Instrumentation and Controls Division

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CONF-910791--1

DE91 009525

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Paper to be presented at the
1991 Summer Computer Simulation Conference
Baltimore, Maryland
July 22–24, 1991

*Research sponsored by the Enrichment Operations Division, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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ABSTRACT

This paper describes a software and hardware simulation of a freezer/sublimer unit used in gaseous diffusion processing of uranium hexafluoride (UF_6). The objective of the project was to build a plant simulator that reads control signals and produces plant signals to mimic the behavior of an actual plant. The model is based on physical principles and process data. Advanced Continuous Simulation Language (ACSL) was used to develop the model. Once the simulation was validated with actual plant process data, the ACSL model was translated into Advanced Communication and Control Oriented Language (ACCOL). A Bristol Babcock Distributed Process Controller (DPC) Model 3330 was the hardware platform used to host the ACCOL model and process the real world signals. The DPC will be used as a surrogate plant to debug control system hardware/software and to train operators to use the new distributed control system without disturbing the process.

INTRODUCTION

The gaseous diffusion process consists of a series cascade of compressors that circulate gaseous UF_6 through separation units to enrich the uranium. The process can be operated efficiently over a wide range of production capacities. Because compressor power consumption is directly proportional to the process inventory level, large plant power swings can be accomplished by removing or freezing UF_6 out of the process (power decrease) or subliming UF_6 back into the process (power increase). The Process Inventory Control subsystem for removing or adding UF_6 is called the freezer/sublimer (F/S). An entire facility will have scores of F/S units operating in coordinated control to provide plant power swings as required. Traditionally, the gaseous diffusion plant was operated for maximum integrated output, and the plant contracted for large amounts of "firm" power. However, because of curtailed demand and the changeover of the enriched uranium market to a competitive environment, production costs are of prime concern. The PICS upgrade will allow the plant to use more of the less expensive "nonfi m" power by operating at higher capacities when this power is available.

The purpose of this project was to provide a process simulation that could be used to (1) validate distributed control system software being developed off-site and (2) facilitate operations training on the new distributed control system without disturbing the on-line process. The project described in this paper was limited to process simulation of a single, typical F/S unit. Figure 1 depicts the physical features of the F/S system and shows the pertinent variables used in the F/S math model. Mass, mass derivative (or mass flow), temperature, pressure, volume, and valve position variables begin with letters *M*, *DM*, *T*, *P*, *V*, and *C* respectively. The relationships between these variables will be developed. First, an overview of the F/S system operating modes is given below.

OPERATING MODES

When it is desired to reduce plant power consumption, UF_6 gas is removed from the plant circuit by opening valve C_B (high-pressure UF_6) and allowing the gas to flow through the C_W control valve into the F/S vessel. This operational mode is called freeze. In

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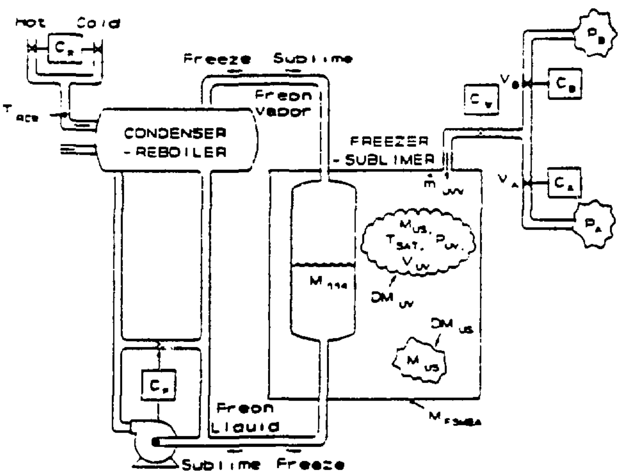

Figure 1. System model diagram

freeze mode, heat exchange tubes inside the F/S vessel are filled with cold liquid Freon (trademark of E. I. du Pont de Nemours and Company). Solid UF_6 frost forms on the outside of the tubes, increasing the amount or inventory of solid UF_6, denoted M_{US}, inside the F/S vessel. This phase change transfers heat through the tube walls, causing evaporation of liquid Freon inside the tubes. The Freon vapor flows to the primary side of the condenser/reboiler (C/R) where it condenses to liquid and returns by gravity back to the F/S vessel. In freeze mode, cold water is supplied to the secondary side of the C/R. The rate at which UF_6 is removed from the plant circuit is controlled by manipulating valve C_W.

