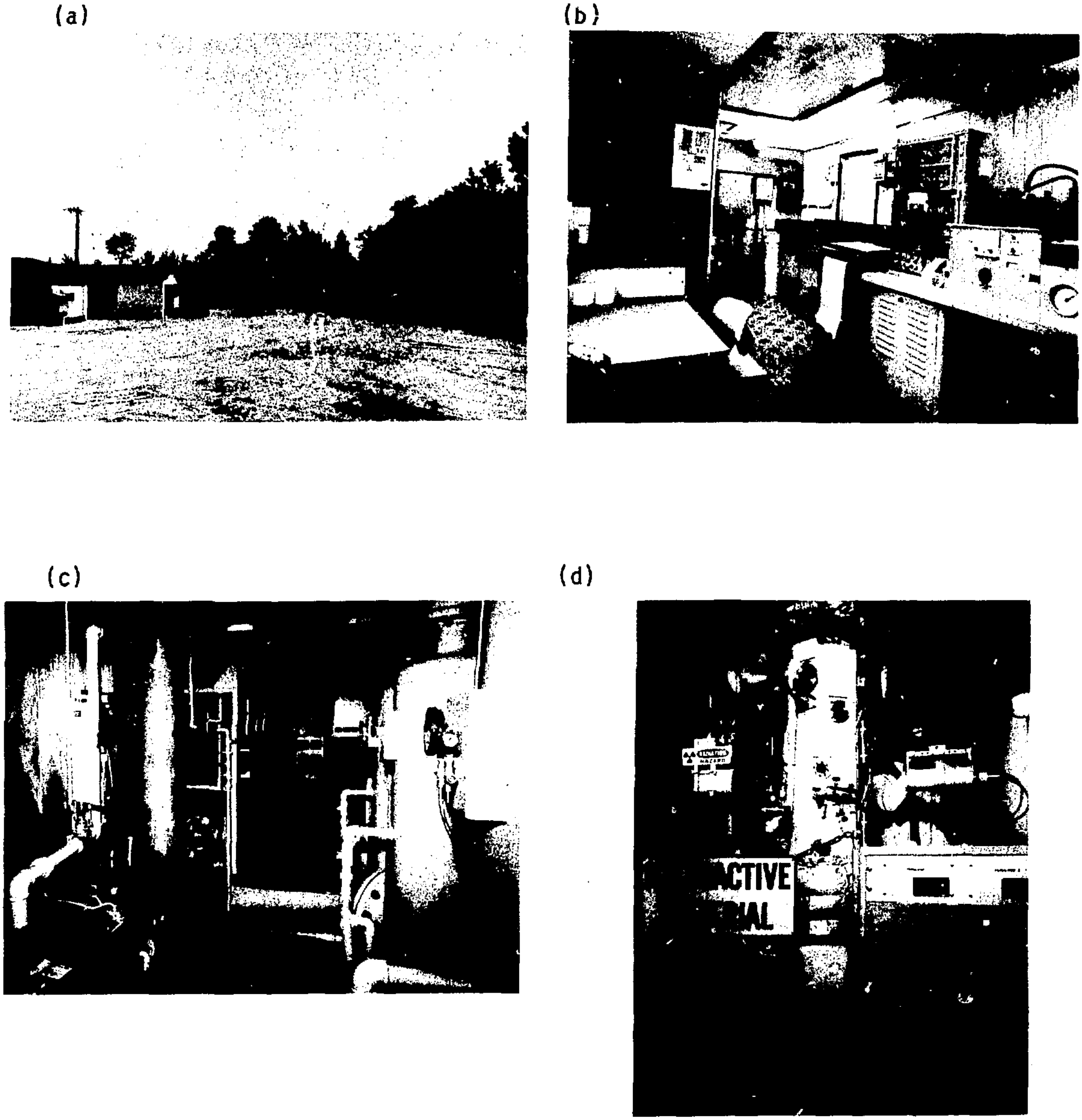


Figure 3.6.1 GS Mobile Pilot Plant at CRNL showing
a) general view of site with workshops and trailers
b) mass spectrometer deuterium analyser
c) water treatment equipment, and
d) GS process equipment with gamma scanning facility mounted on test column.

Most of the tray-related problems encountered at the plants have been identified and solved, and a program has been established to gradually upgrade tray performance according to the needs defined by economics. Laboratory, pilot plant and production plant experience has been used to define and confirm correlations for 31 tray design parameters. This assembled information is used for tray modifications. The R&D effort is expected to continue at the present level for the next five years, with emphasis on new development, such as heat transfer tray efficiency.

