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WARD-2000-31

MASTER

1000 MWe

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Liquid Metal Fast Breeder Reactor

FOLLOW-ON STUDY

WESTINGHOUSE ELECTRIC
TASK I REPORT

Topical Report
**Evaluation of Vented-to-Coolant
Design for Sodium-Bonded
Carbide Fuel Rods**

Prepared for ARGONNE NATIONAL LABORATORY

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United States Atomic Energy Commission Division of Technical Information

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WARD-2000-31

REACTOR TECHNOLOGY (TID-4500)

EVALUATION OF VENTED-TO-COOLANT DESIGNS FOR SODIUM-BONDED CARBIDE FUEL RODS

by

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TABLE OF CONTENTS

Section	Title	Page
ACKNOWLEDGEMENT		vii
1	INTRODUCTION	1
	1.1 Statement of Problem	1
	1.2 Background	1
	1.3 Objective	2
2	SUMMARY AND CONCLUSIONS	3
3	FISSION GAS RELEASE	7
	3.1 Fission Gas Release Rate	7
	3.2 Effects of Assumptions on Fission Gas Release . .	11
4	FUEL ROD CONCEPTS	14
	4.1 Reference Fuel Rod	14
	4.2 Methods for Relieving Fission Gas Pressure	14
	4.2.1 Nonvented Rod Concept	16
	4.2.2 Vented Rod Concept	19
	4.3 Differences Between Fuel Rod Concepts.	27
	4.3.1 Assumptions Made for Vented Design	27
	4.3.2 Assumptions Made for Nonvented Design . . .	29
5	EFFECTS ON PLANT AND REACTOR COMPONENTS	30
	5.1 Gas Purification System	30
	5.2 Sodium Purification System	32
	5.3 Primary Sodium Pumps	35
	5.4 Reactor Vessel, Internals, and Fuel Handling Mechanism	35
	5.5 Shipping of Spent Fuel	35
	5.6 Effects on the Fuel Assembly	36

TABLE OF CONTENTS (Cont)

Section	Title	Page
6	SAFETY CONSIDERATIONS	39
	6.1 Nonvented Fuel Rod Safety	39
	6.2 Vented Fuel Rod Safety	40
7	EVALUATION	41
	7.1 Concept Design Selection	41
	7.2 Economic Evaluation	41
	7.2.1 Capital Costs	42
	7.2.2 Operating Costs	43
	7.3 Evaluation Summary	43
REFERENCES		46
APPENDIX A	FISSION GAS ENTRAINMENT IN THE COOLANT	47
APPENDIX B	FISSION GAS RELEASE RATE FOR THE AVERAGE ROD	54

LIST OF ILLUSTRATIONS

Figure	Title	Page
1	Fission Gas Release as a Function of Average Centerline Temperature	8
2	Axial Distribution of Burnup and Centerline Temperature	10
3	Fission Gas Release from Carbide Fuel	13
4	Radial Temperature Profiles at Axial Hot Spot	15
5	Plenum Length as a Function of Internal Pressure	18
6	Diving-Bell Vent Concept for Fuel Rods	20
7	Effect of Cover Gas Pressure on Standpipe Length	21
8	Elastic Tube Valve Vent Mechanism	23
9	Burp-Proof Vent Mechanism	24
10	Direct Vent Fuel Rod	26
11	Continuous Flow Vent Mechanism	28
A-1	Forces on Bubble	48
A-2	Schematic of Vessel and Radius of Influence, R	51

LIST OF TABLES

Table	Title	Page
1	Comparison of Fuel Rod Parameters for Vented and Nonvented Designs	4
2	Fission Product Release Rates from Fuel to Sodium Bond for the Rare Gas, Alkali, and Halogen Isotopes	33
3	Effect of Cladding Thickness on Breeding Ratio and Critical Mass	38
4	Cost Advantages of the Vented Fuel Concept	45
B-1	Amount of Fission Gas Released from Each Type of Rod	55

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SECTION 1

INTRODUCTION

1.1 STATEMENT OF PROBLEM

The economics of large fast breeder power reactors dictate low fuel cycle cost. Since the fuel inventory and fabrication costs are high, it is necessary to operate the fuel at high specific powers to long burnups. The high burnup, high performance fuel can produce a large amount of fission gas, a portion of which escapes the fuel. The fuel rod must be designed to accommodate the pressure generated by released fission gas. All reactors designed to date have contained the gas within the fuel rod. This is generally done by extending the cladding beyond the fuel to form a plenum. Certain economic penalties are associated with the longer fuel rod. The cost of the vessel, fuel handling machines, pumps and internals is increased. There is also the possible hazard of handling fuel elements with large quantities of radioactive gas and the possibility of fuel assembly blanketing by the fission gas in the event of a cladding rupture. Thus an alternate fuel design, the vented-to-coolant concept, is being considered for LMFBR design. Indeed, current fuel rod cladding technology may require a vented-to-coolant design to achieve high burnup objectives independent of safety or economical considerations.

1.2 BACKGROUND

A preliminary study was conducted under AEC contract to evaluate the vented fuel concept for a sodium-cooled fast breeder reactor.^[1] This study was performed using gas-bonded, uranium-plutonium oxide as a reference fuel. The work was part of the AEC Fast Ceramic Reactor Development Program. Several concepts for relieving the fission gas pressure in the fuel rod were considered along with several vent mechanisms for the particular concept of venting-to-coolant. The diving-bell design was selected for irradiation testing because its simplicity and lack of moving parts offered a high potential for reliability. The

analysis concluded that differences in plant capital cost, where identifiable, were not significant enough to have a bearing on the preferred venting concept; but, the cladding integrity considerations appeared to heavily favor the vented-to-coolant design.

Additional work on venting has been carried on under the Fast Ceramic Reactor Development Program. The major effort of the subsequent work has been in irradiation testing of capsules using the diving-bell vent, sodium-fuel compatibility, and the identification and evaluation of alternate vent mechanisms.

Smidt and Sommer presented a paper^[2] at the 1965 Conference on Safety, Fuels, and Core Design in Large Fast Power Reactors dealing with the application of vented fuel to sodium-cooled fast breeder reactors. The reference reactor had a gas-bonded, mixed oxide fuel and was designed to operate at 1000 MWe to 100,000 megawatt-days per ton. A porous plug of sintered metal was selected for a vent mechanism, but preliminary tests indicated sodium leakage problems. Their study indicated that venting the fission gas to the coolant allowed a two percent savings in plant cost. The greatest savings were due to the reduction in cladding thickness and elimination of the fission gas plenum. The study concluded the most important advantage of venting is the gain in safety by eliminating the possibility of a sudden burst of gas into the coolant.

1.3 OBJECTIVE

Most studies to date have been concerned with the venting of gas-bonded fuel elements. Sodium-bonded carbide fuel rods differ from gas-bonded, mixed oxide elements in several respects. There is no great need to prohibit the coolant from entering the fuel rod, since the fuel is compatible with sodium. Moreover, the vented-to-coolant fission gas release design might be a safety requirement of sodium-bonded fuel rods. If a cladding defect develops, loss of sodium bond is prevented by in-flow of sodium through the vent. A scoping study of the feasibility of incorporating the vented-to-coolant fuel rod design for sodium-bonded rods in a standard closed loop LMFBR design is discussed in this report.

SECTION 2

SUMMARY AND CONCLUSIONS

This scoping study was undertaken to assess the feasibility of venting sodium-bonded mixed carbide fuel elements. The venting-to-coolant concept, because of its more direct approach, was the venting concept selected for a comparison with a nonvented design. Table 1 summarizes the pertinent fuel rod parameters for the designs considered in this study. Although there is some cost incentive for venting, the preliminary cost difference appears to be small and is not the deciding factor.

The cost advantage of the vented concept is due primarily to the effect of the shorter overall height of the fuel rod and the resulting shorter related plant equipment. If a vented rod could operate with a thinner cladding, the lower fuel cycle cost would enhance the operating cost advantage of the vented concept.

The safety considerations may be the deciding factor in evaluating vented versus nonvented fuel concepts. The major safety problem in a vented design is the entrainment of the fission gas in the coolant. This problem can be eliminated by placing surge tanks in the primary loop. The surge tank would lower the coolant velocity sufficiently to allow the fission gas to escape to the cover gas. The safety problems in the nonvented rod cannot be solved as easily. The major problems in the nonvented rod are the loss of the sodium bond in the event of a pinhole failure in the cladding and gas blanketing of the fuel assembly. These problems are connected with the large volume of high-pressure gas contained in the rod, which is a characteristic of the non-vented design. At high burnup, the nonvented rod may also be more prone to fuel rod failures. The large quantity of radioactive gas is also a potential hazard in fuel handling.