To increase plant power consumption, UF_6 gas is returned to the plant circuit by closing valve C_B, opening valve C_A, and allowing the gas to flow out of the F/S vessel into the low-pressure header in the plant circuit. This mode is called sublime. As before, the flow rate is controlled with valve C_W. In sublime mode, the heat exchange tubes in the F/S vessel contain hot gaseous Freon. Heat flows through the tube walls and causes the encased UF_6 frost to sublime. The pressure and temperature of the UF_6 in the F/S vessel are always maintained below the triple point on the phase diagram for UF_6. Freon condenses inside the tube walls, flows down, and is pumped up to the C/R, where it is evaporated and returned to the F/S vessel. The secondary side of the C/R is supplied with hot water.

Two other typical modes of operation are used when F/S is in a standby condition. In standby, the F/S vessel is isolated from the plant circuit by closing valves C_B and C_A. In hot standby, the heat exchange tubes in the F/S vessel contain hot Freon gas and the C/R secondary is supplied with hot water. In cold standby, cold liquid Freon fills the tubes and the C/R secondary is supplied with cold water.

DYNAMIC MODEL

The mathematical model of the F/S was formulated from physical principles and empirical process data. The model was coded in ACSL. Computer simulations were performed, and the model was validated with actual plant data.

The measured weight (pounds) of the contents of the F/S vessel is given by

$$M_{FSMEA} = M_{US} + M_{UV} + M_{114} + M_{MN} \ , \qquad (1)$$

where

M_{US} = inventory of solid UF_6,
M_{UV} = amount of vapor UF_6,
M_{114} = mass of liquid Freon,
M_{MN} = random measurement noise.

The inventory of solid UF_6, M_{US}, is given by

$$M_{US}(t) = \int_0^t DM_{US}(\tau)d\tau + M_{US}(0) \ . \qquad (2)$$

The rate of change of solid UF_6, DM_{US}, has been determined experimentally (Blankenship 1987). DM_{US} depends on the difference of two temperatures,

$$DM_{US}(t) = K_{US1} \times (T_{SAT}(t) - T_{RCW}(t)) + K_{US0} \ . \qquad (3)$$

The parameters K_{US1} and K_{US0} depend upon the level of liquid Freon in the heat exchange tubes within the F/S vessel. When $M_{114} = M_{114\,MAX}$, the freeze mode values of K_{US1} and K_{US0} are used. When $M_{114} = M_{114\,MIN}$, the sublime mode values are used. When $M_{114\,MIN} < M_{114}$

$< M_{114\,MAX}$, interpolated values of K_{US1} and K_{US0} are used. The F/S liquid Freon weight, M_{114} is controlled by the Freon pump and bypass valve shown in Fig. 1. When changing from one state to the other, M_{114} ramps from $M_{114\,MIN}$ to $M_{114\,MAX}$ or vice versa as appropriate. This effect is modeled in ACSL with a limited output integrator. M_{114} is given by

$$M_{114} = \int_0^t DM_{114}(\tau)d\tau + M_{114}(0) \quad . \qquad (4)$$

The Freon level is ramped between its limits by setting DM_{114} equal to a constant according to the state of the Freon pump.

T_{RCW}, the water inflow temperature at the C/R, is either 92.5 or 135°F depending on the mode of operation. The saturation temperature of the UF_6 vapor, T_{SAT}, is determined by two relationships: (1) the ideal gas law and (2) the UF_6 phase diagram. That T_{SAT} roughly approximates the bulk temperature of the UF_6 vapor is assumed. This implies that the UF_6 vapor pressure can be obtained from the saturation temperature line in the phase diagram. A curve fit of empirical data (DeWitt 1960) yields the following relationship between P_{UV} and T_{SAT}.

$$\log P_{UV} = K_{PT_0} + (K_{PT_1} \times T_{SAT}) - \frac{K_{PT_2}}{T_{SAT} + K_{PT_3}} \quad . \qquad (5)$$

After a few algebraic manipulations of Eq. (5), T_{SAT} can be found as one of the solutions of a quadratic equation and expressed as a function of P_{UV}:

$$T_{SAT} = f_1(P_{UV}) \quad . \qquad (6)$$

Application of the ideal gas law gives an expression for P_{UV} in terms of T_{SAT}:

$$P_{UV} = \frac{M_{UV} \times R_A \times (T_{SAT} + 460)}{V_{UV}} = f_2(T_{SAT}) \quad . \qquad (7)$$

We have two equations and two unknowns, viz. T_{SAT} and P_{UV}. Equation (7) is "driven" by the values of M_{UV} and V_{UV}. Assuming that we have values for M_{UV} and V_{UV}, let us focus on the solution of Eqs. (6) and (7) to find the values of T_{SAT} and P_{UV}. The simulation developed for this project solves these equations in a novel fashion. It computes

$$P_{UV} = f_2(T_{SAT_0})$$
$$T_{SAT} = f_1(P_{UV})$$

where

$$T_{SAT_0} = \int [K_{TSAT_0}(T_{SAT} - T_{SAT_0})] \, dt \quad . \qquad (8)$$

Thus, a time-integration operation is used to obtain an approximate trajectory for T_{SAT}. With a suitable choice of K_{TSAT0}, this method has shown rapid convergence after transient events.

