WSRC-MS-97-0339
CONF-970591--7

RAMI Modeling of Selected Balance of Plant Systems for the Proposed Accelerator Production Tritium (APT) Project (U)

by

J. A. Radder

Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

D. S. Cramer

A document prepared for MAINTENANCE AND RELIABILITY CONFERENCE at Knoxville, TN, USA from 5/20/97 - 5/21/97.

DOE Contract No. **DE-AC09-96SR18500**

DISCLAIMER

RAMI MODELING OF SELECTED BALANCE OF PLANT SYSTEMS FOR THE PROPOSED ACCELERATOR PRODUCTION OF TRITIUM (APT) PROJECT

J. A. Radder and D. S. Cramer
Westinghouse Savannah River Company
Aiken, South Carolina 29808

ABSTRACT

In order to meet Department of Energy (DOE) Defense Program requirements for tritium in the 2005-2007 time frame, new production capability must be made available. The Accelerator Production of Tritium (APT) Plant is being considered as an alternative to nuclear reactor production of tritium, which has been the preferred method in the past. The proposed APT plant will use a high-power proton accelerator to generate thermal neutrons that will be captured in ^{3}He to produce tritium (^{3}H). It is anticipated that the APT Plant could be built and operated at the DOE's Savannah River Site (SRS) in Aiken, South Carolina.

Discussion is focused on Reliability, Availability, Maintainability, and Inspectability (RAMI) modeling of recent conceptual designs for balance of plant (BOP) systems in the proposed APT Plant. In the conceptual design phase, system RAMI estimates are necessary to identify the best possible system alternative and to provide a valid picture of the cost effectiveness of the proposed system for comparison with other system alternatives. RAMI estimates in this phase must necessarily be based on generic data. The objective of the RAMI analyses at the conceptual design stage is to assist the designers in achieving an optimum design which balances the reliability and maintainability requirements among the subsystems and components.

Discussion topics include key model parameters defining the model structure and parameter values developed from several sources. These sources are based on: 40 years of multi-facility operations at the SRS involving pumps, motors, valves and heat exchangers; recent commercial nuclear power plant experience with large chiller cooling units; and generic operating experience from nuclear processing facilities at the SRS and power plants from within the commercial nuclear industry.

Model results are reported in two formats. The first involves total system availability rolled up from a tabulation of constituent components, with examples given for the APT Electrical Power and Accelerator Heat Removal systems. Justification is also provided for approximations, used in lieu of more traditional Markov models, that account for various component states resulting from redundancy and repair policies. A second format gives results of total system availability based on a comparison with a similar operating HVAC system at an SRS facility.

Sensitivity and trade studies are illustrated to show potential improvements in overall system availability that could result from modifications to the base system conceptual design or by adopting a proactive maintenance strategy such as Predictive Maintenance (PdM). Certain major components, such as oil filled transformers, are expected to benefit if PdM techniques are used to identify incipient failures before catastrophic component failure occurs, possibly resulting in a significant loss of APT availability. In several instances, this strategy is preferable to installing or stocking a spare component.

BRIEF DESCRIPTION OF THE APT PLANT DESIGN

The APT plant comprises several major system groups that include: Accelerator Systems, Target/Blanket (T/B) Systems, Tritium Separation Facility (TSF) Systems, and Balance of Plant (BOP) Systems. These system groups are briefly described in the following paragraphs.

Within the Accelerator Systems group, low-energy (75 keV) protons are produced by an injector system that directs the resultant beam into a low-energy (LE) linac system. Here, the beam is both focused and accelerated to an energy of 217 MeV. The LE linac design is based on normal-conducting (room temperature), copper accelerating cavities that are cooled by water. Upon exiting the LE linac, the beam enters a high-energy (HE) linac system where niobium, super-conducting accelerating cavities further increase beam energy to 1700 MeV. These super-conducting cavities are cooled by a cryogenics system that uses liquid Helium as a refrigerant. High energy beam transport and expander systems direct the 1700 MeV beam from the HE linac and convert it to a format that is suitable for the T/B assembly. A radio frequency (RF) drive system transforms ac electric power into RF power to establish accelerating fields in both the LE and HE linac systems.

The primary function of the T/B Systems group is to produce tritium and deliver it to the TSF. The 1700 MeV proton beam, generated in the one mile-long accelerator tunnel, is directed onto a tungsten target, which produces neutrons through a spallation process. Additional neutrons are also produced in the blanket assembly that surrounds the target. Neutrons produced by both sources are absorbed by a ^3He sweep gas, part of which is converted to tritium by neutron-proton reactions. This sweep gas continuously flows between the T/B and TSF Buildings. Both heavy water and light water system cooling loops operate to remove heat deposited in the various T/B components.

The TSF receives the sweep gas stream, containing low levels of tritium, from the T/B assembly. Systems in the TSF group process the stream to separate out tritium and cleanse the gas of any impurities before it is returned to the T/B assembly. The TSF systems purify the tritium both chemically and isotopically, then store and load it into shipping containers for transportation elsewhere.

