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## Abstract

THE ANALYSIS AND EVALUATION OF RECENT OPERATIONAL EXPERIENCE FROM THE FORT ST. VRAIN HTGR

The U.S. Nuclear Regulatory Commission's Office for Analysis and Evaluation of Operational Data has established an extensive program for screening, analyzing, and evaluating the operational experience data from all commercial nuclear power plants in the United States. This program is designed to provide feedback from field experience with actual operating events to the NRC's continuing efforts to assure the public's health and safety. Oak Ridge National Laboratory provides technical assistance to AEOD to evaluate the operating experience for Fort St. Vrain.

In November 1981, Fort St. Vrain operated briefly at 100% power as part of the successful completion of power and flow oscillation detection testing following the installation of region constraint devices. In February 1982, the redesign of the helium purification system into two trains was completed to improve the availability and operability of the Helium Circulator Auxiliary System which had been identified as the major cause of water ingress due to upsets in buffer helium supply. Also, in February 1982, a precritical reactor scram resulted in two control rod pairs failing to insert apparently due to high moisture conditions prior to restart; however, this event was believed at the time to be precluded in the future due to the promised lower incidence of moisture ingress.

Water ingress events continued to be a frequent problem caused most often by electrical/control system upsets. The most recent such event was in June 1984, when the circulator upset led to a moisture ingress large enough to cause icing of chillers in the helium purification train but apparently not large enough to be detected as a problem by available analytical monitors. As a result, the reactor was exposed to several hours of undiagnosed levels of "high" moisture, loss of purified helium

flow to control rod mechanisms, and finally a reactor scram in which 6 of 37 control rod pairs failed to insert automatically. Evidence has also been uncovered that high moisture has caused the transport of volatile chlorides throughout the reactor resulting in corrosion of stainless steel control rod cables and possibly hold down bolts used on a helium circulator closure. Moisture has also caused severe leaching of $B_2O_3$ contaminant from the reserve shutdown materials, precluding the complete dumping of material during a surveillance test.

## 1. INTRODUCTION

As described in previous international conferences,[1,2] the U.S. Nuclear Regulatory Commission's (NRC's) Office for Analysis and Evaluation of Operational Data (AEOD) has established an extensive program for screening, analyzing, evaluating, and disseminating the safety-related operating experience data from all commercial nuclear power plants in the United States. The NRC also participates in the exchange of operational event information with other countries through the Nuclear Energy Agency and through bilateral agreements. AEOD evaluates operating experience from foreign reactors through its review of incident reports and provides IAEA member countries with reports of significant U.S. reactor operating experience including that from Fort St. Vrain. The goal of this program is to ensure through feedback that lessons are learned and improvements implemented based upon actual reactor operating experience. Within this program, particular attention is given to the analysis of those reportable occurrences (ROs) documented in Licensee Event Reports (LERs).[3] An LER is required by regulation to be submitted by licensee for any safety-related or safety-significant event as defined in the LER Rule (Title 10, Code of Federal Regulations, Part 50.73, or 10 CFR 50.73). The Nuclear Operations Analysis Center (NOAC) at the Oak Ridge National Laboratory (ORNL) provides technical assistance to AEOD in the evaluation and documentation of operating event experience from the Fort St. Vrain High-Temperature Gas-Cooled Reactor (HTGR), which is the only U.S. nuclear plant of its type.

The Fort St. Vrain operating experience to be discussed here includes notable safety-related events which have occurred since late 1981 when ORNL was first contracted to provide technical assistance to AEOD. Earlier Fort St. Vrain operating experience through the time of successful full-power testing in November 1981 has been summarized by the licensee and the reactor vendor, GA Technologies, Inc. (GA), in papers presented at several different forums during 1982 (Refs. 4-7). In addition, extensive and very useful detailed evaluations of preoperational and startup testing and of the rise-to-power operating experience through completion of the first refueling outage in August 1979 have been compiled into a series of reports under the sponsorship of the Electric Power Research Institute (EPRI).[8-10] Finally, the U.S. Department of Energy's Fort St. Vrain Improvement Plan[11] provides a summary of the major operational limits which have affected the plant since startup.

The events discussed here are categorized based on the major systems affected, namely, (1) primary system and reactor vessel, (2) electrical systems, and (3) the reactor building. In all cases to be discussed, the lessons to be learned are vigilance and prevention. These lessons translate into the need for the recognition and control of unexpected situations and of their potential for branching effects. At Fort St. Vrain, these lessons are found in the effects of moisture ingress, in the challenges experienced to the supply of essential electrical power, and in controlling the environment of the reactor building.