The mass of UF_6 vapor inside the F/S vessel is given by

$$M_{UV} = \int_0^t [DM_{UVV} - DM_{UV}]d\tau + M_{UV}(0) \quad . \qquad (9)$$

The term, DM_{UVV}, is the mass flow rate of vapor passing through the weight-rate control valve C_W into the F/S vessel. This flow can be approximated by

$$DM_{UVV} = K_{CVV} \cdot \Delta P \cdot \sqrt{\frac{P_{UP}}{|\Delta P|}} \cdot \left(1 - \frac{|\Delta p|}{P_{UP}}\right) \cdot \left(1 - e^{\frac{-P_{VACT}}{35}}\right) \qquad (10)$$

The differential pressure, ΔP, across the valve is either $(P_B - P_{UV})$ or $(P_{UV} - P_A)$ depending on the A and B header valve configuration. The upstream pressure, P_{UP}, is either P_B or P_{UV}, also depending on the header configuration. The control signal command to the valve, P_{VACT}, represents percent open. K_{CVV} represents which header (A or B) is open to the control valve C_W. The simulation assumes that the A and B header valves will never be simultaneously open by any amount. The variable, K_{CVV} represents the state of both valves. When $K_{CVV} = -1.0$, header A valve is fully open and header B valve is fully closed. When $K_{CVV} = +1.0$, header B valve is wide open and header A valve is completely shut. When $K_{CVV} = 0$, both header valves are completely shut and the F/S is in a standby mode of operation. K_{CVV} is computed according to the following. Whenever the mode is manually switched to freeze, sublime or standby, it is desired that K_{CVV} change from its current value to $+1.0$, -1.0, or 0.0 respectively. Physically, such a change represents a change in the valve positions of C_A and C_B motoroperated valves. Thus, in the simulation it takes several seconds for each valve to travel from limit to limit (full open → full closed, or vice versa). Also, when one of the valves is closing, the other valve cannot begin to open until the first valve is fully shut. This process is modeled in ACSL by using the output limited integrator.

Because the header pressures, P_A and P_B, are almost independent of single unit F/S quantities, the header pressures are independent forcing functions in the simulation. The A header pressure is approximately 1/5 the B header pressure. In the physical process, P_B depends upon which F/S unit is simulated and the overall inventory of UF_6 vapor in the entire gaseous diffusion plant (Blankenship 1987). At low power, P_B can be as low as 2 psia. For high-power operation, the B header pressure is as high as 19 psia in some locations. During a long freeze (or sublime) cycle, the B header pressure falls (or rises) as much as 6 psia. The high- and low-power steady-state values of P_B vary significantly across all the F/S unit. The simulation model allows minimum and maximum values of P_B to be specified. The value of P_B linearly ranges between $P_{B\,MAX}$ and $P_{B\,MIN}$ as the solid mass inventory ranges from $M_{US\,MIN}$ to $M_{US\,MAX}$.

An overall view of F/S system inputs and outputs is shown in Fig. 2. The MODE input represents the operating mode of the F/S system. MODE assumes one of six values: freeze, sublime, hot standby, cold standby, modified hot standby, and DPC mode. When MODE = DPC, the model uses the measured field signals from the TI D/3 distributed control system for the valve command signals C_R, C_A, C_B, C_F, and C_W. When MODE assumes one of the other values, all the other field signals except C_W are ignored, and the valve settings are determined by the simulation. In ACSL, changes in MODE were accomplished by scheduling discrete events. Figure 3 shows a plot of M_{FSMEA} for a typical simulation run. The run began with the F/S vessel full of solid UF_6 in hot standby. The MODE is switched to sublime for ~1 h and then switched to freeze. When the the vessel becomes full again, the MODE is switched to cold standby.

The ACSL model was validated by comparing it with existing models and by comparing the response plots of the computer simulations with actual process data. Once the model was validated, the ACSL model was translated into ACCOL so that it could be simulated by using a Bristol-Babcock controller. The ACCOL simulation of the F/S executes in real time, and Bristol-Babcock's Toolkit software can be used to monitor and change the simulation parameters on-line. The physical F/S system at Paducah also has an instrument cabinet with interlocks and alarm monitoring logic. The F/S simulator also imitates this logic to facilitate off-site programming and debugging of the TI D/3 distributed control system software (Figure 4). The system will be used later to facilitate operations training on the new TI D/3 system without disturbing the on-line process.