The BOP Systems group contains 17 conventional systems that provide varying degrees of support and integration for the other APT plant systems. Of these, only five BOP systems are viewed as having a direct, critical impact on APT production of tritium operations. Loss of any one of the five is expected to result in an immediate forced outage. The remaining 12 systems (e.g., Radioactive Waste Treatment, Fire Protection) have the potential to shutdown APT production operations should one or more of them be out of service for an extended period of time. The five systems that are critical to APT production of tritium are as follows:

1. Normal Electric Power System - supplies and distributes ac electric power to all Accelerator, Target/Blanket (T/B), Tritium Separation Facility (TSF), and BOP system electrical loads.

2. Heat Removal System - consists of four subsystems that must be available during accelerator operations.
   - Accelerator Heat Removal Subsystem - removes heat generated in components associated with the normal-conducting accelerating structures (LE linac section), klystrons for the RF drive, and the high energy beam transport (HEBT) section of the accelerator.
   - Cryogenic Plant Cooling Subsystem - provides cooling to heat loads produced by the three cryogenic plants which are part of the accelerator super-conducting section.
   - River Water Makeup Subsystem - continuously supplies water to open-loop cooling tower systems to make up for losses caused by evaporation and blowdown. Loss of this system does not result in an immediate APT plant shutdown since the cooling tower basins have sufficient inventory to allow up to 5 hours of operation without makeup.
   - T/B Heat Removal Subsystem - provides cooling to target, blanket, and window heat loads.

3. HVAC System - consists of three subsystems that are required to be available during accelerator operation.
   - Accelerator Tunnel and Klystron Gallery Subsystem - removes heat from waveguide windows and pumps in the accelerator tunnel, components in the klystron gallery, and RF waveguides.

- Target/Blanket Building Subsystem - removes heat from inside the building but its primary function is to control spread of contamination and maintain radionuclide concentrations within acceptable limits.
- Tritium Separation Facility Subsystem - removes heat from inside the facility but its primary function is to control spread of contamination and maintain radionuclide concentrations within acceptable limits.

4. Integrated Control System - brings subsystem controls for the Accelerator, T/B, TSF, and BOP elements together under one main control system.

5. Instrument Air System - provides high-quality compressed air to control valves in heat removal systems and HVAC control systems.

OVERVIEW OF THE BOP RAMI MODEL

The major focus of the RAMI modeling work, at this time, is on the availability of BOP systems as mandated by the annual tritium production goal. Based on requirements for the APT plant, the BOP systems were assigned an aggregate availability goal of 97.3%. To determine how well this target goal could be met, system RAMI models were developed to obtain availability estimates for each of the five critical systems described earlier. Where appropriate, trade studies were conducted to determine potential improvements over the base conceptual design for individual BOP systems. This paper discusses the RAMI work that was performed for three of the critical BOP systems (Normal Electric Power System, Accelerator Heat Removal Subsystem, and Accelerator Tunnel and Klystron Gallery HVAC Subsystem). It also includes discussion on the practical aspects of achieving the availability goal.

Normal Electric Power System

Central to the operation of the APT Plant is the Normal Electric Power System, which provides a support function for all other plant systems. To compute the availability of this system, a spreadsheet was created to roll up the individual availability contributions from 10 major groups of sub-systems or components:

- 230-kV Service (2 auto-transformers)
- 115-kV Service (2 breakers, 2 buses)
- Cryoplant Power Supply
- Klystron Power Supplies (16 high-voltage breakers and transformers, 32 medium-voltage breakers and transformers, 32 control power breakers and transformers)
- T/B Building & Tritium Extraction Building Power Supply
- RF Control Power Supplies (20 medium-voltage fuses and transformers)
- Accelerator Station Power Supplies (10 cooling tower buses, 10 cooling station buses)
- Accelerator Low-Energy Section (1 bus)
- Accelerator Super-Conducting RF Section (8 buses)
- Accelerator Cooling Tower Section (10 buses).

Although more components were included in the spreadsheet, only the number of components that play the most important role is indicated in parentheses. The number and size of buses, breakers, and transformers, as well as any redundancy, were taken into account using an Event Tree approximation model for detailed availability equations. For selected critical components, the difference between the results obtained from this approximation and a Markov model was shown to be negligible. The comparison is discussed in more detail in the next section dealing with Markov and Event Tree approximation models.

In a number of configurations, redundant components reduced the failed state to loss of two-out-of-two or two-out-of-three, which provides a very high availability (~1.0). Taken into account was the amount of time the accelerator beam or subsystems would be lost due to brief automatic or manual switching, as well as typical times estimated for re-establishing the beam after specific perturbations occur. Included also for completeness were the loss of more than one high-voltage transformer (230-kV/ 115-kV), loss of 115-kV buses or breakers, loss of two-out-of-three 230-kV incoming commercial power lines, loss of all commercial power lines due to a blackout in the Southeastern United States, loss of electric power due to tornado and earthquake, and brief electric power losses caused by lightning strikes.

