DEMONSTRATION OF REGULATORY PROCESS CONTROLS ON THE TSTA CRYOGENIC DISTILLATION SYSTEM

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ABSTRACT

Fusion fuel processing systems are expected to rely on multi-column, cryogenic distillation systems for separating hydrogen isotopes. These systems will run continuously and need to respond to feeds varying considerably in both composition and flowrate. These systems will also need to operate with minimal inventories due to the value and safety concerns associated with tritium. These factors result in a clear need for a system of automatic control to maintain the isotope separation system operating properly. Such a system of regulatory (or material balance) controls have been added to the four-column ISS at the Tritium Systems Test Assembly. These controls have been tuned and tested individually. Then the overall system was demonstrated to work successfully. The results of this work is reported in this paper.

I. INTRODUCTION

Hydrogen isotope separation will be a key subsystem of the International Thermonuclear Experimental Reactor (ITER) Tritium Plant. Due to the nature of the fusion reaction, most of the DT used to fuel the ITER reactor will exit unreacted. This effluent will be contaminated with protium, helium and other "impurities". This stream will be purified by the fuel cleanup system so that the isotope separation system (ISS) will be fed only hydrogen isotopes and possibly some helium. The ISS will separate this feed into streams nominally composed of $He/H_2/HD$, D_2, DT, and T_2. These products will be recycled through appropriate fueling systems back to the fusion reactor or returned to storage.

ITER has a goal of operating with long pulse lengths and with relatively high fueling rates, currently estimated as 160 mole/hr. The only established technology currently capable of meeting this requirement is cryogenic distillation, so this has been included in the ITER tritium plant design.

The ITER reactor effluent will result from a variety of operating scenarios which might include steady and pulsed DT operation, D_2 conditioning pulses, discharge cleaning and pumpdown after maintenance. Thus, the torus effluent is expected to vary widely with respect to both isotopic composition and flowrate. Due to safety consideration, the use of buffer volumes which might otherwise be used to damp out these variations is discouraged. This means that the ISS will have to respond properly to feed conditions which change rapidly. Further, large distillation columns and buffer volumes between columns is similarly discouraged, so feed changes will propagate quickly through the entire cascade. Left unchecked this can result in degraded product quality.

Thus, it is apparent that an automatic control system will be required to respond to these changes and maintain product quality. It is convenient to divide such a distillation control system into two parts, namely "regulatory" controls and composition controls. The "regulatory" controls include liquid levels, flowrates, reboiler heats and pressure. A system of regulatory controls has been devised and installed on the four-column cascade of cryogenic columns at the Tritium Systems Test Assembly (TSTA) at Los Alamos National Laboratory. This tritium compatible ISS is designed for approximately $1/10^{th}$ of the ITER flowrate and is dedicated to fusion fuel processing studies. Details of the TSTA ISS have been published previously in [1]. The topic of distillation control has been addressed by many authors [2-9].

Much of the work which will be reported here was performed as part of the US/Japan Annex IV collaboration.

II. REGULATORY CONTROL SYSTEM

The regulatory controls installed on each column include:

1. Liquid level controlled by manipulating bottoms flowrate,
2. Overhead flowrate set to a ratio of the feed flowrate,
3. Column pressure drop maintained by manipulating the reboiler heat, and
4. Column total pressure maintained by manipulating the partial condenser cooling.

The first two control loops ensure that the column material balance is maintained. The third loop provides a means of maximizing the column separating power by enabling operation at close to flooding conditions. This loop is particularly important for small columns with high separation requirements.

These regulatory control loops are shown schematically on figure 1. For simplicity, each loop is shown only once though all four control loops are installed on every column. The only exception is that column H does not have overhead flowrate ratio control implemented. This overhead product can be sent to the Tritium Waste Treatment system for disposal and its flowrate continues to be set manually.

III. CONTROL IMPLEMENTATION

For the overhead flowrate ratio control loop the implementation was very simple. The Master Data Acquisition and Control (MDAC) computer senses the column feed flowrate, multiplies this value by an operator setable ratio, and uses the resulting value to set the overhead flowrate. A running average scheme is used to smooth noise which is naturally present on the feed flowrate measurement.

The remaining three control loops were implemented using PI (proportional integral) algorithms. The algorithm for pressure control was computed locally at the ISS in dedicated hardware. For liquid level and pressure drop control the PI algorithm is executed using FORTRAN on the MDAC computer.