## 2. DISCUSSION OF REACTOR EVENT EXPERIENCE

Since late 1981, Fort St. Vrain has been shut down about 28 of the last 41 months. The effects of operating events have contributed to much of that shutdown time. Although the following addresses safety-related events, the effect on plant availability is also an important consideration.

### 2.1 Primary System and Reactor Vessel

The Fort St. Vrain primary system including the core, control rod mechanisms, coolant ducts, steam generators, and helium circulators is enclosed in a Prestressed Concrete Reactor Vessel (PCRV). The steam generator and helium circulators sit in PCRV penetrations utilizing double closures. The interspace between the double closures of these penetrations as well as the control rod penetrations is purged by purified helium at pressures higher than the primary system. The major concern raised by recent operational events is that of keeping coolant inside the reactor vessel and contaminants out.

In June 1980 and throughout 1981, problems were experienced with purified purge helium leaking from a steam generator penetration interspace into the reheat steam of the secondary system. This leakage led to an excess of noncondensable gases in the condenser. Since an apparent crack in an inaccessible seal weld in the steam generator reheater module was the source of the helium leak, the only practical solution was to reduce pressure in the penetration to just above reheat steam pressure and below primary system coolant pressure. Radiation monitors on the condenser air ejector are used to detect primary coolant leaks. A concern was raised by AEOD with the Senior Resident Inspector (SRI) about possible corrosion due to steam leaks into the penetration if purge flow pressure was inadvertently reduced, but the licensee believed that there were adequate moisture monitors upstream in the purge line to detect steam ingress under low helium flow conditions. The problem of moisture in the penetration interspaces has recently arisen again. In September 1984, the licensee confirmed a suspected water leak in the "A" helium circulator penetration interspace. The moisture detectors in this interspace had alarmed repeatedly for several months but were thought to be malfunctioning by the licensee. The actual presence of substantial moisture was not recognized until the detectors were removed for repair and water ran out.

Subsequently, in November 1984, surveillance testing of a reserve shutdown system (RSS) hopper revealed that half of the boronated graphite balls were stuck together with boric acid crystals. The crystals had resulted from moisture leaching out the $B_2O_3$ contaminant in the $B_4C$. The moisture apparently entered the hopper through the purified helium inlet purge line which was found to have corrosion upstream, possibly due to moisture entering the purified helium stream after exiting the helium purification train This failure resulted in a new safety concern regarding the reliability of the backup shutdown system, and its resolution is currently under review by the licensee and the NRC.

Moisture ingress continues to be a dominant problem at Fort St. Vrain. There have only been two minor steam generator leaks which occurred in November 1977 with the plant at 50% power and in the fall of 1982 following a circulator trip and moisture ingress. In the latter case, nearly two months were necessary to confirm and locate the leak due to the presence of substantial moisture in the shutdown reactor. The timing of the water injection of bearing water accumulators to ensure lubrication during circulator trips is the primary cause of moisture ingress. In turn, the loss of bearing water has been initiated frequently by electrical disturbances affecting bearing water supply instrumentation. Before the separation of the buffer helium supply into two trains in February 1982, the loss of buffer helium in a single train contributed to multiple circulator trips and frequent moisture ingress events. However, this modification, which was performed as part of the Fort St. Vrain Improvement Plan, has failed to alleviate the frequency and severity of moisture ingress.

The most recent and notable moisture ingress event occurred in June 1984. An electrical system disturbance caused a circulator trip and bearing water ingress. The operators were apparently unable to diagnose the extent of moisture ingress and continued operating in an attempt to purge the primary coolant of moisture, as allowed by Technical Specifications. Several hours later, helium purge flow was lost when the chillers iced up in the only available helium purification train. Ultimately, the reactor scrammed on a high pressure/temperature mismatch trip, and six control rod pairs failed to insert automatically. The failure of the control rods to insert automatically upon receipt of a valid scram demand is a common mode failure that constitutes a partial ATWS event (i.e., Anticipated Transient Without Scram) — a significant safety concern. The reactor has since been shut down.

This event is similar to a February 1982 subcritical startup scram in which two control rod pairs failed to insert and in which the manual scram was preceded by high moisture conditions and a loss of control rod purge flow. Based on investigations to date, both partial ATWS events were probably caused by small particles of bearing corrosion in the drive motor bearings. Also discovered was the fact that moist primary system coolant would penetrate into the affected area of the control rod mechanism even if purified helium purge flow were not lost. The mechanism housing was simply not leaktight. The licensee is exploring various design modifications to restrict further moisture ingress from the bearing water system into the primary system and to reduce or eliminate the pathways for moisture entry into the control rod mechanisms from the primary system.