Accelerator Heat Removal Subsystem

This system was also modeled using the detail of the same spreadsheet format to roll up availabilities for the system's nine cooling stations, which are distributed over the length of the mile-long accelerator tunnel. Major components included in the secondary, open cooling-water loops were:

- 27 cooling tower pumps (1743 to 2029 HP each)
- 27 cooling tower fans (150 HP each)
- 18 air-operated temperature/flow control valves (24" to 48" each)
- 12 heat exchangers (Stations 1&2 each have one 46-MW and one 11-MW heat exchanger; Stations 3-8 each have one 60-MW exchanger; Station 9 has one 60-MW and one 10-MW heat exchanger.)

Major components included in the primary cooling-water loops were:

- 30 circulating pumps (12 under 500 HP each and 18 over 1000 HP each)
- 67 air-operated valves (17 @ 12" to 48" each and 50 @ 4" to 10" each)
- 24 Chillers (50% capacity each without any redundancy: two 246-ton, two 268-ton, twelve 279-ton, two 300-ton, two 320-ton, two 714-ton, and two 984-ton)

Accelerator Tunnel and Klystron Gallery HVAC Subsystem

This system was modeled using the detail of the spreadsheet format to roll up availabilities for the 5 different HVAC sections. Major components included in the cooling tower section were:

- 3 cooling tower pumps (410 HP each)
- 3 cooling tower fans (40 HP each)

Included in the chilled water section were:

- 3 chiller units (50% capacity @ 2250 tons each)
- 3 chilled water pumps (50% capacity @ 205 HP each)

Included in the accelerator tunnel section were:

- 12 air handling units (non-redundant @ 200 tons each)
- 6 exhaust air filtering units (24,000 cfm each)

Included in the klystron gallery section were:

- 20 air handling units (90 tons each)
- 25 air exhaust fans (non-redundant @ 10,000 cfm each)

Included in the accelerator power end injector section were:

- 2 air handling units (one @ 15 tons, the other @ 50 tons)
- 1 outside air supply fan (30 HP)

MARKOV AND EVENT TREE APPROXIMATION MODELS

The BOP systems were modeled by using a spreadsheet that incorporates standard, reliability handbook equations. In certain cases, though, where redundant components are incorporated in the system design, input to the spreadsheet consisted of results from Markov and Event Tree models. Since the availabilities of many base conceptual designs for the BOP systems are sensitive to single component failures, use of these models is best explained by the following example of a trade study where the key element is redundancy or added equipment capacity.

The typical trade study, where redundancy or capacity is added to a chosen system design, consists of implementing one or both of these options:

- Backing up a single, 100% capacity unit in the initial design with a redundant unit that is also operating. In this case, instead of a single failure being sufficient to fail the system, two out of two (both) unit failures are required. System failure consists of the first unit failing to run, followed by failure of the redundant unit to continue running while the first one is being repaired or replaced.

- Replacing two normally running, 50% capacity units with two double capacity (100%) units. In this configuration, one unit is normally running and the other redundant unit is in standby. System failure consists of the first unit failing combined with failure of the second unit to start or run, while the first is being repaired or replaced.

These options were modeled in two ways: by a Markov model and an Event Tree (ET) model. The solution to the Markov model assumes a steady state equilibrium is reached as components fail, undergo repair and are placed back into service. In the steady state equilibrium solution to the Markov equations, the populations of each of the possible combinations of failures which define the possible states do not change with time. With a two component redundant system, where 100% capacity components are operating and sharing the load, the possible system states are:

1) Both components are operating and the system is operating.

2) One component is operating, one is failed, and the system is undergoing "tuning" (also called "switch-over") to accommodate the loss of one of the two components that had previously shared the load. In this state, the system is not operating.

3) One component is operating, one is failed, and the system is successfully tuned ("switched") to operate on just one of the two components. In this state, the system is operating.

4) Both components are not operating and the system is not operating.

The Markov model is solved by first estimating the failure, switching, and repair rates for each of the states (from component-specific operating records or generic databases), and then calculating the probability that the system will be in each state. The failure rates are typically represented by lambda (λ), which is the inverse of Mean Time Between Failure (MTBF), and the repair rates are represented by mu (μ), which is the inverse of Mean Time To Repair (MTTR). The MTTR is also used for those cases where the failed component is simply replaced by a spare. Equations using lambda and mu are solved to determine the overall system availability even though some states, for which the system is available, may be degraded; that is, those states do not have full component redundancy.

The lambda's and mu's are usually taken to be unchanged from state to state. This implies, for example, that if one component fails, the rate at which the second fails is the same and not enhanced by failure of the first. Obviously, in the case where a single component must take up the load that two shared previously, there would be a tendency for the failure rate of that component to be somewhat increased. The lack of change in μ also implies that, when both components fail together, additional manpower will be scheduled to maintain overall MTTR at the same value it would be if just one component failed.