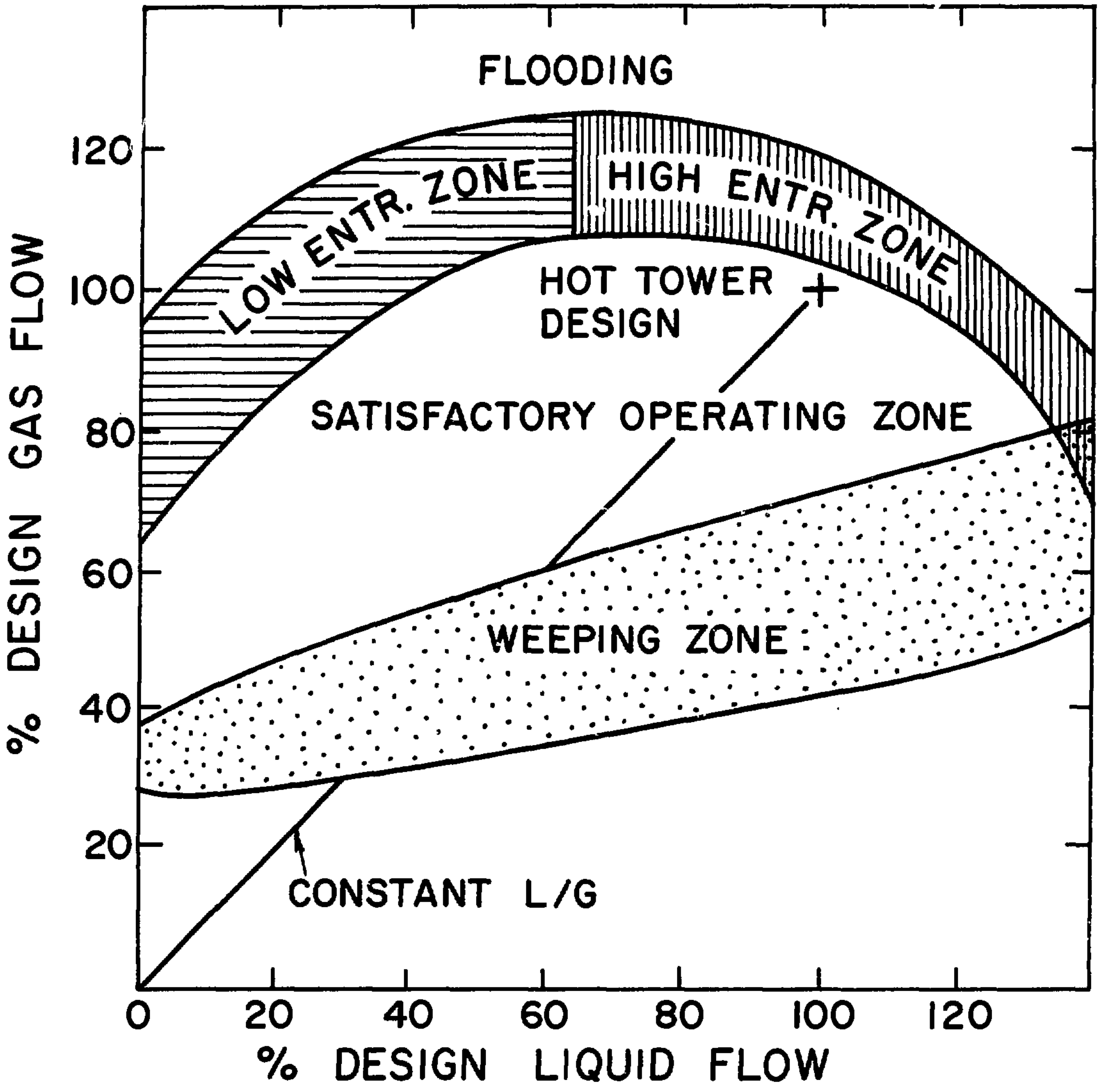
3.6.3 Tray Hydraulics

The two important considerations in tray design are stable hydraulic operation and maximum extraction at design flow conditions. Figure 3.6.2 is a performance chart for a typical hot tower sieve tray, where the satisfactory operating zone is confined within limited ranges of gas and liquid flow rates. Furthermore, GS process operation is restricted to a fixed L/G line as indicated. Deviation in L/G must be maintained within 0.5% to achieve maximum extraction. The ultimate capacity of sieve trays is determined by high entrainment because it reduces the apparent tray efficiency by recycling liquid to the tray above. In GS towers, a loss of 5% production can occur with 3.5% entrainment (defined as kg liquid entrained/100 kg gas) due to reduced hot tower tray efficiency. At turndown conditions, excessive flow of liquid through the perforations (weeping) represents a lower operating limit. Weeping is detrimental to tray efficiency because it reduces gas-liquid contact. When inlet weeping predominates, liquid by-passes two trays causing efficiency to drop sharply. Based on data collected at GS conditions, reliable correlations have been derived to predict entrainment and weeping for industrial trays operating in wide flow ranges.

Tray hardware design combined with effective antifoam agents are the key factors for optimum sieve tray performance. Outlet weir height plays an important role in controlling froth height which also depends on liquid weir loading and gas flow. The higher the froth height the higher is the tray efficiency, up to the point where heavy entrainment occurs. High froth heights also cause higher tray pressure drops, which in turn can result in downcomer back-up problems for foamy systems. Trays originally installed in the Port Hawkesbury and Bruce cold towers were modified during early operation to prevent flooding by reducing the height of the outlet weirs. These changes increased the flow limit from below 90 to above 120% of design flow. It is believed that some of these changes went too far in sacrificing efficiency for stability so that gains in efficiency are possible by increasing weir height. In early days froth heights on GS sieve trays were predicted using a correlation obtained from air/water data measured on a large scale simulator (3.6.2). More recently, a new correlation was derived to predict froth height on GS trays by making use of a large data bank from gamma scanning at the heavy water plants. The same data were used in conjunction with plant pressure drop measurements to derive a tray pressure drop correlation.

Trays have to be designed to contain sufficient downcomer area to prevent choking by the froth flowing into it. Liquid residence time in the

FIGURE 3.6.2 - TYPICAL SIEVE TRAY PERFORMANCE CHART



downcomer must be large enough to allow complete gas/liquid separation between trays. This may be a problem for a foamy system. Downcomer residence time can be optimized by proper setting of the downcomer clearance (underflow weir). However, caution must be exerted to prevent downcomer back-up. Suitable expressions have been derived to calculate the various parameters that affect downcomer performance.