TABLE 1

COMPARISON OF FUEL ROD PARAMETERS FOR VENTED AND NONVENTED DESIGNS

	Base Plant(A) Design	Vented(B) Design	Nonvented(C) Design
Cladding O.D.	0.300	0.300	0.300
Cladding Thickness	0.014	0.014	0.014
Pellet Diameter	0.246	0.246	0.246
Active Fuel Length	55.0	55.0	55.0
Axial Blanket Length (each end)	12.0	12.0	12.0
Sodium Expansion Plenum Length	13.0	8.0	13.0
Fission Gas Plenum Length	---	---	48.0
Vent Mechanism Length	13.0	0.0	---
End Plug (each end)	1.0	1.0	1.0
Total Rod Length	107.0	89.0	142.0
Average Power Rating (kW/ft)	13.2	13.2	13.2
Peak Power Rating (kW/ft)	30.6	30.6	30.6
Average Burnup (MWD/T)	100,000	100,000	100,000
Burnup in Hot Rod (MWD/T)	132,000	132,000	132,000
Peak Fuel Temperature (°F)	2313	2313	2313

- A. The base plant design is a vented design, but the vent mechanism length was selected before a study of venting devices could be made.
- B. The vented design allows the bond to communicate with the coolant. The sodium plenum has been sized to allow for axial fuel swelling.
- C. The nonvented design assumes that fuel is fabricated with the sodium bond filled to the top of the axial blanket. There is no advantage taken of the external coolant pressure.
- Note: All dimensions are in inches and at room temperature except where noted.

The fission gas release rate of the mixed carbide fuel is an important assumption in the comparison; both the cost and safety considerations would be affected if the rate differed significantly from that assumed in this analysis. A much lower rate than that assumed in the analysis would lessen the differences between the concepts, whereas a higher rate would magnify the differences.

Three important factors evolved from the study are: (1) safety may well be the factor determining if a vented fuel concept is to be used; (2) a vented design might be required with a sodium-bonded design to offset loss of bond which might result from a cladding defect; (3) a vented concept might be required to achieve high burnup without excessive cladding failure if the internal gas pressure is limiting.

The development of potential vent mechanisms for sodium-bonded fuels should be undertaken, since the feasibility of the sodium bond design concept might be improved by use of a vented design. The development of a reliable vent mechanism can be simplified by utilizing the compatibility of sodium and stabilized carbide fuel and by allowing contact between the sodium bond and the sodium coolant.

The safety considerations of vented, sodium-bonded fuel rods should also be studied extensively, since safety may well be the factor determining whether venting is used.

Experimental design of a vented, sodium-bonded fuel rod should be undertaken immediately. The program should include a detailed analysis of safety considerations of vented and nonvented fuel rods, quantitative economic studies, and quantitative analysis of fission product release.

A development program should be undertaken to study the rate and amount of gas entrainment in the coolant, the effects of entrained gas on the cladding and on fuel temperatures, and the methods for removing entrained gas from the system. This program should include additional analytical studies of the bubble formation as the gas escapes the fuel rod and of the bubble transport by the coolant in the upper vessel plenum. Another important area of study is the effect of entrained gas on cavitation in the pumps and in the orifices at the inlet of the radial blanket or core fuel assemblies. The analytical studies

should be supplemented by an experimental program which includes model studies of two-phase flow around the primary loop and especially through the core. Initiation of this program has large significance since removal of entrained fission gas could be the limiting condition for use of a vented rod design.

An important difference between the use of a vented concept with oxide and carbide fuels is that the requirement of fuel isolation from the coolant does not exist with carbide fuels. Moreover, with oxide fuels, excessive cladding strain could exist at high burnup which might cause a high cladding failure rate. Under these conditions, reactor shutdown might be required with a nonvented rod design to clean up the coolant. This limitation does not occur for nonvented sodium-bonded rods since a design can be achieved in which the fuel does not restrain the cladding.

SECTION 3

FISSION GAS RELEASE

3.1 FISSION GAS RELEASE RATE

There are few data available on the release of fission gas from uranium-plutonium carbide, (U,Pu)C. Some data are available for hyperstoichiometric (carbon rich) and hypostoichiometric (metal rich) fuels irradiated in a thermal flux. Since the reference fuel for this study is stabilized with chromium carbide (Cr_{23}C_6) to reduce carbon mass transfer, the applicability of the unstabilized data is questionable, but it is being used until data for the stabilized fuel become available. Figure 1 shows the recommended preliminary design curve for the fission gas release of (U,Pu)C used throughout this study. A better fission gas model has since been developed,^[3] which predicts higher release rates, but which was not available in time for the present study. The curve is based on the time averaged centerline temperature of the irradiation specimen and does not account for stoichiometry differences in the specimens or for temperature gradients. The fission gas release rate is assumed to be independent of burnup; no correction is made for the differences in the power rating of the specimens. It is assumed that 30 stable gas atoms are formed for every 100 fissions.

The release of fission gas from a fuel element is dependent upon the fuel temperature and the amount of gas produced. In order to determine the overall fuel rod release rate, it is necessary to know the amount of gas released at each point along the rod. The rod is divided into segments of equal size. The release rate is determined at each point using the curve in Figure 1 and the axial distribution of the centerline temperature. An axial distribution of the normalized burnup is used to determine the relative burnup at each point. The release at each point can then be determined from the release rate and the relative burnup, and averaged to obtain the overall fuel rod release rate.

Figure 1. Fission Gas Release as a Function of Average Centerline Temperature

Figure 2 shows the axial distribution of the centerline temperature of a typical hot rod where the peak temperature is near the fuel temperature limit of 2355°F. The 2355°F temperature limit is determined by the ternary phase melting point of the chromium-stabilized mixed carbide. Figure 2 also shows the axial distribution of the normalized burnup with a peak-to-average ratio of 1.45. These two curves were used to calculate the overall release rate in the hot rod, which was determined to be ≈ 20.0 percent using the method described above. This rate is assumed to be constant throughout life and is not corrected for variations in the temperature profile or the axial distribution of the burnup.

Although the nuclear axial and radial hot channel factors at the beginning of life are both 1.45, the hot channel factors used for determining the end-of-life burnup in the hot rod are reduced to account for shifts in the location of the hot rod and depletion of fissionable material at the hot spot. The time-averaged axial and radial hot channel factors used are 1.30 and 1.32, respectively. The average burnup in the hot rod is 132,000 megawatt-days per metric ton. In the reference design, the fuel pellet diameter was 0.246 inches and the length of the column was 55.0 inches. The total amount of fission gas released from the fuel in the hot rod is 0.01314 cubic feet (at the ice point).

The total hot rod release is required in the analysis of the non-vented concept, but the gas released from the entire core is needed for the vented rod analysis. The average rod release rate is needed for the vented design. The average rod is defined as that rod contributing an equal fraction of the total gas released, assuming all rods in the core were identical. One method of calculating the average release rate would be to calculate the release rate in a rod of nominal dimensions operating at the average power. The major drawback to this method is that the release rate is not linear with temperature, i.e., the difference in the release rates of two rods is not directly proportional to the difference in their centerline temperatures. Another method would be to assume the reactor consisted of a certain number of rods operating at the average power conditions, a certain number operating at above-average conditions, and a certain number of rods operating at below-average conditions. The temperature distribution and subsequent release rates would then be calculated and used to obtain

Figure 2. Axial Distribution of Burnup and Centerline Temperature

the total release from each group. The total amount of gas released from the core would then be the sum of the releases from the three groups. This method would depend on the assumed distribution of the types of rods and also on how the above-average and the below-average conditions were defined. Using a similar model (described in Appendix B) the average release rate was estimated to be 5 percent. It was also assumed that the amount of gas produced in the average rod was the amount produced in a rod operating to the core-average burnup of 100,000 megawatt-days per metric ton. The total amount of fission gas released from the entire core is 102 cubic feet (at the ice point) using the above assumptions.