The Event Tree (ET) approximation model was selected due to its simplicity and ease in modeling failures to start-on-demand for standby equipment and various combinations of failed components. For example, an ET model was used for the HVAC system where failure can only occur if pairs of adjacent fans, or their associated inlet/outlet dampers, fail together (system failure can also occur if three or more combinations of any fans and dampers fail).

The ET model uses first order approximations for failure probabilities as a function of time [i.e., $1\text{-exp}(-\lambda t) = \lambda t$] and multiplication factors that "count" all those combinations which can fail the system. Normally, in the ET model, the average time that would be required to repair a component before the next one failed would be MTTR/2, instead of MTTR. This is because the second component could fail at any point from time zero (i.e., immediately after the first fails) up to time MTTR (i.e., just as repair of the first is being completed and it is being put back into service). The average time, MTTR/2, is a consequence of the fact that the event tree starts at time zero, whereas, in the Markov model, time zero occurred long ago and is replaced with steady state equilibrium between each state of the system. By setting the repair time in the ET model to the value used for MTTR in the Markov model, good agreement between both models can be obtained out to the sixth decimal place. Availability (or, unavailability) due to switching can also be estimated using the ET model, but in most cases this only affects the results beyond the fourth decimal place. The confidence gained from this agreement supports the extension of the ET model to more complex systems and combinations of component failures that can fail the overall system. Examples of the ET model availability estimates are given for the following failure combinations:

- **1 - (MTTR / MTBF)** single running component (100% cap.) fails the system
- **1 - 2 * (MTTR / MTBF)** 1 out of 2 running components (50% cap. each) fails the system
- **1 - 2 * (MTTR / MTBF)^2** 2 out of 2 running components (100% cap. each) fail the system
- **1 - 6 * (MTTR / MTBF)^2** 2 out of 3 running components (50% cap. each) fail the system
- **1 - (MTTR / MTBF) * {(FS + MTTR / MTBF)}** 2 out of 2-100% capacity components fail the system (i.e., one running component fails followed by failure of the standby component to start or, once started, its failure to run until the first can be repaired) where FS is the probability of Failure to Start on demand.

Although it is easy to incorporate different lambda's and mu's for each state in either model, this particular refinement was not made for the BOP analysis. A further refinement could be made to these equations by replacing MTBF in the denominator by (MTBF + MTTR). Except for certain components, such as 115 kV transformers, this was not done since the differences introduced were well within the uncertainties of the values used for the MTBFs.

A trade study was performed for a section of an HVAC system where twelve single fans were traded out for 40 fans with "overlapping" coverage. This new configuration was analyzed for combinations of component failures that could fail the system. In this case, the ET model was used to determine system availability where any two adjacent fans out of the forty could fail the system but any single failure, or non-adjacent combination of two fans, could not. It was assumed that failure combinations of any three or more fans, whether adjacent or not, could also fail the system. The system availability for two adjacent fans failing is given by:

1 - {(first fan fails) * (adjacent fan also fails while first is being repaired)}

= 1 - {(40 - 2 ends) * (2 for either side) + (2 ends) * (1 for one fan on its side)}
 * {(Prob. of one failing in time T is λT)} *
 * {(Prob. of second failing in repair time MTTR is λ * MTTR)}
 * {(time system out of service is MTTR, not MTTR/2)}
 * {(1/Total Time T)}

= 1 - {(78) * (λ * MTTR)^2}

System availability for any three fans failing is given by:

1 - {(1st fails)* (2nd fails while 1st repaired) * (3rd fails while other 2 repaired)}

= 1 - {(any of 40 fans) * (any of the remaining 39) * (any of the remaining 38)}
 * {(Prob. of one failing in time T is λT)}
 * {(Prob. of second failing during repair time MTTR is λ * MTTR)}
 * {(Prob. of third failing during repair time MTTR is λ * MTTR)}
 * {(time system out of service is MTTR, not MTTR/2)}
 * {(1/Time T)}

= 1 - {(59280) * (λ) * (λ * MTTR)^2* (MTTR)}

= 1 - {(59280) * (λ * MTTR)^3}

BOP RAMI MODEL RESULTS

Availability estimates for system base conceptual designs and alternative designs (trade studies) are provided for three selected BOP systems in the APT plant as described below.

Normal Electric Power System

Overall system availability is calculated to be 0.9933 for the base case conceptual design. The dominant contributor to system unavailability is the klystron (RF drive) power-supply segment, which is responsible for 67% of the total system unavailability. This is followed by the RF control power segment and the 230-kV auto-transformers, which respectively contribute 18% and 9% to system unavailability.