A related problem associated with the moisture ingress is the leaching of volatile chlorides from various sources within the reactor and their deposition throughout the primary system. In August 1984, a stainless steel control rod cable broke and was subsequently found to have chloride-induced stress corrosion cracking. The steel cables are being replaced with corrosion resistant inconel cable. In January 1985, the disassembly of a Fort St. Vrain circulator under repair at GA found a steel closure bolt apparently affected by chloride-induced stress corrosion cracking. Concern has been raised about the possibility of the pooling of condensed volatile chlorides on the lower PCRV support floor and any possible connection to the earlier (April 1982) minor leak of radioactive gases into the PCRV liner cooling tubes located there. The chloride problem is still under investigation. The problem represents a lack of making the connection between the level of chloride contaminants in various primary system components, the possibility of moisture-induced leaching, and the potential susceptibility of other components to chloride attack. In the past, concern about the effects of moisture ingress had been concentrated almost exclusively on graphite corrosion.

In March 1984, the tendon wires of the PCRV were subjected to a five-year surveillance. Numerous corroded and broken wires were found. Subsequent investigation has determined that a microbiological agent is at work in the presence both of the sulfonate grease used on the tendon wires and of oxygen from air ingress into the tendon enclosures. The steel wires are being attacked by acetic and formic acids formed by the bacteria. The integrity of the PCRV does not appear to be threatened at this time, but the licensee is developing an accelerated surveillance program and is considering the use of a positive pressure nitrogen blanket to prevent oxygen from entering the enclosures. However, recent tests have shown that the tendon enclosures may be too leaky to hold the nitrogen blanket effectively.

## 2.2 Electrical Systems

The essential and emergency electrical power sources have been designed for an adequate level of independence, redundancy, capacity, and testability to meet the required level of safety. The alternate sources of essential and emergency power include:

1. The main turbine-generator set via the unit auxiliary transformer (UAT)

2. Five 230-kv transmission lines via the reserve auxiliary transformer (RAT)

3. Two independent standby diesel generator (DG) sets rated at 1210 kw and each stated to be capable of supplying essential loads for safe shutdown and cooling

4. DC batteries

5. DC essential instrumentation power from six separate AC busses

At Fort St. Vrain, the unlikely long-term loss of AC electrical power can result in a similar loss of forced cooling (LOFC) due to the loss of electrical systems supporting the motive power (steam or water) for the helium circulators. At least one standby DG set is needed to assure safe shutdown and core cooling without fuel damage. An extended LOFC could lead to substantial fuel damage due to overheating and the release of fission products into the primary system. A permanent LOFC constitutes a Fort St. Vrain Design Basis Accident (DBA). Therefore, in response to NRC concerns on the potential for disruptive faults affecting congested cable areas, the licensee has installed an Alternate Cooling Mode (ACM) electrical system with independent cabling and a separate 2500 kw DG located away from the main plant structure. The ACM duplicates certain functions of the standby DG sets, but, in the event of the loss of all other power sources, the ACM meets minimum requirements to ensure safe shutdown by manual actuation of the reserve shutdown system, continued cooling of the PCRV lines to contain fission products, depressurization of the PCRV through the purification system to limit heat loads on the PCRV upper barrier plates and to filter circulating fission products, and exhausting and monitoring of effluents from the reactor building. Operation of the ACM alone during a permanent LOFC will not preclude core damage but should ensure that fission products are contained within the PCRV.

Because of the importance of the AC power sources, any event affecting their availability receives immediate and intensive attention. Since depressurization must be initiated within two hours of the initiation of an extended LOFC from full-power conditions, troubleshooting and repairing electrical system failures must be accomplished in less than two hours during emergencies. Since 1981, the offsite power grid supplying Fort St. Vrain has failed once during high winds accompanying a snow storm on May 17, 1983. At that time, the reactor had been shut down for about two months so that there was no immediate emergency. However, during this event, the "A" standby DG set was unavailable because of repairs on corroded and stuck check valves in a raw water cooling supply line. (The affected valves had apparently not been inspected since initial installation.) Prior to the event, the "B" standby DG set was running and closed onto essential busses in parallel to offsite power. The loss of offsite power caused an overload trip of the "B" standby DG set. The "B" DG was restarted but could not be closed onto essential loads because time-delay relays failed to reset automatically after load shedding. The load shedding relays were reset by pulling fuses to deenergize the relays, but this effort took 45 minutes to diagnose and accomplish. An AEOD Engineering Evaluation[12] was performed that addressed the potential adverse effects of having offsite and onsite essential power sources closed onto the same loads, especially during grid disturbances when such alignments may exist. A similar failure of the load shedding relays on the same deenergized busses was experienced on December 18, 1984. The reactor was shut down and the plant was deliberately isolated from the grid in order to perform a standby DG load sequencing surveillance. Both DGs failed to complete required load sequencing, and the reconnection to offsite power was delayed because of the failure of the relays to reset. The licensee has now committed to installing a manual deenergization of the affected relays to allow more rapid operator action.