3.2 EFFECTS OF ASSUMPTIONS ON FISSION GAS RELEASE

As cited previously, the hot rod release rate was calculated for a rod operating with a peak fuel temperature of 2355°F, however, the final Task I design has a hot rod with a peak fuel temperature of 2313°F. Using the temperature distribution of the final Task I design and the release rate curve (Figure 1), the overall release rate of the hot rod drops to 16.4 percent. This, too, is the beginning-of-life condition and uses an axial peak-to-average flux ratio of 1.45.

It has been estimated that the hot spot in the hot rod undergoes a decrease in the power rating with time due to depletion of the fissile material such that, at the end-of-life, the power is only 80 percent of the initial power. There is also a shift in the axial peak-to-average flux factor from 1.45 to 1.30. Although the power decreases, the peak fuel temperature in the hot rod at the end-of-life does not drop appreciably because the thermal conductivity also decreases due to the accumulation of solid fission products. The release rate in the hot rod is not constant over life and the time-averaged hot rod release would have to be calculated for various power levels and flux factors. The accuracy would depend on the time step investigated.

Another factor affecting the release rate that was not incorporated in this study is the change in the recommended release curve for mixed carbide. The release curve (Figure 1) does not distinguish between hyperstoichiometric and hypostoichiometric mixed carbide release rates. It is expected that the

Cr_{23}C_6 stabilized fuel will behave like stoichiometric or hyperstoichiometric mixed carbide. Figure 3 shows the recommended design curve for hyperstoichiometric fuel. This release curve is considerably lower than that shown in Figure 1. The hot rod release rate calculated using Figure 3 and the temperature distribution of the final Task I design is 6.5 percent.

The use of 30 stable gas atoms per 100 fissions would be appropriate for a thermal reactor, but it appears that, for a fast flux, about 25 stable gas atoms are formed for every 100 fissions. This change would not affect the release rates, but would affect the amount of gas in the hot rod or released to the coolant.

A change in the amount of gas released from the fuel would affect the size of a various cleanup systems, but would probably not eliminate any system. Since the major portion of the cost of the cleanup systems is not dependent on system size, the above factors should not greatly affect the analysis. The greatest effect would be on the length needed to accommodate the fission gas in the non-vented design, which, in turn, would affect the pump size, vessel height, and pumping power.

Figure 3. Fission Gas Release from Carbide Fuel

SECTION 4

FUEL ROD CONCEPTS

4.1 REFERENCE FUEL ROD

The reference fuel rod consists of a 55-inch active fuel column with a 12-inch blanket on each end. The fuel is contained in a 14-mil-thick, stainless steel cladding having a 0.300-inch outer diameter. The active fuel column contains 0.246-inch diameter pellets of uranium-plutonium carbide, while the blanket has 0.246-inch diameter pellets of uranium carbide. The 13 mil clearance between the cladding and the fuel is filled with sodium to allow for fuel swelling. As the reactor heats up, expansion occurs and the sodium bond level rises. In the nonvented design and certain vented designs, it is necessary to accommodate this increase in sodium volume within the rod above the fuel. The length of rod needed for the expelled sodium is dependent upon the height to which the rod is filled with sodium during fabrication. If the sodium is filled to the top of the upper blanket, a 13-inch plenum above the fuel is needed; this length decreases to 11 inches if the sodium is filled to the top of the active core.

The fuel rod is operating at an average power rating of 13.2 kilowatts per foot and the hot rod has a peak power rating of 30.6 kilowatts per foot. The peak fuel temperature in the hot rod is 2313°F; the radial temperature profiles at the axial hot spot are shown in Figure 4 for both the hot and average rods.

4.2 METHODS FOR RELIEVING FISSION GAS PRESSURE

The pressure within the rod increases as the fission gas escapes the fuel. Since reactor performance dictates a thin cladding, the internal rod pressure must be limited to prohibit cladding failure. Unless some means of accommodating the fission gas is used, the pressure limitations would soon be exceeded. There are three means available to accommodate the fission gas: (1) allow

Figure 4. Radial Temperature Profiles at Axial Hot Spot

additional volume within the fuel rod so that the allowable pressure is not exceeded; (2) remove the fission gas to a plenum external from the fuel rod; (3) vent the fission gas directly to the coolant.

The nonvented concept and the vented-to-coolant concepts are the methods used for the comparison in this study and are described in more detail later in this section. The vented-to-external plenum concept requires a means for transferring gas from the rod to the external plenum. If the external plenum was located apart from the fuel assembly, small tubes would be needed to connect the rods and the plenum. This maze of tubing would greatly clutter the interior of the pressure vessel, making refueling particularly difficult. An alternate approach would have a plenum integral with the fuel assembly; this would also shorten the connection between the rods and the plenum. This concept would allow a short fuel rod without the release of fission products to the coolant, but the hazard of releasing large quantities of gas into the coolant at one time is increased, since a failure in any of the rods or connections would allow the gas to escape from many rods.

4.2.1 Nonvented Rod Concept

In a nonvented fuel rod, the fission gas is accommodated within the cladding above the fuel column. This plenum length is governed by the allowable internal pressure exerted on the cladding by the fission gas. In order to minimize rod failure, it is necessary to design the gas plenum to the hot rod conditions. Some factors affecting the plenum length are the fission gas release rate, the amount of gas produced in the fuel, the temperature of the gas in the plenum, the pressure of the fill-gas, and the allowable internal pressure. The temperature of the fission gas in the plenum was taken to be equal to the 1240°F outlet coolant temperature of the hot channel. The hot rod fission gas release rate was discussed in Section 3; a release rate of 20 percent was used in the determination of the plenum length. Since the hot rod may not be in the same location throughout life, the radial hot channel factor was reduced from 1.45 to 1.32 to account for this effect. Using the reduced hot channel factor, the average burnup in the hot rod is 132,000 megawatt-days per metric ton. With this burnup, a 20 percent release rate, and a production rate of 0.3 stable

atoms of fission gas per fission, the plenum at the end-of-life contains 3.66×10^{-5} pound-moles of fission gas. Since the fabrication of the fuel rod has to take place in an inert atmosphere, it was assumed that the inert gas (helium or argon) was at 60°F and a pressure of one atmosphere. The increase in gas temperature as the rod is heated causes an increase in the fill gas pressure to 50 psia. This lowers the allowable partial pressure of the fission gas. An analysis (performed under a Westinghouse-funded project) was made of the stresses in the cladding, and creep was found to limit the internal pressure. The allowable internal pressure in 14-mil-thick, Type 316 stainless steel is 466 psia. This allowable pressure is actually the allowable pressure differential across the cladding. If the external rod pressure would always be maintained while the rod is hot, it would be possible to allow a higher internal pressure. The coolant pressure at the point of maximum cladding temperature is the amount the internal pressure could be increased. However, this pressure increase was not utilized in this study because an accident could be hypothesized where the cover gas pressure is lost while the reactor is still at power. The effect of pressure on the plenum length is shown in Figure 5. It can be seen that the pressure in the 400-500 psia range has a great effect on the plenum length. Anything that would lower the fission gas pressure or increase the allowable internal pressure would have a great effect on the plenum length. The pressure decrease due to the solubility of the fission gas in the sodium bond was investigated and found to be negligible. The sodium solubility of krypton was used in the analysis because there is a scarcity of information on the solubility of fission gas (xenon and krypton). The equation for krypton solubility in sodium reported in ANL-6875^[4] is:

$$\text{atom fraction of Kr} = \exp \left[-9.645 - \frac{8252}{T} \right], \text{ where } T \text{ is the temperature (°K).}$$

A non-vented fuel rod would require a 48-inch plenum for the fission gas in addition to the 11- or 13-inch plenum needed to accommodate the expelled sodium bond. The 11-inch sodium plenum corresponds to filling the rod to the top of the active core, whereas filling to the top of the axial blanket requires a 13-inch plenum.

Figure 5. Plenum Length as a Function of Internal Pressure

4.2.2 Vented Rod Concept

For this study, the vented-to-coolant concept is considered. The fission gas is allowed to enter directly into the coolant stream as it is released from the fuel rod. Two criteria were initially placed on the vent mechanism. These were: (1) the fission gas should be delayed at least five days from the time it is produced to the time it is released to the coolant, and (2) coolant-bond integrity must be maintained. These criteria were not firm and could be relaxed if they greatly impaired a design.

