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Idaho National Laboratory
Idaho Falls, Idaho 83415

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Benjamin Allen Baker[a*], Kurt D. Fielding[a], Jacob E. Hansen[b], and Tanner Ellsworth[b]

[a]*Idaho National Laboratory, Reactor Physics Division, Idaho Falls, Idaho*

[b]*Endigit Inc., Layton, Utah*

*E-mail: ben_baker33@hotmail.com

Enhancements to the new TREAT Automatic Reactor Control System (ARCS)

Abstract – The Transient Reactor Test (TREAT) facility recently replaced the automatic reactor control system (ARCS). This paper discusses some of the enhancements that were made during the ARCS replacement such as calculations to take into account the non-adiabatic effects and increasing the dynamic range for power and period indication. The paper also discusses upgrades that had been planned but were unable to implemented and potential upgrades for the future.

Keywords: TREAT; ARCS; reactor control system

I. INTRODUCTION

The Transient REActor Test (TREAT) facility is a transient test reactor that was restarted in 2017 after being shutdown in 1994. The TREAT reactor was restarted as part of the accident-tolerant fuels testing program.[1,2] The fundamental component of TREAT is a computer control system called the Automatic Reactor Control System (ARCS). ARCS has a computer that controls the TREAT transient rods to produce power histories that are shaped to meet the requirements set by the experimenter.[3,4,5] The ability of ARCS to control the TREAT reactor power in a well prescribed manner from neutronics conditions such as temperature feedback and control rods is therefore of utmost importance to the mission of TREAT for creating shaped transients.

When TREAT was restarted, ARCS ran on several INTEL 8086 CPU boards and was written in assembly code from the 1980s. A decision was made to replace the ARCS system with a modern software and hardware platform. The system was upgraded to several PXI chassis running a real-time operating system that executes LabVIEW code. In addition, the code was setup in a way that a majority of code could be run without hardware and I/O, making it possible to run the code on a desktop computer for simulation purposes. This program is called pocket ARCS or PARCS, and a lighter and faster version is called small ARCS. ARCS is composed of many “nodes” with specific purposes. The control node is responsible for commanding the control of the transient rods, the monitor node is a plays a data acquisition and supervisory role, the simulator node performs simulation of the core and rods and the program timer node provides digital signals to external systems. The reactor operates in four modes: Full Simulation, Partial Simulation, Actual Transient and Rod Drop. The full simulation mode performs a transient while simulating the reactor core and rods. The partial simulation mode simulates the reactor core but moves the transient rods while the reactor is shutdown. The actual transient and rod drop modes are self-explanatory. For an extensive overview of the entire ARCS system and theory, the reader is directed to Ref 6.

As part of the new ARCS system, several enhancements were suggested. Only some of the enhancements were able to be implemented in the allotted project time. There were several minor improvements performed in the upgrade such as increasing the energy reactivity feedback table from 4 elements to virtually unlimited elements, changing the algorithm to use engineering units instead of optimized units necessary to meet critical time constraints, use of specified transient rod worth coefficients instead of a limited 10 point calculation for the rod fit coefficients and improved user inputs.

This paper covers the major enhancements that were implemented as well as possible future enhancements that were proven but never implemented fully for one reason or another. It will cover the addition of a non-adiabatic coefficient to account for the heat loss which influences the temperature feedback and aids in better predictions of the control rods during long transients and improves the physics characterization. The power visibility of reactor was increased to improve the reliably of the inputs to the control algorithm. The first future improvement is a controlled shutdown to reduce wear on the shock absorbers which would reduce maintenance and reactor down time. The second future enhancement would simplify the user definition for a transient and aid in achieving a transient that is closer to the ideal transient desired by the experimenter. The third future enhancement proposes a novel framework which would allow any control algorithm to be tested at TREAT with few licensing requirements.

II. NON-ADIABATIC CALCULATION

One of the fundamental assumptions in the original ARCS code is that the core is adiabatic, or has no heat lost. This assumption is good for transients in TREAT that last less than 60 seconds. However, there have been transients that have lasted close to an hour.[7] In these experiments, the actual final rod positions were ~3 inches less than the simulated final rod positions which translates to a difference in reactivity of 0.9$ or 0.64%$\Delta k/k$. Where $\Delta k/k$ is the change in the effective multiplication factor and $ is the $\Delta k/k$ value divided by the delayed neutron fraction. The reactivity difference was attributed to the adiabatic assumption which results in a higher temperature than is realistic and increases the reactivity feedback in the simulation. The increased feedback in the prediction results in the rods moving more than would happen in a real reactor run.