Other operating experiences with the DG sets show that there have also been occasional problems with engine exhaust temperature sensors. During the load sequencing surveillance test on December 18, 1984, a failed cell on one bank of new DG batteries resulted in a low exhaust temperature signal, forcing shutdown and declutch of both engines on the "A" DG set. Another independent, random failure of a temperature switch caused the trip of one engine of the "B" DG set. With only one DG set at 50% capacity, the automatic load sequencing logic was not met, thereby requiring manual action which was to switch to offsite power. That attempt was delayed by the load shedding relay problem described previously. However, the situation was compounded but not really affected by a timer motor failure on one of two redundant load sequencing delay timers used to give the DG sets enough time to reach operating status before being closed onto essential busses. The failure of both timers could have similarly prevented automatic load sequencing. Troubleshooting these concurrent failures took sufficient time that the surveillance could not be completed the same day. Although plant personnel would expedite repairs and exhaust all avenues of recovery during an actual loss of AC power, the potential for common-mode failure of automatic load sequencing and the time delays experienced have raised questions about the adequacy of emergency power systems at Fort St. Vrain. Efforts to improve the reliability of the system are in progress.

The ACM DG set has also experienced random failures. On October 17, 1981, the ACM DG failed to start during surveillance testing because of a faulty starter solenoid. The Technical Specifications allow the ACM to be inoperable up to seven consecutive days for maintenance, and two days were required to repair the solenoid since at that time a replacement part was not readily available. On July 25, 1983, the ACM DG failed to start because too much water had evaporated from the cells of the starting batteries, which are located in an adjacent building to which the batteries had been moved to avoid freezing and boiloff problems experienced previously when located in the ACM DG shack. Ventilation had been lost in the building, resulting in high ambient temperatures. Recharging the batteries to full charge required about 12 hours. The incidents experienced with the ACM illustrate the kinds of problems and potential for delay in availability which are part of the evaluation of operating events involving electrical systems.

During loss of offsite power, the main turbine generator set is expected to remain on line, providing house loads. The large heat capacity of the HTGR core and lack of critical heat flux concerns eliminate the need for an anticipatory reactor trip on turbine trip in common use for light water reactor plants with one turbine. Probabilistic analyses by GA Technologies for similar large HTGRs claim that the main turbine will trip at a rate of only $10^{-1}$/demand during grid failures. In the past, Fort St. Vrain has experienced difficulty in achieving successful turbine runback from 70% power. The 100% power test performed in November 1981 culminated in a successful turbine runback following the successive trips of two helium circulators; however, this event did not involve loss of grid power. The licensee is still committed to performing a B-series startup test of turbine generator load shedding from and recovery to 100% power. This test will probably be performed near the end of the current cycle.

Other electrical system upsets have also occurred. The most notable was caused by a cooling oil pressure sensor on a newly installed 4160/480 volt load center transformer. The fault occurred twice leading to transients on instrument busses and caused circulator trips which resulted in moisture ingress. The first occurred on May 29, 1984, during Cycle 4 rise-to-power, and the second occurred on June 22, 1984, initiating the sequence of events leading up to the partial ATWS event on June 23, 1984. The second event occurred because plant personnel were unable to diagnose the cause of the first event and apparently had no reason to suspect a faulty sensor.

Since 1981, both the UAT and RAT have experienced faults. On March 9, 1983, with reactor at 30% thermal power while removing moisture from the primary coolant, a phase-to-ground fault occurred on the UAT due to an arcing short caused by the moisture leakage into a bus duct from the duct cooling system. There were no moisture detectors on the ducts. The damage included burned cables and melted insulators and required ten days for repairs. Essential loads were being carried by offsite power from the RAT at the time of the incident, so no transient resulted. On December 8, 1983, high winds at the site caused a fire detector to come loose and malfunction, activating the RAT deluge system. Since most of the essential loads were being carried by the UAT at that time, there was only a minor transient involving some building cooling systems, and the RAT was restored within 20 minutes. Both of these incidents illustrate the susceptibility of the plant auxiliary transformers to externally induced events which could have led to more severe transients or loss of essential power if a combination of these or other events had occurred.