Several possible designs can work within the proposed restraints; among these are the diving-bell vent, the elastic tube valve, the mechanical check valve, and the porous plug vent. The diving-bell vent (Figure 6) has been tested under AEC contract^[1] for use with gas-bonded oxide fuel. This type of vent mechanism has the desirable feature of no moving parts, since it relies on the pressure of the compressed gases to prohibit sodium from flowing into the rod. The vent consists of a standpipe fastened to the cladding such that the only path a fluid can take from the rod's lower portion to the rod's upper portion is through the middle of the standpipe. The rod's upper portion contains several holes in the cladding to allow the fission gas to escape. These holes also allow the sodium coolant to enter the fuel rod; however, the standpipe is sized so that the sodium will never rise above the end. Since the coolant pressure at the holes is known and the pressure of the gas in the rod is at atmospheric conditions initially, the volume decrease of the gas when the reactor starts up can be determined. This volume decrease is the volume of sodium that must be accommodated around the outside of the standpipe. The standpipe length is dependent upon the cover gas pressure, the inner and outer diameters of the standpipe, and the void volume in the fuel rod.

In the present study, it was desired to avoid allowing the bond to enter the standpipe; therefore, a plenum for the expelled sodium bond, similar to that in the nonvented design, is needed. This plenum would initially be filled with gas which is compressed when the reactor is at power; this large void greatly increases the standpipe length. Figure 7 illustrates the effect of the cover gas pressure on the standpipe length; the cover gas pressure in the base plant design was 45 psi. The standpipe length is the same length as the plenum

Figure 6. Diving-bell Vent Concept for Fuel Rods

Figure 7. Effect of Cover Gas Pressure on Standpipe Length

in the nonvented design, even with an extremely small standpipe, using the criteria of coolant-bond integrity and standpipe-bond clearance.

The porous plug vent mechanism is another version utilizing no moving parts; however, little work has been done on the development of a suitable material. This vent would have a metallic or ceramic plug in the end of the fuel rod with one side exposed to the coolant and the other side exposed to the fission gas. The vent would have to allow the fission gas to pass while keeping out the sodium coolant. Some investigations into the wetting characteristics of metallic vents were done at Karlsruhe^[5] and it was found that wetting did occur with sodium at 1100°F. An extensive experimental program is necessary to verify the suitability of the porous plug before it can be considered a reliable vent mechanism.

The mechanical check valve type vent was not given serious consideration for a reference vent mechanism because it also entails a large development program to ensure a workable design. The major obstacles are the size and reliability requirements; any mechanism must fit within a 0.3-inch diameter. If a mechanical valve could be designed so that backflow of the fission gas could never occur, the mechanism could be used in combination with a standpipe to prohibit sodium contact.

An example of an elastic tube valve vent is shown in Figure 8. In the valve pictured, the lower end of the plunger is welded to the cladding, while the other end is interference fitted to the cladding. A hole through the plunger allows the fission gas to travel to the upper end of the fuel rod. The fission gas pressure increases until the cladding and plunger separate and the gas escapes through holes in the cladding located between the interference fit and the welded end of the plunger. Valves similar to those shown in Figure 8 have been tested in 1200°F NaK and resisted penetration by the NaK for up to 45 hours.^[6]

Another disadvantage of the diving-bell vent is the effect of a possible large release of gas when the cover gas pressure is suddenly reduced during operation. A burn-proof vent (Figure 9) was designed in the Fast Ceramic Reactor Development Program^[7] to prevent this large gas release. The gas release from the

Figure 8. Elastic Tube Valve Vent Mechanism

Figure 9. Burp-Proof Vent Mechanism

vent depends upon the pressure difference across the tube and not on the external coolant pressure. The major drawback with this vent, and with most elastic tube vents, is the sodium penetration into the rod.

None of the preceeding vent mechanisms present a clear cut advantage over the others. A major obstacle in the vent design is the criterion of no coolant-bond interaction. Since the fuel in the reference design is already in contact with sodium, there is no concern about incompatibility between the fuel and coolant. The main disadvantage with bond-coolant contact is the deposition of fission products in the primary system. An analysis was made of the effect of fission products in the primary system. For this analysis, it was assumed that the bond was expelled from the fuel rod at a linear rate such that all the bond is expelled at the end of three years (the core residence time). The activity of the expelled bond was assumed to be zero at the beginning-of-life and, at the end-of-life, equal to the activity in the bond with no bond-coolant interaction. The exact expulsion rate is not known because it depends on the vent design, the amount of coolant-bond interaction within the rod, and the number of thermal cycles the rod undergoes. The analysis identified the shielding requirements of the cold traps in the sodium cleanup system as the principal problem area when the fission products are allowed to escape to the coolant. However, the fission products do not greatly increase the shielding requirements since their activity is masked by the intrinsic activity of the sodium.

Direct release of the fission gas without a vent mechanism is possible when the coolant and bond are allowed to contact; several holes in the end cap, similar to that shown in Figure 10, would permit the gas to escape as it collects in the top of the fuel rod. This type of vent allows the shortest fuel rod. The only region needed above the axial blanket is for the axial expansion of the fuel column due to thermal expansion and swelling; although the use of this vent type requires that the bond and coolant be allowed to communicate, it may be desirable to keep as much of the bond within the rod as possible. If experiments indicate that there is little mixing between the bond and coolant, most of the fission products in the expelled bond could be accommodated above the fuel with little penalty in fuel rod height.

Figure 10. Direct Vent Fuel Rod

Figure 11 shows an extension of this direct vent concept, the continuous flow vent. The continuous flow vent would have holes in the end caps similar to the direct vent, but would also have additional holes located near the bottom of the fuel rod. These holes would be sized to orifice the flow to the desired rate. This concept would minimize the possibility of fission gas collecting between the fuel and cladding in the core region and causing local hot spots. Some sort of filter would be placed in the rod's top to prohibit large fuel fragments from escaping or clogging the vent holes.

In all of the vented designs, it is desirable to place a small rupture disc in the mechanism, so that the pressure would be relieved in a controlled manner in the event of a vent mechanism failure. The disc would prevent cladding rupture and, even with the coolant-bond integrity criterion, a controlled failure is more desirable than a ruptured cladding, especially since the cladding rupture occurs in the core region.

4.3 DIFFERENCES BETWEEN FUEL ROD CONCEPTS

The principle differences between the two concepts are the length of the fuel rod, the amount and activity of fission gases released to the coolant, and the amount and activity of solid and soluble fission products in the coolant.

4.3.1 Assumptions Made For Vented Design

It was necessary to start the base plant design with preliminary information. The vented concept was selected for the base plant design; a total of 26 inches was allocated to accommodate a vent mechanism and a sodium expansion plenum. A plenum length of 11 to 14 inches is needed for sodium expulsion if the bond sodium is to be kept out of the vent mechanism; the length depends on the as-fabricated sodium level.

Five percent of the fission gas produced in the reactor was assumed to be released to the coolant; the fission gas was also assumed to remain within the fuel rod for five days after production. Initially, a criterion of no bond-coolant contact was used, but later investigation indicated there would be only a small effect on the system if the bond and coolant mixed. The bond was assumed to contain five percent of the solid fission products.

Figure 11.
Continuous Flow Vent Mechanism

There were no failures assumed for the vented design since one of the principal causes of failure, fission gas pressure, has been eliminated. A rupture disc in the mechanism would ensure that a clogged vent would not lead to failure. Another major cause of failure is excessive fuel swelling. Allowances have been made in the fuel-clad clearance to accommodate the swelling, but there is a possibility that some rods could fail due to the fuel swelling. However, the principal effects of a rod failure are the release of the fission gas and the escape of the bond. Since the vented rods allow the fission gas and bond to mix with the coolant, failures would not affect those portions of the system, such as the gas purification and sodium cleanup systems, which must be sized to handle failures.

4.3.2 Assumptions Made for Nonvented Design

The principal assumptions for the nonvented concept are concerned with fuel rod failures. It was assumed that one percent of the 40,992 rods in the reactor failed, with none of the failures occurring before a 1.5 year residence time. The failures were assumed to occur at a linear rate from 1.5 years to 3 years. The failed rods were assumed to be a combination of hot, warm and average rods. A warm rod is defined to be a rod with half of the fission gas release of the hot rod. Of every 10 failed rods, there would be 1 hot rod, 3 warm rods, and 6 average rods. For computational purposes, every failed rod would be equivalent to 1.92 average rods.