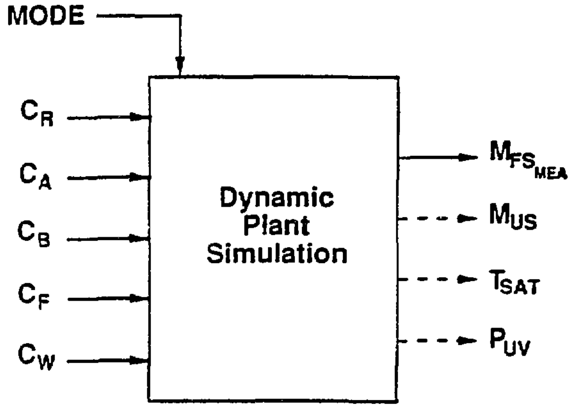

Figure 2. Dynamic model

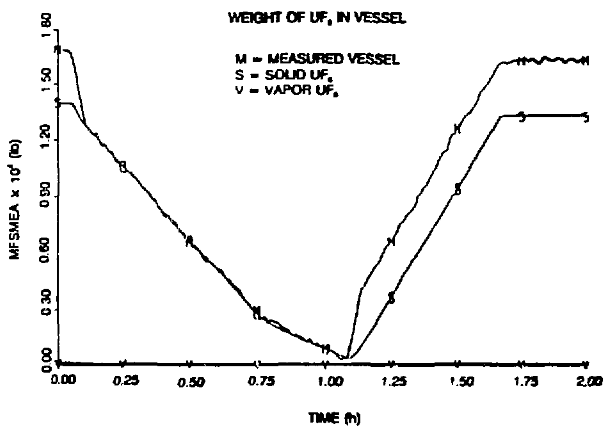

Figure 3. Simulated vessel weight

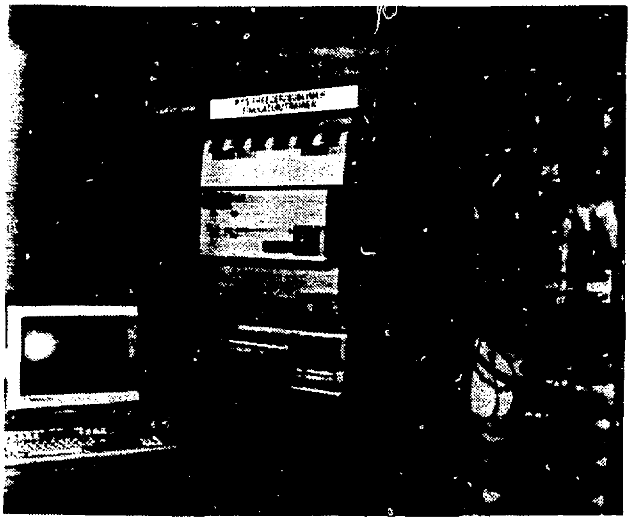

Figure 4. Freezer/sublimer simulator/trainer

CONCLUSIONS

Aside from its primary objectives, this project demonstrated a methodology for simulator/trainer development. The system model was initially expressed in ACSL because of the high-level software tools available in ACSL. ACCOL was used because it is the language used by the Bristol hardware system.

NOMENCLATURE

M_{FSMEA} ≙ Measured weight of the F/S vessel contents (pounds)
M_{US} ≙ Inventory of solid UF_6 (pounds)
M_{UV} ≙ Amount of vapor UF_6 (pounds)
M_{114} ≙ Mass of liquid Freon (pounds)
M_{MN} ≙ Random measurement noise (pounds)
DM_{US} ≙ Rate of change of solid UF_6 (pounds/second)
DM_{UV} ≙ Rate of change of liquid UF_6 (pounds/second)
DM_{UVV} ≙ Mass flow rate of UF_6 vapor (pounds/second)
DM_{114} ≙ Derivative of M_{114} (pounds/second)
T_{SAT} ≙ Saturation temperature of UF_6 vapor (°F)
T_{RCW} ≙ Water inflow temperature of condenser/reboiler (°F)
P_{LV} ≙ Pressure of UF_6 vapor (psia)
P_A ≙ A header pressure (psia)
P_B ≙ B header pressure (psia)
P_{VACT} ≙ Control valve position (%)
V_{UV} ≙ Volume of UF_6 vapor (ft^3)

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VITA

Charles L. Carnal received the B.S. degree in Engineering Technology from the University of Tennessee at Martin in 1978, the M.S. degree in Electrical Engineering from the University of Tennessee Space Institute in 1980, and the Ph.D. in Electrical Engineering from the University of Tennessee at Knoxville in 1984. Dr. Carnal is a registered Professional Engineer in the State of Tennessee.

From 1979 to 1981 he worked as a controls engineer at the Arnold Engineering Development Center, Arnold Air Force Station. Since 1984 he has been at Tennessee Technological University where he is currently an Associate Professor of Electrical Engineering. He has served as a consultant to various industrial and government organizations. His research interests include control systems, modeling, simulation, signal processing and system identification.