In summary, during the past three and a half years, the Fort St. Vrain electrical system has been challenged frequently. Circumstances at the time of each challenge have been such that except for the June 1984 event, the transients were minor and the safety-related implications appear negligible at first glance. However, a combination or different sequence of events have potential implications, and efforts are under way to improve the reliability of the system.

## 2.3 Reactor Building (RB)

The reactor building (RB) is a filtered, vented confinement building enclosing the PCRV and essential piping and cabling. Because the

PCRV provides a radiological barrier, personnel access to the RB is available even with the reactor operating at full power. Also, the layout of essential equipment within the RB but outside the PCRV is made in principle to allow safe shutdown and cooling even if environmental conditions in one part of the building cause failure of part of the equipment and limit personnel access. Some of the notable reactor building events are discussed as follows.

On August 26, 1981, with the reactor shut down, hot slag from welding a pipe hanger fell into oil-absorbent material placed beneath a cable tray to soak up fluid which had leaked from a hydraulic shock absorber (snubber). A fire started, damaging 31 of 36 cables in the tray including 16 essential cables. The fire was extinguished by contractor personnel in about five minutes, but was not reported to the licensee for two hours. On July 26, 1983, a welder was found working inside the RB without a fire-resistant drop cloth to catch hot slag or a fire watch. In this case, there was no fire. On January 26, 1985, with the reactor shut down, a reactor scram was initiated by high neutron flux rate. The scram was attributed to the effect of electromagnetic fields generated by a welding machine high frequency start operating in close proximity to the flux detector cables. Further investigation has revealed that the welding machine starter was apparently grounded to the cable conduit. There were apparently no "safe grounds" designated for welding machine use. These events illustrate the importance of controlling the RB environment to hazardous conditions which may be generated by workers, tools, or other maintenance equipment, and the events provide lessons for all operating reactors.

During August 6-8, 1983, a reheat steam leak underneath the PCRV caused impedance variations in cables of the helium circulator speed-high trip. The impedence variations led to loss of one channel of the speed-high trip logic (2/3 channels generate a trip); however, loss of electrical current on a speed-high trip channel did cause the trip of a speed-low channel. The licensee diverted the steam leak and later repaired the steam leak and replaced the cable with one having higher quality insulation. This event was reviewed[13] in some detail because of the concern that the unlikely occurrence of a postulated PCRV penetration failure (DBA No. 2) could lead to an extended LOFC (DBA No. 1) due to circulator damage because of overspeed. This situation could only occur if the speed-high trip functions were all lost due to the effects of the hot helium blowdown and if an independent failure occurred on the speed-low trip logic. Our review found that adequate cable separation existed to preclude loss of all speed-high cables and that the design pressure differential could not be experienced simultaneously by all four helium circulators for any given PCRV penetration failure.

## 3. CONCLUSIONS

Fort St. Vrain operating experience since late 1981 has been dominated by long periods of shutdown often due to safety implications of operating events which required significant maintenance. Many events which have obviously not caused shutdown have raised safety-related concerns. The sources, the effects and, perhaps most importantly, the detection of moisture ingress are the most significant operational problems. Although none of the challenges experienced to the essential electrical supplies have proven to be a serious problem with regard to adequate core cooling, there have been a number of potentially serious challenges which were minimized by the operating mode of the reactor.

The evaluation of the operating events at Fort St. Vrain has provided insight into necessary improvements in HTGR design and operation. The lessons learned can only be obtained through experience and are particularly valuable for the development of advanced designs such as the HTGR. The analysis of operating data provides insights into component and system interactions and reemphasizes the importance of integrating the design, construction, operation, and requirements for emergency response in commercial power reactors. Such experience illustrates that diligence, attention to the technical details, an intuitively questioning attitude, and the delegation of responsible authority are necessary to ensure safe operation and availability. In addition to ORNL's and NRC's independent assessment of operating experience from Fort St. Vrain, the licensee, the U.S. Department of Energy, and industry groups maintain vigilance of both domestic and foreign reactor experience applicable to the HTGR. The continued evaluation and feedback of operating experience is essential to ensuring the viability and success of the HTGR as a safe and economic competitor in the commercial nuclear power market.

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