Attachment
to P-86^58

CHERNOBYL NUCLEAR REACTOR ACCIDENT

AND ITS IMPLICATIONS

UPON

FORT ST. VRAIN

PUBLIC SERVICE COMPANY OF COLORADO

MAY 9, 1986

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FOREWORD

This analysis was prepared in response to two questions posed by the Nuclear Regulatory Commission as a result of the Chernobyl nuclear reactor accident. The two questions can be summarized as follows:

1. What sequence of events would be required to create a graphite fire accident at Fort St. Vrain (FSV)?

2. Were a graphite fire to occur at Fort St. Vrain, what means are available to cope with this accident and what would be the consequences of such an accident?

The term "graphite fire" has not been used in this analysis. The concept of a free burning fire or open flames with respect to a graphite mass in a confined volume having a restricted source of oxygen is inappropriate. The term "graphite oxidation" is therefore used in this analysis.

A credible mechanism could not be identified that would cause a sufficient number of failures to result in significant Fort St. Vrain graphite oxidation. However, to respond to the basic intent of the questions, the attached analysis postulates sufficient failures of the largest redundant reactor pressure boundaries to achieve a worst case graphite oxidation accident scenario. It should not be concluded that this postulated accident scenario, or any lesser graphite oxidation accident scenario, has a realistic opportunity to occur.

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I. INTRODUCTION

The recent accident at the Chernobyl RBMK nuclear power plant in the Soviet Union has resulted in Nuclear Regulatory Commission inquiries concerning the possibility of graphite oxidation at Fort St. Vrain (FSV). This scenario was previously addressed and reviewed thoroughly during the licensing of FSV. The FSV construction permit and operating license were issued based on the NRC's conclusion "that the potential amount of air ingress and oxidation.... would be small and would not appreciably affect the radiological consequences."*

Public Service Company of Colorado (PSC) and GA Technologies (GA) have conducted another review of FSV in light of the Soviet accident. This review's purpose is to determine if graphite oxidation, such as experienced at Chernobyl, could occur at FSV and how such a postulated reaction could be extinguished.

To have graphite oxidation, sufficient oxygen and heat must be present in the Prestressed Concrete Reactor Vessel (PCRV), which provides both primary and secondary containment of the reactor. To achieve this oxidation in the inert helium atmosphere of the core, the PCRV must be breached in such a manner as to create an air flow path. Only one combination of failures can be postulated which would establish the "chimney effect" flow conditions necessary to obtain significant oxidation.

This chimney effect can only be established by the simultaneous failure of both primary and secondary closures of a top PCRV penetration, and a similar failure of both closures of a bottom PCRV penetration. This incredible accident, well beyond the Fort St. Vrain design basis and FSAR licensing basis, was developed to consider massive graphite oxidation as a worst case bounding scenario for air ingress into the PCRV. This postulated event is essentially the occurrence of two simultaneous Design Basis Accident No. 2 (DBA-2), Rapid Depressurization/Blowdown, each of which has a 1 x 10E-9 per year probability of occurrence.

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* Safety Evaluation by the Division of Reactor Licensing USAEC in the Matter of Public Service Company of Colorado, Fort St. Vrain Nuclear Generating Station, Docket No. 50-267. June 21, 1968, PP 73-75.

This paper presents the results of this review:

- The fundamental design differences between the reactors with regard to graphite oxidation and accident initiation
- The FSV FSAR licensing basis air ingress events (DBA-2)
- The selection of a Double DBA-2
- The probability of occurrence of such a scenario
- The resulting air ingress and graphite oxidation
- Mitigating actions to stop air ingress and the graphite oxidation
- An estimate of offsite radiological dose consequences

Based on available information and this review, PSC and GA concluded that the RBMK reactor design aspects, which appear to have been a major contributor to the Chernobyl accident, are not present at FSV. The non-mechanistic accident scenario necessary to permit significant air ingress at FSV is highly incredible. The air ingress, and thereby the graphite oxidation, could be halted within 24 hours by flooding the Reactor Building with firewater up to the bottom PCRV penetration. Offsite dose consequences would still be within 10CFR100 guidelines for the Low Population Zone.