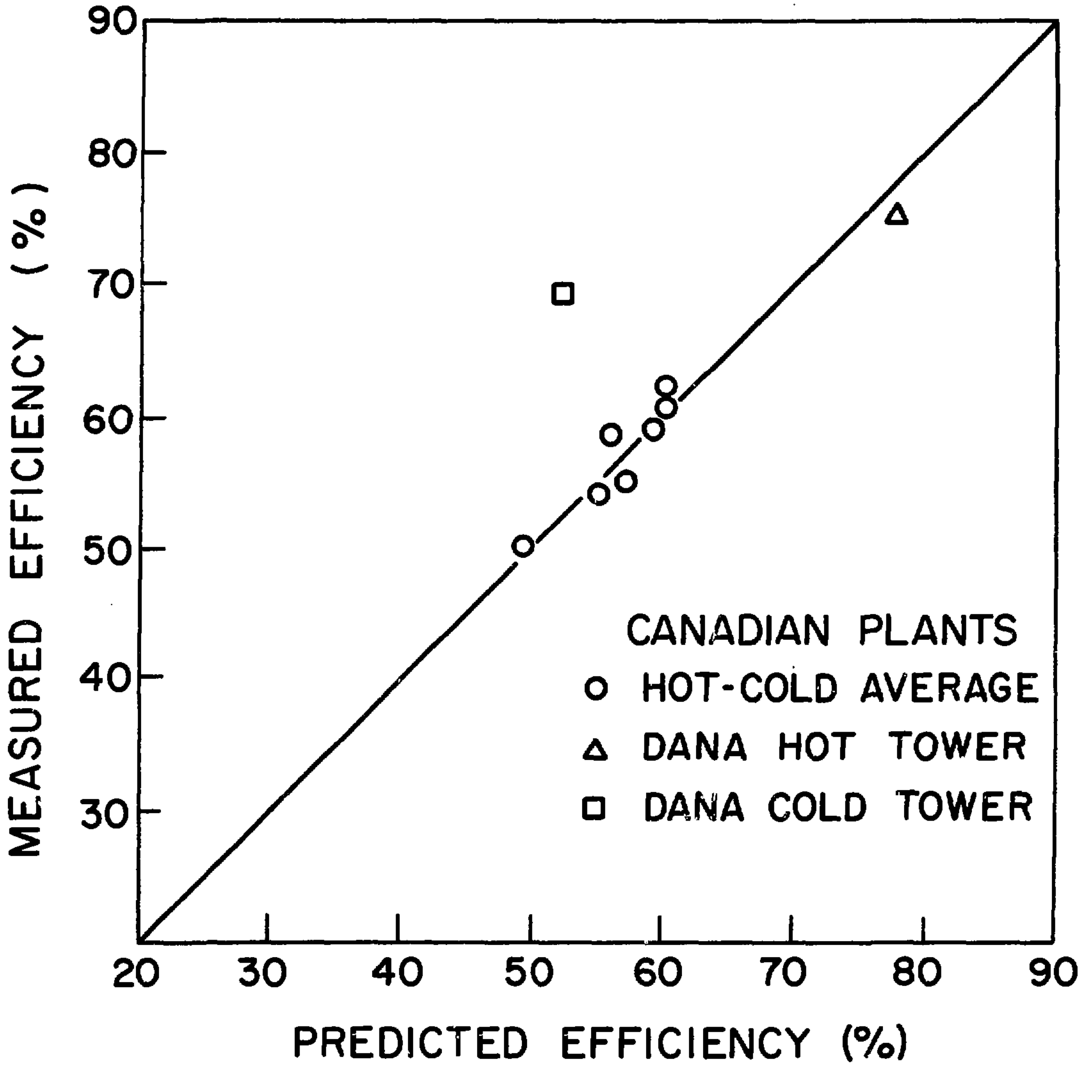
The active area on the tray is the surface on which gas and liquid are contacted. It is given by the area of the tower less the areas of downcomers. It is very important to establish the design of sieve tray panels that occupy the active area in terms of relative open hole area, hole diameter and distribution of liquid flow-promoting devices that will force liquid flow on the tray to follow an ideal path. Relative open hole area plays a decisive role in determining tray pressure drop and turndown capacity. Normally open hole area on GS trays is adjusted to suit the capacity of the circulating blower. Typically the total tray pressure drop is no greater than 800 Pa/tray and turndown is about 70% of design flow for 25% weeping. Hole diameter has a weak influence on hydraulic performance, but smaller holes result in higher tray efficiency for trays operating in the low gas velocity region. On the other hand, hole pluggage due to sulphur compound deposits creates more severe operation problems on smaller hole size trays than on trays with larger holes. Hole diameters are usually in the range of 0.5 to 1.5 cm, depending on the particular requirements of certain tower regions. Proper distribution of flow-promoting devices on the tray active area is of great importance to obtain maximum tray efficiency within existing hydraulic restrictions. At present tray vendors possess the technology for flow promoter design, but theoretical and experimental studies are underway at CRNL to develop a more advanced understanding of this subject (3.6.3).

3.6.4 Tray Efficiency

Tray efficiency depends on three sets of parameters; system properties, vapour and liquid loading, and tray geometry. The designer has little control over the first set but can effectively deal with the other two. A tray efficiency model has been developed at CRNL (3.6.4, 3.6.5) that is capable of accurately predicting tray efficiency for given pressure, temperature, flow conditions and tray geometry. The model takes into account effects of entrainment, weeping, gas mixing, liquid mixing in the downcomers and two-dimensional liquid flow distribution on the tray surface.

Predictions of plant tray efficiencies by the model have been in very good agreement with direct plant measurements, as shown in Fig. 3.6.3. It is interesting to note that a discrepancy was found with the cold tower efficiency of the Dana plant measured by Proctor (3.6.1), using a technique of altering the ratio of gas-to-liquid flows in the towers. This discrepancy, which is worth about 17 percentage points in tray efficiency, explains why cold tower trays in Canadian plants did not achieve design performance. Proctor had to derive tray efficiency numbers from overall tower performance under extremely pinched conditions. It is likely that his measured value for the cold tower is erroneous.

FIGURE 3.6.3 - MEASURED vs PREDICTED TRAY EFFICIENCY FOR GS PLANTS



3.6.5 Plant Tray Modifications

Great benefits from tray modifications have been realized at the heavy water plants since 1976 when more firmly based correlations on tray design began to evolve. Those changes directed at improving tray efficiency are listed in Table 3.6.1. It can be seen that the production gains were substantial.

Other tray changes involved increasing the open hole area of the trays in the top of the hot tower of BHWP E1A. This change successfully demonstrated that a higher open hole area tray reduced entrainment.

A redesign of the transfer trays in the dehumidifier sections of the first and second stages at PHHWP resulted in dramatic improvement in plant performance. Through gamma scanning these trays were recognized as a "bottleneck" to increased production because they limited flows. Analysis of the trays confirmed the problem and new trays were designed to perform a heat transfer function rather than simply a transfer function. These tray changes, along with a number of other equipment improvements, resulted in a 10% increase in production, of which a significant fraction was attributed to the tray program.

Table 3.6.1 Benefits of Plant Tray Modifications

Location	Changes	Tray Efficiency Gain	Production Gain
PHHWP Stage 1	Raise CT weir on alternate trays	1.5% points	1%
GBHWP Stage 3	Raise weirs in CT and HT	23% points	12%
GBHWP Stage 1	Raise weirs in CT Replace multipass trays with 2-pass trays in HT	11% points	2.4%
GBHWP Stage 1	Raise weir in CT Replace multipass trays with flow promoted 2-pass trays in HT	13% points	2.8%*

* if all first and second stage towers were modified, production gains would be 23.9%.

3.7 Gamma Scanning - D.A. Spagnolo, CRNL

3.7.1 Introduction

During the early years of operating the Canadian heavy water plants, design flows were not achieved because of hydraulic instability on the trays. Determining the type and location of the instability was extremely difficult because the plants were not instrumented for analysing tray performance. The large towers, high operating pressure and toxicity of H_2S deterred new tower penetrations, and this limited new instrumentation. To provide a means of detecting tray damage and studying tray operation without penetrating the tower walls, the gamma scanning technique was refined for large diameter towers by CRNL (3.7.1, 3.7.2). Some earlier scanning had been done on the smaller SRP towers in the USA by Dupont (3.7.3).

Gamma scanning has since developed to the stage where it is routinely used at all Canadian heavy water plants for maintenance planning, troubleshooting, and performance evaluation.

