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The Potential for Containment Leak Paths Through Electrical Penetration Assemblies Under Severe Accident Conditions

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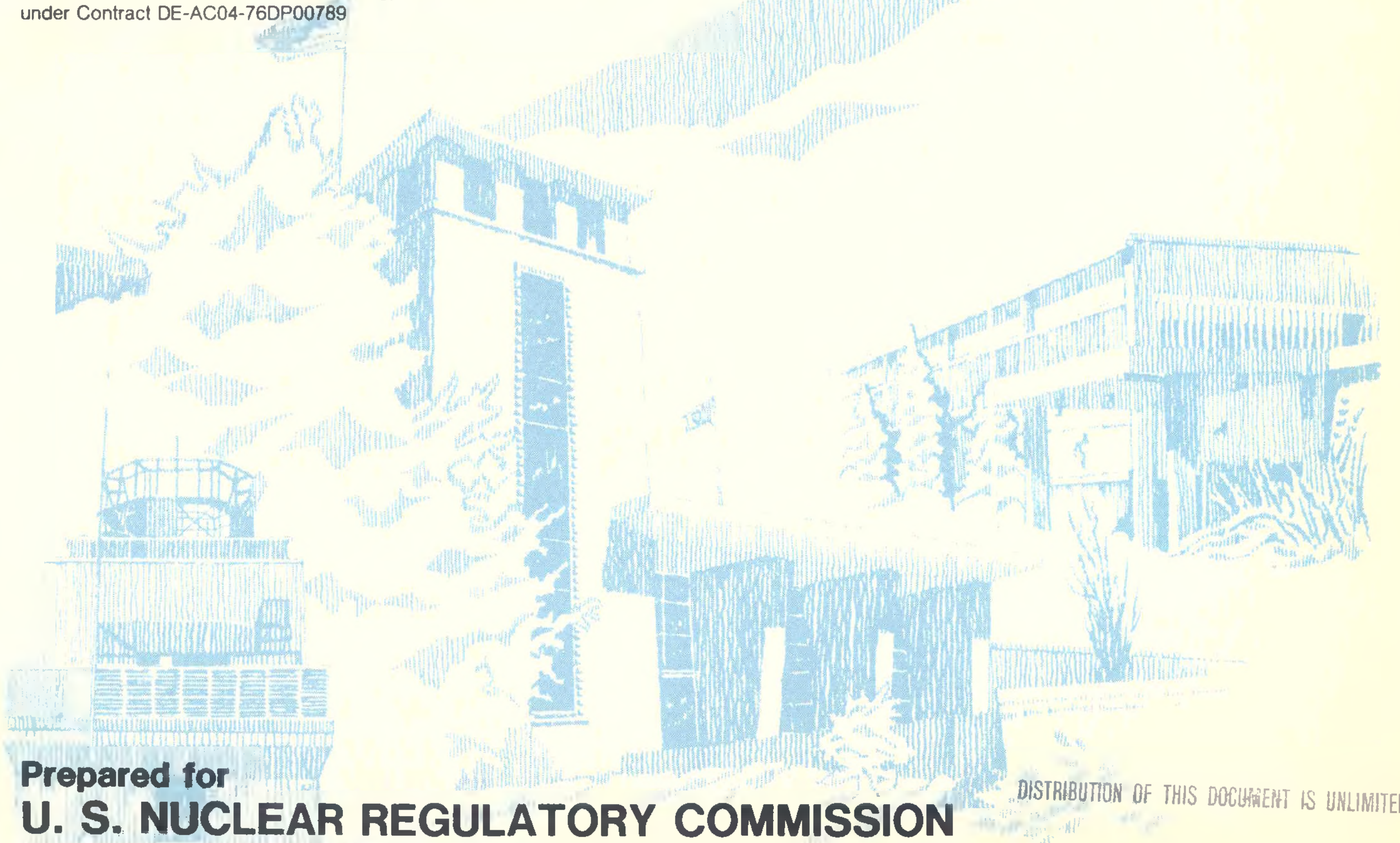

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The Potential for Containment Leak Paths Through Electrical-Penetration Assemblies Under Severe Accident Conditions

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Abstract

The leakage behavior of containments beyond design conditions and knowledge of failure modes is required for evaluation of mitigation strategies for severe accidents, risk studies, emergency preparedness planning, and siting. These studies are directed towards assessing the risk and consequences of severe accidents. According to NUREG-0772 (The Technical Bases for Estimating Fission Product Behavior During LWR Accidents): "One of the largest uncertainties associated with predicting the amount of radionuclides released . . . results from limitations in the ability to predict the timing, mode, and location of containment failure."

Studies are underway to understand the functional failures of containments. Some of these functional failures may occur in the containment or in the penetrations. Each containment building has a large number of penetrations; therefore, there are a large number of potential leak paths. Three parallel NRC programs—the Containment Integrity Program, the Penetration Integrity Program, and the Electrical Penetration Assemblies Program—are concerned with the study of containment physical integrity beyond design conditions.

An accident sequence analysis conducted on a Boiling Water Reactor (BWR), Mark I (MK I), indicated very high temperatures in the dry-well region, which is the location of the majority of electrical penetration assemblies. Because of the high temperatures, it was postulated in the ORNL study that the sealants would fail and all the electrical penetration assemblies would leak before structural failure would occur. Since other containments had similar electrical penetration assemblies, it was concluded that all containments would experience the same type of failure. The results of this study, however, show that this conclusion does not hold for PWRs because in the worst accident sequence, the long time containment gases stabilize to 350°F. Many electrical penetration assemblies have been designed and tested to this temperature and, therefore, should have a very low potential for leakage. BWRs, on the other hand, do experience high dry-well temperatures and have a higher potential for leakage. To evaluate the physical integrity in each plant requires individual investigation because loss of physical integrity depends on the seal materials, which vary from plant to plant.

Acknowledgment

Although this report could not have been completed without the support of large numbers of people, it would be difficult to acknowledge each individually. Particular appreciation, however, is extended to the members of IEEE-317 Committee on Electrical Penetrations who were very helpful by providing information on the history of electrical penetration assemblies, the companies, and the people involved.

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Executive Summary

This report summarizes a study funded by the Nuclear Regulatory Commission (NRC) to assess the potential for leak paths to develop through electrical penetration assemblies in Light Water Reactor containment buildings under severe accident conditions that lead to high internal pressures and temperatures. Some of the severe accident conditions result in pressures and temperatures that exceed the static loads used for designing and testing of penetrations and containment buildings. These loads are obtained from accident scenarios that result in degraded reactor cores that in turn generate large amounts of steam and other gases. The reactions can create very high internal pressures and temperatures. As the pressure and temperatures increase, the physical integrity of the containment barrier will eventually be lost with a subsequent threat to public safety.

This program is a direct result of a severe accident study on Browns Ferry 1, a boiling water reactor (BWR) with a Mark I containment design. The Browns Ferry study, conducted by Oak Ridge National Laboratory (ORNL), postulated an early failure mode through electrical penetration assemblies (EPAs). The significance is that all previous risk studies assumed that the containment building failed first. The accident progressions in the study calculated extremely high temperatures in the dry-well area. These high temperatures (500°F) were assumed to soften the sealants in the electrical penetration assemblies; then the sealants could be blown out by an increase in pressure. The ORNL study concluded that all containments would suffer the same consequences. In evaluating the impact of the conclusions from the study, there are three important questions to address:

1. Are the high temperatures applicable to all containments?
2. Do all EPAs leak at 500°F?
3. If this is true, how are leak paths and leak rates to be determined?

The plan for the EPA Program was divided into two sequential tasks. The first task was to obtain background information and to evaluate capabilities of EPAs. The second task is a test program to corroborate the ability to predict leak paths and leak rates in EPAs.

As part of the first task, the following activities were conducted:

- Designs and materials for EPAs were collected, documented, and described.
- Severe accident loadings were studied:
  - Analytical correlations for estimating leak rates were reviewed.
  - Experimental data from industry on EPA behavior were collected and evaluated.
  - Typical temperatures and pressure profiles on generic containments were obtained, including large dry Pressurized Water Reactor (PWR), ice condenser (PWR), and Boiling Water Reactors (BWR).
- The behavior of EPAs for leakage and/or failure in generic containment buildings—large dry, ice condenser, and BWR—were evaluatead.
- An overall assessment of EPA behavior was documented, and an appropriate test program was recommended.

The second task, which is the major effort in time and funding, is based on a recommended program of three tests to validate the predicated behavior of EPAs.

This program, sponsored by the Electrical Engineering Branch of NRC, is one of a number of NRC programs studying containment integrity. These studies are in support of a much larger effort by NRC called the Severe Accident Research Program (SARP). SARP is coordinating the results of studies on risk analysis, accident progressions, containment integrity, penetration integrity, and other NRC programs.

The Potential for Containment Leak Paths Through Electrical Penetration Assemblies Under Severe Accident Conditions

Introduction

Purpose

The purpose of this technical study is to assess the potential for leakage of electrical penetration assemblies under severe accident conditions. This report will also outline procedures for developing a test program to predict pressure and temperature failure thresholds associated with severe accident conditions. Only internal pressures and temperatures will be considered; no seismic loads will be included.

Program

Since the accident at Three Mile Island, a major effort in safety studies has been directed toward the risk and consequences of severe accidents. These efforts are the direct result of the Nuclear Regulatory Commission's proposed ruling on how to deal with degraded-core accidents. Many study groups have been formed to investigate the impact of these types of accidents. One such study group is the Industry Degraded Core Rulemaking Program (IDCOR). Other studies are the Severe Accident Sequence Analysis Program (SASA) and Reactor Safety Study Methodology Applications Program (RSSMAP). Since the programs are quite broad, an in-depth discussion of each is beyond the scope of this report (an initial introduction to RSSMAP and IDCOR can be found in Reference 1). There is an important connection between those programs and this study, which is providing an assessment of the timing, mode, location, condition, and probability of loss of physical integrity for electrical penetration assemblies.

One such accident study on a BWR, Browns Ferry 1, has reported on the high temperatures generated in the dry well.[2] The study concludes that because of limited temperature capabilities of the EPA sealants, the time to loss of EPA integrity is much lower than previously reported. This reduction in time would be very important to the planning and management of accident strategy. In addition, the Browns Ferry 1 study concluded that since all other power plants had similar EPAs, leakage would occur in those penetrations as well. In order to evaluate these sweeping conclusions, the Electrical Engineering Branch of the Division of Engineering Technology, NRC, has sponsored this study to provide a broader review of the performance of EPAs.

Scope of Study

This EPA Program is divided into two major tasks: to obtain background information and evaluate the behavior of EPAs under severe accident conditions; and, to develop and carry out a test program to corroborate the ability to predict leak paths and leak rates in EPAs. All the discussions in this study on leaks, leakage, or leak rates are in reference to physical integrity, and not electrical capabilities.

The following activities were conducted as a part of the first task and are included in this summary report:

- Background information was collected; descriptions of designs and materials for typical EPAs were documented.
- Analytical studies or correlations for estimating leak rates of EPAs under severe accident loads were reviewed.
- Experimental data from industry, useful in the assessment of the potential for leaks developing in EPAs under severe accident conditions, were collected and evaluated.
- Worst case temperature and pressure profiles from severe accident scenarios in three generic

types of containments were obtained. The three containment types were selected on the basis of ongoing SASA studies and were not intended to be inclusive for all containments. The three selected were large dry (PWR), ice condenser (PWR), and a BWR (MK I).
- The behavior of EPAs for leakage and failure in the three generic types of containments (large dry, ice condenser, and BWR) were evaluated.
- All of the above topics were documented in a summary report. Overall EPA behavior was assessed and an appropriate test program recommended.

These topics were included because they are important to understanding the behavior of EPAs and are covered in this report. More lengthy subjects have been relegated to the Appendices in order that conclusions and assessments can be reached more directly.

The second major task in this program involves the testing of EPAs. This task is important to validate the predicted behavior of EPAs under severe accident temperatures and pressures. The test effort is based on a recommended program of three tests.

Background and History

This section gives an introduction to electrical penetration assemblies. The first part includes a description of early electrical penetrations, the design evolution, and a brief look at the functions of EPAs. In collecting background information, it is also useful to look into operational experiences of EPAs. This section will touch briefly on the EPA vendors. A lengthier discussion of EPA vendors can be found in Appendix A.

Penetration Characterization

A large number of functions in the reactor building are controlled, powered, or sensed by electrical means. Providing communication or interaction with the interior of the reactor building requires thousands of electrical conductors. Since these conductors must pass through the containment walls, they must provide a gastight seal to prevent release of radioactive materials. All containment buildings and structures are designed to provide safety against accidental release of radioactivity to the outside environment. As a consequence, electrical penetrations must also be designed and fabricated to prevent leakage under postulated accident conditions. Each conductor must maintain physical integrity and meet certain electrical design requirements such as resistance, current, insulation, dielectric strength, and voltage. These requirements are quite diverse and, historically, have changed with time. The standard for the design, construction, testing, and installation of electrical penetrations was first introduced in 1971 with revisions in 1976 and 1982.[3] Prior to 1971, electrical penetrations were not required to satisfy a particular standard. Not only has the IEEE standard changed, but also licensing requirements are different from the late 1960s. These changes along with the different types of containment buildings have resulted in a large number of electrical penetration designs. There are at least 11 different combinations of containments using reinforced concrete, steel, and tendons in a variety of geometric configurations.[4] The EPAs are designed to accommodate these various containment buildings. As pointed out by Verber,[5] adequate precautions are required in the design, fabrication, and installation of penetrations, or leakage can occur through one or more of the following paths:

- Between strands of a multiwire conductor
- Between the conductor and its insulation
- Between layers of insulation, jackets, or shields
- Through voids in sealing materials, jacketing, insulation, or filler materials
- Through gasketed flanges or joints
- Through voids or pinholes in welded joints.

These problems can be solved by proper selection of materials, quality manufacturing processes, and good design practices.

If a multistrand conductor is used, one or both ends of the cable should be sealed with either solder or other materials to prevent leakage. Another approach is to use a solid-wire conductor. However, leakage can still occur between the conductors and insulation as well as in between the other layers in the cable. Cables should consist of materials that bond or adhere well to each other. Of course, the ends of the cables can be sealed or potted at one or both ends to prevent leakage along the cable. Leakage along the cable and through the insulation and protective shielding not only leads to breaches in physical integrity, but also allows the possibility of moisture entering and changing electrical characteristics of conductors needed in the operation of safety-related equipment.

Since there are thousands of wires used in a typical installation, the cost of penetration assemblies can represent a sizable capital investment. In early design, inexpensive methods were used to seal electrical penetrations. These methods used existing fabrication approaches and sealing materials. The three common approaches used packed, potted, and gasketed methods (Figure 1). The early potted methods were applied to cables passing through a nozzle and potted in place. Later nozzles were U-shaped tubes or troughs into which the potting material was poured around the cables and allowed to cure in place. Additional sealant layers could be added to minimize leakage.

The packed method of sealing around cables worked like the packing around the faucet in a kitchen sink. The packing material was compressed tightly around the cable or stem by a threaded gland nut. The packing material was in a confined space, and the turning of the gland nut forced the resilient material to compress onto the conductor. The gasket method involved insertion and compression of O-rings or gaskets between parts of the penetration assembly. These three methods, or portions of these methods, can still be found in present day electrical penetration assemblies but are produced with improved fabrication, quality control, and environmental capabilities.