II. DESIGN DIFFERENCES: FSV vs. RBMK

Although both reactors have a graphite moderator, there are significant fundamental differences between the FSV high temperature gas-cooled reactor (HTGR) and the Chernobyl pressure tube-type heterogeneous uranium-graphite boiling-water reactor (RBMK). These include the fuel design, the primary coolant, the primary system enclosure, the core cooling capability, and the secondary radioactivity barriers. Based upon the available information, it appears that many of the design features which may have exacerbated the accident at Chernobyl are not present at FSV.

A. FUEL DESIGN

The FSV HTGR utilizes ceramic coated Th/UC and ThC2 fuel particles embedded in a graphite matrix within graphite fuel blocks, which are cooled by helium flowing through channels in the block. The particle coatings are the primary barrier to fission product release.

RBMK utilizes stainless steel and zirconium-niobium alloy clad UO2 fuel elements within process tubes located within the central holes of graphite columns. It is believed, based on available information, that chemical interaction between the metallic cladding, and possibly the process tubes, with the water coolant may have generated sufficient heat and a hydrogen gas byproduct to initiate burning of the RBMK graphite moderator. The FSV helium coolant is chemically inert.

It has been reported, in recent Senate testimony by Harold Denton of the NRC, that the RBMK core design features a positive temperature coefficient of reactivity, a feature not allowed under the NRC General Design Criteria.

Finally, the RBMK core operates at temperatures closer to those at which the buildup of lattice dislocation (Wigner) energy in graphite can be a consideration. If the RBMK reactor operated for a significant time prior to the accident at less than full power, Wigner energy buildup may have been a factor in the course of the accident. The buildup of Wigner energy, which can lead to a rapid increase in temperature upon release, is not a consideration in FSV. At FSV operating temperatures, graphite lattice dislocations are annealed out continuously, and significant buildup of Wigner energy can not occur.

B. PRIMARY COOLANT

The FSV HTGR coolant is helium that is circulated downward through the core to the steam generators located beneath the core before returning to the top plenum through the helium circulators. Cold reheat steam from the turbines drives the helium circulators.

The RBMK coolant is light water that is boiled as it passes through the core in the pressurized metallic tubes. The steam produced in the reactor is fed to the turbine via a separator drum, and its condensate is directed to the reactor circulation loop. Thus the RBMK reactor is a direct cycle system with multiple potential pathways for air ingress into the core and for fission product escape to the atmosphere.

C. PRIMARY SYSTEM ENCLOSURES

The entire FSV helium primary coolant system is enclosed within the structurally redundant steel-lined Prestressed Concrete Reactor Vessel (PCRV) that operates at a pressure of 700 psia. The PCRV is designed to withstand over 1700 psig without failure and has multiple plant protective systems and safety valves that prevent pressure from exceeding the design pressure of 845 psig. The PCRV liner serves as the second barrier to fission product release (the ceramic carbon fuel particle coatings serving as the primary barrier to fission product release). PCRV penetrations are each provided with two structurally independent, redundant closure seal assemblies. The primary closures, located at the PCRV interior, in effect serve as an extension of the PCRV liner as the second fission product barrier. The secondary closures are located at the PCRV exterior. In conjunction with the PCRV prestressed concrete, the secondary closures serve as the third barrier to fission product release and perform a function that is largely analogous to that of an LWR containment building.

The Chernobyl core is contained within a low pressure reactor enclosure in a concrete well, confined by metal lower and upper supports and a metal cylindrical jacket. The reactor space is filled with a mixture of helium and nitrogen with surrounding spaces filled with backup nitrogen. In the RBMK design, the boiling water coolant passes through the low pressure enclosure space to and from the turbines. This design does not feature any components which provide high pressure containment capability.

D. <u>CORE COOLING CAPABILITY</u>

The FSV plant has two main loops, either of which is capable of removing decay heat with the primary system pressurized or depressurized. Each loop has two circulators with multiple, diverse motive power sources. There are also multiple, diverse heat sinks that include feedwater, firewater, and condensate. In all there are twenty-six different cooling configurations for decay heat removal. The all ceramic core design provides up to five hours before resumption of core cooling is needed upon loss of forced helium circulation from full power.