SECTION 5

EFFECTS ON PLANT AND REACTOR COMPONENTS

In the comparison of the vented and nonvented concepts, it is necessary to know what the effect on the reactor and plant components will be.

5.1 GAS PURIFICATION SYSTEM

A purification system is provided for the inert cover gas which is over all sodium surfaces in the primary system. The purification system also removes gaseous fission products and sodium vapor from the cover gas and provides a means of circulating purified argon through the control rod and orifice mechanism, pump seals, the IHX, and the overflow tank. The reactor cover gas (argon) enters the reactor at a temperature above sodium's melting point and sweeps across the sodium surface picking up sodium vapor and fission gas. The reactor cover gas is combined with gas from the pumps and other primary components and the combined gas stream flows into sodium vapor traps. The sodium vapor is removed by trapping in condensing-impingement vapor traps, which also pre-cool the argon. The argon is further cooled by a shell and tube economizer and passed through absorption beds of activated charcoal. When the beds are saturated, they are regenerated by heating and flushed with pure argon. The fission gas is vented to the radioactive gas system.

The gas purification system design is based on the following criteria:

- a) a vented core concept with the fission gas vented to the coolant at the following rates:

Kr^{85} : 7×10^{-6} lb/hr
Other Kr: 43×10^{-6} lb/hr
 Xe^{133} : 5×10^{-6} lb/hr
Other Xe: 757×10^{-6} lb/hr
Total gas release: 812×10^{-6} lb/hr,

- b) all the fission gas released to the coolant is released to the cover gas,
- c) there is zero delay time before the fission gas leaves the fuel rod and enters the cover gas and no gas absorption in the coolant,
- d) total argon flow rate to the reactor of 250 lb/hr with inlet conditions of 250°F and 45 psia,
- e) retention time of Kr in delay beds before breakthrough occurs is 10 days.

If a nonvented fuel rod is used, the major components of the purification system affected are the absorption beds and the liquid nitrogen refrigeration units. The size of these two components is dependent upon the failure rate assumed for the nonvented rods, and, in particular, the worst case of failure. The worst case in the nonvented concept is based on the following:

- a) the linear failure of 8 rods during the last 10 days of the three year period,
- b) a total of 406 rods have previously failed and are releasing fission gas to the system,
- c) the residence time of the fission gas in the reactor cover gas volume is 30 minutes.

The heat load in the system for the nonvented concept is about 27 percent lower than that in the vented concept design due to the lower decay heat in the absorption beds.

The assumed failure rate for the nonvented concept should not greatly affect the design since the decay heat is only 0.7 percent of the sensible heat that has to be removed from the system. There would be almost no change in the system if a lower failure rate was assumed, and only a much larger rate would have an appreciable effect. In the vented concept, the decay heat load is about 38 percent of the sensible heat of the system, so the amount and activity of the fission gas reaching the absorption beds would have more effect on the system. The amount of gas reaching the absorption beds is affected mainly by the assumed release rate of fission gas from the fuel rods and, to a smaller

extent, by the quantity of gas entrained in the sodium. The activity of the gas depends on the time for the gas to enter the coolant after being produced, the time the gas remains in the coolant stream before reaching the cover gas, and the time needed for the fission gas in the cover gas to reach the absorption beds. The decay heat in the vented case stated above uses the conservative assumption that the gas immediately enters the absorption beds after being produced. The decay heat would be roughly halved if a five-day delay time were used.

5.2 SODIUM PURIFICATION SYSTEM

A sodium purification system is provided to monitor sodium purity, maintain primary sodium purity (21 ppm carbon and less than 10 ppm oxygen), and to provide sufficient tankage to allow removing all the primary system sodium from the reactor vessel and primary coolant systems. During operation, a portion of the coolant is passed through cold traps, either continuously or intermittently, to maintain the desired oxygen level. Hot traps are also provided to maintain the proper carbon content. Although the cold traps are provided to remove oxygen, fission products and mass corrosion products will plate out in the cold traps. These products do not greatly affect the sizing of the cold traps, but their activity will affect the shielding required for cold trap removal. The fission gas containment concept used does not affect the sodium purification system because the size of shields required for the cold traps are primarily affected by the intrinsic activity of the sodium and not by the fission product activity. The concentrations of fission products released to the sodium bond over the in-core residence of the fuel rod are presented in Table 2. If all the sodium bond was released to the coolant, it would have an activity of 4.3 millicuries per gram of sodium. The intrinsic activities of Na^{24} and Na^{22} are 15 millicuries and 1.5 microcuries per gram of sodium, respectively. The Co^{58} activity is 15 microcuries per gram of sodium due to activation of the nickel in the coolant as a result of corrosion. In the worst case, where all of the bond escapes to the coolant, the activity of the fission products would be about 20 percent of the total activity. The fission products would affect the time needed to allow the cold trap activity to decay to a point where removal is possible.

TABLE 2
FISSION PRODUCT RELEASE RATES FROM FUEL TO SODIUM BOND
FOR THE RARE GAS, ALKALI, AND HALOGEN ISOTOPES

Isotope	Release Rate to Na Bond at End-of-Life (atoms/sec)	Concentration in Na Bond at End of 3-yr Life (g/cc Na)
H-3	0.6×10^{16}	$2.16 \times 10^{-5(b)}$
He-3	26.0×10^{16}	(a)
Br-81	1.3×10^{17}	1.1×10^{-4}
Br-82	3.7×10^{14}	1.3×10^{-8}
Kr-82	17.4×10^{16}	(a)
Kr-83	26.0×10^{16}	(a)
Kr-84	38.4×10^{16}	(a)
Kr-85	9.7×10^{16}	(a)
Kr-86	62.0×10^{16}	(a)
Rb-85	3.9×10^{17}	3.7×10^{-4}
Rb-87	8.6×10^{17}	8.3×10^{-4}
I-127	3.0×10^{17}	4.2×10^{-4}
I-129	8.6×10^{17}	1.2×10^{-3}
I-130	1.7×10^{13}	6.0×10^{-10}
I-131	2.6×10^{16}	7.6×10^{-6}
I-133	4.7×10^{15}	1.5×10^{-7}
I-135	1.8×10^{15}	1.9×10^{-8}
Cs-133	3.8×10^{18}	3.9×10^{-3}
Cs-134	3.5×10^{17}	5.3×10^{-4}
Cs-135	4.3×10^{18}	6.3×10^{-3}
Cs-136	4.6×10^{11}	7.0×10^{-18}
Cs-137	4.8×10^{18}	7.2×10^{-3}
Xe-128	1.3×10^{16}	(a)

TABLE 2 (Cont)

FISSION PRODUCT RELEASE RATES FROM FUEL TO SODIUM BOND
FOR THE RARE GAS, ALKALI, AND HALOGEN ISOTOPES

Isotope	Release Rate to Na Bond at End-of-Life (atoms/sec)	Concentration in Na Bond at End of 3-yr Life (g/cc Na)
Xe-130	1.0×10^{16}	(a)
Xe-131	193×10^{16}	(a)
Xe-132	378×10^{16}	(a)
Xe-133	2.9×10^{16}	(a)
Xe-134	460×10^{16}	(a)
Xe-135	0.22×10^{16}	(a)
Xe-136	540×10^{16}	(a)

Notes:

- a. No retention of noble gases in bond
- b. H-3 assumed to remain in bond, e.g., NaH

5.3 PRIMARY SODIUM PUMPS

A potential advantage of the vented fuel rod concept over the nonvented concept is the shorter fuel rod. This advantage is reflected in the size of the pumps needed and also in the power needed to operate the pumps, since the increased length of the nonvented rod would increase the pressure drop due to friction. The longer fuel rod would also require more grids. The pressure drop changes about 8 psi for every foot of change in the rod length.

5.4 REACTOR VESSEL, INTERNALS, AND FUEL HANDLING MECHANISM

The longer fuel assemblies in the nonvented concept require many of the other reactor components to be larger. The increased fuel assembly height will affect the following:

- a) The fuel handling system and fuel storage system will have to be sized to handle longer fuel assemblies.
- b) The increased assembly height will result in a longer vessel and an increase in the volume of surrounding concrete.
- c) The height of the hot cell will have to be increased to handle longer assemblies.
- d) Both upper and lower core internals will be larger.