The "position form" of the equation for PI action at time, t, is:

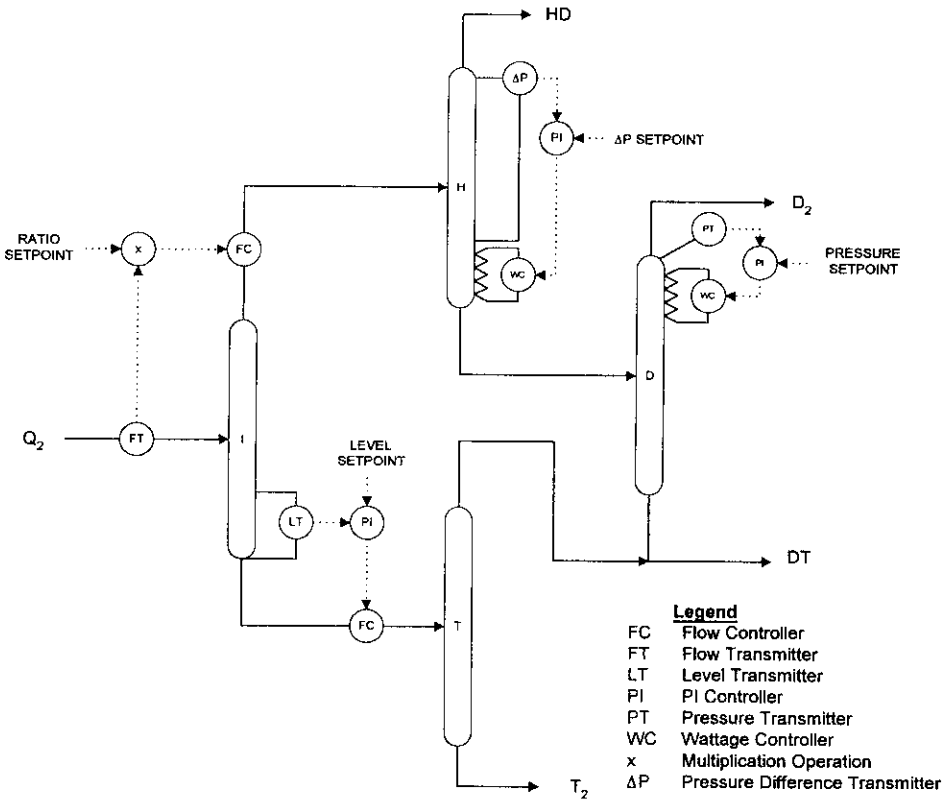

Figure 1 Schematic of ISS Regulatory Controls (though present on every column, for simplicity, each control loop is shown only once)

$$y_t = \bar{y} + K_c \cdot e_t + K_r \int_0^t e_t \cdot dt \qquad (1)$$

where

e error which is $= x^{set} - x$
x^{set} control variable set point
x measured value of the control variable
y controller output to the manipulated variable
$\bar{y}$ bias value of the controller or the controller output when e is zero
K_c proportional gain
K_r integral reset

When $t = i$, equation (1) is:

$$y_i = \bar{y} + K_c \cdot e_i + K_r \int_0^i e_i \cdot dt \qquad (2)$$

And at $t = i+1$, equation (1) can be written as:

$$y_{i+1} = \bar{y} + K_c \cdot e_{i+1} + K_r \int_0^i e_i \cdot dt + K_r e_{i+1}(t_{i+1} - t_i) \qquad (3)$$

Subtracting (3) from (2) gives the "rate form" for the PI equation:

$$y_{i+1} = y_i + K_c(e_{i+1} - e_i) + K_r e_{i+1} \Delta t \qquad (4)$$

This equation is simple to implement on a digital computer and is the form that was employed on MDAC. For MDAC $\Delta t \cong 3$ seconds.

IV. CONTROLLER TUNING AND DEMONSTRATION

A. Run 1

A first experiment was conducted to test liquid level and overhead flowrate control on column I alone. This ISS run showed that indeed MDAC could be used to successfully perform the desired control functions. Initial tuning of the new loops was performed.

B. Run 2

Next liquid level and pressure drop control was added to column H and tested in a second experiment.