The relatively high unavailability of the klystron segment is due to the sheer number of electrical components that are required to distribute ac power to 234 klystrons and their associated control power supplies. Starting from the 115-kV buses, there are 16 high-voltage breakers (eight on each bus) that deliver 115-kV to 16 respective step-down transformers, each of which supplies 4160-V to two medium-voltage breakers. Each breaker is then connected to a separate 4160-V supply bus, making a total of 32 breakers and 32 supply buses at the 4160-V level. Each of these 32 buses supplies power to a group of seven to eight klystrons and a control circuit. Each of the 32 control circuits powers a 4160-V/120-V transformer via a 4160-V breaker. Should any one of the klystron segment components (a grand total of 160) become unavailable, either 4160-V main power or 120-V control power would be lost to seven or eight adjacent klystrons. This would result in a loss of the accelerator beam and a forced outage to restore the affected electrical component to an available state.

The source of unavailability for the RF control power segment is also due to a relatively large number of components (54), any one of which causes a loss of the accelerator beam upon its failure. A resulting forced outage will last approximately the time it takes to repair or replace a failed component. In the case of the 230-kV auto-transformers, unavailability is driven by the long MTTR of 1 year. A failure in one of these large, 600 MVA transformers would result in a manufacturer having to build a replacement, since nearly all transformers of this size are special order and the APT transformers are no exception. However, the conceptual design for the APT electrical system is based on two 100% capacity, fully redundant auto-transformers. Recovery from a failure in one of the two is accomplished by switching its loads over to the other transformer.

Several trade studies of alternative designs were conducted to determine if electrical system availability could be improved to an even higher value and whether removal of certain redundant components, as a cost savings measure, would significantly impact availability. These studies are described as follows.

Predictive Maintenance Program Added - Case A

The impact of a limited predictive maintenance (PdM) program for components that are included in the sets of dominant contributors to unavailability was examined. The PdM considered for each component type and the percentage of incipient failures that are expected to be captured, before they cause catastrophic failure, are described below:

- Oil filled transformers with load tap changers - gas and oil quality analyses combined with infrared thermography surveys are estimated to eliminate 70% of the anticipated failures
- Dry transformers - infrared thermography is estimated to eliminate 60% of the anticipated failures
- Circuit breakers (115-kV only) - infrared thermography surveys combined with on-line duty monitors (to determine/schedule maintenance) are estimated to eliminate 50% of the anticipated failures.

With a limited PdM program, system availability increases by less than 0.5% to 0.9972. It may not be possible to justify the cost of including these or other additional components in such a program without further detailed analysis.

Redundant Bus-Tie Components Removed - Case B

Approximately two dozen, 4160-V bus-ties for loads such as cooling towers, klystron cooling, and T/B equipment were removed to determine whether this would have a significant impact on overall electrical system availability. Results show that availability decreases to 0.9932 by an insignificant amount (~0.01%). Depending on whether bus-tie removal adversely impacts the ability to perform electrical system maintenance while the APT is operating, an attractive cost savings measure may be achievable.

PdM With Bus-Ties Removed - Case A & B Combined

This case represents a combination of the above two studies: a limited PdM program combined with the removal of two dozen 4160-V bus-ties. Results show that availability increases by less than 0.5% over the base case to 0.9971. A summary of availabilities for the various cases is given below in Table 1.

Table 1 - Summary of System Availabilities

Case	System Concept	Availability
Base	Base Conceptual Design	99.33%
A	Limited PdM	99.72%
B	Bus-Ties Removed	99.32%
A & B	PdM With Bus-Ties Removed	99.71%

Identification of Transient Initiator

While developing the base case model for the electric power system, a new effect was identified where brief (<10 cycles) voltage transients can have a larger impact on APT plant availability than previously expected. Forty years of experience with both the 115-kV transmission system and 13.8-kV distribution system, on the SRS 300 square-mile site, indicates that lightning strikes cause brief voltage transients several times a year. Since these transients are short-lived, and the newer 230-kV transmission system has both superior aerial ground-wire protection and lower resistivity soil grounds, the previous experience was not expected to be important to APT plant availability. However, it is now recognized that this may not be the case, as illustrated by the following scenario.

A nearby lightning strike on the transmission lines causes 230-kV bus voltage at the APT substation to approach zero as 230-kV breakers operate to clear the disturbance. Although the transient is over in 3 to 5 cycles (0.05 to 0.08 seconds), the accelerator protective trip system reacts at least 500 times faster to simultaneously trip the beam and shed several hundred megawatts of RF load. As required by the Southeastern Electric Reliability Council rules, the electric utility would quickly respond to this load rejection event by immediately backing off excess power generation. To restore APT plant production operations, RF equipment would now have to be re-loaded back onto the grid at the utility mandated ramp rate. Consequently, this new scenario involves a "cold start-up" of the accelerator as opposed to a brief interruption of electrical service.

Accelerator Heat Removal Subsystem

Overall system availability is calculated to be 0.9361 for the base case, which represents the current system conceptual design with major components as described earlier. The dominant contributor to system unavailability is the set of non-redundant chiller units which is responsible for 89% of the total system unavailability.