The RBMK plant has two identical independent loops each with four pumps, any one of which could circulate the coolant to remove decay heat. Thus, based on the diversity of its primary and secondary systems, FSV has a clear advantage regarding core cooling reliability.

E. <u>SECONDARY CONTAINMENT</u>

Both the RBMK and FSV plants are housed in a Reactor Building. However, the FSV secondary penetration closures on the PCRV provide an independent penetration closure to provide radioactivity retention. Thus, FSV has a secondary containment built into the massive PCRV that protects the ceramic fuel. Penetration closures are constructed to the requirements of ASME Section III. The FSV Reactor building also confines and delays release of radioactive material. It features a filtered ventilation system for fission product cleanup. A louver system protects the building against over-pressurization.

F. CONCLUSION

There are many more differences than similarities between the FSV HTGR and the Chernobyl RBMK. Many of the design features that appear to have played a major role in the Chernobyl accident are not present at FSV. The FSV plant has clear and well recognized safety advantages that were intrinsically designed in from the conceptual design phase. Prevention against graphite oxidation by air was a major consideration in the selection of ceramic high-temperature fuel, the helium coolant, and the PCRV design with two independent closures at each penetration.

III. FORT ST. VRAIN LICENSING BASIS

The potential consequences of air ingress into the PCRV were considered during the design and licensing of Fort St. Vrain. The licensing basis presented in the FSAR considers a wide spectrum of incidents and accidents. Of these events, Design Basis Accident No. 2 (DBA-2), Rapid Depressurization/Blowdown, has the largest potential for air ingress and graphite oxidation. DBA-2 is described in FSAR Section 14.11, and consists of a hypothetical simultaneous failure of the two independent closures in the PCRV bottom head access penetration. An analogous failure for an LWR would involve simultaneous failure of the primary coolant boundary and the containment, which is a scenario considered to be beyond the design basis for an LWR.

The FSAR provides a discussion of the credibility of this accident. The accident is considered to be entirely hypothetical because the PCRV penetrations have been designed to prevent such failures. Design features incorporated to achieve this objective include: redundant closures designed and fabricated to ASME Section III requirements to withstand up to 2.1 times Reference Pressure (2.5 times normal operating pressure); two independent means of transferring the pressure loads from the primary closures to the PCRV concrete; and structural independence of the redundant closures.

An evaluation has been conducted of the median frequency associated with DBA-2. The median likelihood of this accident was estimated to be approximately 1 x 10E-9 per year, with an uncertainty factor (P95/Median) of less than 90. This accident frequency is well below that which is usually considered to be "significant".

Nevertheless, in DBA-2 a rapid, uncontrolled primary system depressurization (about 2 minutes in duration) is postulated due to the hypothetical simultaneous failure of the two independent closures in the PCRV bottom head access penetration. Failure of the closures of this penetration results in the largest possible PCRV depressurization area and rate. The reactor coolant with its circulating activity is released from the PCRV to the Reactor Building, along with a fraction of the removable plated out fission products. The results of the FSAR analysis of this event show that adequate primary circuit cooling would be maintained following the depressurization by use of the circulators on either steam or water turbine drive with the reduced coolant density. No damage to the circulators would occur during the depressurization. Maximum fuel temperature following the depressurization remains below that at which, according to the conservative fuel failure model in the FSAR, rapid fuel particle coating degradation is expected to occur.

Section 14.11.2.3 of the FSAR discusses the potential for ingress of air into the PCRV following the DBA-2 blowdown. The primary air ingress mechanisms are breathing due to PCRV cooldown and diffusion of air through the open penetration. Analyses of these phenomena, which are discussed in detail in the FSAR, indicate that the resultant graphite oxidation rate is less than 3 lbs. per hour, and the heat generated from the reaction is less than 1% of the reactor decay heat.

In summary, the consequences of air ingress and graphite oxidation were considered in the FSV licensing basis. No accidents that led to significant air ingress were identified. The accident resulting in the largest air ingress, DBA-2, is a purely hypothetical accident and is estimated to have a very small median frequency, 1 x 10E-9 per year.