The liquid level control loop was relatively straightforward to implement and tune based on experience from the previous run. Using a gain of 750 and a reset of 10 the data shown on figure 2 were collected for this loop. The liquid level setpoint was changed from 27 to 33 mm. As shown, the bottoms flowrate was automatically manipulated (decreased) to bring the level up to the new setpoint. The level properly reaches and maintains its setpoint about five minutes after the setpoint change.

Figure 3 shows data collected for the column H pressure drop loop with a gain of 2 and a reset of 0.016. The ΔP setpoint is changed from 3.5 to 4.5 torr. The reboiler heat is automatically increased to bring about the desired change. The ΔP increases to its setpoint after about 40 minutes. Though this control appears a bit slow, this is not a loop that needs fast action. Being slower, this loop should be more robust.

C. Run 3

Next the following control loops were added to both columns D and T:

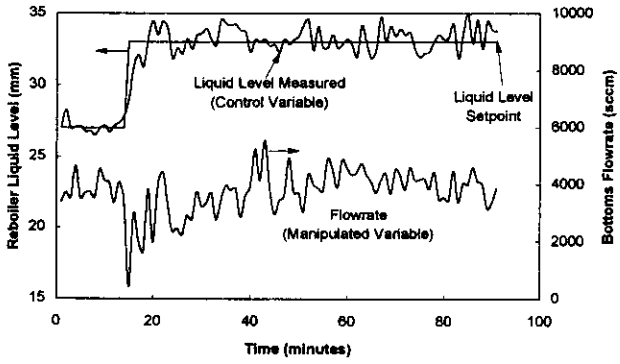

Figure 2: Column H liquid level control using gain=750 and reset=10.

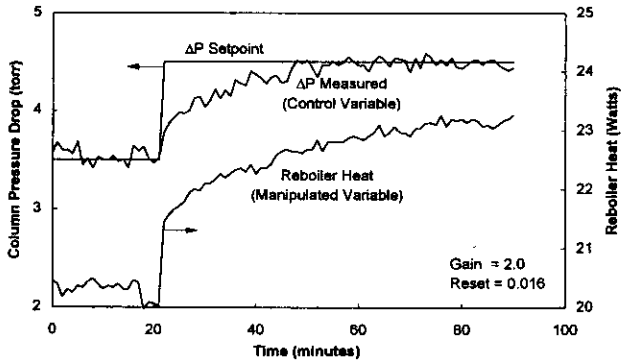

Figure 3: Column H ΔP control using gain=2 and reset=0.016.

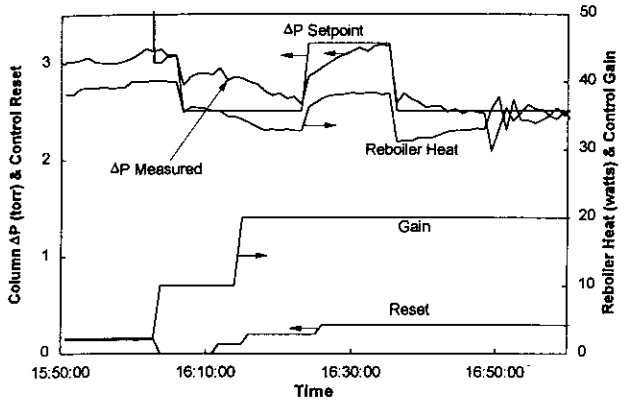

Figure 4: Tuning of ISS column I ΔP Control on 4/13/94

1. Control column ΔP by manipulating the reboiler heat
2. Control liquid level by manipulating bottoms flowrate using a PI algorithm
3. Control overhead product rate as a ratio of the feed composition

Additionally, pressure drop control was added to column I. A third experiment was conducted to tune and test these new control functions. Example results from column I pressure drop tuning are shown with figure 4. Shown are the ΔP setpoint, measured ΔP, reboiler heat, controller gain and controller reset. As shown, with the gain set to 20 and the reset at 0.3 the controller provided good control. However later testing showed that these controller settings were too aggressive, resulting in oscillatory behavior. Reducing the gain to 10 solved this.

After tuning the column D liquid level control loop it was determined that reasonable tuning parameters are gain=600 and reset=10. This loop was tested by increasing and decreasing the level setpoint by 10 mm and the results are shown on figure 5. When the level setpoint is increased, the bottoms flowrate is properly decreased to zero. However, since the bottoms flowrate is small (most of the flow is going out as distillate), it takes a long time for the level to increase to the setpoint. This indicates nothing wrong with the controller, but only reflects a physical limitation of the operating parameters which were being used. When the level is subsequently decreased, the bottoms flowrate is properly increased. The liquid level drops to the setpoint, overshoots, and settles to the setpoint level. Again due to the low bottoms flowrate and the physical limitation of zero flowrate, there is some minor oscillatory behavior. This should not occur when the distillate flowrate is a smaller fraction of the column D feed flowrate.