II.A Model and Experiment for Non-Adiabatic Coefficient

In the ARCS algorithm, the energy of the core is used as the metric to determine the reactivity feedback instead of temperature. The reactor physics is truly dictated by the temperature, and energy is a way to express the average core temperature. An experiment was devised to measure the heat loss by holding the reactor power, building ambient air temperature, and reactor cooling air flow rate constant for several hours. This type of run is performed during each core change as part of the core re-characterization and is called the heat balance procedure. The temperature and energy were assumed to follow models given below. The internal energy for the core at the beginning of the run is the zero-reference point.

(1)

(2)

Where:

= Temperature over time

= Non-Adiabatic Energy over time

= Initial temperature

= Asymptotic temperature

= Asymptotic Energy

= Non-Adiabatic or Heat Loss coefficient

During the heat balance, there are 12 thermocouples embedded in the fuel elements which record the temperature over time. The data from these thermocouples were fit to the temperature model with focus on the curvature part of the data where the exponential is most prominent as shown in Fig. 1 below. The data was recorded on the first and second heat balances performed after TREAT was restarted on Nov 28 and 30th, 2017. The coefficient was intended to be used as a simplified general parameter to achieve an acceptable range for the heat loss and not as an extensive treatment for the heat loss calculation. For this purpose, special treatments were not used to correct measured values based on the thermocouple location. The non-adiabatic coefficient from the data was found to range from (-2E-4 to -3.4E-4 sec^{-1}). The value is expected to vary a little based on the system conditions such as air flow rate and the core configuration.

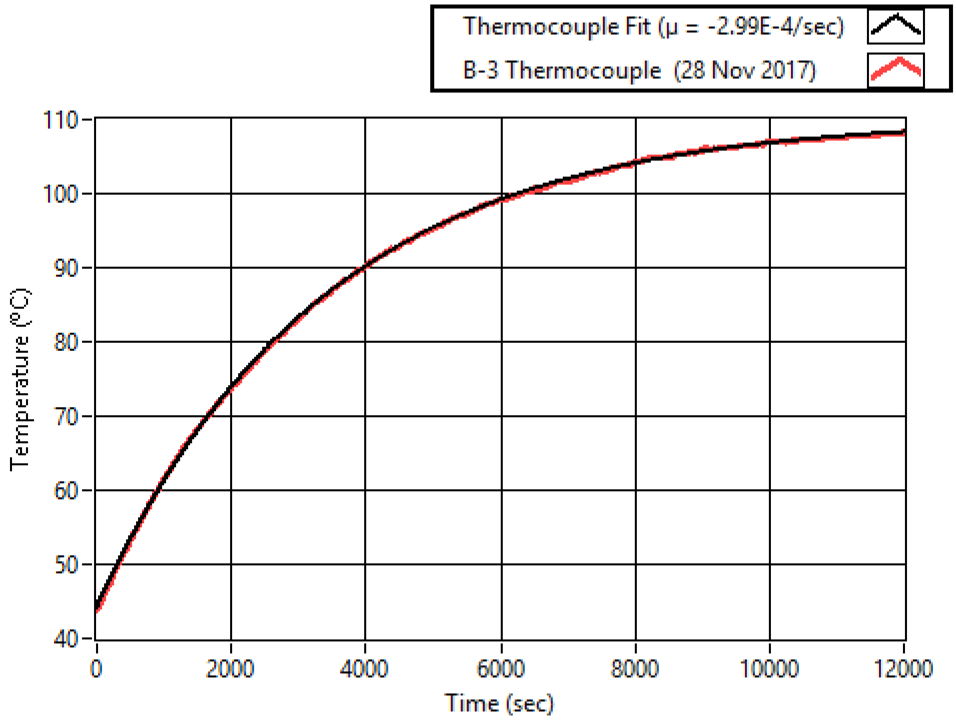

Figure 1. Thermocouple B-3, yielding a heat loss coefficient of -2.99E-4/sec

Using the assumed models for temperature and energy for a constant heat source, a discretized energy calculation can be derived for each time-step. The core simulator was modified to account for heat loss by applying the exponential decay of the energy or heat to the prior accumulated energy during each timestep as shown below.