The set of 24 non-redundant chiller units makes a significant contribution to system unavailability because it is assumed that any failure of a single unit results in accelerator shutdown. All of the chillers are 50% capacity units, configured in pairs to achieve 100% capacity for the heat loads they serve. Loss of a single unit in any pair will cause reduced cooling of the components associated with that pair. Because the MTTR for a chiller is in excess of 40 hours, it is expected that the associated cooling-loop would experience significant temperature rise well before chiller repairs can be completed. This temperature rise will cause significant dimensional changes to occur in some components due to thermal expansion. For components in the accelerator room-temperature section, such as the radio frequency quadrupole (RFQ), coupled cavity linac (CCL), and coupled cavity drift tube linac (CCDTL), this would likely cause the beam to be out of phase, resulting in a protective beam trip. Other components, like the nine sets of klystron bodies that must be maintained at 23 °C (77 °F) ±2 °C (±3.6 °F), would likely force a shutdown of the accelerator after reaching temperatures significantly higher than their operating band would allow.

Several trade studies of alternative designs were performed to determine if the system availability could be improved to an acceptable value within some reasonable cost. These studies are described as follows.

Fully Redundant 100% Capacity Chillers - Case C

By increasing the cooling capacity of each chiller unit to 100%, the set of chillers can be made fully redundant, requiring only one chiller in a pair to operate while the other remains in standby as an installed spare. Start-up times for the standby chiller are 5 minutes (or less) to fully assume the load that the tripped chiller was previously carrying. If the chiller units were upgraded to 100% capacity, system availability would increase by nearly 6% to 0.9919 and the entire set would then contribute less than 2% of the unavailability (as opposed to 89% in the base case). Air operated valves would then surface as the dominant, yet smaller, contributor to system unavailability.

Adding a third, 50% capacity chiller to each existing pair was not considered for several reasons. First, the footprint of a chiller skid is approximately 450 sq. ft. for all size units and, therefore, significant floor space would be required to install the additional units. Each mechanical service building would need to be redesigned (or planned equipment installations would need to be re-located) to accommodate one or more additional chillers, depending on where the building is located along the tunnel. Second, the cost of doubling the capacity of the 24 existing chillers (making them 100%) is close to the cost of adding 12 new 50% chillers on skids. Figures provided by a manufacturer show the incremental cost of upgrading a chiller from 300 to 600 tons to be $115 per ton, while the cost for a separate 300 ton unit is $285 per ton. Costs of upgrading the larger chiller units are about the same price per ton as a separate new unit. The cost of upgrading 24 chillers is estimated to be $1.3M, which is close to the $1.1M cost of adding 12 new 50% capacity units. Finally, the cost of additional plumbing and electrical cabling for a third set of new chillers would be significant.

Portable Spare Chiller - Case D

Providing a portable spare chiller could improve system availability if it is assumed that replacement time is significantly less than the MTTR for a failed chiller. Replacement time is defined to be the length of time required to move and install a spare so that it can take over the function of a failed chiller unit. In order to optimize the maximum gain that a portable spare could be expected to provide, the following are assumed:

- There are two portable spares - one sized for chillers nominally in the 300 ton range and the other sized for chillers in the 700 to 1000 ton range. Two spares are assumed in order to reduce the impact of a second chiller failure when one of the spares is in use. The large spare would purchased as a temporary replacement for the 4 chillers that are in the 700-1000 ton range. However, it would probably find more use as a spare following a second chiller failure in the set of 20 smaller units. A 1000 ton chiller can be set up to replace a 300 ton unit by loading it to ~30% of rated capacity.

- Trailers, rigging equipment, and sufficient manpower are readily available to move the spare into place.

- A spare chiller will have a 24 hour replacement time, which is one-half the chiller MTTR.

With the spare chiller concept, system availability increases by nearly 3% from 0.9361 to 0.9633, which is about one-half the gain noted in Case C. Although the costs of providing two spares is significantly less than upgrading the base conceptual design to 100% capacity units, there are other considerations that need to be addressed. Based on a chiller MTBF of 19,631 hours and 24 chillers, approximately 10 failures per year could be expected to occur in the heat removal system. The time and costs involved in making 20 spare chiller moves (10 round trips) per year must be considered before making any valid comparisons between this concept and the one for chiller upgrade. Also, there will be additional costs associated with storing the spare chillers in some type of "temporary" shelter to prevent their degradation by elements of the weather.

Improved Chiller Diagnostics - Case E

Improved diagnostics for failures due to freon leaks (30% of total failures) and control problems (31% of total failures) will reduce chiller MTTRs. Early detection of freon leaks can also prevent more serious consequential failures, such as freezing in evaporator tubes, that require significantly long repair times. By providing the following features, reductions in diagnostic time and prevention of costly failures can be realized:

- Portable halide detectors for detecting and locating freon leaks early

- Microprocessor diagnostics, installed on the chiller skid packages, to detect both incipient and catastrophic control system failures.

Based on discussions with commercial power plant maintenance personnel, who are knowledgeable on chillers, it is estimated that enhanced diagnostics could reduce the chiller MTTR from 48 to 30 hours. The system availability, with such improvements in place, increases by approximately 2.5% to 0.9597. Costs for these improvements are not well known but they are expected to be significantly less than costs associated with either one of the other concepts presented above in Cases C and D.