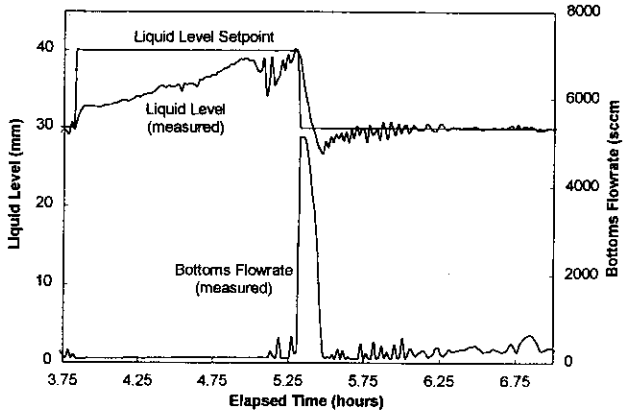

Figure 5: Liquid level control for column D, Gain=600, Reset=10

After tuning column T it was determined that reasonable tuning parameters are gain=400 and reset=10. This loop was tested by increasing and decreasing the level setpoint by 10 mm and the results are shown on figure 6. When the level setpoint is increased, the bottoms flowrate is properly decreased to zero. The level increases properly to the setpoint after which the flowrate increases again to maintain the setpoint. When the level setpoint is decreased the flowrate increases to remove material from the column. The level decreases to the setpoint, overshoots once, and settles to the setpoint. This is considered good liquid level control.

By way of comparison, the column T liquid level control was tested using less aggressive settings of gain=200 and reset=5. The results are shown on figure 7. As expected the control is more sluggish, though not bad. Due to the physical limit of zero flowrate, the response to the setpoint increase is about the same for the two controller settings. For the setpoint decrease, however, the bottoms flowrate reaches a smaller maximum and the level

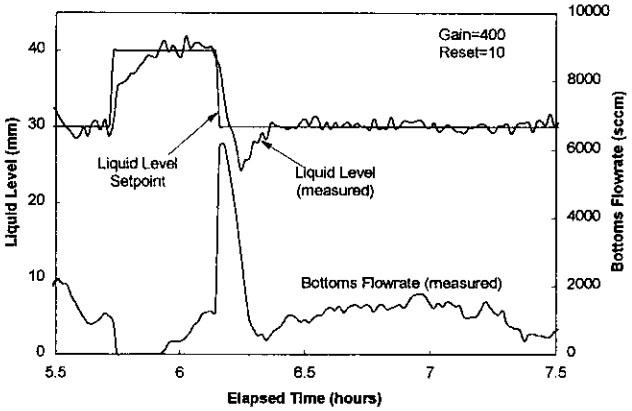

Figure 6: Liquid level control for column T, Gain=400, Reset=10

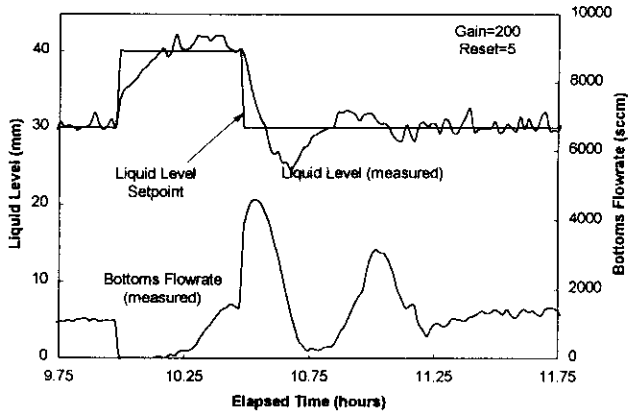

Figure 7: Liquid level control for column T, Gain=200, Reset=5

overshoots the setpoint twice. It is concluded that the settings of gain=400 and reset=10 are better than these settings.

The liquid level control for columns I and H had been tuned previously, but having had more experience with this process, these loops were reexamined during this run.