Ontario Hydro operates two scanning units at the BHWP. NSRF uses a portable scanning unit owned by AECL-CC and conducts scans for PHHWP and GBHWP on a contract basis. CRNL provides the development and maintenance of the equipment for the heavy water industry and operates a portable scanning unit for its GS pilot plant.

Information on gamma scanning is exchanged and discussed through the Gamma Scanning Working Party, which periodically meets and is made up of representatives from the heavy water plants, scanning and development groups.

3.7.2 Equipment

When gamma rays penetrate a vessel, some rays are absorbed or deflected while others pass through. The fraction that penetrates depends on the strength of the radiation source, and the density and thickness of the intervening materials. If the source strength and vessel thickness remain unchanged, density differences within the vessel can be related to the number of rays that penetrate. This ability to detect density differences is the basis for the gamma scanning technique.

Scanning involves the synchronous raising (or lowering) of a gamma source (normally Co-60) and a scintillation detector on opposite sides of the vessel as illustrated in Fig. 3.7.1. The equipment consists of a gamma source, a detector, collimators, elevating devices, electronics to analyse the detected signal, and some type of information output display. The latter can range from a simple strip chart recorder to a sophisticated on-line computer. All equipment is commercially available except for the holding and elevating devices, which were designed and developed by CRNL.

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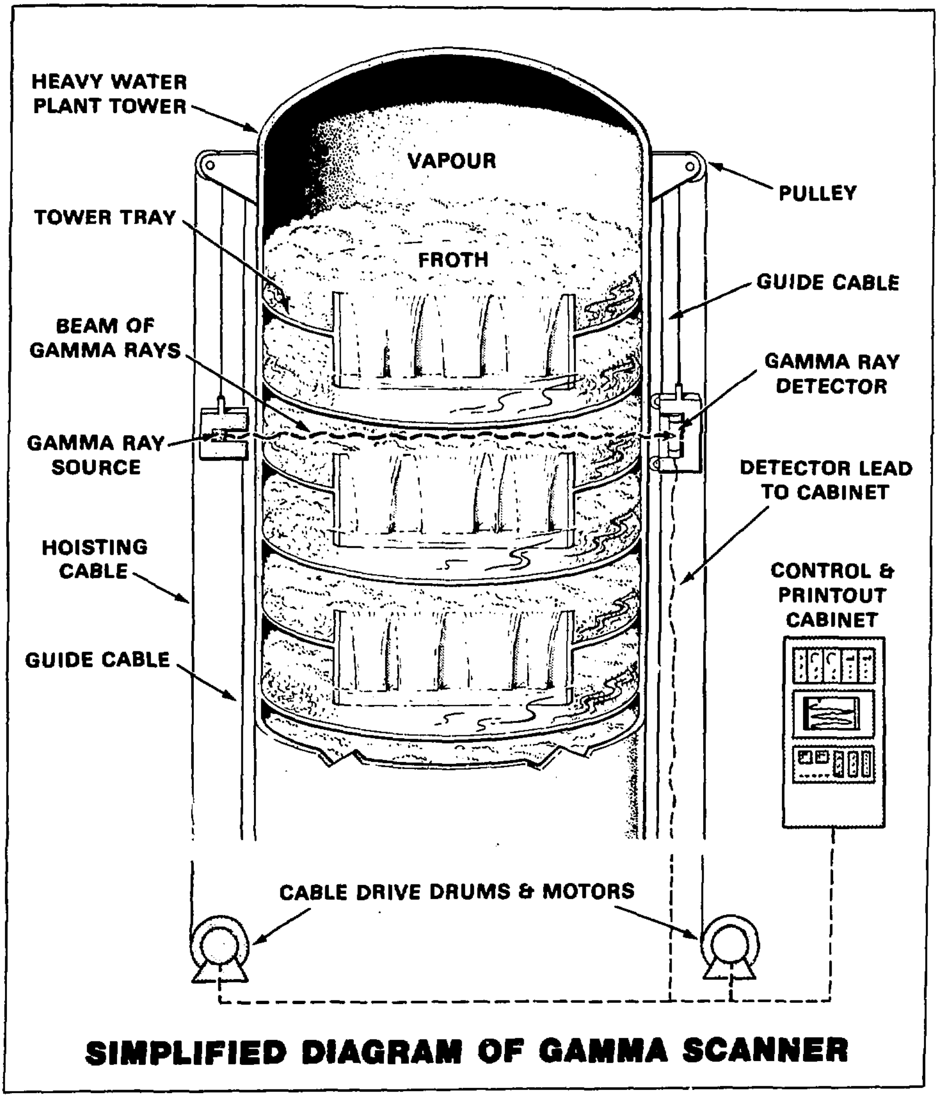

Figure 3.7.1

Simplified Diagram of Gamma Scanner

3.7.3 Applications

3.7.3.1 Tray Hydraulics

Gamma scanning can provide valuable hydraulic information on the performance of sieve trays. Froth height, liquid holdup and froth density are readily attainable, and can be applied to:

- evaluate the effectiveness of tray modifications, which in turn is used to develop tray models and optimize tray design,
- determine the effects of changes in operating conditions on tray performance,
- evaluate chemical process changes,
- establish the location and mechanism of tower loading and instability, and
- detect changes in tray operation arising from foaming or mechanical damage.

Scanning is extensively used to measure froth heights on sieve trays. From such data, outlet weir heights have been either reduced to improve hydraulic stability or increased to improve mass transfer efficiency. For example, scanning established that the cause for low tray efficiency in a particular tower at Glace Bay HWP was due to low froth height and liquid holdup on the trays. Raising the weirs to increase froth height and liquid holdup increased tray efficiency by 20 percentage points.

Similarly, scanning has been used to evaluate the influence of hole size and open hole area of sieve trays. Here several trays in a section of a tower at the Bruce HWP were changed and "before" and "after" scans were compared. In the studies of open hole area, scanning was used to determine the upper flow limits for the various trays.

Horizontal scanning involves the incremental movement of the detector circumferentially around part of the tower while keeping the position of the source fixed. Such scanning at the Bruce HWP revealed that froth heights on side downcomer trays were more uniform than on center downcomer trays. The lower hydraulic gradient on SDC trays was interpreted to mean a more uniform flow distribution and thus higher tray efficiency. The scanning confirmed the need for new types of directional flow and entrance promoters for CDC trays.