Many of the early designs were field manufactured; however, as more stringent requirements were placed on the assemblies, it became difficult to field-qualify the parts. This led to preassembled units that were fabricated and tested in the manufacturing plant. This evolved into the "canister" design used in the early 1970s. The canister designs were a single unit that was shipped to the nuclear plant ready for installation in a nozzle (or sleeve) in the containment wall. The canister had either a provision for welding to the sleeve, or it could be bolted to a mating flange already welded to the nozzle. The flanges and canister were all double-sealed and had internal passages for monitoring pressure. This ability to monitor the pressure throughout the numerous passages in the assembly is referred to as the "unitized" method and is an important safety feature that can be used to detect some changes with operation and time.

The canister-type assembly provided a significant improvement in reliability. By designing assemblies with a high density of conductors, the number of penetration assemblies could be reduced. However, if any operational problems developed (particularly if the assembly was welded in place), replacing the canister was difficult. In addition, there were related inconveniences if other circuits were needed for safety-related functions such as reactor monitoring. The next important design change occurred as a result of trying to avoid replacing all the conductors in an assembly. To overcome this difficulty, a "modular" concept was developed. The modular designs incorporate grouping of conductors that can be readily replaced if necessary. Depending on power requirements, a module can either contain a single conductor or several hundred conductors.

All the current EPAs use the modular design. These modules are double-sealed and mounted to a header plate. The header plate has passages to each of the modules so that pressure is maintained as if it were a single unit (i.e., "unitized"). The header plate then interfaces with the nozzle either by bolting or welding. If bolted, the flange to header interface uses a dual O-ring seal with a passage that can be pressure-monitored with the modules or separately. The welded

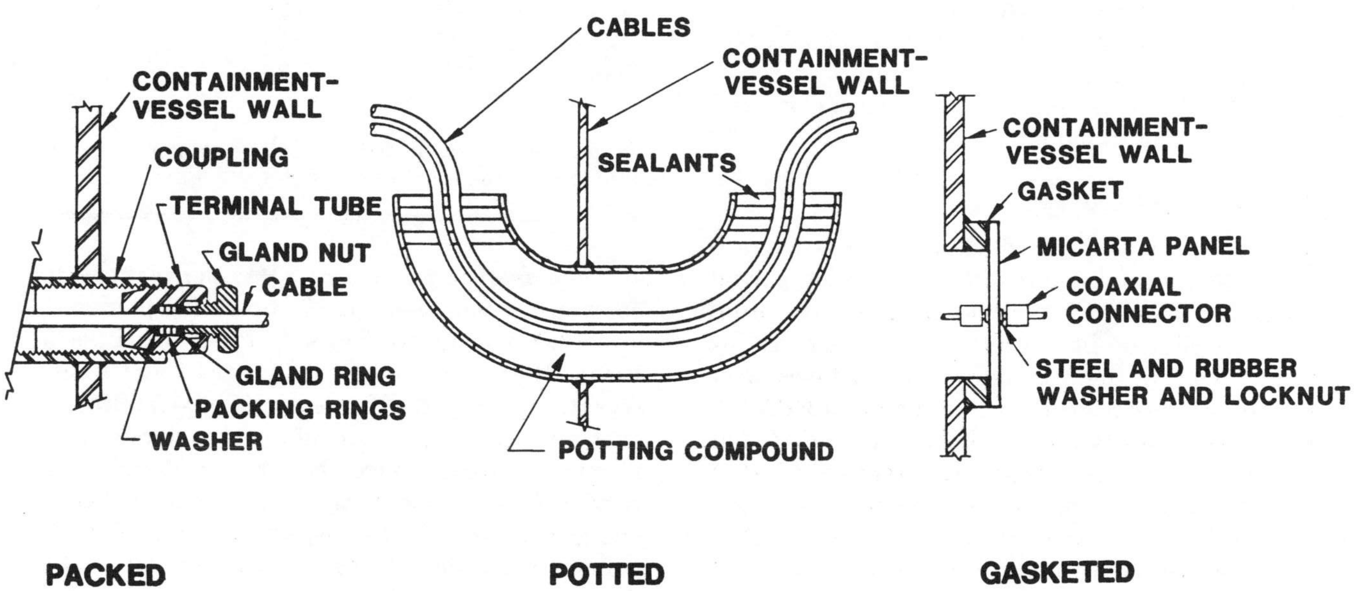


Figure 1. Three Methods for Sealing Electrical Penetrations of Reactor Containment Buildings[5]

interface can be used with a single weld; or, if pressure monitoring of the weld is desired, a separate ring can be welded to enclose the original weld and provide a means of monitoring the enclosed passage.

Electrical penetration assemblies can be divided into four functional categories. A brief discussion of their use may help explain the diversity in designs. The four categories are related to the type of service provided, and each category has different design requirements.

Medium Voltage Power (5 to 15 kV). These penetrations provide electrical service to the high power demand needed by the reactor coolant-pump motors and recirculation-pump motors.

Low-Voltage Power (Up to 1 kV). These penetrations are used with high horsepower motors, fans, heaters, lighting panels, and other equipment.

Low-Voltage Control. These penetrations are used primarily for control in control drives, low horsepower motors, reactor protective systems, motor-operated valves, or switching.

Instrumentation. These services are typically very low power and are used for sensing such as control rod position, neutron monitoring, environmental sensing, and communication.

All four of these categories perform important safety-related functions and are considered as Class IE equipment. Equipment in this category is required to function during abnormal environments and during design-basis-accidents (DBA). Since EPAs provide both an electrical safety-related service and physical integrity, they are required to meet the standards of both the ASME Boiler and Pressure Vessel Code and industry electrical standards.

EPA Experiences

In this study it was deemed necessary to investigate the historical background of EPAs. A partial introduction to early EPA development and the problems involved can be found in three articles by Verber.[5-7] During the 70s, only a few articles were published on the design and performance of EPAs.[8-10] The lack of published data should not imply that EPAs have not been given proper attention. Most of the information on design, development, and qualification has been published in-house by the manufacturers to support licensing, records, and documentation. Much of this information may be considered proprietary by the manufacturer.

A large number of contacts have been made to develop some historical perspectives on EPAs. The data banks and contacts with industry representatives have provided useful information. From these contacts, it was ascertained that there were eight major suppliers of EPAs. Three of these (Conax, D. G. O'Brien, and Westinghouse) are still currently supplying assemblies, while five (Amphenol, Crouse-Hinds, General Electric, Physical-Sciences, and Viking) are no longer supplying EPAs.

Data banks were also used for resource information. Computer listings of EPAs were obtained from the Southwest Research Institute (SwRI) Equipment Reliability Data Bank, Nuclear Safety Information Center, NUS Equipment Qualification Data Bank, and the Franklin Institute Research Laboratory Data Bank. The Licensee Event Reports (LERs) were reviewed along with information reported in the Nuclear Power Experiences (NPE). The experiences or events reported in the NPE[11] suggests that EPAs usually have a good performance record, especially when compared to the other types of penetrations in a containment building. Table 1 contains a summary of results and a definition for experiences applicable to Reference 11.

Table 1. Nuclear Power Experiences[11] (Data Thru August 1982)

	Number of Experiences* With All Penetrations	Number for EPAs	Number for EPA Leakage
PWR	263	20	9
BWR	113	18	7
Total	376	38	16

*Experiences are selected operating problems: equipment breakdowns, malfunctions, outages, etc.

The average number of EPAs per plant is about 55, which means that with 70 operating plants, there are ~3800 installed EPAs.[12] Based on these 3800 EPAs, there have been about 0.87% EPA events reported of which 0.42% were leak-type failures. However, all of these events did not lead to complete loss of physical integrity since there was a double seal or barrier. In all incidents that could be identified, only one seal leaked. In the experiences for all types of penetrations, the most serious (from number of incidents and leakage) has been in personnel locks and equipment hatches.

The NSIC data base was searched for LER information on EPAs. The data search used the words "containment penetration," "electrical," "failures," "leak detection," and "leak rate." The LER search found 18 incidents of leak-type failures in electrical penetrations (Table 2). Nine out of the 18 were very similar occurrences at the LaCrosse Nuclear Power Station. The mode of failure was a cracked gland. Fifteen out of 18 failures resulted from failure of one of the double seals and was an "operational" type of failure. The remaining three failures are revelant to severe accident loadings because they were potential "through leak paths."

Table 2. Licensing Event Reports From Nuclear Safety Information Center (Data Thru February 1983)

Containment Penetrations	Total NSIC Listings	Penetration Failure	Leak Type Failure
All	1057	427	265
Pipe	313	59	20
Electrical	284	83	18

NOTE: Numbers in the above tables are dependent on interpretation and judgment of many people; their completeness cannot be assured.

The major portion of the information obtained from data banks was received from the SwRI Equipment Reliability Data Bank.[13] SwRI lists 170 000 items of equipment of which 2721 are EPAs. SwRI declined to supply information that would identify a specific nuclear plant. However, the information supplied in Table 3 represents 18 suppliers of EPAs for 63 operating plants listed by the name of the nuclear supply system manufacturer. The number of EPAs in Table 3 represents only a partial listing.

Some of the early plants (for example, Big Rock Point and Yankee Rowe) have field-manufactured EPAs. It is not clear from the SwRI data whether these are represented by the other vendors listed or are just not included in Table 3.

Since the objective of this study is to evaluate the potential for leakage in EPAs, it would also be useful to know the location of any of those identified. Table 4 was assembled from information obtained from the major vendors and data banks. One utility supplied information and represents the only operating plants for which we have accurate numbers of EPAs listed (Browns Ferry 1, 2, and 3).

Table 3. Listing of EPA Suppliers for Operating Plants*

	SwRI Manuf Code	Babcock & Wilcox (9)**	Combustion Engineering (8)**	General Electric (20)**	Westinghouse (26)**	Total (63)**
Amphenol	A380	48	153		159	360
Bechtel	B130				2	2
Cargoaire Engr	C130			16		16
Ceramsel, Inc	C210				6	6
CB&I	C310	37		85	622	744
Conax	C515	108		3	102	213
Crouse-Hinds	C720				104	104
Des Moines Steel	D132	1				1
Ebasco Svs, Inc	E065				50	50
G&W Elec	G005			5		5
Gen Elec	G080		40	215	46	301
O'Brien	O005			47	221	268
O'Conner Assoc	O006				1	1
Physical-Sciences	P215			64		64
Pratt, Henry Co	P340			1		1
Prog Fab, Inc	P415	3				3
Viking	V120	258	31		115	404
Westinghouse	W120				178	178
Total		455	224	436	1606	2721
Ave No. EPAs Per Plant		51	28	22	62	

Notes: Four plants not listed: Arnold, Big Rock Point, LaCrosse, and Yankee Rowe.

Equipment reporting by utilities is optional; therefore, the numbers listed may not represent totals. There is also only a partial listing of manufacturers. Examples of several vendors not listed include General Cable, Okonite, and Raychem.

*Source: SwRI Equipment Reliability Data Bank (as of 11-15-82)
**Represents number of operating plants

Table 4. Operating Plants and Major EPA Suppliers

Plants Listed in SwRI Equipment Reliability Data Bank	MAJOR EPA SUPPLIER: AMPHENOL	CONAX	CROUSE-HINDS	GENERAL ELECTRIC	D. G. O'BRIEN	PHYSICAL SCIENCES	VIKING	WESTING-HOUSE
Arkansas Nuclear One - 1		x			?			
Arkansas Nuclear One - 2	x							
Beaver Valley - 1							x	
* Browns Ferry - 1				3		27		
* Browns Ferry - 2				3		27		
* Browns Ferry - 3				29				
* Brunswick - 1								x
* Brunswick - 2								x
Calvert Cliffs - 1	(25)	x						
Calvert Cliffs - 2	(25)	x						
* Cooper				x				
Crystal River		x(9)			?			
Davis-Besse - 1	x	x						
Donald C. Cook - 1		x						
Donald C. Cook - 2		x						
* Dresden - 2				20				
* Dresden - 3				x				
* Edwin I. Hatch - 1&2				x				
Fort Calhoun		x			?			
H. B. Robinson			(52)					
Haddam Neck		x						
Indian Point - 2		x						x
Indian Point - 3								x
* James A. Fitzpatrick		x		x(12)				
Joseph M. Farley		x		x(16)				x
Kewaunee					x			
Maine Yankee					x			
* Millstone - 1				(x)				
Millstone - 2		x		x				
* Monticello				x	x			
* Nine Mile Point					x			
North Anna - 1		x			x			
North Anna - 2		x						
Oconee - 1					x		36	
Oconee - 2					x		36	
Oconee - 3					x		35	
* Oyster Creek				x				
Palisades							24	
* Peachbottom - 2			x					
* Peachbottom - 3			x					
* Pilgrim - 1		(+)		x		(10)		
Point Beach - 1								x
Point Beach - 2								x
Prairie Island - 1		x			x			
Prairie Island - 2		x			x			
* Quad Cities - 1				x				
* Quad Cities - 2				x				
R. E. Ginna			(52)			x		x
Rancho Seco		x		?				
Salem - 1		x		?				
Salem - 2		+		?				
San Onofre - 1		x					x	
St. Lucie		x						
Surry - 1	(3)	x			x			
Surry - 2	(3)	x						
Three Mile Island - 1		x		x				x
Three Mile Island - 2				x				
Trojan	(14)				?			
Turkey Point - 3								
Turkey Point - 4								x
* Vermont Yankee				x				
Zion - 1					x			
Zion - 2					x			
Total Number of EPA's Listed in SwRI Data Bank	360	213	104	301	268	64	404	178
Plants Not Listed in SwRI Data Bank								
* Arnold				(4)				
* Big Rock Point		x		x				x
* La Crosse - No Data								
Yankee Rowe								x

( ) Numbers in parenthesis are the number of EPAs reported in FIRL Data Bank
x Information from vendors
* BWRs

Suppliers and Vendors

One of the subtasks of this study was to identify origins of various EPAs. Included in this subtask was to collect descriptions of typical designs and to determine material content of EPAs. These descriptions appear in Appendix A, which contains an introductory description and background for the eight major suppliers of EPAs. These descriptions focus on the materials relevant to leakage or loss of physical integrity for severe accident loads. The descriptions in Appendix A (as well as throughout this report) are primarily describing the seals or sealant materials used in EPAs.

Other than eight major suppliers of EPAs, there are many other vendors. Some of the other vendors have assemblies listed in the SwRI Equipment Reliability Data Bank (Table 3). The Data Bank listed 18 suppliers of EPAs. Whether these are actual suppliers or represent an incorrect identification would take additional investigation. Three other manufacturers have also been suggested; therefore, there may be a total of 21 EPA suppliers: 8 major and 13 minor. The minor suppliers could possibly account for the field manufactured units. The 8 major suppliers account for 70% of the EPAs listed in the SwRI Data Bank. The remaining 30% can be divided into two groups: Chicago Bridge and Iron (CB&I) and the remainder. The remaining 12 account for 3%, while CB&I accounts for 27% of the total. This creates a large anomaly because CB&I is *not even considered to be a supplier of EPAs*. There may be an incorrect identification in the EPAs supposedly supplied by CB&I.

Existing Capabilities of EPAs

The purpose of this section is to review the existing capabilities of EPAs in relation to design basis accidents, fault current effects, leakage in seals and gaskets, and aging. Evidence of existing capabilities can be derived from the evaluation of prototype testing, qualification testing, material testing, and/or analytical correlations.