(3)

Where:

= time-step

= time between time-steps

= Energy added between time-steps

The equation was validated by simulating one of the transients that was run in Ref. 7 with and without the non-adiabatic coefficient implementation in the simulator code and finding the coefficient that best matched the real transient. The transient held a constant 600kW for ~36 minutes. The adiabatic simulation predicted a final rod position of ~29.5 inches, while the real reactor run had a final rod position of 26.3 inches. The reason for the discrepancy was an overestimate of the feedback due to the adiabatic assumption. After applying the equation to the core simulator, it was found that the non-adiabatic coefficient needed to be ~ (-2.4 E-4 sec^{-1}), which fell right in line with the range from the thermocouple data.

The choice of a non-adiabatic coefficient was added to the simulation code as a tuneable parameter set by reactor engineering for simulations. As of this writing, the coefficient is only applied to the core simulator to account for the heat loss so that the rod positions will trace closer to reality. The control algorithm does not adjust for the heat lost.

An investigation to determine the consequence of including/excluding the adjustment for heat loss in the control algorithm found that there was little difference in the results for two reasons. The first reason was because the algorithm uses a subtraction between the measured energy and the reference energy. As long as both of those energy values are calculated in the same manner (adiabatic or non-adiabatic), the difference does not change by much. The second reason is that the feedback curve is rather linear. The essence of taking the heat loss into account is to determine how much feedback is being applied, and the more deviant the function is from a straight line, the more of an error will exist. For all intents and purposes, transients that last up to an hour do not need to have the heat loss taken into account in the control algorithm, but the heat loss does need to be accounted for in the core simulator in order to obtain accurate feedback in the core while performing simulations before the real transient.

III. POWER VISIBILITY EXTENSION

In the original ARCS system, the ARCS linear neutron detector was used exclusively for the power indication. The ARCS linear detector is capable of detecting powers from ~1kW to 10GW. However, the TREAT reactor usually starts transients ~50W and can go up to ~20GW. The reactor does not have a power limitation, but transients are limited by the maximum temperature allowed for the fuel cladding. In addition, the ARCS log chamber has a similar power applicability range and is used by a period circuit to give period indication.

The two detector's applicable power regions caused the control algorithm to receive a false indication for power and period outside of these power ranges. To compensate, the ARCS program would start the transient with an initial rod step insertion, and the control algorithm would not engage until the ARCS linear detector signal had an appreciable signal of 5 volts on the starting range which corresponded to 0.5MW. The control algorithm did not have much of an issue with the powers past 20 GW since the reactor feedback would soon cause the power to fall back into detectable limits, and control functions were usually limited in scope after a large excursion. However, it was recognized that the algorithm would be slightly biased after surpassing 10 GW and would influence complicated control maneuvers after the power spike.

III.A. Power Signal Splicing

To increase the dynamic range of the power indication and control, the signals from two existing instrument detectors were added to the control algorithm. These isolated signals are from the reactor trip system (RTS) steady state (SS) and transient (trans) log B chambers.

The reactor trip system was originally designed as a safety system to protect a new core as part of a TREAT upgrade project in 1985. But the new core was never installed before TREAT was shutdown in 1994. Currently with the original core still installed, the RTS system is not a considered a safety system despite its name. The RTS-SS-Log B channel has reasonable detectability readings from ~0.1 W to 1 MW.

The RTS-Trans-Log B channel has reasonable detectability readings from ~100 kW to 100 GW.

A power splicing algorithm was developed to merge the signals from the RTS chambers with the ARCS linear signal. The algorithm uses the RTS chamber reading if the ARCS linear power is above or below a threshold and mixes the readings of the ARCS linear and RTS signals in a transition zone. The mixing or splicing of the signals is a way to join the two signal indications in a smooth manner in case the detector signals vary significantly.[8,9]

Below is the piecewise indication of how the power was determined.

(4)

The splicing algorithm is shown below.

(5)

(6)

In addition to the splicing function, failsafe measures were taken to revert the resultant signal back to the ARCS linear detector if an RTS log detector power value is outside a reasonable expected range.

The ARCS linear detector low power resolution was also increased with a modification to allow the user to select the starting range. In the old ARCS system, the starting range was fixed to 1E-7 amps full scale. However, the detector has an additional 4 lower ranges from 1E-8 to 1E-11 amps, that were not being used. Lowering the detector allowed bottom range does not increase the detector's operability range, but it does improve the amplification of the signal for lower powers indication and control. The modification allows the user to start on either the 1E-8 or 1E-7 range, for better starting resolution.

III.B. Period Signal Extension

While power is a fundamental parameter for the control equation, period is also required. Period is really a derived quantity from power. However, the original ARCS used a period circuit on the ARCS logarithmic power channel as a means of creating a period signal. This period signal suffered from the same dynamic limitations as the power signal from which it was derived (ie. Limited applicability to ~1kW to 10GW).