A scan of a typical operating tower consists of a series of peaks and valleys as shown in Fig. 3.7.2. The peaks of high gamma transmission represents the low density vapour phase. The valleys of low transmission are caused by the dense froth on the tray decks and by the metal trays and tray supports. Irregularities in scan patterns are usually evidence of internal structural damage. Broken trays do not support their normal levels of water and froth and abnormal tray spacing is usually indicative

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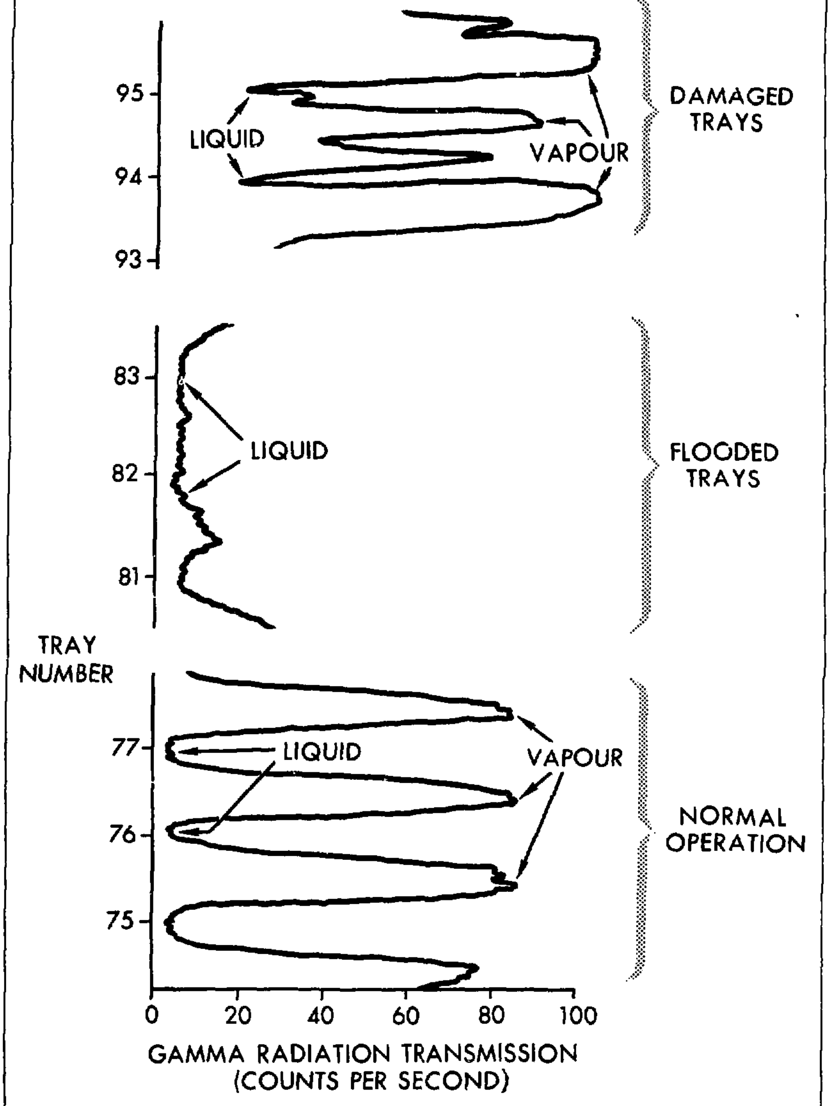


TYPICAL GAMMA SCAN RECORDS SHOWING NORMAL & ABNORMAL CONDITIONS IN AN OPERATING TOWER

Figure 3.7.2

of displaced trays. Knowing the location of damage and the number of trays involved prior to a tower shutdown is important to allow adequate time to order materials and to schedule the shutdown.

Scanning has also been successfully used to locate tray loading instabilities. The absence of peaks on a tower scan (Fig. 3.7.2) indicates the absence of a vapour space between trays and thus, the presence of flooded trays.

Scanning has been used to evaluate new antifoams during plant trials by determining the effect of the antifoam and its concentrations on tray froth heights.

3.7.3.2 Tray Blockage

Iron sulphide, because of its inverse solubility with temperature, can deposit on sieve trays in hot sections of the towers. The iron sulphide crystallizes around the tray perforations, causing gradual reduction in the open hole area of the tray. A qualitative means of monitoring the progress of this fouling during plant operation using gamma scanning was developed to more efficiently schedule tower shutdowns for tray cleaning.

Scanning provides a profile of froth height against tray number as shown in Fig. 3.7.3. A deposition gradient occurs with highest deposition occurring on the top tray of the hot tower. As deposition progresses with time the slope of the froth height versus tray number profile changes. The profiles illustrated in Fig. 3.7.3 are for constant operating conditions. The froth heights can be qualitatively related to actual plug gauge measurements taken during plant shutdown.

3.7.3.3 Heat Exchanger Fouling

The vertical process steam heat exchangers in the humidification circuit is another place where iron deposition can be severe. Fouling of these exchangers reduces heat transfer efficiency and makes cleaning necessary. Monitoring fouling during plant operation with gamma scanning enables more efficient shutdown scheduling for cleaning. Fouling can be monitored in two ways:

1) qualitatively by following the decrease in condensate level at the bottom of the exchanger, and

2) quantitatively by following the actual deposit thickness in the exchanger tubes.

Thus a vertical scan of the exchanger yields a gamma intensity profile (Fig. 3.7.4) which for a clean exchanger is relatively uniform from top to bottom and has a relatively high condensate level. For a fouled exchanger the gamma intensity decreases with height, indicating an increase in deposit thickness. Also, the condensate level decreases to provide a larger heat transfer surface.