Design Basis Accidents or Events

Determining the existing capability of EPAs is quite a major undertaking because of the large variety of EPAs in existing and proposed plants. Each utility determines or calculates the design and qualification environments for each plant. The maximum loads encountered normally occur from a hypothetical load called the Design-Basis-Event (DBE) or Design-Basis-Accident (DBA). Both terms have been used to reference the highest pressure, temperature, and time condition for the EPA design. Because of the variation of internal components of reactor and coolant systems, the DBA results vary from plant to plant. In addition, the DBA temperatures and pressures can be different within the plant, depending on the location of the pipe break.

The industry is supporting an Equipment Qualification Data Bank. This Data Bank is being maintained by NUS Corporation. The Data Bank had 78 EPAs on their listing as of November 1981. A portion of this data can be found in Table 5, which shows the range of pressures and temperatures for which certain EPAs have been qualified. The lowest temperature and pressure applies to the Amphenol EPAs: 230°F and 54.7 psia. The highest pressure and temperature is for the General Electric EPAs: 352°F and 138.7 psia.

The existing capabilities of the EPAs in Pilgrim (a Mark I BWR) was reported in 1971.[14] The medium voltage power (MVP) assemblies used an alumina ceramic seal that gave it a temperature capability to ~1800°F. The low voltage power (LVP), control, and instrumentation assemblies used a slightly different material, a silica-ceramic seal that is also effective to 1800°F. The EPAs used for neutron monitoring were reported to have a completely different temperature capability, estimated to be 300°F. This is because neutron monitoring circuits are typically coaxial and triaxial cables and, in this case, the limiting temperature was in the connector that attached to the EPA. The EPAs all have fused seals that are reported to be good for temperatures above 1000°F.

Other data on qualification environments are contained in References 5 through 10. Reference 6, for example, reports that a General Electric canister-type EPA "... will maintain physical integrity for at least 2 hours under the following maximum conditions inside the containment dry well (Dresden 2): 320°F, 125 psig, and 100% relative humidity." Reference 8 for General Electric EPAs states "... assemblies can withstand primary containment temperatures to 300°F and pressures in excess of 100 psig ... ". Reference 10 contains design information on Westinghouse EPAs and reported that "... the modules are steam tested for the first 6 hours at 340°F and 3.2 atm with a spray of borated water; then 6 hours at 320°F; then 260°F for 24 hours and 230°F for 9 hours. The pressure is dropped in steps from 3.2 atm to 0.35 atm." As part of the aging process, the assemblies also were subjected to 300°F for 524 h to simulate a 40-yr life at 160°F.

From the amount of prototype and qualification testing undertaken by the various manufacturers, it is expected that there is a very low probability of loss of integrity below 340° to 350°F and 100 to 115 psig. There are a few plants that have field-manufactured EPAs, but it would be difficult to determine with any assurance the pressure and temperature at which loss of integrity would occur. Several of these early plants are no longer in operation, although some, such as Big Rock Point and Yankee Rowe, are still operating. The physical integrity of EPAs in the plants just mentioned will be discussed further in the next section pertaining to fault currents.

Capability beyond the DBA environments is the topic of discussion in another section.

Fault Currents

A very important design requirement for EPAs is the fault current, which is a high-amperage short-circuit load. Even though the short circuit may last only a few cycles, the tremendous heating of the conductor will also heat up the insulation and sealant and could lead to loss of physical integrity. The importance and ramifications of fault current was pointed out in Reference 9. The USAEC and the industry recognized the possible problem induced by fault currents. A new requirement was added to IEEE Standard 317 in 1976 (paragraph 4.2.5, "Rated Maximum Duration Short Circuit Current") to meet test requirements for maintaining containment integrity. This supplemented Regulatory Guide 1.63, paragraph C-1, which states: "The electrical penetration assembly should be designed to withstand, without loss of mechanical integrity, the maximum possible fault current versus time conditions that could occur given single random failure of circuit overload protection devices."

Failure could occur whenever the fault current heats the conductor and causes the insulation or seal to deteriorate with time and temperature. Since the mid-seventies, all EPA manufacturers have designed and tested to the fault current conditions. Some of the earlier manufacturers also considered fault current effects in their designs (i.e., Physical-Sciences, Viking, and General Electric). There is uncertainty about Amphenol, Crouse-Hinds, and early Westinghouse designs since no drawings are available. The 1975 Westinghouse article discusses current carrying capability in EPAs but does not cover fault currents.[10] Conax has reported fault current testing of an MVP in April 1972, while D. G. O'Brien conducted similar tests in 1975.

Table 5. Existing Capability for Electrical Penetrations Equipment Qualification Tests

	Temperature (°F)	Pressure (psia)	Radiation (Mrads)	Plants
Amphenol	230	54.7	100	ANO 2
	300	74.7	100	Trojan 1
Conax	275	76.7	100	ANO 1
	340	124.7	200	Salem 1 and 2
Crouse-Hinds	340	75.0	213	H. B. Robinson
	340	119.7	200	Point Beach 2
General Electric	340	74.0	100	Cooper 1
	352	138.7	100	Pilgrim 1
Physical Sciences	310	74.7	?	Pilgrim 1
	340	63.7	1000	Peach Bottom 2 and 3
D. G. O'Brien	270	42.0	300	Zion 1
	300	86.7	626	Nine Mile Point 1
Viking	312	79.7	100	Oconee 1, 2, and 3
Westinghouse	340	70.7	117	Brunswick 1 and 2
	340	77.7	126	Brunswick 1 and 2

The information above is from the NUS Equipment Qualification Data Bank. The high-low values indicate the ranges for which various manufacturers have qualified EPAs. Since this table represents only a portion of the EPAs, the full range for each vendor may not be included.

The important design considerations for optimum fault current resistance are a high temperature seal capability, cable supports interior to the assembly, conductor connections, conductor and cable restraints, and thermal expansions. One vendor (Viking) provided a means of high pressure relief through a popout plug.

Fault current loads can be quite large, and these loads act normal to the conductors. Although the loads are large, they act only between the circuits that develop the short circuits (see Appendix C). Since the conductors affected are all in one electrical penetration assembly, no forces act outside of the sleeve. The internal cables are supported by support plates. It is these plates that are loaded.

The physical integrity of EPA seals under fault current conditions is very dependent on temperature and time. This is because of the variety of materials used in EPA seals. Some typical seal materials are listed in Appendix C (Table C1). The materials listed in this table are in older plants. The limiting temperatures may or may not be applicable to severe accident loads because of the shorter time duration of the fault current and which seals are affected. The EPA may have multiple seals (like flange O-rings) that would not be affected by the fault current load but would be affected by a severe accident load.

Existing Capability Under Severe Accident Loads

The amount of analytical and experimental data on existing capability under severe accident loads is very limited. Only one analytical study was found that would be applicable to EPAs under severe accident conditions; the available test data is not very extensive. There are five tests that give some useful results. These results are discussed in the following sections by the vendors who carried out the test or study.

Conax

The Conax Corporation is the only organization that had carried out any analytical study useful for assessing the capability of EPAs under severe accident loads. The analysis was not a stress analysis, but an analysis of the thermal behavior of a Conax assembly in a LMFBR sodium fire. The containment temperatures can get quite hot (>1100°F); the thermal analysis of the EPA indicates that even when the inboard end sees the high temperature, the temperature drops off very rapidly and the outboard end sees only a small temperature rise. This condition was simulated in a test conducted by Conax.[15] The test specimen consisted of a 1-in.-dia by 33-in.-long stainless-steel tube. The module contained six conductors and was sealed with 6 and 4 in. of polysulfone at the inboard and outboard ends, respectively. The inboard end of the module was placed in a high temperature furnace, while the midsection and outboard end were in two additional furnaces set at 125°F. The high-temperature furnace was programmed for the following sequence: increasing from 94°F to 1105°F in 4 h, then decreasing to 805°F in 10 h, and a constant temperature of 805°F for an additional 140 h. The results of the test were that the inboard seal was vaporized, but the outboard seal still maintained physical integrity. The temperature of the outboard end never exceeded 152°F. (This large gradient was also found to exist on a thermal analysis performed for an EPA in Browns Ferry 1; see Appendix D.) The heat conduction along the sleeves and conductors was not sufficient to deteriorate the outboard seal.

D. G. O'Brien[16]

The D. G. O'Brien electrical penetration assemblies all have glass-to-metal seals. These seals are used both in containment buildings and in deep water applications. In these applications, the glass-to-metal seals are exposed to high pressures (5000 to 10 000 psi). Prototypes have been tested to these pressures. A glass-to-metal seal should, by its nature, be able to withstand high temperatures also. The glass softening temperature for D. G. O'Brien's penetrations was reported to be above 1200°F. A thermal evaluation of D. G. O'Brien penetrations has not been undertaken analytically. Experimentally, however, there are two tests that provide some indication of temperature capability. The first tests were prototype tests conducted for the MH-1A Floating Nuclear Power Plant. In these tests the EPAs were exposed to an environment of 270 to 280 psig and 371° to 382°F. In another test series, a prototype penetration was inadvertently exposed to an estimated high temperature of 515° to 550°F for a 48-h period. The penetration was to be tested over the weekend in a sealed chamber with an atmosphere of 52-psig steam and 270°F temperature. The controller malfunctioned, and the unit was exposed to double the temperature; no estimates of the pressure are available. No leak failures occurred.

Viking

Earlier Viking EPAs that used the glass-to-metal seal were subjected to a qualification test.[17] This test was conducted to meet military service conditions. These conditions were 575°F for 400 h and no leakage occurred. This condition is higher than what the expected capability would be for an organic seal.

Viking also produced an epoxy-sealed module (Vikron) that was installed in Beaver Valley. The epoxy in these modules has a continuous usage rating of 392°F, but can withstand higher temperatures. The developers of the Vikron seal have reported that physical integrity can be maintained through DBA conditions up to 200 psig and 600°F.[18]

Westinghouse

Westinghouse EPAs have been qualified to the condition of IEEE standards. As reported in Reference 19, the modular designs have been qualified to 340°F and 46 psig. In assessing the design and other tests that Westinghouse has conducted, it appears that the penetrations have a capability above these conditions. The modules have two sets of paired O-rings (Appendix A, Figure A4): one pair made with silicone and one pair with ethylene propylene rubber (EPR). These O-rings should provide leak tightness for over 1000-psig pressure. The EPR is expected to have a temperature capability up to 400°F; the silicone rubber O-rings that generally have higher temperature capabilities should be usable to 600°F. There has been no evidence of any combined temperatures and pressure tests beyond 340°F. Westinghouse did conduct a test on an epoxy cylinder that indicated a substantial heat resistance. The epoxy cylinder simulated a wall feed-through configuration and had a No. 4 AWG cable embedded in the epoxy. After 5 h with the inside furnace temperature at 1090°C, the outside end was within temperature limits required to maintain integrity.[19] The glass-reinforced header plates used in the Westinghouse design should retain their rigidity to prevent the sealant from being blown out. Full details of the test were not supplied by Westinghouse because of proprietary considerations.

Aging

Aging is a generic problem for containments and reactors and not just for electrical penetration assemblies. Whenever there are materials that can change with exposure to temperature, radiation, and time, the possibility exists that the material properties will change. This change in material, in most cases, leads to a degradation of properties. If the degradation can be determined beforehand, the part can either be designed to last for a prescribed time or be replaced at appropriate intervals of time. Studies in this area are continuing, and typical developments can be found in Reference 20.

The most severe aging effects have been noted in organic materials such as plastics, rubber, etc. Many materials used in the nuclear power plant environment usually have extensive testing to qualify them for use. Because of the variety of plastics and rubbers, and the possible radiation dose rates and synergistic effects on these materials, the applicability of the results may be questionable. Although the IEEE-317 (1976) standard specified certain aging tests to qualify a design for nuclear power plant use, it does not omit the possibility that the items may not survive the 40-yr life required for the plant.

Since many EPA designs use organic materials for gaskets, O-rings, and seals, the problem of aging should be included in their reliability considerations. However, the inclusion of these considerations into a limited program relies heavily on engineering judgement. The limited effort should be viewed as a basis to support a methodology for predicting potential leaks in EPAs. The methodology incorporates multiple sources of information, analysis, and research to achieve this goal.

Penetration Failure Modes – Leakage

The parameters that influence leakage in EPAs are important to severe accident studies. These studies, to determine the risk and consequences from severe accidents, are dependent on a failure model that shows where, when, and how containments leak. The leak paths in EPAs are influenced by the behavior and type of seal materials used. The purpose of this section is to discuss the seal materials used in EPAs, since these materials have the greatest potential for leakage.

EPA Seal Materials

In determining the suitability of seal materials used in EPAs under severe accident conditions, a major concern is temperature-dependent properties. High pressures and high temperatures are produced from the energy released in a degraded core accident. The high pressures may eventually cause the containment to leak. The high temperatures may cause a significant reduction in material properties that, in turn, would promote the onset of leaking.

The material used in EPA seals can be divided into two general categories for study. The first group is the organic seals, such as plastics and rubber. The second includes the inorganic materials, such as glass, ceramics, and metals.

The plastic materials with the broadest application and longest history of use for EPA seals have been the epoxies. The epoxies are all-purpose adhesives and potting materials. They have good electrical and mechanical properties, heat resistance, dimensional stability, and will bond to most materials. They were used in the very early field-manufactured electrical penetrations for potting and sealing. Some epoxy formulations can be cured without heat or pressure. Those cured without heat typically have a lower temperature capability. Some early plants still repair leaks with a field application of epoxy.

Whether this affects the containment barrier depends on whether the repairs are inside (inboard) or outside (outboard) the containment. When the requirements for better reliability and qualification were imposed, the EPAs were then fabricated in the shop as assemblies. The epoxy seals then could be premolded and installed in the assemblies. The premolded epoxies could be cured at high temperatures and pressures; also fillers could be added that would increase their temperature capability. The major suppliers that use epoxy sealants were Amphenol, General Electric, Westinghouse, and (later on) Viking. (No information was obtained on Crouse-Hinds EPAs since they were purchased by Westinghouse; however, the seal design is probably similar; i.e., epoxy.)

Another polymer used in EPA seals is polysulfone. This material has one of the highest heat-deflection temperatures for thermoplastics; it is tough, and has excellent electrical properties and dimensional stability even at high temperatures. Polysulfone is also sensitive to ultraviolet light and should not be exposed to sunlight. The temperature capability of this material is probably above 500°F, but in the compressed state this is greatly reduced. The manufacturer recommends replacement of parts after exposure to 340°F for 6 hours.

The second major category of sealants contains the inorganic materials. The most common are the glass-fused seals that were used to give a hermetic seal. The glass materials are fired at 1600° to 1800°F so that glass flows in and around the solid conductors. Not only is a good seal developed, but glass also has excellent electrical properties. Fused ceramics are also used, particularly on the medium voltage power (MVP) modules. The fused ceramics are shaped so that metal can be used in the seal design. This seal is fabricated by the addition of a metal shell which is silver brazed to the ceramic. The metal shell then can be welded to a header plate or bushing. The vendors using glass-to-metal seals exclusively are D. G. O'Brien and Physical-Sciences. Viking used glass-to-metal seals in all of their early designs. Table 6 contains a summary of temperature capability for some typical sealants used in EPAs; however, Table 6 does not include the seals used in field-manufactured units, metal-to-metal seals, and other unique variations.