IV. FSV ACCIDENTS BEYOND DESIGN BASIS

The accident analyses in the FSV FSAR indicate that the potential for air ingress into the PCRV is small. However, non-mechanistic hypothetical accident scenarios beyond the design basis have been considered in light of the Chernobyl accident. The purpose of these evaluations was to determine whether any remotely plausible scenario that involves significant graphite oxidation exists.

A. SELECTION OF DOUBLE DBA-2

Based upon these evaluations, it was determined that the largest air ingress one could plausibly postulate would result from a Double DBA-2 accident in which simultaneous failures of both independent closures in two separate PCRV penetrations occur (a quadruple failure initiating event). Air ingress resulting from any other remotely plausible scenario would be bounded by this Double DBA-2 event.

For Double DBA-2 to result in significant air ingress, one penetration failure must occur in the top of the PCRV, while the second failure simultaneously occurs in the bottom of the PCRV. These failures could produce a flowpath ("chimney") via which air could be drawn into the lower opening and convected through the steam generators and the reactor core to the reactor top plenum, where it is discharged through the upper opening. If both openings occur in the top of the PCRV or both occur in the bottom, the necessary convective flow path would not be established, and the consequences of Double DBA-2 would be similar to those of the FSAR DBA-2. In addition to the location of the double failures, the timing of the failures is important. The double failures must occur at essentially the same time. The PCRV blowdown transient can be as short as two minutes. Once PCRV pressure has been reduced to atmospheric, a second penetration failure becomes even more incredible.

The incredibility of this two-penetration failure is confirmed by the NRC conclusion "that a sudden total failure of both the inner and outer closures of any one of the PCRV penetrations would represent a conservative upper limit to the spectrum of hypothetical failures that might conceivably occur in the primary system envelope".*

B. PROBABILITY OF OCCURRENCE

As discussed in Section III, of this paper, the median frequency of the FSAR DBA-2 is estimated to be 1 x 10E-9 per year. The median frequency of a Double DBA-2, with failures occurring simultaneously at the top and bottom of the PCRV, has not been specifically calculated. The frequency is certainly significantly less than 1 x 10E-9 per year. At such low frequencies, associated uncertainties are high. However, even at the upper limit of the uncertainty band, the accident frequency is so small that the accident is considered to be highly incredible.

C. AIR INGRESS AND GRAPHITE OXIDATION

Air Ingress Rate:

To calculate the rate of air ingress and graphite oxidation associated with a Double DBA-2, it was conservatively assumed that the upper and lower PCRV access penetrations failed. The effective flow areas associated with these failed penetrations are the largest in the top and bottom head of the PCRV, 59 sq. inches and 87 sq. inches, respectively. It was assumed that forced circulation is shut off or is not available. This assumption is appropriate since core cooling would not be effective with openings of these sizes in the PCRV. It was assumed that the subsequent core heat up and cooldown would proceed as described in Section 14.10 of the FSAR, and that the PCRV liner cooling system would continue to operate.

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* Safety Evaluation by the Division of Reactor Licensing USAEC in the Matter of Public Service Company of Colorado, Fort St. Vrain Nuclear Generating Station, Docket No. 50-267, January 20, 1972, page 35.

The rate of air ingress would increase with time as the reactor core heats up. The results of the ingress analysis show that the maximum air ingress rate is less than 500 scfm when maximum core temperatures are attained.

Graphite Oxidation Rate:

Graphite will oxidize in the presence of air at elevated temperatures. Since graphite is porous, the overall oxidation process involves four basic steps: (1) transport of oxygen to the surface, (2) diffusion of oxygen into the porous media, (3) chemical reaction and (4) diffusion of the reaction products, carbon monoxide and carbon dioxide, out. At low temperatures, 600 to 900 degrees F, steps (1) and (2) are fast relative to chemical reaction and the oxidation occurs homogeneously throughout the material. At high temperature, above 1500 degrees F, the rate of reaction is fast relative to transport, and oxidation occurs primarily on the surface. The overall oxidation rate, therefore, is equal to the rate of transport of oxygen to the surface. At intermediate temperatures simultaneous diffusion in depth and chemical reactions occur creating an oxidation "profile". At high graphite temperatures, the predominate reaction is:

$$C + 1/2\ O_2 \rightarrow CO + 52{,}000 \text{ Btu/lb mole of C}$$

During most of the Double DBA-2 core heatup, high graphite temperatures would prevail. Oxidation would occur primarily on the surfaces of the graphite and would be limited by the rate of air transport to the surfaces.