FIGURE 3.7.3: TRAY DEPOSITION PROFILE

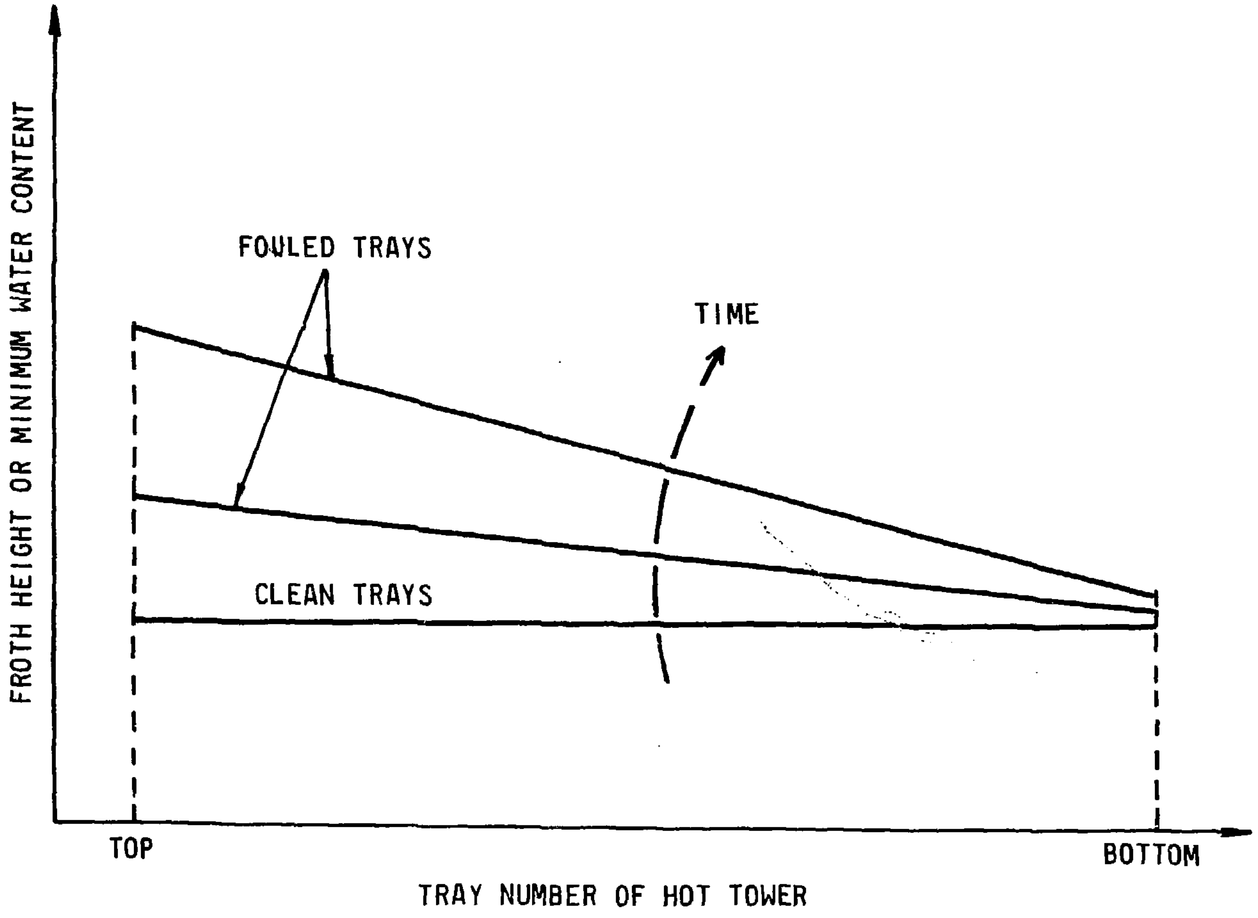
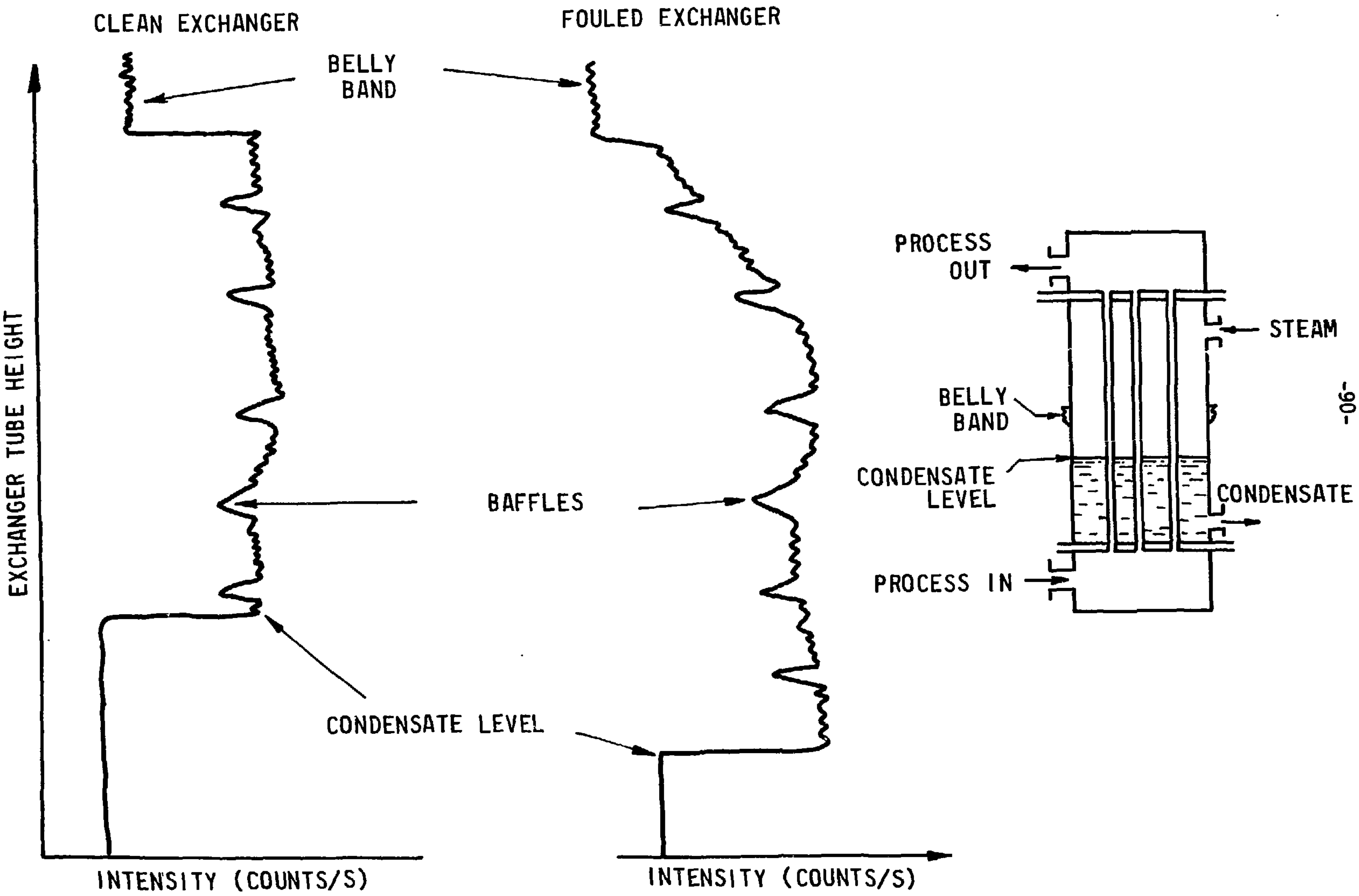


FIGURE 3.7.4: GAMMA SCAN PROFILE OF A STEAM HEAT EXCHANGER



From gamma measurements of a fouled exchanger and its reference clean scan, the thickness of the deposit can be calculated. These calculated thicknesses have agreed well with those measured directly with plug gauging during a shutdown.