Table 6. Estimated Severe Accident Temperature Capability for Typical EPA Sealants

Vendor	Type of Material	Approximate Long Time (h) Temperature Capability (°F)
Amphenol	Epoxy	400 – 500
Conax	Polysulfone	340
Crouse-Hinds	Epoxy (?)	400
General Electric	Epoxy	500
O'Brien	Glass	500
Physical-Sciences	Glass	1200
Viking	Glass	1200
	Epoxy	500
Westinghouse	Epoxy	400 – 500

The metal-to-metal seals fall into two subcategories—the first is a mechanical seal, and the second seal is formed by the melting or fusing of metal. The second group includes soldering, brazing, and welding. Solders have the lowest capability because they are limited by their low melting point (300° to 450°F). Silver braze has been used in some EPAs and has a usable temperature to 1100°F (Appendix C). Welding is extensively used in EPAs and, if the EPA is fabricated properly, the weld should not be a limiting factor. The mechanical seals behave in a manner similar to gaskets and are discussed in the next section.

Gaskets and O-Rings

Gaskets have been previously defined as a material used to develop a seal by compression. These materials are made from plastics, rubbers, and metals. The commonly used organic materials are silicone rubber, viton, and ethylene-propylene type rubbers (EPR/EPDM). The most common geometry are the O-rings and flat gaskets. Some special configurations are referred to as Q-rings and C-rings. The Q-rings are used in Amphenol EPAs while C-rings were used in early General Electric units. All these gaskets and O-rings are used in units that are mechanically assembled. If the EPA is entirely welded, such as the Physical-Sciences units in Browns Ferry 1 and 2, no gaskets are used; however, when an EPA is bolted to the nozzle, an O-ring or gasket is needed. The EPA designs, such as Amphenol, Westinghouse (which uses four O-rings), General Electric, and Conax (MVP units), that require the modules to be mechanically fastened to the header plate also need gaskets. D. G. O'Brien has a modular design but welds all of their modules to the header plate. Table 7 shows the temperature capability of several typical elastomers used in O-rings and gaskets.

Table 7. Estimated Useful Lifetime vs Temperature of Typical Elastomers Used in O-Rings and Gaskets[21]

Material	400°F	500°F
EPR/EPDM	1577 min	53 min
Viton	9 mo	22 days
Silicone	2 yr	4 mo

Metal gaskets in the form of O-rings and other special configurations are used in EPAs. Metal O-rings have been used extensively in nuclear applications.[22] In using metal O-rings, special preparation of the surface is required as well as consideration of the compatibility between the environment and the dissimilar metals. The service temperature of a metal O-ring is based on the type of steel used and the coating. A sample of usable service temperatures for metal O-rings can be found in Table 8.

Table 8. Coating Materials and Usable Service Temperatures for Steel O-Rings[22]

Coating Material	Service Temperature (°F)
Teflon	500
Silver	1300
Gold	1900
Copper	1900
Nickel	2200

There is another type of metal gasket design that is used in Conax and Viking (Vikron) modules. The Conax design uses a threaded bushing (called the midlock cap) that pushes a metal-ring gasket between the header plate and module. Torquing the midlock cap wedges the metal gasket to create high-contact stresses thereby providing the metal-to-metal seal.

Structural Interaction

The interaction of the nozzle and containment structures under loading can cause deformations that may be important because of the potential for leakage. Under severe accident conditions, the large pressures and temperatures eventually lead to containment leakage. Structural interactions are higher for the larger penetrations (such as personnel locks and equipment hatches) than on electrical penetration nozzles. Gross containment failure and penetration interactions are being studied in other NRC Programs.[4]

The structural portion of the EPA designs falls under the guidance of the ASME Codes and typically have a design factor of 3 or more. The allowable design stress is typically less than 33% of the minimum ultimate tensile stress at temperature (see Higginbotham in Reference 1). A large combination of loads are usually considered in designing containments and penetrations. To determine if the factor of 3 is applicable to each containment requires a case by case study. Two examples follow. The first is Browns Ferry 1, where the containment design pressure is 60 psig; therefore, the EPA structure should be adequate to 180 psig. The Browns Ferry 1 structural capacity is estimated to be 160 psig, so the containment structure has the lower failure pressure.[2] In another example, Watts Bar has a design pressure of only 15 psig; therefore, the expected design ultimate pressure for the EPA would be ~45 psig. However, Watts Bar has a much higher ultimate capacity because of a thicker steel shell. The equipment hatch was found to have the limiting ultimate pressure with a capacity of 140 psig.

Leakage

The next step beyond determining the potential for leakage is to quantify the leak rate. The leak rate is needed to determine the amount of gas and aerosols escaping through the containment barrier (such as gaskets and seals) and thus provide an assessment of the risk. The leakage or leak rate of radioactive materials is dependent on different parameters: the source, particulate size, driving pressure, gasket characteristics, hole size, etc. The purpose of this section is to discuss these parameters.

Gasket leakage can occur by two basic methods: through the seal and past the seal.[21] Important parameters effecting seal performance are

- Pressure
- Temperature
- Gas and aerosols properties
- Seal dimension
- Geometric shape of seal
- Seal material
- Surface conditions
- Preload
- Time

These parameters influence the mechanism for leakage and are not necessarily independent. The leakage through the seal is called permeation and the leakage past the seal is "through a clear passage." Permeation is a function of the diffusion and solubility of a gas in the seal material. The permeation rates vary with temperature and are significantly different for combinations of gases and materials. In evaluating leak rates, it becomes very important to know whether permeation or a clear path is the dominating mechanism.

Leakage "past the seal" is an important mechanism and is influenced by the parameters listed above. All the parameters are important for achieving and maintaining a good seal; however, the loss of a seal is effected mainly by the seal materials. The change in material properties of elastomers that are a function of temperature and/or time can lead to gross leaks. These properties are creep and stress relaxation. Compression set (a quantitative indication of these properties) is commonly listed for elastomer O-rings. Compression set is a permanent change of shape that can lead to increased leakage. At high temperatures some elastomer materials become soft and may flow under pressure. The useful life of elastomers are frequently predicted by use of the Arrhenius equation.[20]

Theoretical predictions of the complex nature of leakage through seals has not been very reliable. Because of this, extensive testing has been conducted on these materials, but results still show wide variations in expected behavior. Full-scale testing will help alleviate some of these problems. However, the test gas used will not represent the variety of gases and particulates found in severe accident conditions.

In summary, we should be aware of the complex nature of leakage and its relationship to the assessment of EPA performance under severe accident conditions.

Postulated Failure Modes in Generic Containments

The purpose of this section is to review the design of EPAs and their expected behavior under severe accident loads, and to provide an assessment of their capability. Three generic types of containments were selected for this portion of the study: a large dry (PWR), an ice condenser (PWR), and a Mark I (BWR). In each case the containment EPAs are described as well as the severe accident condition encountered and the expected failure mode.

Large Dry – Bellefonte

The Bellefonte Nuclear Power Station is a PWR with a large dry containment. The design pressure is 50 psig, and the internal volume is 3.4×10^6 ft^3. The containment is prestressed concrete with cylindrical walls, 3 ft thick. These prestressing tendons are the principal structural members for internal pressures that exceed the design loads. The ultimate capacity of the containment building is predicted to be 139 psig. The 1/4-in. steel liner is included in this strength estimate and the average material properties were used in the calculations.

The EPAs in Bellefonte will be installed in steel nozzles in the containment walls. The nozzles are typically 54 in. long and have two diameters (see Figure 2). The larger diameter nozzles are made with an 18-in. schedule 80 steel pipe. The smaller diameters use a 12-in. schedule 40 steel pipe. TVA is installing 69 EPAs into the nozzles and will have an additional 38 nozzles as spares. Of the 69 EPAs being installed, 65 are 12 in. in diameter and 4 are 18 in. in diameter. The larger diameter is for the MVP used to power the coolant pumps. The EPAs are all welded to the nozzles with the header plates on the outboard end. The pressure monitoring system (since it is attached to the header plate) is also exterior to the containment building. The EPAs are of the modular type and are being supplied by two vendors: Conax and Westinghouse.

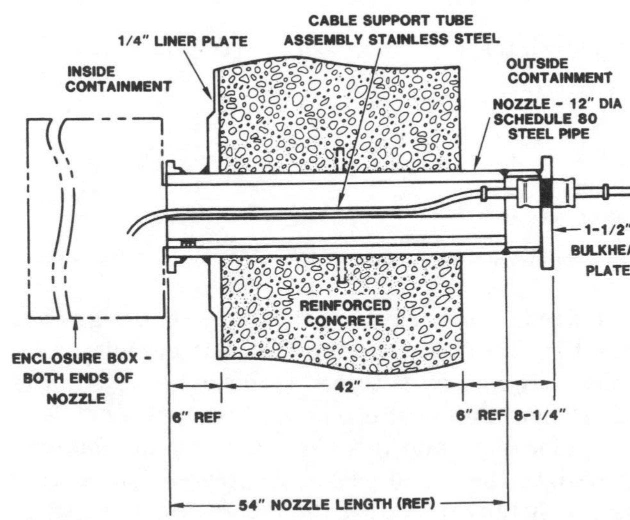


Figure 2. Westinghouse EPA Installed in Bellefonte 1 and 2

Conax is supplying 42 of the 69 EPAs to be installed in Bellefonte. Except for the medium voltage power (MVP) units, all the Conax modules are 1 in. in diameter and 68 in. long. The MVP units require a larger diameter conductor and are 2-1/2 in. in diameter and 75 in. long. The 1-in.-dia modules are the standard Conax design using a solid conductor, insulated with a polyimide film, and sealed into both ends of a stainless-steel tube with polysulfone. The stainless-steel tubes are secured to the header plate with a metal seal that is squeezed by torquing the midlock cap. The MVP units use a different sealing system that includes a ceramic terminal bushing at each end of the assembly. The seal between the solid conductor and the ceramic bushing uses a metal-to-metal seal. Between the ceramic bushing and header plate is a threaded steel bushing that uses a viton O-ring for a seal. A metallic bellows is included in the design to allow for thermal expansion under fault current loads.

Westinghouse is supplying 27 EPAs to Bellefonte. These provide service for low-voltage power, control, and instrumentation. The Westinghouse modules are all standard 5 in. in diameter and 12 in. long (Appendix A, Figure A4). These modules are installed on the outboard side of the containment (Figure 2). The modules all have multiple barriers; in contrast to the Conax design, both seals are located outboard.

The maximum loadings have been estimated in severe accident studies and are discussed in Appendix B. The maximum temperature for Bellefonte never exceeds 350°F because the excess water in the containment building during the accident progression keeps the atmosphere in a saturated steam state.

The potential for leaks to develop in Bellefonte EPAs is extremely low. Although the EPAs are qualified to 340°F, the outboard end of the nozzle will not reach that temperature. The massive concrete wall acts as a heat sink and will keep the outside end far below the temperature limits of the organic seals.

Ice Condenser – Watts Bar 1 and 2

The Watts Bar Power Station is a PWR with an ice-condenser type suppression system. The design pressure is 15 psig and the internal volume is 1.2×10^6 ft^3. The containment consists of a free-standing steel shell. There is a 5-ft distance between the steel shell and the outer concrete biological shield building. The steel shell consists of cylindrical side walls and a spherical dome. The failure pressure of the containment is predicted to be 120 to 170 psig in the steel shell. However, the equipment hatch is predicted to fail at 140 psig because of large plastic deformations in the outer ring and flange.[23]

The EPAs in Watts Bar are installed in steel nozzles that are 24 in. long and made from Schedule 80 pipe (see Figure 3). The nozzles come in two diameters—18 in. and 12 in. There are 15 of the larger diameter and 38 of the smaller diameter. This gives a total of 53 EPAs plus one spare 12 in. nozzle. There are 4 EPAs for medium voltage power (MVP), 42 for low voltage power and control, 3 for thermal couples, and 4 for neutron monitoring. Except for the MVP units, the modules are the same size. They are the standard Conax design (1 in. in diameter and 34 in. long). The solid conductors have a Kerite insulation and are sealed at both ends with a polysulfone. The modules are mounted to the header plate with a metal seal and a midlock cap. The header plates are welded on the outboard end of the nozzles. The EPAs have a double seal arrangement so that the pressure barrier can be monitored.

The MVP units are constructed differently. They have large solid conductor (2-1/2 in. dia) to carry the load. There are six modules to each assembly. The modules are about 3 in. in diameter and 54 in. long.

The header plates for the MVP units have the header plates inboard instead of outboard like all other Watts Bar EPAs. The MVP modules are fastened to the header plate by two threaded bushings. One bushing is brazed to the ceramic high-voltage standoff end and the other bushing is welded to a steel support pipe. The seal to the header plate is accomplished by two viton O-rings. The double barrier provides a means of monitoring pressure in each module.

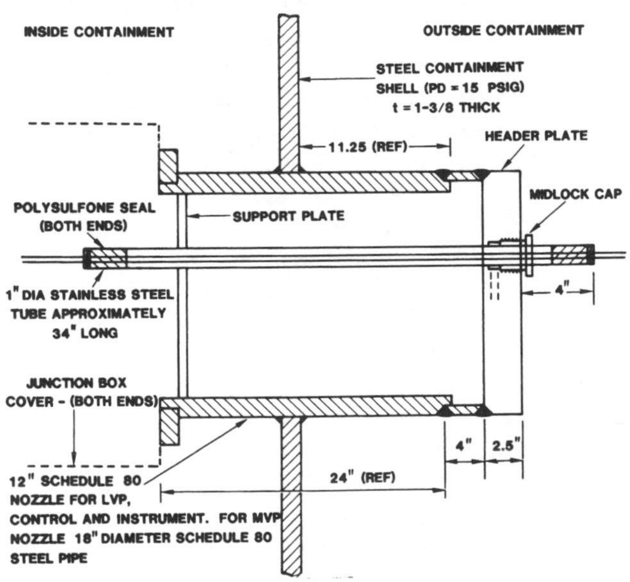


Figure 3. Watts Bar 1 and 2 – Electrical Penetration Assembly (Conax)

All the EPAs except the MVP have spare ports in the header plates so that additional modules can be added later. The spare ports are sealed with a plug. The EPAs in Watts Bar have 1000 ports in use, plus an additional 200 ports for future use.

The severe accident loadings are discussed in Appendix B. These loadings show that the compartment temperature, where the majority of the EPAs are located, is about 340°F. When the loading reaches the estimated containment failure pressure (140 psig), the corresponding wall temperature is 340°F.

Since the Watts Bar is a free-standing steel shell and the nozzles for the EPAs are only 24 in. long, the units will follow the same temperature history as the containment wall. It is felt that the potential for leakage should be relatively small, since the EPAs have been qualified to 340°F. However, none of the qualification tests included leak rate measurements at the same pressure, temperature, and time as encountered in a severe accident.