A period can be calculated from the RTS-SS-Log B channel power signal for period indication at low powers. The definition for inverse period is given below.

(7)

Where:

= Inverse Period (sec^{-1})

= Power

The algorithm selected to calculate the derivative from the RTS-SS-Log B power signal uses a smooth noise-robust differentiator to reduce the amplification of noise and is repeated in Eq. 8.[10] A trade-off had to be made between a time lag in the period value and the noise from the signal. The ARCS period signal, albeit an analog derivative of the power, suffers from the same trade-off. The ARCS period signal is delayed on the order of ~10-20 ms. The calculated derivative using the RTS-SS-LOG-B channel is delayed by 10 time-steps, which is 20 ms for the normal setting of 2 ms per calculation cycle. The effective time constant is therefore less than 20ms and within an acceptable range.

(8)

Where:

P_i is the power value at time-step i

Δt is the difference in time between time-steps

The algorithm for determining which period to use is performed in a similar manner to the power splicing. For low powers, the calculated period is used. A transition zone is used to mix the two values, and the ARCS period signal is used for powers above 500kW.

(9)

Where the period splicing calculation is shown below and follows a linear hand-off instead of a logarithmic.

(10)

There was no splicing for the period in powers ranges above 10 GW, unlike the power splicing algorithm, because of time constraints and the small benefit that would be gained. In the control equation, there are three error groupings that are used to determine the total error and subsequent rod movements. The error groupings are period, energy and delayed neutron concentrations. The period error does not have a memory effect like the energy and delayed error terms. This means that there is no error carry over after the reactor comes back down below 10 GW. The power is used in both the energy and delayed terms and does have lasting effects when the values are incorrect, which is why it was more important to increase the dynamic range of the power.

IV. FUTURE CHANGES

During the ARCS replacement, there were many items/ideas and changes that were realized. Some of these ideas were implemented but found to be missing a few extra components and were put off for future changes, while others were proven in code but never implemented for testing because of scope limitations. This section provides insight into some of those features and possibilities for the future.

IV.A. Controlled Shutdown

At the end of each transient, there is a call to the scram circuit to shutdown the reactor. There are three banks of control rods, two of those banks are for shutdown not transient operations. These other two banks of rods produce considerable wear on their shock absorbers from frequent scrams at the end of transients. Based on wear, the shock absorbers must be periodically replaced at considerable cost and plant downtime. There was a desire during the ARCS replacement to provide a means for the transient to end by inserting the transient rods, thus putting the reactor in a sub-critical configuration and allowing the operators to manually insert the other banks.

The code was modified to optionally allow a controlled shutdown. However, during functional testing it was discovered that a part of the manual rod position reset circuit was overlooked. This caused the transient rods to return to the transient non-zero starting positions when control was transferred back to the operators. Because of time constraints, the option was disabled in software until a future date when the transient rod position reset circuit can be modified to accommodate the controlled shutdown method.

IV.B. Generic Power and Rod Histories

In the control algorithm, the transient is formed by combining independent segments together where each segment defines a segment type and termination criteria. The segment types are either power related or rod position related. The power related segments use two functions to establish the desired power history. These two functions are shown below.

(11)

(12)

Where R is the power ramp rate and all others have been defined.

The rod related segments are rod stop and clip. The rod stop simply commands the rods to go to the last reported rod position before the command was given, and the clip command sends the rods to 0 inches, or all the way in.

It was realized that generic segments could be defined for the power and rod positions. If a generic power vs time data could be provided, then it would eliminate the responsibility for someone to generate piece-wise functions made of either period, ramp, rod stop or clip segments and provide a cleaner interface between what is desired by the experimenter and performed by TREAT.

Providing a generic desired rod positions vs time data segment would be rather straight forward. The commanded rod position is simply the desired rod position over time and the segment could be terminated by the normal options or with one where the data runs out.

The generic power vs time function would also be rather straight forward. In order to satisfy the control equation, the desired power would be used to derive the desired period and desired delayed contributions and could all be calculated before the transient begins. With the desired or demanded values already calculated, they can be used directly in the control equation derived in Ref 4. This would bypass the need for the added calculation for the fixed period or ramp functions to generate the desired power, period and delayed concentrations and only rely on measured data.

These generic segments were never implemented in the ARCS replacement, but a preliminary test was performed to prove the principle. Fig. 2 compares the original method with the generic power segment methodology. The transient performs a flat top at 45 MW, followed by a flat to at 3 MW. The 3MW cannot be sustained due to the rods being fully withdrawn at the end until the transient is terminated. The comparison turned out rather well for not using any tuning at all.