3.7.3.4 Liquid Level

In addition to measuring steam condensate levels in vertical heat exchangers, gamma scanning has been used to measure the level of liquid H_2S in storage tanks when level instruments have failed. Scanning has also successfully diagnosed poor operation of packed absorber towers by identifying areas where flooding has occurred. Scanning has also detected sulphur/water interface levels in condenser receivers and knock-out drums.

3.8 Water Distillation - M.R. Galley, AECL-Chemical Company

3.8.1 Introduction

The GS process plants in Canada were all designed to use water distillation for upgrading the product from the 10% to 25% range to reactor grade. The water distillation (DW) units at the four Canadian plants are each quite different in design and configuration. The DW unit at Port Hawkesbury was supplied by Sulzer and consists of two columns, one packed with Sulzer BX packing and the other containing very small Dixon rings packed into many parallel vertical support tubes. All packing materials are phosphor bronze with an adherent black copper oxide coating to promote good wetting. Early operating data for this DW unit was not recorded because its operation was overshadowed by problems in the GS units, but one or more attempts at packing surface regeneration were made in the early 1970s. By 1975 it was apparent that loss of copper oxide coating, or contamination by materials that made the oxide non-wetting, was causing a severe loss of theoretical plates. At about this time CRNL began a program of testing various proprietary DW packing materials to determine their capabilities and to find means of obtaining good surface wetting characteristics. It soon became clear that phosphor bronze packings worked well only if they were protected from acid conditions and contamination by oil and other organics.

3.8.2 Packing Fouling and Cleaning

The problem of cleaning and regenerating fouled packing was also investigated and procedures were recommended to the operating plants. Some procedures to re-establish the oxide coating involve the use of pure oxygen which could pose safety hazards in equipment that might be contaminated with residual organics. Alternative procedures using air have been developed but are somewhat less effective in establishing an adherent oxide with acceptable surface characteristics. More recently a different approach has been taken and this involves the use of feedwater additives which make the water wet the packing without creating a foaming problem. If this approach is successful it may be possible to use almost any convenient inert material for packing manufacture.

3.8.3 Plant Systems

When the Glace Bay plant was rehabilitated, two of the old DCL towers were converted to a DW unit. The first tower was packed with plastic Pall rings and the second tower was filled with canisters of Sulzer CY packing. The plant was commissioned with water of questionable purity and performance rapidly deteriorated. When the whole plant was shutdown for heat exchanger repairs in 1977, the DW was inspected and cleaned. The plastic Pall rings, which had a high pressure drop and were leaching organic material, were removed and replaced by phosphor bronze Mini Rings, which had been tested at CRNL. The DW unit performed at close to design conditions for a short while and then deteriorated to a plateau level, well short of design performance expectations. Subsequent tests and inspections have shown a loss of theoretical plates in both columns, due partly to loss of oxide surface. However, the substitution of Mini Rings did cure the pressure drop problem in the first column.

In the course of these packing studies in support of Glace Bay and Port Hawkesbury, CRNL initially ran tests in the upgrader column of the NRU reactor and later assembled a dedicated test facility for packing performance evaluation. Considerable precision in deuterium analysis is necessary because of the low separation factor and the restricted length of the test column but the deuterium isotopic analysis facilities at CRNL proved adequate for this purpose.

The packed column DW units at Glace Bay and Port Hawkesbury continue to operate at well below their design ratings and this situation is tolerated because production rates can be maintained by drawing product at below reactor grade. This water is then sent to CRNL for final upgrading by electrolysis. Work on new packing development has essentially ceased pending a decision on whether to continue the current mode of operation or to modify the plant DW units. New developments in hydrogen water exchange technology and the CECE process may eventually make DW systems obsolete.

The DW unit at the Bruce A heavy water plant uses sieve tray columns and has operated very well at design throughput. The only changes made were to remove outlet weirs from the trays to reduce pressure drop and increase efficiency of overall operation. The chief disadvantage of sieve tray columns in DW service is the very large inventory of heavy water resident in the unit. The Bruce B plant has a Sulzer DW unit for the F2 finishing unit. Based on feedwater treatment experience at Port Hawkesbury and Glace Bay a potassium permanganate reaction step was included in the feed treatment system to remove oil and other organic species. Although this system has provided feedwater within Sulzer specification, there is evidence that some of the copper oxide coating has been removed from the packing close to the water distributors in the first stage towers. For the F4 finishing unit ultrafiltration equipment was installed. This decision was based on a trial of an ultrafiltration unit in the F2 unit (which demonstrated oil removal to less than one ppm) and on a cost comparison with the carbon filter/potassium permanganate reactor unit.

4. ECONOMIC BENEFITS - A.R. Bancroft, CRNL

4.1 R&D Effort

Effort at the various sites expressed in professional man-years (pmy) is shown in Table 4.1. At CRNL, WNRE and OHR this was mainly engineers of various disciplines and chemists. Working with them in the laboratories was a staff of 1.2 technicians and technologists per professional and the normal construction, maintenance, analytical and other support services This effort can be very clearly identified in support of the various parts of the GS program. For some fields where expertise had been firmly established within the power reactor program, considerable benefit was derived by consultation alone and R&D projects were not required.

Table 4.1

SUMMARY OF GS PROCESS R&D EFFORT IN PROFESSIONAL MAN-YEARS AND 1981 DOLLARS

	AECL-RC		AECL-CC		AECL	OH	TOTAL EFFORT	
	CRNL	WNRE	HO	GBHWP	CONTRACTORS	BHWP	pmy	$million (1981)
1969	2						2	0.5
70	2						2	0.5
71	4						4	1.0
72	7				1		8	2.0
73	10	2			2	7	21	3.9
74	31	4			11	8	54	14.0
75	26	6			5	9	46	11.3
76	20	4	2	2	3	6	37	9.1
77	15	1	2	3	2	10	33	7.2
78	14		2	4	2	8	30	6.4
79	8		2	4	2	9	25	4.4
80	8		2	2	1	9	22	3.7
Total	147	17	10	15	29	66	284	64.0

At the heavy water plants the R&D effort cannot be so clearly identified, because some functions of the plant operating staff are to identify problems, propose and implement solutions and assess the changes. This process is closely interwoven with R&D. All three operating plants have Technical Departments that perform these functions. Bruce and Glace Bay plants have Technology Groups within these Departments whose function is longer-term problem-solving, i.e. on the time scale of months to years rather than days to months. For the purpose of this analysis only the individuals in these Technology Groups are included in Table 4.1.