To calculate the graphite oxidation rate associated with the Double DBA-2 accident, it was assumed that all of the air entering the bottom of the PCRV is drawn upward through the core. In fact, some air would be expected to flow around the outside of the core barrel and not come into contact with the graphite. Average initial core graphite temperatures were assumed to be about 1600 degrees F, and the core support structures (posts, blocks, and bottom reflectors) were assumed to be initially at about 1400 degrees F. At these temperatures, most of the incoming oxygen will be consumed by the core support structures. As core heatup proceeds, the core support area temperature can approach 1800 degrees F, increasing the likelihood of preferential oxidation in that area.

If it is assumed that, for reasons discussed in subsection IV.D, the air flow is terminated after 24 hours, the following oxidation results are obtained. Core support post temperatures would reach about 1500 degrees F. Their structural integrity would be maintained, with less than 0.33 inches being oxidized from the post radius. The core support post diameter is 6 inches, and each post bears an average compressive stress of 350 psi. Loss of 0.33 inches from the post radius results in an increase in the average compressive stress to 440 psi, well below the 8000 psi comprehensive strength of the material. The maximum oxidation rate in the center of the core, where temperatures would reach 4800 degrees F, would be less than 0.1 weight percent (w%) per hour (assuming that all oxidation is concentrated in the active core) or less than 2.5% in 24 hours. Since fuel particle coating failure during the first 24 hours of this accident is expected to be only about 12%, the resulting release of fission products from the oxidized graphite is somewhat minimized.

If no action were taken to terminate the air flow, graphite oxidation could continue indefinitely.

As noted previously, at these high graphite temperatures the rate of oxidation is limited by the rate of air transport to the graphite surfaces. All oxygen which contacts the graphite will be consumed. Because the amount of air flow is limited to less than 500 scfm, the total exothermic heat generated by the oxidation is estimated to be less than 5% of the core decay heat five hours after shutdown. Therefore, oxidation would not increase core temperatures significantly, nor would it cause self-sustaining core burning. Burning refers to rapid oxidation in which the heat of combustion exceeds the rate of cooling by air flow or by radiation, thereby leading to a self-sustained process. For an HTGR fuel block in unrestricted air flow, this phenomenon would occur at about 1800 degrees F. Since temperatures in the core are driven to much higher values during a core heatup by the decay heat, the question of self-sustained burning is not pertinent. It is sufficient to state that all oxygen that contacts the core will be consumed. If the supply of air is cut off, oxidation will cease.

D. MITIGATING ACTIONS

To stop the graphite oxidation resulting from a Double DBA-2, it is necessary only to stop the flow of air through the PCRV. The most direct and simple means of doing this would be to flood the lower 3-1/2 floors of the Reactor Building. This action would create a water level high enough to seal off the bottom access penetration of the PCRV, thereby blocking the air flowpath.

The volume of water required is about 2.5 million gallons. This water could be obtained from the storage ponds located outside of the plant, which have a minimum inventory of 20 million gallons, via one or more firewater pumps. Using only one pump, it is estimated that the lower 3-1/2 floors could be flooded in about 24 hours. The time required would be proportionately reduced with more pumps. Water ingress into the PCRV resulting from liftoff of spray as the water level approaches the lower opening would be expected to be small relative to the water ingress scenarios already evaluated in the FSAR.

Reactor Building access for this action would be necessary only to run fire hoses into the building. Dose rates in the Reactor Building one hour following DBA-2 have been estimated to be about 16 rads/hr, a value sufficiently low to allow access for this purpose.

E. <u>DOSE CONSEQUENCES</u>

Offsite dose consequences resulting from a Class 9 accident scenario such as a Double DBA-2 would be much more severe than those calculated for the FSAR design basis accidents except during the initial stage. Double DBA-2 doses have been estimated under the following assumptions:

1. Accident occurs at 105% reactor power.

2. Offsite doses resulting from the initial depressurization are the same as those for DBA-2 in the FSAR, using FSV FSAR assumptions.