Mark I BWR – Browns Ferry 1, 2, and 3

The Browns Ferry 1 Nuclear Power Station has a MK I type of Boiling Water Reactor (BWR). The design pressure of Browns Ferry 1 is 56 psig and has an internal volume of 300 000 ft^3. The containment is a steel shell in the shape of light bulb and torus. The light bulb portion is the dry well and the connecting torus section contains water for the suppression pool. For accident situations, the atmosphere from the dry well is directed into the wet well where it is both cooled and scrubbed of any particulates. The steel shell varies in thickness over the length of the containment. The steel shell is separated from the concrete biological shield by 2-1/4 in. of urethane insulation. In accident scenarios where the temperature and pressure are increasing, the steel shell can deflect outward approximately 2 in. The containment failure pressure was estimated to be 160 psig.[2]

Brown Ferry 1 has 30 EPAs in the dry well region and 2 in the wet well. Because the dry well is the critical area in terms of temperatures and pressures, the wet-well EPAs will not be discussed. The EPAs in the dry well are welded to steel nozzles ~84 in. long (Figure 4). The EPAs in the dry well were supplied by two vendors: Physical-Sciences and General Electric. Physical-Sciences supplied 27 EPAs and General Electric supplied 3. The Physical-Sciences EPAs are all of the canister type. These canisters are double-ended; i.e., one set of seals are at each end of the penetration. The Physical-Sciences seals are of the glass-to-metal type that have a high temperature capability (see Appendix A, Figure A7).

The three EPAs supplied by General Electric are the Series 100 module type. These modules are mounted outboard of the containment. They are single-ended (the double seal is at just one end of the nozzle). The seals are made with a castable epoxy; therefore, they have a much lower temperature capability than those supplied by Physical-Sciences (see Figure 5).

The containment pressures and temperatures were calculated for eight different severe accident scenarios;[2] however, only four are shown in Appendix B (Figure B4). The degree of conservation is unknown in those calculations and are used here without any changes.

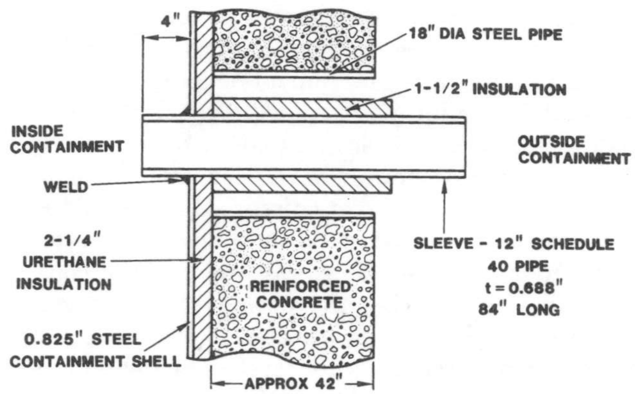


Figure 4. Browns Ferry 1 and 2 Electrical Penetration Sleeve (Nozzle)

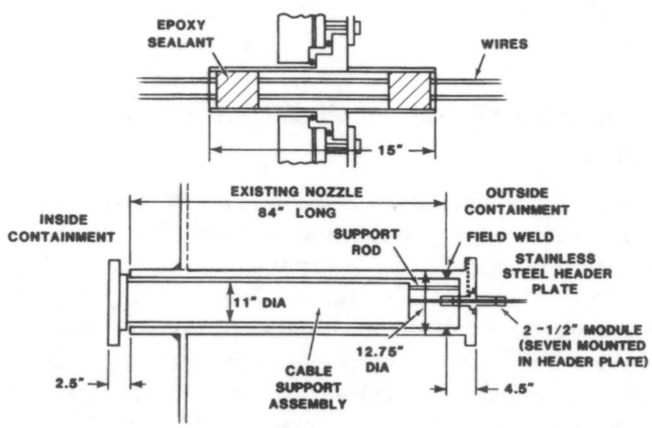


Figure 5. Browns Ferry 1 and 2 General Electric Modular Type EPA

The assessment of the behavior of EPAs in Browns Ferry 1 is very different from that in Bellefonte and Watts Bar because in many of the accident scenarios, the dry-well temperature will get extremely high. The lack of cooling water and the smaller dry-well volume causes the high temperatures. The assumptions on containment failure in Reference 2 are as follows: all EPAs are at the threshold of leaking at 400°F (477 K) and leak grossly at 500°F (533 K). The accident scenarios (Figure B4) consider containment failure as gross failure of the epoxy seals. However, only 3 (out of 30) of the EPAs have epoxy seals and are located over 7 ft from the inside of the containment. In this configuration, there is some question as to what temperature the seals might experience. The thermal response at the outboard end is certainly more complex than assumed in Reference 2.

Some thermal models were developed in this study to analyze the thermal behavior of the nozzle and EPA. The first model was a conduction-only model and used the dry-well wall temperature as a thermal input (Appendix D). The conduction through the EPA nozzle, sleeves, and conductors is very small and results in only a 20°F temperature change for the longest time and highest temperature. This first thermal model would be applicable for the case, where the fluid flow from the containment into the EPA is restricted. If this is the case, the epoxy seals will not become soft because they remain below 150°F.

The second model evaluates the thermal behavior when energy is transported by convection and diffusion. This model is sensitive to the fluid-flow rate and the ability to reject heat at the outboard end. (This model is discussed in Appendix D.) The thermal models of the EPAs indicate the outboard seal temperatures are below 400°F for the accident scenarios in Reference 2.

Browns Ferry 3 is very similar in design to Browns Ferry 1 and 2; however, it has different EPAs. There are 29 EPAs in the dry well of Browns Ferry 3 and are all supplied by General Electric (GE) Company. All of the EPAs are of the early GE canister design, which used an epoxy seal located at each end of the canister. The seals are approximately 8 ft apart. This type of canister EPA was also used in Dresden 2 (Appendix A, Figure A6). Under a severe accident condition, as might be experienced in the dry well of a Mark I BWR, the inboard end of the EPAs would exceed 500°F, causing failure of the inboard seal. Thermal response of the inboard seal should follow closely the wall node (1) in Figure B4. The EPA seals are surrounded by the nozzle, sleeve, and header plate, which provide some thermal mass and delay the time for the seal to heat up. This thermal mass is greater than the containment shell that is represented by wall node (1); therefore, the wall temperature will be a conservative estimate of the EPA seal temperature.

Loss of the inboard seal will not cause loss of physical integrity as there is still a second barrier—the outboard seal. Failure of the outboard seals depends on the ability to transfer heat to the outboard end of the EPAs. The thermal modeling that was done for the Browns Ferry 1 and 2 applies also to Browns Ferry 3 EPAs. (Details of the thermal modeling are discussed in Appendix D.) One of the heat paths is by conduction. The calculations show that the conduction path only raises the outboard seal by 20°F and is not sufficient to degrade the seal. The other thermal paths are diffusion, convection, and radiation. The radiation method of heat transfer is negligible because all the EPAs are shielded by the junction boxes covering the ends. The heat transfer through mass diffusion can be quite large. The diffusion thermal models indicate the outboard seal temperatures will only reach 350°F because the steam in the gases condense at the cooler end of the nozzle. During the condensation phase, the temperature is dependent on the containment presure. Another aspect of the conditions limiting temperature is the large specific volume of steam; i.e., it takes a large quantity of steam to produce one pound of water.

Since the EPAs in Browns Ferry 3, as well as 1 and 2, do not exceed 350°F during the overpressurization of the containment, the mode of failure is not through the EPAs. The mode of failure is not necessarily in the containment structure, but in the inboard seals in other penetrations. In all of their containment buildings, the utility is using or replacing seals with EPDM rubber gaskets that lose their properties at 500°F. For example, if the equipment hatch seals are located inboard so that they experience the same temperature as the steel shell (wall node temperature), then these seals become a potential source of leakage. Using the wall node temperature as the seal temperature, the times to containment failure are as shown in column 1 in Table 9.

Table 9. Containment Failure Times (min) for EPDM Rubber Seals

Sequence	EPDM* Rubber Seal	Containment Failure Times[2] Overtemp. (500°F)	Overpressure (160 psig)
TC	730	692	961
TQUV	210	193	288
AE	216	17	183
S1E	50	40	200

*At 500°F

As Table 9 shows, the wall node temperature that should be used in estimating the temperature of the inboard seals has a significant impact on only one sequence; i.e., in the AE sequence, the EPDM rubber seal failure time is longer than the time to reach 160 psig.

Summary

Observations and Conclusions

The direction of this study has been on the potential for EPAs to develop leaks under severe accident loads, but other relevant information was included. The following is a summary of the results obtained from a 4-mo study on electrical penetration assemblies:

- Although not perfect, the EPA operational performance record was much better than for other types of penetrations.
- The results from a review on LERs for EPAs showed that only three had "through leakage."
- The EPAs designs since the mid-1970s are unlikely to leak in environments up to 350°F and 100 to 120 psig, since many of the designs have been qualified to these conditions.
- The EPA designs before the mid-1970s (in particular, field-manufactured units) are so diverse in design that they will require individual evaluation.
- The resulting temperatures from severe accident progressions in two specific containments can be applied generically. The maximum temperature in both containments is approximately 350°F; therefore, the EPA seals are unlikely to degrade, causing leakage. The two containments are:
  - Bellefonte – Large dry PWR
  - Watts Bar – Ice condenser PWR
- The EPA seal behavior in Browns Ferry 1 is not the same as reported in Reference 2. This is because 27 EPAs have glass-to-metal seals and only 3 have epoxy seals. The three epoxy seals are located outboard and are not subjected to the same thermal environment as in the dry well.
- The majority of leak-rate testing is done before and after other types of testing. Leak rate measurements at severe accident pressures and temperatures are needed.
- The Conax high-temperature test was for LMFBR environments. The test was conducted at extremely high temperature (1100°F) and showed that conduction and convection transmit very little thermal energy. The test did not include steam, which can be an important heat-transfer mechanism.

Recommendations for Testing

We feel that a test program can validate the conclusions from this study. The following are proposed test items:

- The General Electric modular design used in Browns Ferry 1 has an epoxy formulation and the seals are located at the outboard end of the nozzle. The test of this configuration would also provide experimental information on the heat-transfer modes.
- The General Electric canister design used in Browns Ferry 3 used an early epoxy formulation and has seals located at both ends of the assembly.
- The D. G. O'Brien Type J modules because they have a different pressure capability than Type K.
- The Conax design to test the midlock cap and seal configuration, since the leak rate is not known at accident conditions.
- The early Westinghouse designs, since they have a lower rated epoxy seal and O-rings.
- The Viking epoxy module (Vikron) because it has a midlock cap and seal similar to Conax.

Not recommended for testing are the Physical-Sciences EPAs, because they all have glass-to-metal seals; Crouse-Hinds, because of unavailability of units; and Amphenol, since they use an epoxy seal.

Additional Recommendations

The following additional recommendations are made. Although they are beyond the scope of this report, they are of interest to containment integrity:

- Continue or initiate studies on other BWRs, because of the need to evaluate their "containment failure models."
  - Determine if the high dry-well temperatures calculated in Browns Ferry 1 accident scenarios are applicable to other BWRs: Mark II, Mark III, and Pre-Mark.
  - Study the structural capability of the steel containment shell at high temperatures (~1000°F).
  - Investigate the capability of seals in other penetrations.
  - Continue the study of EPA geometry and seal behavior in all other BWRs.
- Recommend a maintenace surveillance program for organic seals used in gaskets and O-rings, since some materials have limited useful lifetimes.

Program Plan

The program outlined here will provide measurements of leak rates in EPAs at temperatures and pressures associated with severe accident conditions. The types of EPA sealants considered are epoxy, polysulfone, and glass. The specific loading conditions to be investigated include the pressures, temperatures, and time associated with severe accidents in the BWR Mark I and the PWR. All of these combinations of sealants and environments could be considered; however, only three tests are being proposed in the present plan because of funding, time constraints, NRC priorities, and the availability of test units.

The BWR environmental loads were the most challenging to the EPA seals and will provide the most severe test condition. The EPAs in the PWRs should be tested also because the severe accident environments exceed the level to which they were qualified. Although this difference is minimal, the tests will be measuring leak rate at elevated temperatures and pressures that were not reached in the qualification tests. The epoxy seals have a much lower temperature capability and have been in use longer and more extensively. The early epoxy formulations generally have a lower temperature capability, but these early models are not likely to be available for testing. The proposed tests are denoted in Table 10. If any General Electric EPAs with epoxy seals become available, they could then be used in Test 1.

Table 10. EPA Test Matrix

Test No.	Type of Seal	Type of Environment	EPA Manufacturer
1	Epoxy	PWR	Westinghouse
2	Polysulfone	BWR	Conax
3	Glass	BWR	D. G. O'Brien

Additional work will be necessary to adapt leak-rate measurement methods to this test series. Measuring leak rates is substantially different than detecting leaks. Most leak-rate testing conducted by the industry on EPAs is done before and after other testing, primarily because of convenience and costs. Since leak rates are not measured routinely at high temperatures, some effort will be required to develop this methodology. These measurements are expected to be made above the typical qualification test level (i.e., 350°F and 100 psig).

The program plan will use existing facilities at Sandia National Laboratories. The test facility consists of a large steel tank, steam generator, controls, and associated recording equipment. Some development work will be needed to adapt the EPAs to the steel tank. The steam generator should have no problem supplying energy for the PWR severe environments; however, since BWR environments are so much higher, additional development effort may be required.

The preparation and testing of each unit is expected to take 3 to 6 mo. The preparation includes the additional of instrumentation, such as thermocouples, and any prewiring of circuits. An additional feature of these tests is the monitoring of the circuits and connectors in the EPAs to determine if they can function during a severe accident environment.

Results from these tests are expected to determine the leakage behavior and leak rate in selected EPAs. These results will be recorded in a report for each test, and an overall assessment will be included in a final report. The program is scheduled for completion by the end of FY1984.

APPENDIX A

Brief History of Vendors and EPA Development

Figures

Vendors and Suppliers

The purpose of this Appendix is to provide a short history and background on the major vendors and suppliers of electrical penetration assemblies. This section also contains schematics of representative EPAs. These drawings show the diversity of designs, materials, and configurations. There have been eight major EPA suppliers of which three are still active. The descriptions in the following sections are not intended to be an endorsement of any kind.

Active Vendors

Three of the major vendors are still supplying EPAs to nuclear power plants. Each vendor has a different design. A brief history and description of these designs are given.

Conax[15]

Conax has been supplying EPAs since 1972. They have assemblies in 66 US nuclear power plants of which 28 are currently operating (see Table 3), and 38 plants are in construction or just beginning operation. Conax has licensed AUXITROL in France to produce the Conax design which is widely used in France, Belgium, and Spain.

The Conax designs are the modular type and are based on the principal of compressing or squeezing a soft sealant material around solid conductors. The squeezing action is accomplished by swaging a stainless-steel tube around the sealant with the conductors suspended in the sealant material. Each stainless-steel tube is a module that can be mounted to a header plate. The stainless tubes are typically 1 in. in diameter and from 12 to 72 in. long. Each tube has a seal at both ends to provide a double seal. The interior of the tube is pressure monitored through a small vent hole. The resilient material in current designs is a polysulfone 4 to 6 in. long, which provides a longer path for leakage to develop (see Figures A1 and A2).

The Conax modules are mounted to a header plate. This header plate can either be welded or bolted to the containment nozzle. Figure 3 shows a typical welded installation applicable to Watts Bar 1 and 2. All of the EPAs in Watts Bar are welded except for the medium voltage power (MVP) assemblies. These are bolted to flanges on the inside of the containment building. The header plate has provisions for monitoring the double O-ring seal and the internal pressure of each module. The modules are attached by a leak-tight metal sealing technique referred to as the mid-lock cap that is torqued into place, forcing an inner ring to compress against the header plate and the stainless-steel tube to provide a metal-to-metal seal. This squeezing action occurs in two places, one on each side of the vent hole in the module, providing a double barrier or seal so that the module pressure can be monitored by one source (i.e., "unitized").