5.5 SHIPPING OF SPENT FUEL

The longer fuel assemblies in the nonvented concept would require longer shipping casks; however, the fuel cleanup prior to shipping may be more difficult with vented fuel rods. Many fuel shipping procedures would call for steam cleaning the fuel prior to shipment and the use of water cooling in the spent fuel shipping casks. The shipping casks for vented fuel rods will probably have to be doubly-contained and the inner container, if not the outer container, will have to be cooled with NaK or sodium. Any failed, nonvented fuel rods will also have to have double-containment, and it may be possible that all the nonvented rods will use double containment.

5.6 EFFECTS ON THE FUEL ASSEMBLY

The major difference between the vented and nonvented concepts is the length of the fuel rod. A nonvented fuel rod has a plenum above the axial blanket which can be from 49 inches to 61 inches long. The exact length depends on the height to which the bond is filled during fabrication and on how much the external coolant pressure can be utilized. Eleven inches of plenum are needed to accommodate the expelled sodium bond if the rod is fabricated with the bond filled to the top of the active fuel. If the bond is filled to the top of the axial blanket, the plenum has to be 13 inches long. The plenum length needed for the fission gas has to be 48 inches if no external coolant pressure is used to raise the allowable internal pressure. The reactor has a 45 psia cover gas pressure and the pressure at the point of maximum stress is about 100 psia. The required plenum length drops to 38 inches if this pressure is used to raise the allowable internal pressure. However, if the external pressure was utilized and the reactor were to lose the cover gas pressure while at power, the pressure in the fuel rod would exceed the allowable limit.

Since the nonvented fuel rod is operating with a much higher internal pressure than the vented rod, although both have the same cladding thickness, it might be possible to operate the vented rod with a higher cladding surface temperature. A higher cladding surface temperature would allow a higher mixed mean outlet temperature or a lower coolant velocity. A higher mixed mean outlet would increase the power output of the reactor. A lower coolant velocity would lower the corrosion rate and lower the pressure drop through the core, thereby decreasing pumping cost.

It is also possible to reduce the cladding thickness in the vented concept to take advantage of the lower internal pressure. Two alternatives to take advantage of a thinner cladding are: (1) maintain the same outer diameter and rod pitch and increase the fuel pellet diameter, and (2) maintain the same fuel pellet diameter and rod pitch and reduce the outer diameter of the rod. A rough estimate has been made to evaluate the effect of reducing the cladding thickness from 14 mils to 10 mils. At the Third Geneva Conference, David Okrent presented a paper^[8] which evaluated the effects of various structural materials on the breeding ratio and critical mass for a 5000-liter oxide reactor. The

changes in breeding ratio and critical mass were obtained for the case where stainless steel is replaced by zirconium; then, these were corrected for the fact that zirconium is not a void. The effect on the breeding ratio and critical mass was obtained by correcting Okrent's numbers for the change in the volume fraction of structure for a reduction in cladding thickness from 14 mils to 10 mils while keeping the fuel volume fraction constant. The breeding ratio is increased 1.0 percent, while the critical mass is decreased 0.9 percent. If the rod outer diameter is held constant and the pellet diameter is increased, the fuel volume fraction increases from 30 percent to 32.6 percent. The breeding ratio is estimated to increase 1.3 percent when the sodium is replaced by fuel. The critical mass is estimated to increase 2.3 percent. These results are tabulated in Table 3.

A 14 mil cladding was used for both the vented and nonvented designs in this study. The cladding thickness was selected before a detailed analysis of the stresses had been made. The cladding was evaluated for thermal ratcheting, creep and strain cycle fatigue, including the effects of corrosion at a loss of 1 mil per year. The analysis concluded that a 14 mil cladding was necessary for a nonvented design; this thickness is based on limiting the creep strain to 0.4 percent with an internal pressure of 470 psia. The vented rod was shown to be operable with a thinner cladding; a 12 mil cladding thickness was acceptable and a 10 mil thickness appeared feasible. Inspection of tubing with a 10-mil-thick wall is the major area of concern, since current ultrasonic methods of detecting defects become questionable. Thickness reductions due to corrosion is another problem area with a 10-mil cladding, since reductions of 3 to 4 mils would result in a serious loss of strength and reliability at the end-of-life.

TABLE 3
EFFECT OF CLADDING THICKNESS ON BREEDING RATIO AND CRITICAL MASS

	Change in Cladding O.D.	Change in Pellet Diameter
Cladding thickness (in)	0.010	0.010
Cladding O.D. (in)	0.292	0.300
Cladding I.D. (in)	0.272	0.280
Pellet diameter (in)	0.246	0.254
Volume fraction	0.300	0.326
Change in breeding ratio (percent)	+1.0	+1.3
Change in critical mass (percent)	-0.9	+2.3

Note: Reference case is 14 mil cladding thickness, 0.300in. cladding O.D., 0.246in. pellet diameter, and fuel volume fraction of 0.300.

SECTION 6

SAFETY CONSIDERATIONS

6.1 NONVENTED FUEL ROD SAFETY

In order to contain the fission gas within a reasonable length plenum, the gas has to be contained at a high pressure. This pressure is limited by the mechanical strength of the cladding. A large volume of gas under high pressure presents several potential safety problems. The nonvented fuel rod is more susceptible to failure because the stress is increased by the internal gas pressure. Even if the fission gas does not increase the failure rate, it probably increases the severity of a failure. In the event of a cladding rupture, the fission gas will escape the fuel rod and enter the coolant stream, possibly blanketing adjacent fuel rods with gas and causing the failure to propagate throughout the fuel assembly. To date this sequence of events has been speculative. Extensive analytical and experimental work is required in this area.

Another possible limitation of the nonvented fuel element is the loss of the sodium bond through a pinhole failure. If a pinhole failure occurred in or below the core region, a portion or all the bond above the failure would be forced out of the rod by the expanding fission gas. The fuel rod is designed with a large gap between the fuel and cladding to prevent cladding strain due to the fuel swelling. The conductance across the gap is good with a sodium bond, so thermal performance is not greatly impaired. However, if the sodium bond near the region of peak heat flux was expelled and replaced by gas, the fuel might melt, even if the gas were pure helium. The benefit of a smaller gap due to fuel swelling is counteracted by the decrease in gas conductivity caused by the dilution of the helium fill gas with fission gas. Use of a vented concept which permits interchange between coolant sodium and bond sodium eliminates the problem of loss of sodium bond.

6.2 VENTED FUEL ROD SAFETY

The safety problems with the vented fuel rod are mainly concerned with the presence of fission products, particularly gaseous fission products, in the coolant and cover gas. When communication of the coolant with the bond is allowed, there will be additional activity in the sodium. This additional activity will increase the shielding required for the primary loop and also complicate any detection system for failed fuel. However, the increased activity should not be a large effect since the principal sources of activity are the Na^{22} and mass corrosion product activity. There is also the possibility that fissionable material will enter the coolant stream and deposit somewhere in the loop. However, this is also a problem with failed fuel in the nonvented concept. The loop must be designed to minimize the locations where fissionable materials can collect.

The major safety problem in the vented concept is gas entrainment in the primary coolant. Several potential problems can result from gas recirculation, such as cavitation of the pumps and radial blanket orifices, cladding hot spots, and flow blockage. The reference design utilizes a loop-type primary system. With this type of system, it appears that the fission gas bubbles are swept from the upper vessel plenum before they can escape to the cover gas, for nozzle velocities greater than about 5.5 feet per second; the nozzle velocities in the reference design are about 20 to 30 feet per second. A more detailed discussion of gas entrainment is presented in Appendix A. Rather than redesigning the vessel for lower nozzle velocities, the preferred alternatives would be the installation of surge tanks or gas getters into the primary loop. More detailed analytical work and experiments are required to establish the effect of entrained fission gas on local heat transfer.

SECTION 7

EVALUATION

7.1 CONCEPT DESIGN SELECTION

The comparison of vented and nonvented fuel rod concepts is centered in two areas, safety and cost. The cost comparison can show some advantage, even a slight advantage, of one concept over the other, but the safety considerations cannot be compared as easily.

In order to make a comparison between the concepts, it is necessary to select a single design for each concept. A direct-release vent (Figure 10) with an 8-inch clearance between the top of the axial blanket and the end plug to allow for axial expansion of the fuel, was selected for the vented concept. In the nonvented concept, it was assumed that the sodium bond extended to the top of the axial blanket when fabricated and that no advantage could be made of the external coolant pressure. The nonvented fuel rod would need a 61-inch plenum above the fuel to accommodate the released fission gas and the expelled sodium bond. Using these assumptions, the vented fuel rod would be 53 inches shorter than the nonvented rod. It was decided to compare the two designs using the same cladding thickness and to assume the same reactor operating conditions.