It was determined that reasonable tuning parameters for column I are gain=400 and reset=10. These values are the same as column T which has a reboiler with the same dimensions. This loop was tested by increasing and decreasing the level setpoint by 10 mm and the results are shown on figure 8. When the level setpoint is increased, the bottoms flowrate is properly decreased. The level increases to the setpoint after which the flowrate increases again to maintain the setpoint after a slight overshoot. When the level setpoint is decreased the flowrate increases to remove material from the column. The level decreases to the setpoint, overshoots once, and settles to the setpoint.

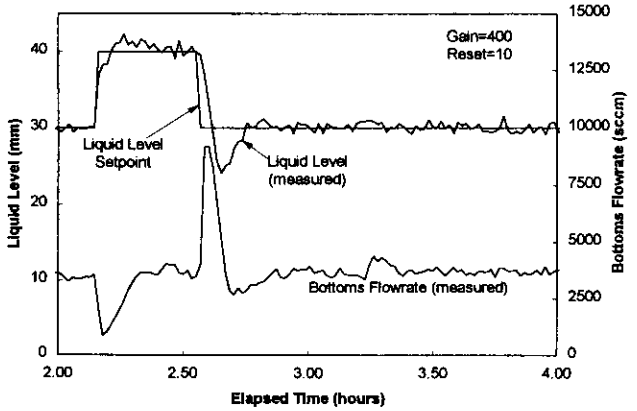

Figure 8: Liquid level control for column I, Gain=400, Reset=10

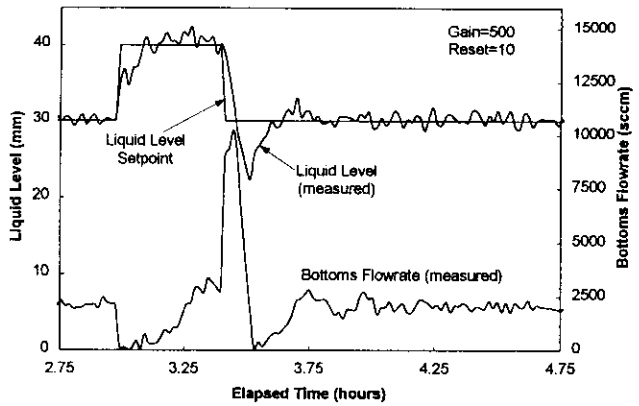

Figure 9: Liquid level control for column H, Gain=500, Reset=10

It was determined that reasonable tuning parameters for column H are gain=500 and reset=10. These values are intermediate between columns T and I which have the smallest reboilers and column D which has the largest reboiler. This loop was tested by increasing and decreasing the level setpoint by 10 mm and the results are shown on figure 9. When the level setpoint is increased, the bottoms flowrate is properly decreased. The level increases to the setpoint after which the flowrate increases again to maintain the setpoint. When the level setpoint is decreased the flowrate increases to remove material from the column. The level decreases to the setpoint, overshoots twice, and settles to the setpoint.

During this run the distillate flowrate was controlled as a ratio of the column feed flowrate for columns I, D and T. This control loop worked well and is, for the most part, unremarkable. It was noted that if the ratio is set to a value approaching 1.0 that the liquid level control can become difficult, because there is little flow out the bottom. Then for liquid level setpoint increases the bottoms flowrate cannot be decreased much since it is already almost zero.

V. INTEGRATED CONTROL EXPERIMENT

After completing the tuning portion of the third run, an experiment was conducted to demonstrate how the liquid level and ratio control loops of the entire four-column cascade work together. The ratio control setpoints for columns I, D and T were set to 0.35, 0.809 and 0.692, respectively. The top flowrate on column H was set to 270 sccm, recycling back to the feed of column H. All four liquid level control loops were set to control at 30 mm. Then, the loop flow was increased (using a buffer volume and flow controller external to the ISS) from 6 SLPM to 8 SLPM. Thereafter, the loop flow was reduced to 4 SLPM. Finally, the loop flow was restored to 6 SLPM.