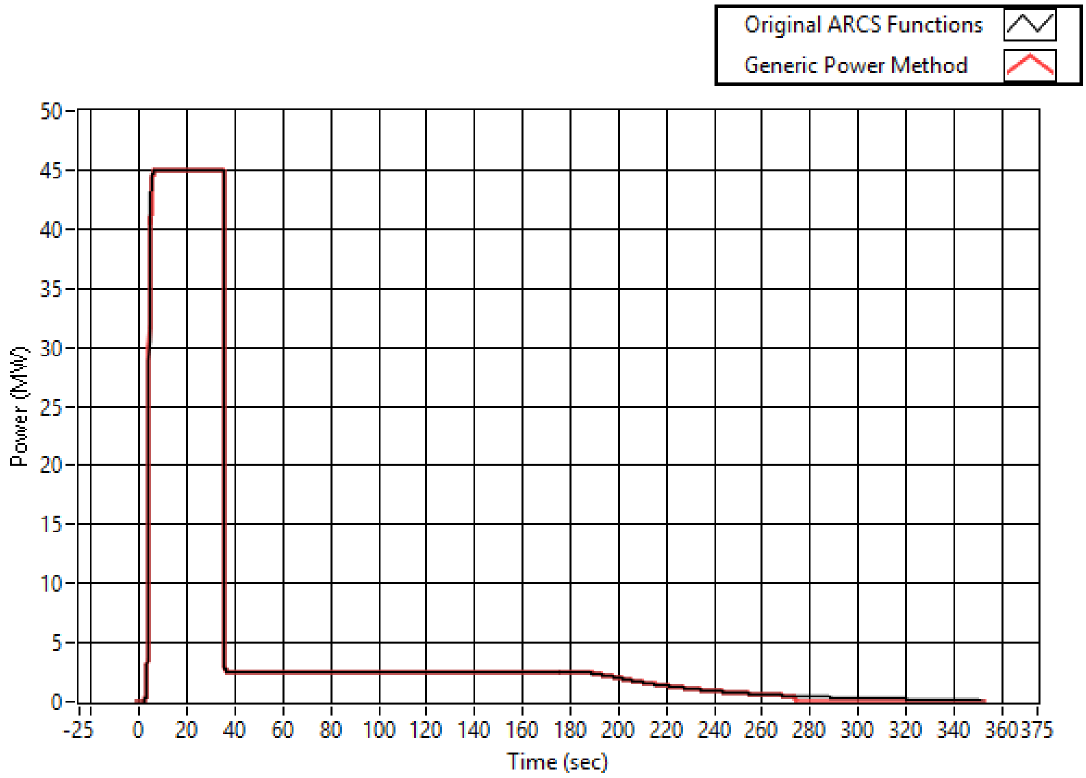

Figure 2. Proof of principle for a generic desired power vs time input

IV.C. Control Algorithm Framework

During the replacement, it was realized that it would be possible to abstract the control algorithm to become a modular component independent of any limiting trip function. TREAT's limiting conditions are more about the temperature of the cladding, and ARCS is not being credited for any safety function. With this logic, it shows that it would be possible to create a framework that provided the outside structure of a control algorithm to deal with scrams and defence-in-depth measures while allowing the internal details of the control algorithm to change.

Providing a framework would reduce the needed regulatory burden for making changes to the algorithm as well as allow others to test their own control algorithms or perform fuels testing that requires controlling the reactor with specific interfaces.

V. CONCLUSIONS

The TREAT reactor has undergone a replacement of its automatic reactor control system. In the process of replacing the system, several enhancements were made. A correction for the non-adiabatic condition was implemented to improve the accuracy of the simulations. While this correction had a large impact on some simulations, it only weakly influenced the control algorithm and was therefore not included in the final code. The dynamic range for power and period indication was increased using splicing techniques so that the control algorithm can have indications in regions that were once blind.

Several future improvements were also discussed. A controlled shutdown method was implemented in the code for the purpose of reducing wear on the shock absorbers but needed a circuit modification to be fully operational. Generic power and control rod segments were proposed to provide more options in the development of a transient and furthers the goal of a customer receiving the requested power history from the control system. The generic power segment approach was proven in a development environment but was not implemented in the final ARCS code. Lastly, it was realized that TREAT could be used as a framework to allow any control algorithm the ability to be tested with little regulatory burden. To achieve this novel approach some minor changes to the safety analysis report would be required.

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