In Table 2 below, availability of the Heat Removal System conceptual design is summarized along with availabilities for the other concepts used in the trade studies.

Table 2 - Summary of System Availabilities

Case	System Concept	Availability
Base	Base Conceptual Design	93.61%
C	Fully Redundant Chillers	99.19%
D	Portable Spare Chiller	96.33%
E	Improved Chiller Diagnostics	95.97%

Accelerator Tunnel and Klystron Gallery HVAC Subsystem

Overall system availability is calculated to be 0.9848 for the base case, which is derived from the current system conceptual design with major components as described earlier. Three dominant contributors provide more than 90% of the system unavailability and are listed below according to their percent contribution:

- **RF waveguide duct exhaust air fans (41%)** - 25 fans provide forced air cooling for the RF waveguides by drawing air from the Klystron Gallery through the concrete ducts that enclose them. Each exhaust fan provides forced air cooling to approximately 10 adjacent waveguides. It is assumed that the accelerator would be required to shutdown if any 1 of the 25 fans were to fail during accelerator operation. Reasons for this assumption follow.

The waveguides are heated at a rate estimated to be in the range of 150 to 250 watts per linear foot, and the cooling fans operate to maintain their temperature below a 140° F limit. With a loss of cooling due to fan failure, waveguide electrical resistance increases with temperature causing the heat-up rate to increase as the waveguide gets hotter. This temperature excursion occurs within minutes and would likely cause gaskets and nearby electrical cables to melt. There are also concerns that the waveguide warranty would be voided (i.e., temperatures will greatly exceed 140° F limit) and a personnel burn hazard will be created. Consequently, loss of a single fan is expected to result in accelerator shutdown. Approximately 6 fan failures per year are estimated to result in forced shutdowns.

- **Accelerator tunnel air handling units (32%)** - 12 air handling units (AHUs) are situated along the one-mile length of the tunnel and provide a heat removal function while the accelerator is operating. The failure of any 1 of 12 AHUs is expected to result in accelerator shutdown due to excessive heat buildup in critical components located within the section of the tunnel that the particular AHU serves. Because each AHU is ducted to serve a long section of the tunnel, no cooling is provided to the area by the other units. It is expected that there will be 2 forced shutdowns per year to repair failed AHUs.

- **Motor operated dampers for AHUs (18%)** - a damper is located on the inlet and outlet of each AHU. Spurious closure of either damper on a particular AHU is equivalent to its failure. Therefore, closure of any 1 of 24 dampers results in accelerator shutdown. Three forced shutdowns per year are expected to occur as a result of damper failure.

Several trade studies of alternative designs were performed to determine whether system availability could be improved to an acceptable value within some reasonable cost. These studies are described as follows.

Air Handling Unit Design Change - Case F

The 12 AHUs, along with their related duct-work and inlet/outlet dampers, could be replaced by a set of 40 smaller, well-distributed AHUs that do not require duct-work or dampers. The effects of this design change are several. First, no single AHU failure can cause heat buildup in critical accelerator components because adjacent units will provide sufficient heat removal due to overlapping coverage. It is estimated that at least two adjacent AHUs would have to fail in order to cause accelerator shutdown. Second, ductwork and motorized dampers are eliminated by the new design, resulting in a significant potential for cost savings. Repair times are also reduced since the smaller units can be located in a more accessible location. Third, more flexibility in operations is realized because different numbers of AHUs can be scheduled to run during the year as outside ambient temperature changes (the original design requires all 12 AHUs to run).

If this design change were made, system availability would increase by ~0.8% to 0.9921 with 76% of the unavailability coming from the RF waveguide exhaust fans described earlier. No forced shutdowns are expected to result from AHU failures, and scheduled or corrective maintenance could be performed with the APT on-line.

Waveguide Exhaust Fan Design Change - Case G

The 25 exhaust fans that provide forced air cooling could be made redundant by adding a second fan in parallel. Each set of 10 waveguides would then be served by two fans instead of one. The size of each fan is only 10 HP so costs associated with the change (25 additional fans) should not be unreasonable. If this change were made instead of the AHU design change in Case F, system availability would increase by ~0.6% over the base case to 0.9909. No forced shutdowns would result from exhaust fan failures but AHU failures would still result in an accelerator shutdown.

Exhaust Fan and AHU Design Changes - Cases F & G Combined

If the above changes are combined, system availability increases to 0.9982 which represents a 1.3% increase over the base case. This compares well with the measured availability of a similar system at SRS, where the system was only forced to shutdown for one day in two years of continuous operation (i.e., availability of SRS HVAC system is 0.9986). Failures of exhaust fans and AHUs, either separately or together, will not result in a forced shutdown and maintenance can be performed when the APT is operating. However, with this design change, there will be 28 additional AHUs and 25 additional exhaust fans that must be maintained when compared to the base design.