7.2 ECONOMIC EVALUATION

The economic evaluation of the differences between the vented and nonvented concepts was made by estimating the cost of modification in the base plant design. The base plant design was a vented design. It was assumed that 26 inches were required for a vent mechanism and a plenum for the expelled sodium bond. The evaluation is also dependent upon the assumed fission gas release rate of 20 percent. No optimization was made in the nonvented concept; in fact, the cost differential was obtained on a per-foot-of-fuel-rod basis, where possible.

There are two cost differentials between the concepts, a capital cost difference and an operating cost difference. The capital costs include most of the plant costs, but do not include fuel fabrication. The operating costs include fuel fabrication and pumping power. No benefits for the vented concept were derived from the fact that a vented rod may be able to operate with a thinner cladding, higher cladding surface temperature or higher burnup.

7.2.1 Capital Costs

Since the vented design will have more fission products present in the coolant, the nonvented design will have a cost advantage in the sodium and gas purification systems, and possibly in shipping and the failed fuel detection system. The cost differences in the shipping and fuel detection systems have not been determined in this study; there may not even be a difference. Since the fission product activity is masked by the activity of the mass corrosion products, the cost difference in the sodium purification system is negligible. The gas purification system for the nonvented design is estimated to cost about \$22,000 less than that required for the vented design. The cost savings are due primarily to the smaller absorption beds and nitrogen refrigeration units.

The vented design has a cost advantage in the vessel and internals, fuel handling mechanisms, thermal and neutron shields, reactor containment and pumps. The cost saving is primarily a function of the shorter fuel rod in the vented design. The vessel, refueling machines, building and related equipment are estimated to cost about \$150,000 more for every foot increase in vessel height. This would give the vented design a cost advantage of approximately \$660,000; this does not include the cost saving in core internals and instrumentation.

The pressure drop in the core increases about 8 psi for every foot increase in the rod length. The pumps would cost about \$13,000 less than the reference design for an 8 psi drop in head and would cost about \$55,000 more if the head were increased 8 psi. Since the exact pump costs were not obtained for the two designs which were assumed representative of each concept, the average cost change of \$34,000 per foot of rod was used. Thus, the pumps needed in the non-vented design would cost about \$150,000 more than the vented design.

7.2.2 Operating Costs

The pressure drop through the core using a nonvented fuel rod is about 35 psi more than it is using vented rods. The pump operating cost is estimated to increase \$46,000 per year for every 8 psi head increase. This is based on a total reactor flow of 258,000 gpm, a pump efficiency of 87 percent, and a power cost of 0.5 mils per kilowatt-hour. The vented design would therefore save about \$200,000 a year in pump operating cost.

No operating costs were obtained for the nitrogen refrigeration units needed for the gas purification system; the nonvented design would have a slightly lower operating cost due to the smaller heat load.

Fabrication costs for the vent mechanism have not been determined, but the assumed design is not much more complicated than the end plugs. If it can be assumed that the costs for inserting rupture discs and filters for solid fission products will not increase the fabrication costs appreciably, the fabrication cost difference between the vented and nonvented rods will be the cost difference in the cladding. The reactor core requires about 42,000 fuel rods and each rod has a core residence of 3 years, although a portion of the reactor is refueled every year. If the reactor had one-third of the core replaced every year, the nonvented design would require about 62,000 more feet of cladding than the vented design just for the fuel rods alone, neglecting that required for the radial blanket. If the cost of stainless steel is assumed to be \$1.50 per foot, the vented design would have an additional savings of \$93,000 a year.

7.3 EVALUATION SUMMARY

The cost advantages of the vented concept have been summarized in Table 4. The vented concept has about an \$800,000 advantage in the capital cost of the plant and an additional savings of \$300,000 a year in operating costs. The economics evaluation does not include an interest charge or capitalization costs, nor has there been an estimate of the maintenance costs for either design. The analysis could also be greatly affected if the vented fuel rod could operate with a thinner cladding.

The cost advantage is not great enough to give either design a distinct advantage over the other. Fission gas release from mixed carbide is not known with great assurance. If the actual release rate was much lower than the assumed 20 percent used in this study, much of the cost advantage of vented rods would disappear. The deciding factor in the selection of the concept may be the safety advantages. It is not known whether the nonvented concept has a safety advantage in the failed fuel detection system. The safety advantage of the nonvented design due to less gas entrained in the coolant may be minimized by the installation of a surge tank in the primary loop of the vented design. The vented concept may have the biggest advantage in safety since the sodium bond is maintained in the event of a pinhole failure and the possibility of gas blanketing is minimized.

TABLE 4
COST ADVANTAGES OF THE VENTED FUEL CONCEPT

Design Area	Cost Advantage
A. Capital Costs	
1. Vessel, fuel handling, building, etc.	\$660,000
2. Pumps	\$150,000
3. Gas Purification System	(\$ 22,000)
4. Sodium Purification System	---
5. Core Internals & Instrumentation	*
6. Shipping	*
7. Failed Fuel Detection System	*
TOTAL	\$788,000
B. Operating Costs	
1. Pumping Cost	\$200,000/year
2. Fuel Fabrication	\$ 93,000/year
3. Nitrogen Refrigeration Units	*
TOTAL	\$293,000/year

Note: *indicates costs were not available.
Parentheses indicate cost penalty.

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APPENDIX A

FISSION GAS ENTRAINMENT IN THE COOLANT

As part of the vented versus nonvented fuel rod evaluation, a scoping analysis was made of vented fission gas disposition. Both recirculation in the primary coolant system and detrainment at the sodium-argon gas interface compete for the released fission gas. Several potential problems can result from recirculation of the gas: cavitation in the pumps and radial blanket orifices, and cladding hot spots. This appendix summarizes the results obtained by using a model which predicts the fraction of released fission gas in the primary system. The model requires refinement and experimental verification and is intended only to scope the gas disposition problem.

The conclusion drawn from application of the model is that virtually all the released fission gas recirculates in the primary system. Thus, before the vented fuel concept becomes a practical reality, all the released fission gas should be removed from the primary system coolant. Surge tanks and/or gas getters may provide a method for gas removal. The principal reason for the high recirculation rate is the high ratio between the coolant velocity in the vessel outlet nozzle and the bubble rise velocity in the upper plenum.

The model consists of two main parts: (1) determination of the radius, r_b , of a fission gas bubble when it is released from the fuel rod, and (2) determination of the radius of influence, R , within which fission gas bubbles escape through the reactor vessel outlet nozzle.

A fission gas bubble released from the fuel rod in a flowing liquid is subjected to three kinds of forces (Figure A-1): (1) the surface tension forces holding the bubble to the fuel rod, (2) the buoyancy force tending to lift the bubble, and (3) the shearing force tending to carry the bubble along with the coolant.

Forces on Bubble

Figure A-1

The buoyancy force, F_B , on the bubble is:

$$F_B = \frac{4}{3} \pi r_b^3 g (\rho_1 - \rho_2) \quad (\text{A-1})$$

where:

$r_b \equiv$ radius of the fission gas bubble

$g \equiv$ gravitational acceleration constant

$\rho_1 \equiv$ coolant density

$\rho_2 \equiv$ fission gas density.

The surface tension force, F_s , tending to hold the bubble to the fuel rod is given by:

$$F_s = 2\pi \xi r_b \sigma \quad (\text{A-2})$$

where:

$\xi \equiv$ ratio of the cavity radius to the bubble radius ($\xi = 2/3$)

$\sigma \equiv$ surface tension.

The drag force of the coolant on the bubble is dependent upon the bubble Reynolds number, Re_b , defined as:

$$Re_b = \frac{2r_b U_\infty}{\nu}$$

where:

$U_\infty \equiv$ the coolant velocity flowing past the bubble

$\nu \equiv$ kinematic viscosity.