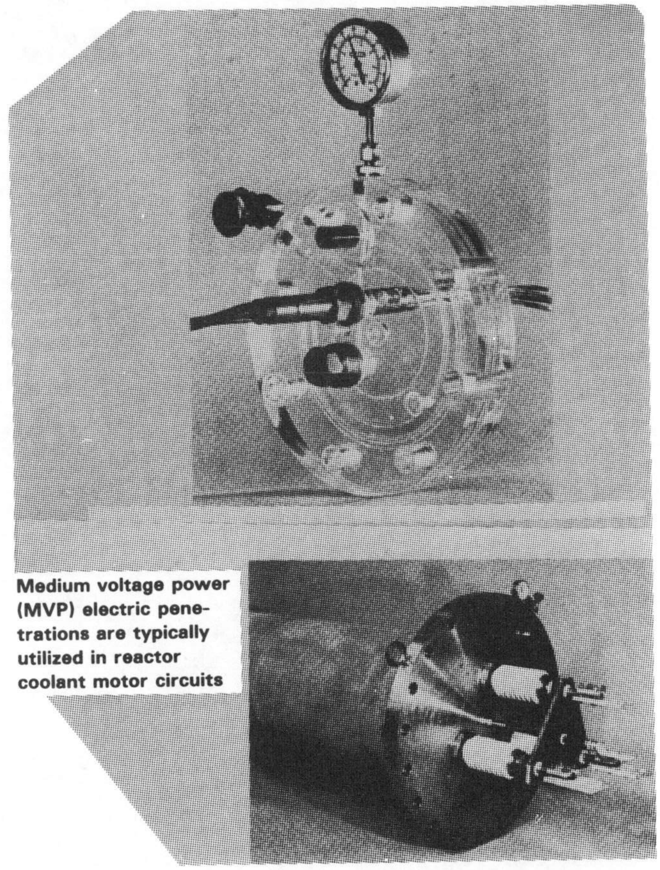


Figure A1. Top See-Through Model for Showing "Unitized" Pressure Monitoring. Bottom-medium voltage power assembly.[15]

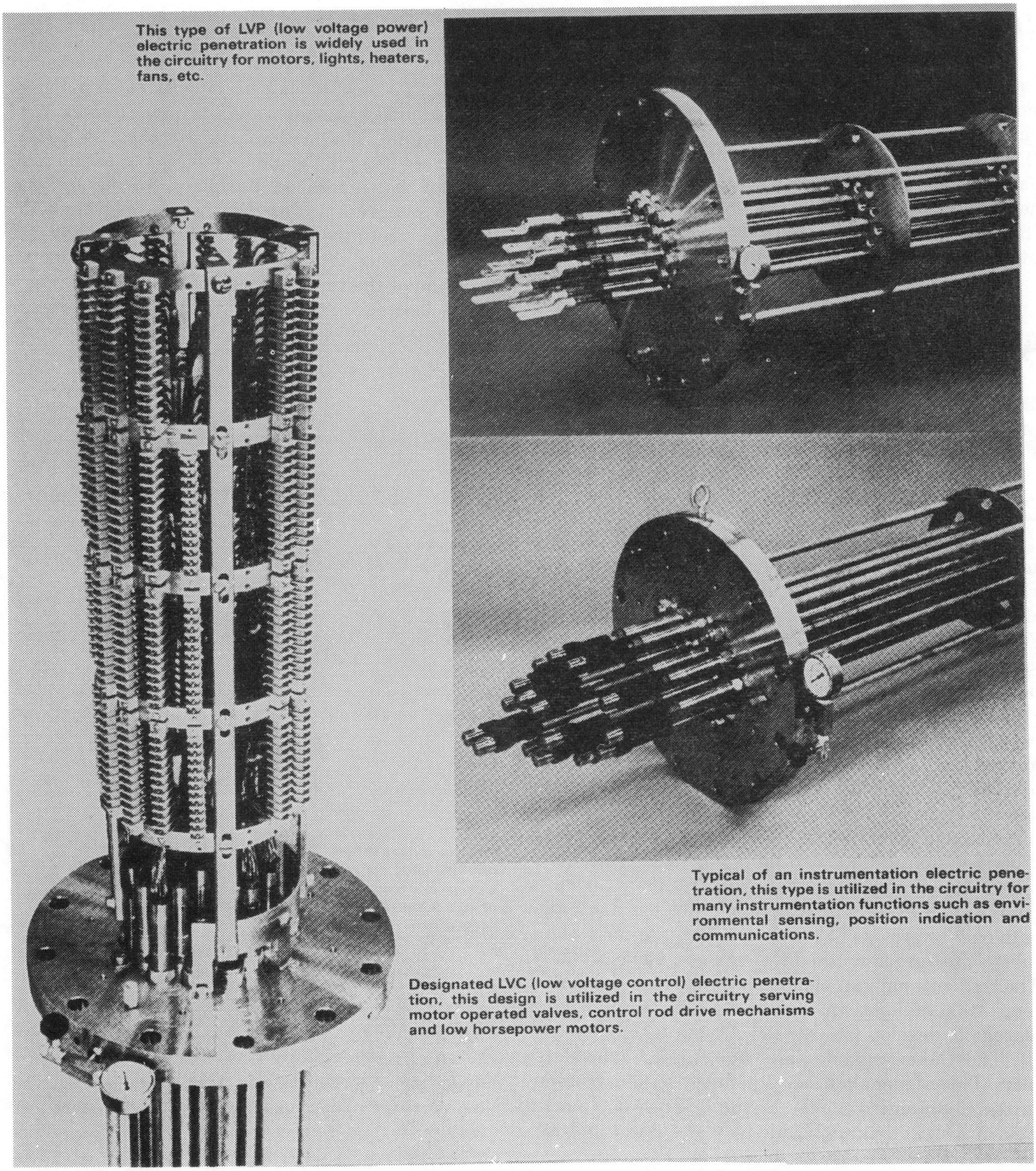


Figure A2. Conax Electrical Penetration Assemblies (LVP, Instrumentation, and Control)

D. G. O'Brien[16]

D. G. O'Brien has supplied over 1100 electrical penetration assemblies to the nuclear industry. They have EPAs in about 20 nuclear power plants; 13 are presently operating (see Table 4). O'Brien has also supplied EPAs to experimental and training reactors. Their first penetration was developed and delivered in 1965 for a barge-mounted nuclear power plant. The first nuclear power plant that used O'Brien EPAs was installed in Nine Mile Point in 1969. Although O'Brien has supplied over 700 EPAs, the number from the SwRI Data Bank listing (Table 3) is only 268, which indicates a large difference. This illustrates again the large gap between what is in actual operation and what the utilities are reporting to SwRI.

D. G. O'Brien uses glass-to-metal seals exclusively in all their penetration designs. The glass-to-metal seal has been made in-house for over 20 yrs. The seal is fused with solid conductors so that no leakage occurs through the conductor. The glass and metal parts require a proper matching of the coefficient of thermal expansion. The mechanical and chemical bond that results from the fusing operation provides a positive barrier to gases and moisture. The conductors are fused into two different parts of the connector body, then these two parts are welded to a stainless-steel shell. A vent hole drilled into the shell provides pressure monitoring of the interior. The connector body is double-welded to a header plate that has monitoring ports drilled into it (Figure A3). O'Brien refers to this as a modular assembly because the various conductors are isolated into groups. However, since modules are welded to the header plate, any conductors needing replacement would require replacement of the entire header plate and modules. One method for circumventing this problem is to install spare conductors. These extra circuits then can be used as necessary.

The D. G. O'Brien glass-to-metal seals provide a good high-temperature capability. Glass also has a long life and is radiation tolerant.

Westinghouse[19]

Westinghouse has been supplying electrical penetration assemblies since the very early 1970s. These assemblies are currently in use in 14 plants placed in operation before 1981. They also have EPAs in 10 other plants that have just gone into operation or are expected to go into operation in 1983. Westinghouse is supplying penetrations to another 12 plants that will be in operation after 1983. This company also supplies EPAs to other countries and are involved in 18 plants outside the US. In the early 1970s Westinghouse absorbed Crouse-Hinds in order to broaden their product line.

The very early Westinghouse designs were of the canister type (some 10 plants are of that design). During the mid-1970s, Westinghouse initiated development of the modular design.[10] In 14 power plants, the EPAs are all modular designs; in 8 other plants, the EPAs are modular except for the medium voltage power (MVP) units. Westinghouse also has supplied retrofit units to 6 other plants.

All the Westinghouse EPAs are based on an epoxy sealant system. Information has not been made available for the early Westinghouse designs; however, Reference 10 contains information on designs for 1975 and after. The basic module is shown in Figure A4. The module is ~12 in. long and 5 in. in diameter. This 5 in. diameter allows installation of up to three modules in a standard 12-in. schedule 40 nozzle. Each module could have just one conductor (as in the case of medium voltage assembly) or it could have many hundreds of wires (as seen in low-voltage control modules). Westinghouse uses a solid conductor through a center disk made of glass-reinforced epoxy. This disk also has space for pressure monitoring. On each side of the disk (~2-1/4 in.) an epoxy compound is applied for the primary sealant (Q-1). The next layer of epoxy (Q-2) is primarily applied for potting purposes and provides restraint for the wires or pigtails. This Q-2 epoxy also has a mechanical restraint to the outer stainless-steel shroud by swedging the shell 3/4 in. from each end. The stainless-steel shroud is welded to a ring containing a small flange and four O-rings grooves. Two O-rings are placed on each side of the monitoring-access port: one pair is made of ethylene propylene rubber (EPR); the other is a silicone material. The silicone rubber O-rings provide a higher temperature capability then the EPR material. The O-rings develop the sealing preload by proper dimensions between the inner and outer bores. The O-rings are resilient and are compressed when installed into the header plate. Using three bolts, hold-down clamps are used to secure the modules. The header plates are typically welded to the nozzle to complete the pressure barrier and have a "unitized" capability of monitoring all the pressures simultaneously.

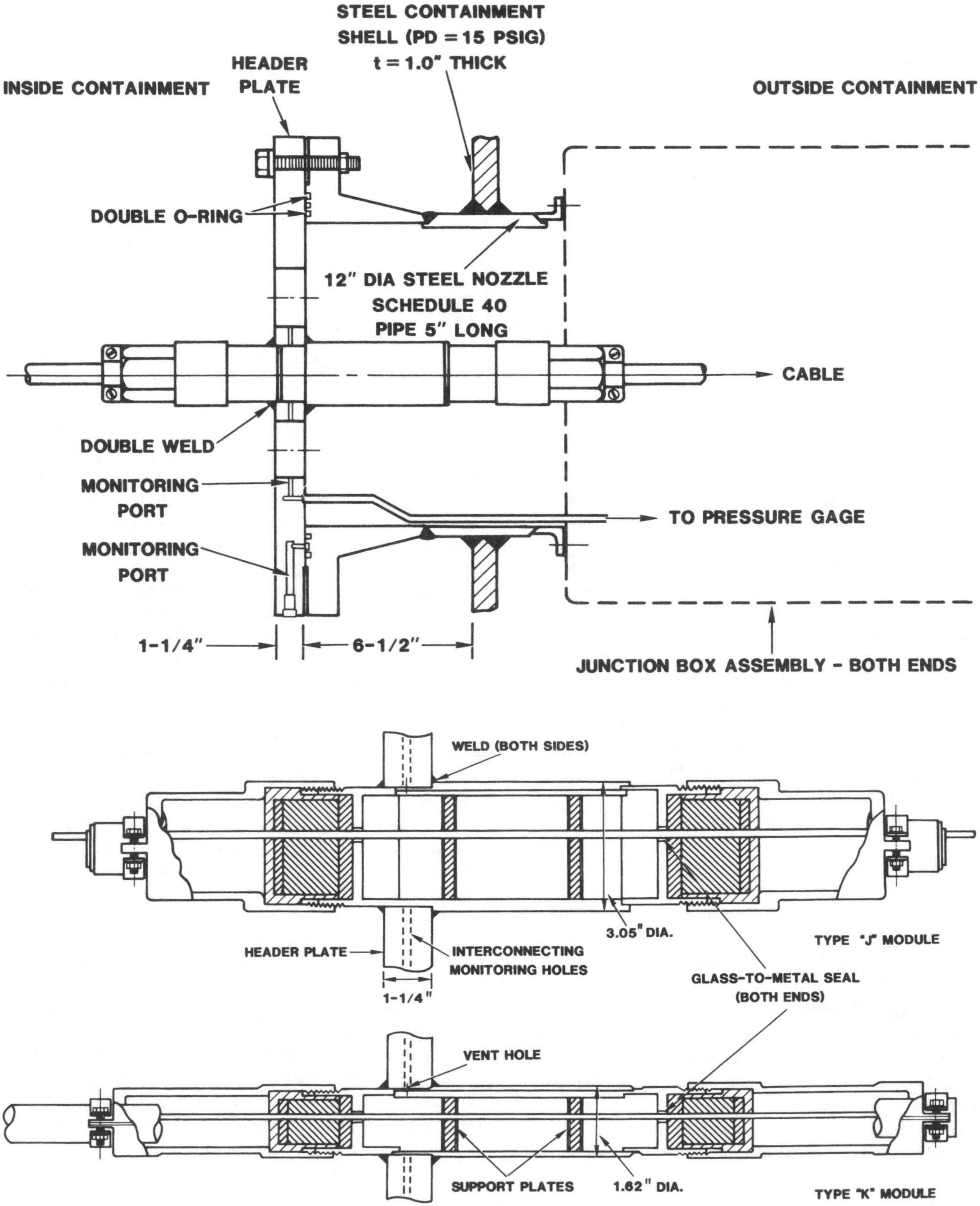


Figure A3. D. G. O'Brien Electrical Penetration Assembly

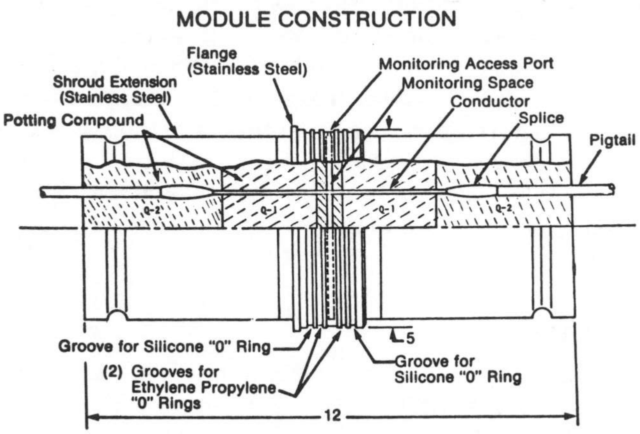


Figure A4. Westinghouse EPA Module

Inactive EPA Vendors

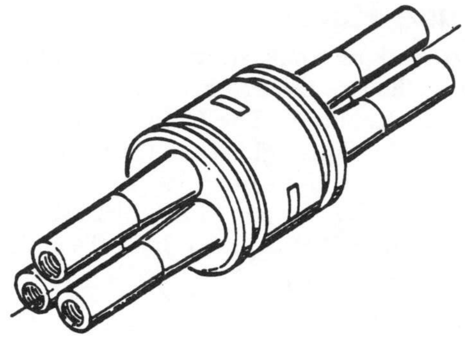
Amphenol[24]

Amphenol originally started supplying EPAs in 1968 and 1969 to Surry 1 and 2. They also supplied EPAs to Trojan, Davis-Besse, Calvert Cliffs 1 and 2, and Arkansas Nuclear One 2. Ampenol has supplied EPAs to 12 different nuclear plants of which 7 are presently operating.