Water Cooling for Waveguides - Case H

A proposal has been made to replace forced air cooling of the waveguides with a water cooled system. Although there are sparse details on how this system would be designed, the concept is as follows. Each waveguide would have a set of 1/4" to 3/8" diameter copper tubes bonded to it along its length for water to flow through. Cooling water would be provided to a header that supplies water to 10 individual waveguides. The header would receive water from a section of the accelerator heat removal system that provides non-chilled cooling water to the klystron collectors and splitters. Temperature control for each group of 10 waveguides would be regulated by an air operated valve located between the associated header and the cooling water supply line. There would be approximately 25 headers with temperature control valves to serve all of the waveguides. Assuming that the AHU design change (described above in Case F) is also part of this proposed water cooling design, system availability would be 0.9961 which is comparable to the combined fan and AHU design change. Availability results for the above five cases are presented below in Table 3.

Table 3 - Summary of System Availabilities

Case	System Concept	Availability
Base	Base Conceptual Design	98.48%
F	AHU Change	99.21%
G	Exhaust Fan Change	99.09%
F & G	Combined AHU and Fans	99.82%
H	Water Cooling and AHU	99.61%

CONCLUSIONS

Using base conceptual designs to compute the aggregate availability of BOP systems results in a value of 91.2%, which falls significantly short of the BOP target goal of 97.3% by approximately 6.3%. In all cases, the predominant sources of unavailability (~80% for the overall BOP) can be attributed to non-redundancy in major BOP system components such as chillers, exhaust fans, and air handling units. Limited sensitivity studies show that one of the few ways to improve availability would be to dramatically increase MTBFs for these major system components. However, this seems unlikely in a practical sense based on reviews of component-specific operating records and generic databases. Decreasing the same major component's MTTRs, although possible in theory, does not appear to be practical either since the MTTRs already border on being optimum. Although PdM appears to be promising, insufficient data is currently available to make the statement that PdM alone could compensate for lack of redundancy or capacity in system design. Consequently, a change in system design may provide the answer.

By using different combinations of alternative system designs from the previous trade studies (Cases A through H), the BOP target availability goal of 97.3% can either be met or exceeded. Four of the more cost effective options suggested for consideration are:

- Option 1: Providing fully redundant chillers for the Accelerator Heat Removal System would, by itself, increase overall BOP availability to 96.6%. Adding more capacity to the accelerator tunnel HVAC, by reconfiguring the air handling units (i.e., replacing 12 existing units with 40 smaller units that have sufficient cooling capacity to allow overlap coverage), would build upon the chiller modification and raise BOP availability to the required goal of 97.3%.

- Option 2: Providing additional exhaust fan capacity to make the forced air cooling system for the RF waveguides fully redundant would, if combined with Option 1, increase BOP availability beyond the budget goal to 97.9%. Implementation of this option would also eliminate 6 forced shutdowns (of the APT plant) per year, resulting from the single failure of exhaust fans.

- Option 3: If a waveguide water cooling concept were traded for the RF forced air cooling system in Option 2, this would result in an overall BOP availability of 97.7% which is again in excess of the target goal. Again, shutdowns due to the single failure of exhaust fans would be eliminated.

- Option 4: Removing cross-ties between selected, redundant buses in the electrical power system would be a cost savings measure that could be applied to any of the above options without a measurable change in overall BOP availability.

ACKNOWLEDGMENT

The information reported in this paper was developed during the course of performing work for Los Alamos National Laboratory, which is operated by the University of California for the U. S. Department of Energy under contract W-7405-ENG-36.

REFERENCES

1. Los Alamos National Laboratory, "Accelerator Production of Tritium Conceptual Design Report", April 15, 1997.

2. W. Grant Ireson, ed., "Reliability Handbook", McGraw-Hill, 1966.

3. Institute of Nuclear Power Operations, "Nuclear Plant Reliability Data System - General Report", November 8, 1996.

4. Personal communications with maintenance engineers at PECO Energy Co., Arizona Public Service Co., and Wolf Creek Nuclear Operating Corp. regarding chiller performance and repair, November 1996.

5. Various personal communications with Mahlon Wilson of Los Alamos National Laboratory regarding APT accelerator systems, November 1996 through February 1997.

6. Personal communications with Clay Young of South Carolina Electric & Gas regarding electrical system component repair times and transmission system response to lightning events, October 1996.

7. Personal communications with Dan Rees of Los Alamos National Laboratory regarding APT accelerator protective trips and RF system operation, October 1996.

8. Transmission & Distribution World, "A Proactive Approach to Maintenance", April 1996.

9. Pickard, Lowe, and Garrick, Inc. "Seabrook Station Probabilistic Safety Assessment, PLG-0300, December 1983.

10. Institute of Electrical and Electronic Engineers, "Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear Power Generating Stations", IEEE-STD-500, 1984.

11. Institute of Electrical and Electronic Engineers, "IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems", IEEE-STD-493, 1990.

12. Personal communication with John Wilson of Carrier Corp. regarding estimates for cost per ton of chiller cooling capacity, January 1997.