3. Fuel failure is consistent with GA core heat-up simulation test results. Fission product release fractions are consistent with FSAR models.

4. Offsite doses during the first 24 hours after depressurization result from the core heat-up source term, and oxidation of fission product bearing graphite. Air flow rate is conservatively assumed to be 1,000 scfm for 24 hours.

5. Air ingress into the PCRV after Reactor Building flooding is negligible.

6. PCRV leakage rate after 24 hours is 6%/day, based on expansion during heat-up.

7. Meteorology, breathing rates, etc. are the same as assumed for DBA-2 in the FSAR.

8. With Reactor Building Ventilation System operating, release is elevated. Without ventilation system, release is at ground level.

9. Ventilation filter efficiency is at FSAR values.

Two hour doses at the Exclusion Area Boundary (EAB) (590 m radius) for this accident are the same as those given for DBA-2 in the FSAR: 2.5 rem whole body, 17.4 rem thyroid, and 4.8 rem bone. These doses are within 10CFR100 two hour guidelines for the EAB.

The following EAB doses were calculated for this accident for the first 24 hours after the accident:

	Whole Body	Thyroid	Bone
With ventilation	43 rem	770 rem	4.8 rem
Without ventilation	11 rem	1313 rem	8.2 rem

The following 30 day offsite doses were calculated for this accident for the Low Population Zone (LPZ) boundary (16,000 m radius):

	Whole Body	Thyroid	Bone
With ventilation	1.5 rem	32 rem	0.66 rem
Without ventilation	0.3 rem	53 rem	0.78 rem
10CFR100 guidelines	25 rem	300 rem	-----

Additional dose accumulation from 30 to 180 days would be minimal relative to these values.

Thyroid doses with ventilation are lower than those without ventilation due to the removal of iodine by the Reactor Building Ventilation System filters. Whole body doses, on the other hand, are dominated by noble gases, which are not removed by the filters. Operation of the Ventilation System forces the noble gases out of the Reactor Building at a faster rate, providing less time for radionuclide decay to reduce the offsite dose. Hence, whole body doses are higher with the Reactor Building Ventilation System operating.

It can be seen that, in spite of the extreme severity of this accident scenario, the offsite dose consequences are within 10CFR100 guidelines for the LPZ and are exceeded only in the immediate vicinity of the plant.

V. CONCLUSIONS

A comparison of the RBMK reactor design and FSV indicates that there are more differences than similarities between the designs. Many of the design features that appear to have played a major role in the Chernobyl accident are not present at FSV.

The consequences of air ingress into the PCRV and graphite oxidation were considered during the licensing of FSV. No accidents that led to significant air ingress were identified. The accident resulting in the largest air ingress, DBA-2, is estimated to have a median frequency of only 1 x 10E-09 per year.

While one can postulate scenarios beyond design and licensing basis that cause significant air ingress at FSV, such as a Double DBA-2, the probability of occurrence is extremely remote, much less than 1 x 10E-09 per year. At these low frequencies, such accidents can only be judged to be highly incredible.

Nevertheless, the consequences of a Double DBA-2 accident, involving simultaneous failure of both closures of both the top and bottom PCRV access penetrations, have been assessed. Simple, direct means exist to terminate air flow and graphite oxidation within at most 24 hours by flooding the Reactor Building up to the level of the lower PCRV opening. During these 24 hours, core support graphite oxidation and oxidation in the center of the core would be minimal. Structural integrity of the core would be retained. Self-sustained graphite burning would not occur, and graphite oxidation would stop upon termination of air flow. The offsite dose consequences of this scenario are still within 10CFR100 guidelines at the Low Population Zone boundary, under the conservative FSV dose calculation assumptions in the FSAR.

Based upon this evaluation, it is concluded that an accident directly comparable to the Chernobyl accident can not occur at FSV due to fundamental design differences. The probability of any remotely comparable accident is much less than 1 x 10E-9 per reactor year, and the dose consequences are within 10CFR100 guidelines at the LPZ boundary. Therefore, it is concluded that the risk to public health and safety from accidents at FSV remains small.