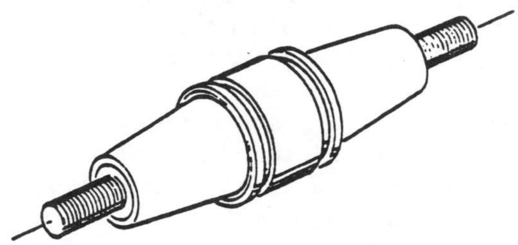
The Amphenol EPA has a modular design and uses an epoxy for the primary sealant. Early epoxy formulation was more flexible and, as design requirements changed, Amphenol developed a new formulation in 1977. This new formulation was more rigid and also had a higher temperature capability, believed to be around 400°F. Amphenol last supplied EPAs to nuclear plants in 1981.

The modules are fabricated with a proprietary epoxy compound cast around solid conductors. These conductors can vary in number from just one (as in the case of the MVP module) to 30 to 40 as in the case of low voltage and instrumentation modules (Figure A5). The modules are installed to a header plate with two Q-ring gaskets. The Q-ring gasket has an EPR seal and is backed up with a metal ring. The Q-rings are placed at each end of the module and then clamped to the header plate with a separate ring. All Amphenol EPAs use flanges to bolt the assembly to the containment nozzle. The double O-ring used in the nozzle flange is made from a silicone rubber.

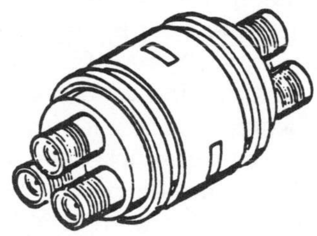
NOTE: Amphenol EPAs are experiencing electrical safety problems and are currently under review by the Inspection and Enforcement Branch of NRC.



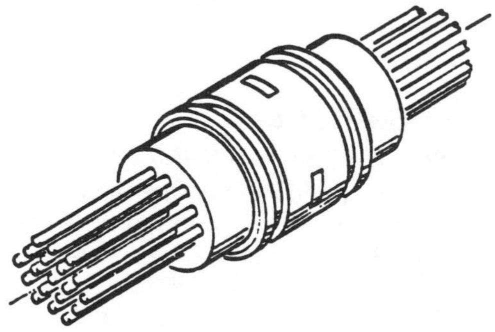
Low Voltage Power Modules



Medium Voltage Power Module



Triax Module



Low Voltage and Instrumentation Module

Figure A5. Amphenol Modules

Crouse-Hinds

Crouse-Hinds only supplied EPAs to two nuclear plants in the late 1960s. These plants are R. E. Ginna and H. B. Robinson. The Crouse-Hinds facility was taken over by Westinghouse in the early 1970s so that Westinghouse could supply EPAs to provide a complete turnkey operation to the utilities. Subsequent Westinghouse EPAs probably reflect the original Crouse-Hinds designs.

General Electric[25]

General Electric (GE) was a major supplier of EPAs in the late 1960s and early 1970s, supplying EPAs to 25 US nuclear power plants. The first GE EPAs were supplied to Oyster Creek in 1968. All these early designs were of the canister type with an epoxy sealant (Figure A6). All the plants supplied by GE used the canister type, except for Shoreham in 1975-1976. The epoxy used in the early designs was supplied by 3M Company (Scotchcast No. 8) until it was taken off the market. This forced GE to develop another epoxy sealant. General Electric now has two basic EPA models: the canister type referred to as Model FO1, and the modular type Series 100. The Series 100 modular type has a mechanical bond between the seal and sleeve (see Figure 5). A slight variation in the modular type EPA used a chemical bond between the sealant and sleeve, and was referenced to as Series 200.

The GE canister-type EPAs are double sealed. At each end there is a glass-epoxy header plate that has a solid conductor passing through. These conductors are then sealed and potted in place (Figure A6). According to the development engineer, these designs were qualified to 340°F and 103 psig, which is the saturated-steam state.

Physical-Sciences

Physical-Sciences has supplied EPAs to seven nuclear plants in the period from 1968 through 1971: 27 EPAs each in Browns Ferry 1 and 2, and 30 each in Pilgrim and Peach Bottom 2 and 3. Physical-Sciences had a special order to supply a few EPAs to Oyster Creek 1 and Monticello. All of these plants are boiling water reactors (BWRs).

The Physical-Sciences EPAs were all of the canister type and double-ended (with a seal at each end). All of the seals were of the hermetic type. These were standard connectors welded to the header plate to provide a leak-tight seal. An epoxy compound was added on the inside of the header plates for potting only (Figure A7). The potting provided electrical protection and mechanical alignment for the conductors and wires; the primary seal was in the hermetic connectors. These connectors were all glass-to-metal sealed except for the high voltage which used a silica-ceramic called DUROC. These seals were all fused giving a high temperature capability of ~1500°F. The silica-ceramic is analogous to Corning Ware.

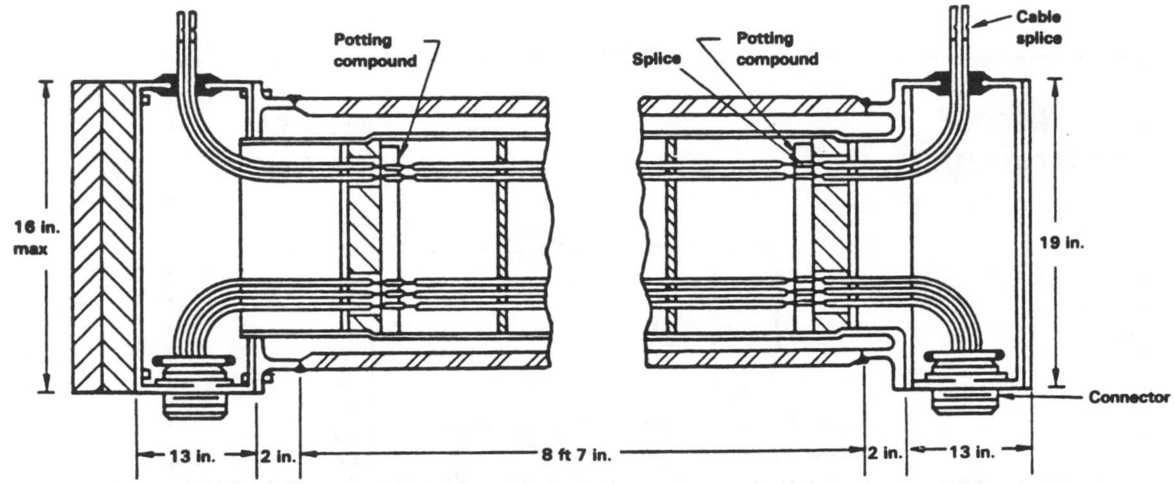
Physical-Sciences went through several corporate changes that resulted in their dropping the EPA product line.

Viking[18]

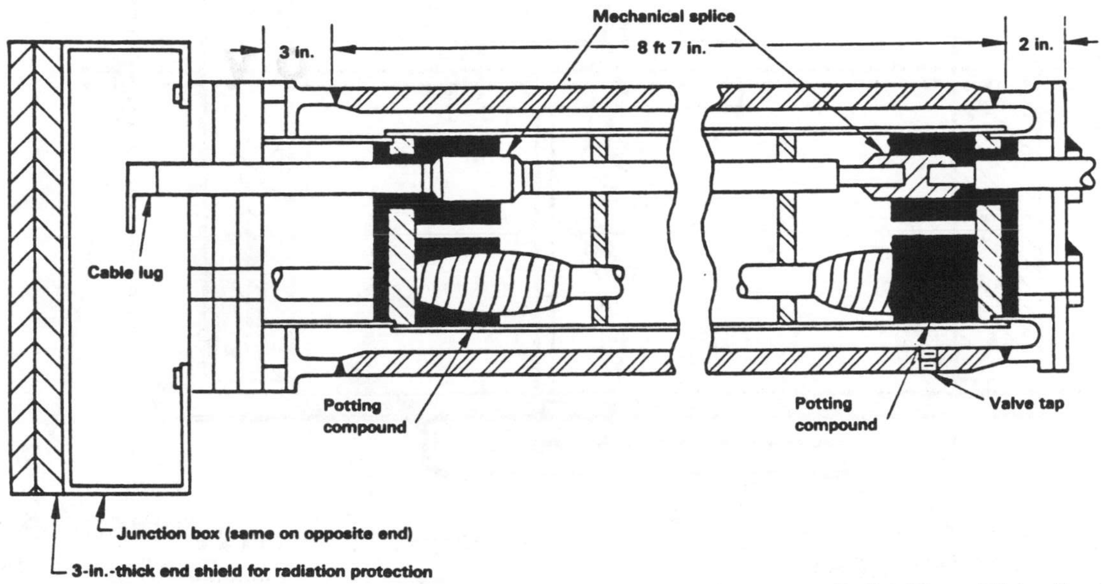
Viking was one of the early vendors of electrical penetration assemblies. They first supplied Palisades in 1967. Later, they supplied EPAs—all of which were the canister type—to San Onofre 1 (1968) and Oconee 1, 2, and 3 (1968-70). Viking also supplied a small add-on number (16) to Maine Yankee (1970). Later Viking switched to a modular design and supplied EPAs to Beaver Valley 1 and 2.

The early canister designs all had glass-to-metal seals. These were standard-size connectors but were made in-house at Viking facilities and were electron-beam welded (EBW) to a thick header plate. The glass-to-metal seals were made from a lead-free compression-type glass with a glass softness temperature of 1200°F. The coefficient of thermal expansion of the center conductor matched that of the glass, while the header plate had a coefficient of thermal expansion that would compress the glass upon cooling from the softness temperature. These early designs were all of the canister type and had double seals. However, in some configurations the double seal would be at one end of the canister (single-ended), and some designs had a seal at each end of the canister (double-ended). The Viking canisters bolted in place to a matching flange welded to a containment nozzle. These flanges have silver-plated metallic double O-rings with an expected temperature capability estimated to be 2200°F.

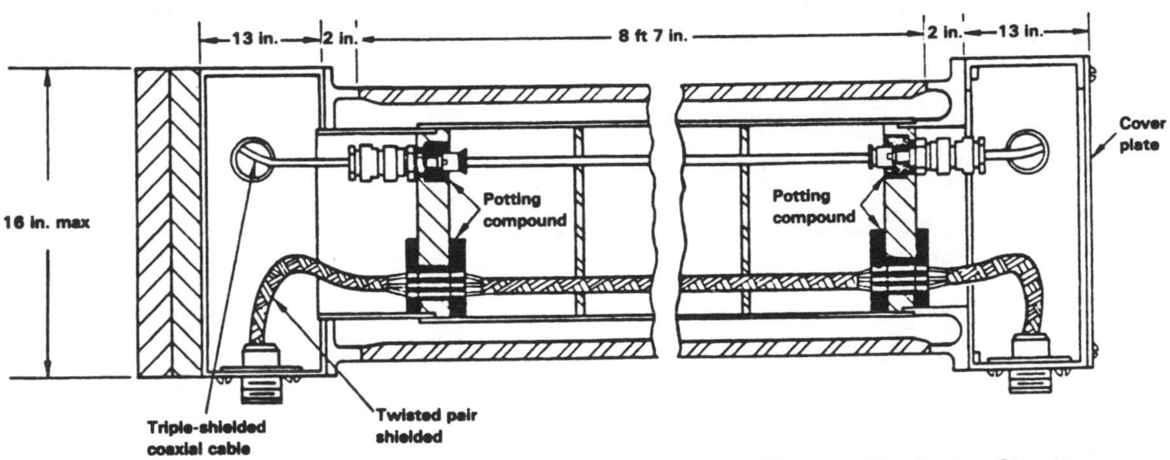
According to the development engineer for Viking, the glass-to-metal seal was more expensive then competitive epoxy-sealed EPAs; therefore, they developed an epoxy-sealed design. This design also changed to a modular concept. The modules varied from 3/4 to 2-1/2 in. in diameter. The modules are about 5 or 6 in. long and are surrounded by a stainless-steel tube that is swaged in the center and each end. This swaging action provides a mechanical lock to the epoxy. These modules are mounted into the header plate and locked in place by the wedging of a tapered brass ring and a threaded ring. The threaded ring is torqued into place; the brass ring is squeezed on the stainless-steel sleeve (see Figures A8 and A9). (This concept is also used in Conax design.)