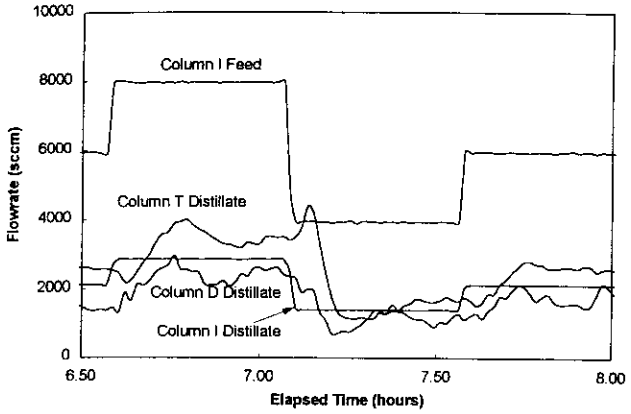

Figure 10: Integrated control experimental results-overhead flowrates

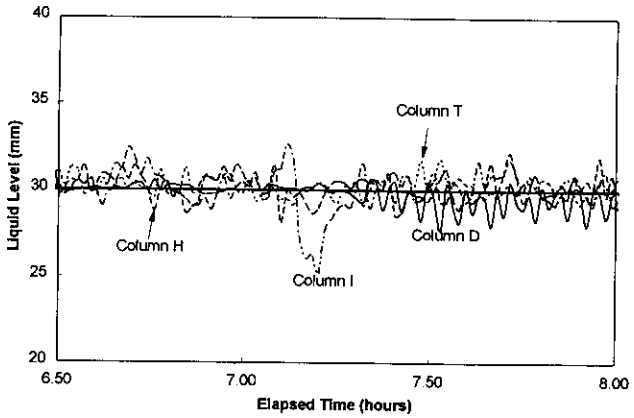

Figure 12: Integrated control experimental results-liquid levels

The results of this experiment are given in figures 10-12.

Figure 10 shows the ratio control response of the overhead product flowrates. The top of column I responds in a very steady fashion to the feed flowrate changes. This is because it is being set as a ratio of the column I feed rate which is very steady since it is fed directly by the external flow controller. The top of D and T increase and decrease properly, but their response is more noisy. This is because they are being driven indirectly by the liquid level control from columns H and I, respectively.

Figure 11 shows the bottoms flowrates for all four columns during this experiment. The flowrates increase and decrease as necessary to maintain the liquid levels at their setpoints. This is done very well as shown by figure 12 which shows the liquid levels. When the column I feed is increased by 2 SLPM to 8 SLPM, no level varies by more than 2 mm from setpoint. When the feed is decreased by 4 SLPM to 4 SLPM, the levels stay within 4 mm of setpoint. When the feed is increased back to 6 SLPM the levels stay within about 2 mm of setpoint.

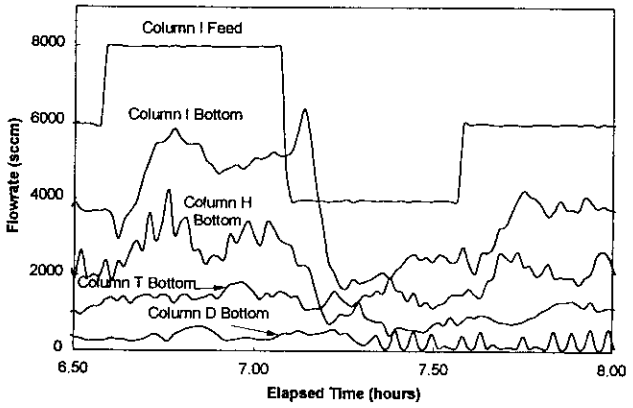

Figure 11: Integrated control experimental results-bottom flowrates

The liquid level control demonstrated in this integrated experiment is very good. Indeed, it may be too good. To maintain levels this steady, bottoms flowrates changed considerably. It may be better to "detune" the liquid level control somewhat. This would allow the level to vary more, but would not move the bottoms flowrates around so much.

VI. CONCLUSIONS

Regulatory controls have been implemented on the TSTA four-column cryogenic distillation system. As described in this paper these new control loops have been installed, tuned and demonstrated. Particularly as evidenced by the "integrated control experiment", the ISS can now automatically respond properly to large variations in the feed flowrate. Liquid levels were maintained within 4 mm of setpoint when subjected to a 100% change in the feed flowrate.

These tests showed that the ISS material balances can be automatically maintained. That is, the columns do not over fill or run dry. However, these tests did not account for product composition changes that occurred during process upsets. Nor did these tests address the issue responding to feed composition changes. Composition control is required for this purpose and will be the focus of future ISS development work at TSTA.

These control systems are viewed as an essential feature for an ISS such as the one envisioned for ITER which will be operated round-the-clock for long periods and be responding to various reactor operating scenarios.

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