In the AECL-Chemical Company Head Office only that effort that was directly associated with the R&D program and projects has been included. AECL contractor effort can be very clearly related to projects because the contracts were specific rather than general.

The important observations are 1) a rapid build-up over the period 1972 to 1974 to a total of 54 professionals, and 2) a slower decline to an effort of 22 in 1980.

The required R&D effort depends on the state of maturity of the process. During the next decade the effort is expected to decline slowly, if at all, from 1980 levels to ensure adequate support for operating plants and the continuing evolution of improvements.

For the purposes of this analysis in comparing production gains against R&D costs we can use approximate costs of $250 000 (1981 Canadian dollars) per professional man-year in an AECL R&D laboratory and $100 000 in a project office. These costs include overheads and the accompanying technical staff in the case of the laboratory. The Ontario Hydro costs are calculated on a different basis and averaged $160 000. The total cost of the effort identified in Table 4.1 is then $64 million.

4.2 Benefit Analysis

In the same way that the dividing line between R&D effort and plant trouble-shooting effort is not clearly defined, so the benefits attributable to these activities cannot always be resolved. The annual production figures given in Table 4.2 show the usual maturing period during which plant staff learn about plant equipment and process and eliminate restrictions to production. This effort concentrated on increasing 1) plant reliability, 2) process flows and 3) extraction (or depletion). The benefit of R&D support is more rapid learning and defining of solutions, which can be translated to a more rapid approach to maturity and probably to a higher mature production rate.

Table 4.2

CANADIAN HEAVY WATER PRODUCTION 1970 - 1980 (Megagrams)

	Port Hawkesbury	Bruce	Glace Bay	Annual	Total Cumulative
1970	13			13	13
71	63			63	76
72	183			183	259
73	129	281		410	669
74	294	640		934	1603
75	175	605		780	2383
76	112	800	39	951	3333
77	225	655	63	943	4277
78	282	736	176	1194	5471
79	242	638	236	1116	6587
80	321	653	249	1223	7810

The data in Table 4.2 confirm that experience at Port Hawkesbury was of considerable benefit to the nearly identical Bruce plant. (The single units at Port Hawkesbury and Glace Bay and the two at Bruce were all designed with a nominal capacity of 400 Mg/a.) Port Hawkesbury reached the 300 Mg per year rate in the fifth year, while Bruce did so in the second year. The large R&D effort during the period 1974 to 1976 was important in reaching the 1976 production rate of about 800 Mg per year and maintaining the rate over 600 Mg per year thereafter at Bruce. It was not until 1980, following major maintenance and an important tray change, that Port Hawkesbury was able to exceed the 300 Mg per year rate. It is important to remember that calendar years are arbitrary time periods that are not always a fair indication of plant performance because of the compulsory shutdowns for safety inspections. The Glace Bay plant, which is more difficult to operate because of process complexity and had poorer trays installed during construction, has steadily improved by making major improvements throughout the maturing period.

The justification of the GS R&D program was not based on a benefit/cost analysis before the program was committed. The evolution of the CANDU reactor and the electricity supply in Ontario using the CANDU reactor demanded a dependable and economical supply of heavy water. The judgment of AECL and OH managements based on many years of R&D activities in the nuclear field was that the required R&D effort was necessary for security of supply, but would also be rewarded economically. That judgment has been confirmed.

R&D spending in various industries as a function of product value varies considerably with the type of product. In the United States (1950-1974) it was above 7% for high technology industries (scientific instruments, electrical equipment, chemicals), in the range 2 to 7% for mixed technology (machinery, rubber, plastics, petroleum) and below 2% for low technology fields (glass, paper, metals, food, textiles). No target was set for R&D spending on the GS process, but in retrospect it has been 2.8% of the product value for the first decade. (The product is valued within the program at $300/kg for this analysis. The selling price depends on a number of factors and varies with time.) During 1974, which was the year of peak effort and was also before the main benefit of that effort had been realized, the spending rate was 5.0%. Although effort is still declining the average for the three year period 1978-80 was 1.3% of product value. For 1980 it was 1.0%. It will be lower during the second decade. These numbers appear to be in line with spending by others in the chemical processing industries and indicate that the criteria used by management to approve R&D spending were normal.

4.3 Project Benefits

Once new technology has been made available through an R&D program its application to a production plant must meet the financial criteria applicable at this time. The R&D costs incurred in developing the technology do not enter into this analysis because their costs have already been covered. Retrospective analysis of the benefits and costs of an R&D

program serves to test the validity of decisions and to identify means of improving future ones. However, the approval of R&D funds for future investment always depends on anticipated benefit.

For a process industry in its infancy, the benefits of an R&D program are generally reflected in increased productivity and in some instances are relatively easy to quantify. As the industry matures the benefits shift from increasing productivity to sustaining productivity. This latter benefit is difficult to quantify.

A breakdown of the demonstrated benefits and costs is listed in Table 4.3. The benefit of the overall program is more difficult to quantify than specific areas and it is currently estimated to be $240 M, at a benefit to cost ratio of 4. This is understandably lower than the ratios for specific activities because it includes some of the related services, such as analytical chemistry, materials development, mechanical equipment development and gamma-scanning for which there was R&D spending. The benefits for specific activities show a substantial benefit for R&D spending and clearly justify the selected R&D program. Since there is generally several years time lag between spending R&D funds and verifying its benefit, some of the benefits anticipated from the spending during the past decade will continue to accrue well into the next decade. This will improve the benefit to cost ratio for the program.

Table 4.3

GS PROCESS R&D BENEFITS

Activity	Benefit M$	Cost M$	Benefit/ Cost
Process Simulation	96	8	12
Sieve Trays	42	7	6
Antifoam	20	1	20
Entire Program	240	64	4

5. ACKNOWLEDGEMENTS

Many individuals have contributed to the generation of GS process information over the past decade. It is appropriate to mention those individuals who were responsible for identifying the need and organizing the program early in the decade, some of whom continued to provide guidance throughout the entire period: H.K. Rae, AECL Heavy Water Program Director; R.F.U. Icely, BHWP Plant Manager; J.C. Paquin, BHWP Technical Manager (and later AECL-CC Technical Director); and S.M. Davies, PHHWP Technical Manager.

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3. PROBLEMS AND SOLUTIONS

3.1 Process Analysis and Control

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