For $1 < Re_b < 10^5$, the drag coefficient, C_D , on a sphere in a flowing liquid is about 0.5; the drag force, F_D , is then:

$$F_D = C_D \frac{\pi}{2} r_b^2 \rho_1 U_\infty^2 = \frac{\pi}{4} r_b^2 \rho_1 U_\infty^2 \quad (A-3)$$

The sum of the forces acting on the bubble must be equal to zero just before the bubble detaches from the fuel rod.

$$F_B + F_D - F_s = 0 \quad (A-4)$$

Substituting Equations A-1, A-2, and A-3 into Equation A-4 and solving for r_b yields:

$$r_b = \frac{3}{4g(\rho_1 - \rho_2)} \left[\sqrt{\frac{\rho_1^2 U_\infty^4}{64} + \frac{8}{3} g (\rho_1 - \rho_2) \xi \sigma} - \frac{\rho_1 U_\infty^2}{8} \right] \quad (A-5)$$

This is the maximum radius that a bubble can have before it detaches from the fuel rod. It is assumed that the bubble will retain its size after it detaches from the rod.

As the bubble travels upward with the coolant, there are two competing phenomena. The buoyancy force on the bubble tends to force the bubble to rise to the cover gas, while the drag force tends to carry the bubble along with the coolant and out of the vessel through the outlet nozzles. The radius of influence, R , is defined as the distance from the centerline of the exit nozzle to the upper plenum of the vessel within which the fission gas bubbles will

escape the vessel through the outlet nozzles. A schematic of the vessel showing the radius of influence is contained in Figure A-2. If it is assumed that a sphere with radius, R , contains 40 percent coolant, then

$$\frac{2}{5} (4\pi R^2) U_{\infty} \approx U \pi r_1^2 \quad (A-6)$$

where:

$U_{\infty} \equiv$ velocity of coolant in upper vessel

$U \equiv$ velocity of coolant in outlet nozzle

$r_1 \equiv$ radius of outlet nozzle.

Equation A-6 can be rearranged to yield:

$$U_{\infty} \approx \frac{5}{8} \left(\frac{r_1}{R} \right)^2 U \quad (A-7)$$

The velocity of the bubble due to the buoyant force, U_{st} , is given by Stokes equation,

$$U_{st} = \frac{2}{9} \frac{(\rho_1 - \rho_2)}{\mu} g r_b^2 \quad (A-8)$$

where $\mu \equiv$ the absolute viscosity of the coolant. The velocity of the coolant can be separated into a horizontal component, U_x , and a vertical component, U_y , defined as follows:

$$U_x = U_{\infty} \cos \theta = U_{\infty} \frac{\sqrt{R^2 - \ell^2}}{R} \quad (A-9)$$

and

$$U_y = U_{\infty} \sin \theta = U_{\infty} \frac{\ell}{R} \quad (A-10)$$

Figure A-2. Schematic of Vessel and Radius of Influence, R

where

$\ell \equiv$ distance from point of bubble release to the centerline of the outlet nozzle.

The time for the bubble to rise above the outlet nozzle, t_1 , is given by:

$$t_1 = \frac{\ell + r_1}{U_{st} + U_y} \quad (A-11)$$

If the horizontal travel of the bubble in the time t_1 is greater than, or equal to

$$\sqrt{R^2 - \ell^2},$$

the bubble will escape the vessel through the outlet nozzle, i.e.,

$$U_x t_1 = \sqrt{R^2 - \ell^2} \quad (A-12)$$

Equation A-7, A-8, A-9, A-10, A-11 and A-12 can be combined and solved for the radius of influence, R , such that:

$$R = \left[\frac{45}{16} \frac{r_1^3 \mu U}{(\rho_1 - \rho_2) g r_b^2} \right]^{1/3} \quad (A-13)$$

It can be seen from Equations A-5 and A-7 that the bubble radius is a function of the coolant velocity in the outlet nozzle, therefore, the radius of influence is also a function of the velocity in the outlet nozzle.

Using coolant and vessel parameters typical of an LMFBR, the model predicts zero percent recirculation of the fission gas when the coolant velocity in the outlet nozzle is less than 5.5 feet per second; there will be 100 percent recirculation when the nozzle velocity is greater than 9 feet per second. Since the coolant velocities in the outlet nozzles of the 1000 MWe reactor are greater than 20 feet per second, the model predicts that all the fission gas will be

recirculated. If this phenomenon occurs, it will be necessary to install surge tanks or gas getters into the primary piping.

An extension of the model will be made to increase bubble size by increasing the size of fission gas holes in the fuel rod and decreasing the drag force on the bubbles. The effect of this modification will be to increase the fission gas bubble size and to decrease the recirculation ratio. (The bubble size predicted by the current version of the model appears to be small.) However, even a change of an order of magnitude in bubble size will not change the conclusion that a method must be provided to remove the fission gas from the coolant and thereby prevent recirculation.

APPENDIX B

FISSION GAS RELEASE RATE FOR THE AVERAGE ROD

The total amount of fission gas released from the fuel rods to the coolant is needed for the evaluation of a vented design. It would be a simple matter to determine the amount released if all the fuel rods released the same amount. However, the fuel temperature and the fission gas production rate vary across the core causing different releases.

One method of calculating the amount released would use the nominal fuel rod release, since the temperature distribution of the nominal rod is readily obtainable, as is the amount of fission gas produced in the rod. The release rate for the nominal rod is 0.33 percent using the methods described in Section 3. The hot rod release rate is 20 percent using the same calculational procedures; there is also more gas produced in the hot rod since it operates to a burnup of 132,000 megawatt-days per metric ton rather than the average burnup of 100,000 megawatt-days per metric ton. Thus, one rod operating at the hot conditions would release more fission gas than 80 rods operating at nominal conditions. Therefore, use of the nominal rod to predict the total core release would probably underestimate the release.

It would be very difficult to calculate the amount of gas released from each rod in the core, even if the temperature distribution of each rod were known. However, the core could be assumed to be represented by a certain number of rods operating at different power ratings. For calculational purposes, it is assumed that the core consists of five different types of fuel rods. These five rod types are the hot rod, the above-nominal rod, the nominal rod, the below-nominal rod, and the cold rod. The temperature distributions, the amount of gas produced and the release rate are known only for the hot and nominal rods; the other rod types are defined as variations of the hot and nominal rods. The above-nominal rod is defined as a rod having half the fission gas release of the hot rod, which means it has a 10 percent release rate and operates to

132,000 megawatt-days per metric ton. The below-nominal rod is defined to have half the release of the nominal rod, whereas the cold rod is defined to have negligible release. The release rates of the below-nominal and cold rods are 0.1665 percent and 0 percent, respectively. The amount of fission gas released from a rod can be calculated as follows:

$$N = \gamma F b \bar{B} M \quad (B-1)$$

where

- $N \equiv$ pound-moles of fission gas released
- $\gamma \equiv$ number of stable gas atoms per fission
- $F \equiv$ fission gas release rate
- $b \equiv$ ratio of burnup in rod to average burnup
- $\bar{B} \equiv$ average burnup in atom-fraction
- $M \equiv$ pound-moles of heavy metal in fuel rod.

Since γ , $\bar{B}$, and M are the same for all the fuel rods, they can be combined in a new constant C . Equation B-1 then reduces to:

$$N = F b C. \quad (B-2)$$

The amount of gas released from each type of fuel rod is summarized in Table B-1.

TABLE B-1

AMOUNT OF FISSION GAS RELEASED FROM EACH TYPE OF ROD		
Hot Rod	$N = 0.2 \times 1.32 \times C$	$= 0.264 C$
Above-Nominal Rod	$N = 0.1 \times 1.32 \times C$	$= 0.132 C$
Nominal Rod	$N = 0.0033 \times 1.0 \times C$	$= 0.0033 C$
Below-Nominal Rod	$N = 0.001665 \times 1.0 \times C$	$= 0.001665 C$
Cold Rod	$N = 0.0 \times 1.0 \times C$	$= 0.0$

It is assumed that, for every 14 fuel rods in the core, there are:

1 hot rod,
3 above-nominal rods,
6 nominal rods,
3 below-nominal rods,
1 cold rod.

The total amount of gas released from these 14 rods is:

1 x 0.264 C = 0.264 C
3 x 0.132 C = 0.396 C
6 x 0.0033 C = 0.020 C
3 x 0.0017 C = 0.005 C
1 x 0.0 = 0.0

Total gas released = 0.685 C

This would also be the total amount of gas released if the average release rate $\bar{F}$, was used.

$$14 \times \bar{F} \times C = 0.685 C$$

$$\bar{F} = 0.049 \approx 5\%$$

The average release rate in the core is 5 percent, based on the assumed distribution.