A. Low-Voltage Power and Control Cable Penetration at Dresden 2.



B. High-Voltage Power Cable Penetration at Dresden 2 Accommodates 4169-Roll 3-Phase Motor Leads.



C. Typical Shielded-Cable Penetration at Dresden 2 Handles Reactor Neutron-Monitoring Circuits.

Figure A6. General Electric Canister EPA

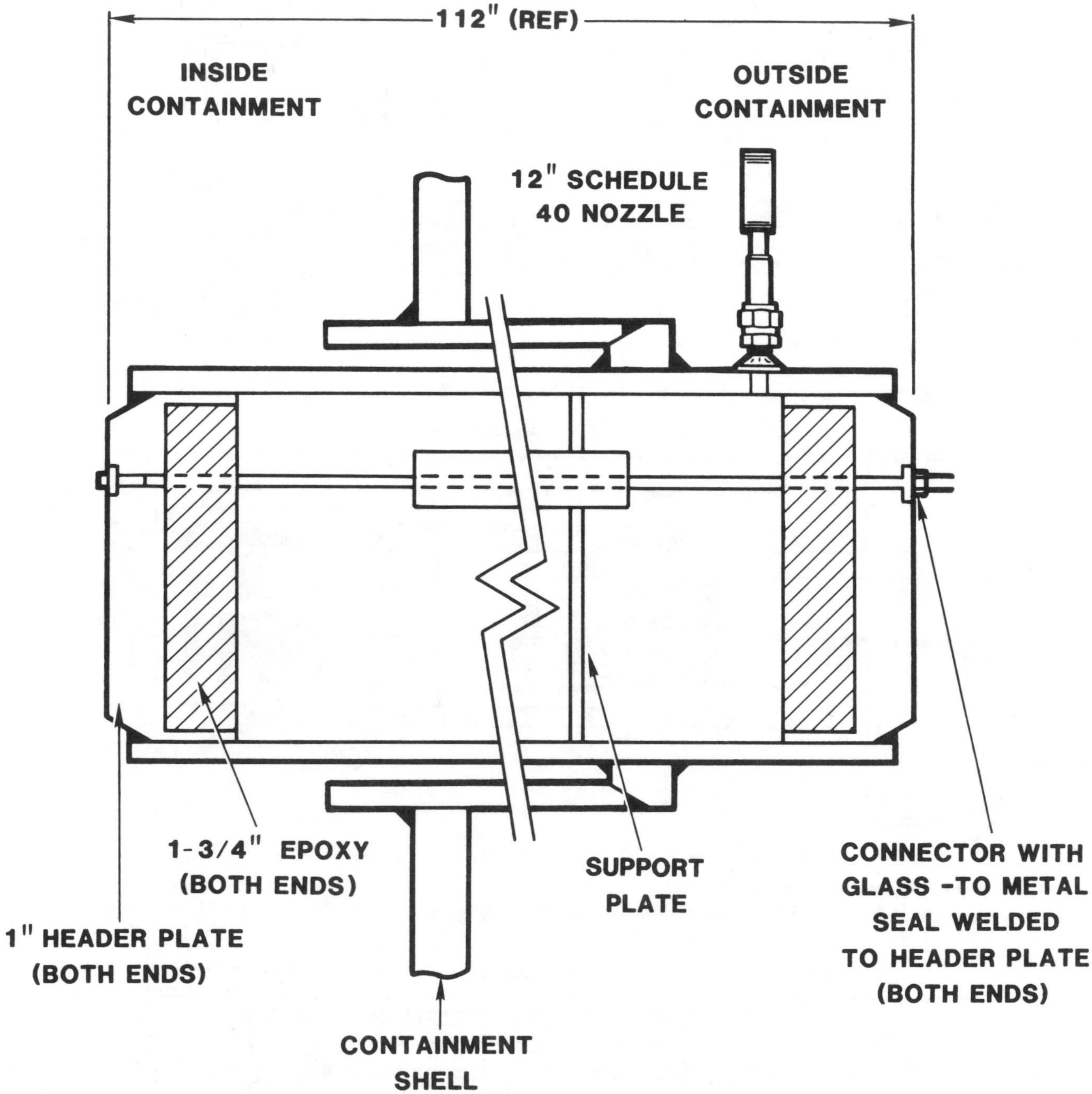


Figure A7. Browns Ferry 1 and 2 Physical-Sciences Canister Type EPA

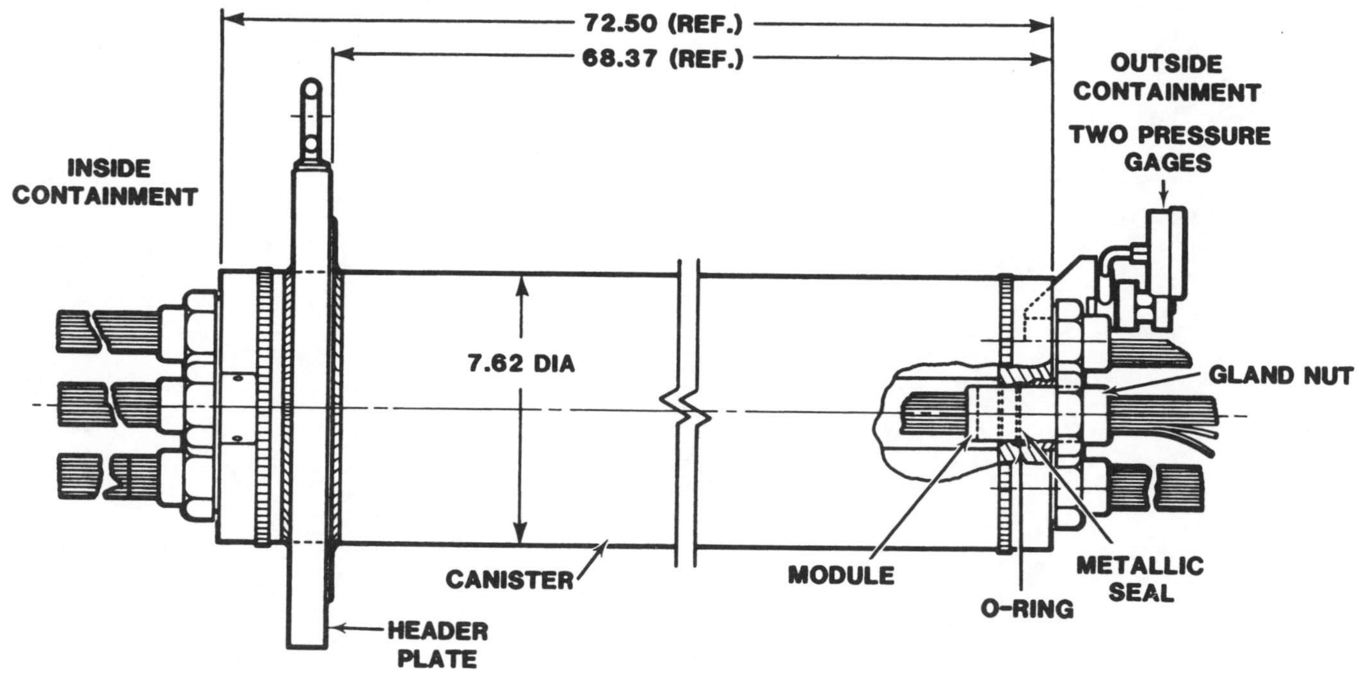


Figure A8. Viking EPAs

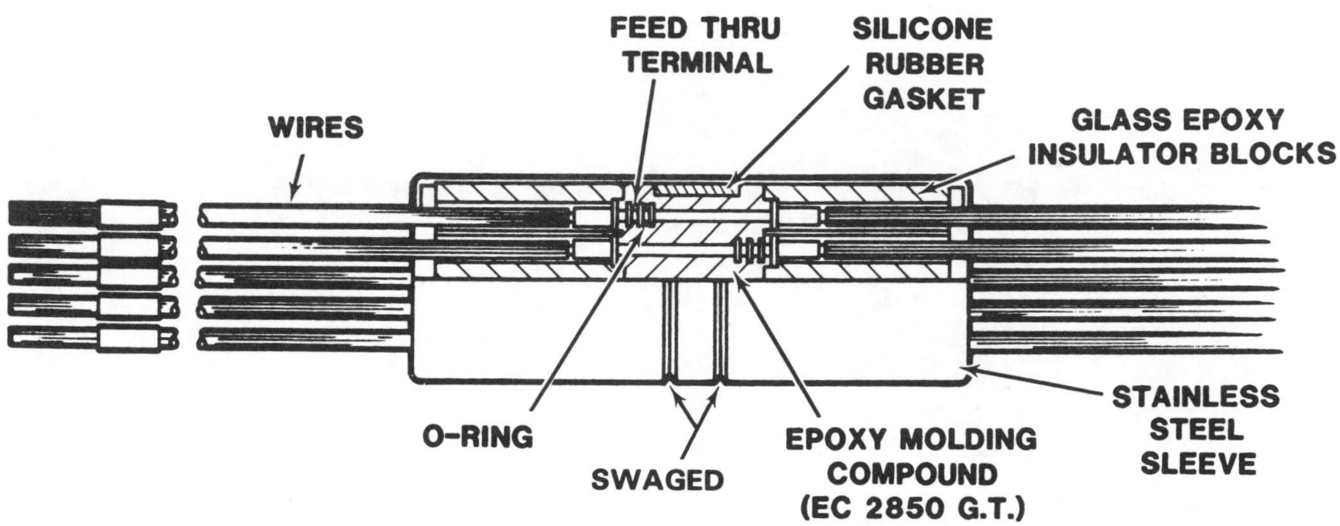


Figure A9. Viking Penetration Module

The Viking facilities were sold to Pyle-National. However, they did not continue supplying EPAs. The servicing and consultation of Viking EPAs are being carried on (by agreement) by Celmark Engineering in Chatsworth, California.

A series of leaking incidents has occurred at Oconee power plants with Viking medium voltage power (MVP) electrical penetration assemblies. These EPAs account for five of the nine leaking experiences for PWRs.[11] The leaks occurred in the transition between the bushing and header plate. Complete physical integrity was not lost in these incidents, since one of the remaining double seals still provided a barrier. The cracks developed because a plate was added to the ends of the conductors by the utility. A spacer plate was installed and caused a slight misalignment that, under thermal cycling and operation, caused the bushing to crack. The utility developed an installation process to correct this problem. Previous applications of this same bushing had revealed no problem.

APPENDIX B

Loads From Severe Accident Studies on Generic Containments

Figures

A large effort has been in progress for the past few years involving the development and improvement of thermal-hydraulic calculations used for generating the environmental conditions in the interior of containment buildings. These calculations have been performed with various computer codes such as MARCH, RECAP, etc, which require a large amount of input to properly model the containment building, the thermal-hydraulic interaction, and the chemistry of the reacting materials. The pressure and temperatures reported here are from three such studies.

Loads Calculated for Bellefonte – Large Dry PWR

Bellefonte is a large dry pressurized water reactor with a prestressed-concrete containment building. The plant is scheduled for operation in 1987-1988.

Load studies have been carried out on similar types of containments. In Reference 26, for example, the loads for severe accidents were calculated for Zion. The analyses consider the progression of core melt down, containment response, and consequences to the public for many specific accident sequences within the categories of Loss-of-Coolant Accidents (LOCAs), transient-initiated accidents, and containment bypass accidents. From all the accident progression studies, two were selected that produced the maximum containment pressures and temperatures. These are the cases when both the heat-removal systems and cooling fans are inoperable. The accident sequences are called TMLB′ and AHCG. The Zion accident progression is shown in Figure B1. Because both Bellefonte and Zion are large dry containments, it was assumed that the worse cases for Bellefonte would be similar to Zion.

TMLB′—The TMLB′ accident sequence is initiated by a transient (T) and involves the loss of both main (M) and auxiliary (L) feedwater and failure of AC electric power (B′) to engineered safety features (ESFs). A plausible TMLB′ scenario would begin with a loss of offsite power. The three diesel generators that supply one of the units would then have to fail to start or load resulting in a station blackout (a total loss of both onsite and offsite AC power) to one of the two units. Station blackout would disable all ESFs including emergency core cooling, containment sprays and fan coolers, and motor-driven auxiliary feedwater.

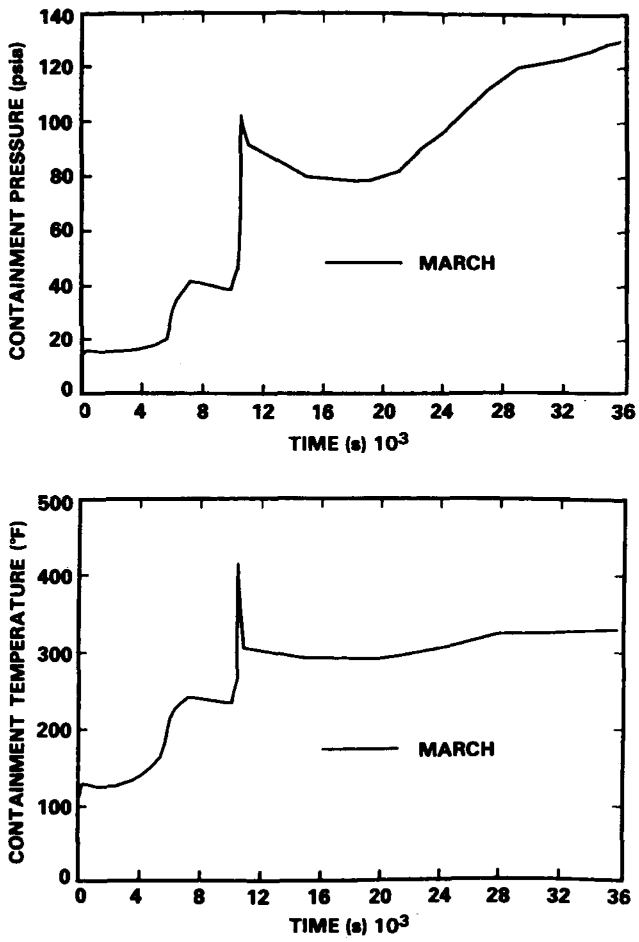


Figure B1. TMLB′ Accident Progression for Zion

AHCG—In the AHCG sequence, a large LOCA(A) is followed by emergency core cooling recirculation failure (H). Also, containment heat removal via the containment sprays or fan coolers is not available (CG). Without containment sprays or fan coolers, containment failure would occur eventually. The time to failure depends on the amount of refueling water storage tank (RWST) inventory that has been added to the containment. The minimum time to containment failure caused by overpressure occurs when just enough RWST water is added to permit saturation of the containment atmosphere at the containment failure pressure.

When the accident progression is at 783 min (Figure B2), the containment atmosphere is at 150 psia and the temperature is 341°F. This is very close to the temperature obtained from the saturated-steam state.

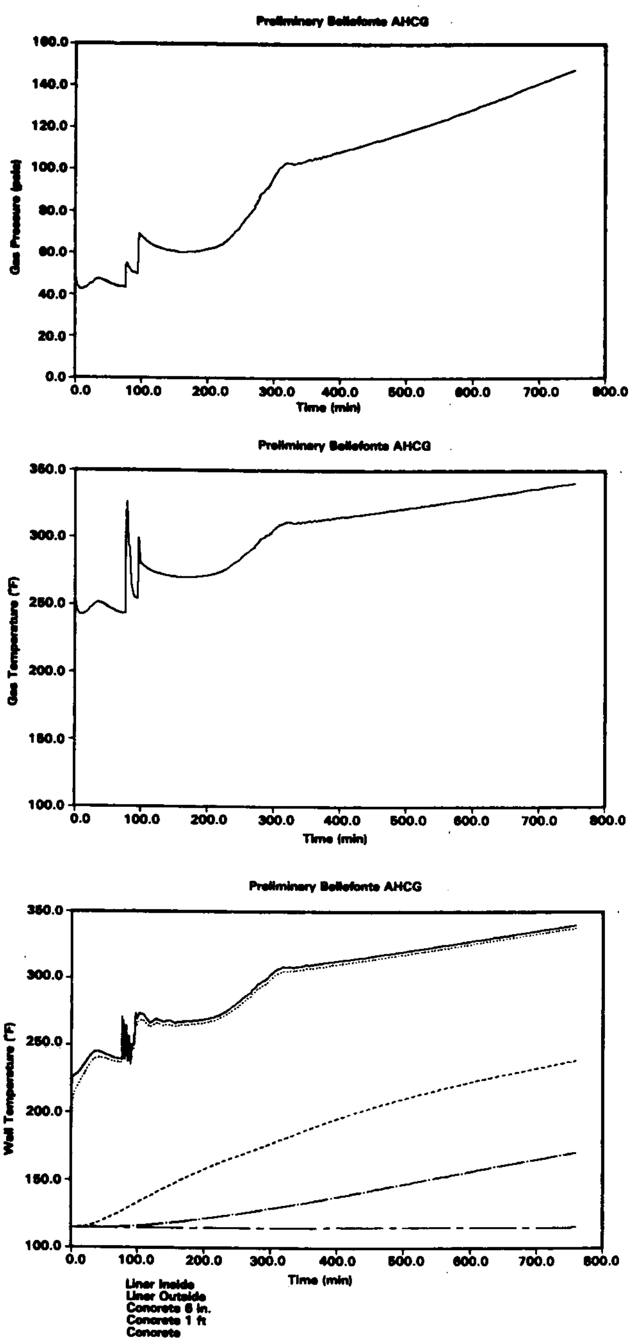


Figure B2. Preliminary AHCG Accident Progression for Bellefonte

In accidents such as TMLB′ or AHCG, the containment pressure and temperature would be high for a prolonged period of time because of failure of the containment heat-removal systems. The containment atmosphere would be saturated with steam during this period. Eventually, unless containment heat-removal systems were restored, the pressure would buildup to the containment-failure threshold (~135 psig for Zion). The steam saturation temperature, corresponding to the containment failure pressure, thus represents an upper bound temperature to which penetrations could be continuously exposed during severe accidents.

Based on preliminary calculations, Bellefonte has an estimated failure pressure of ~140 psig, which is slightly higher than the estimated failure pressure of ~135 psig for Zion. For Bellefonte, the upper bound containment temperature to which penetrations could be continuously exposed would be ~350°F. However, Bellefonte also has a larger containment free volume than Zion so that more time would be required to buildup to its upper bound temperature. This is indicated by the containment pressure-temperature response to an AHCG accident indicated in Figure B2. The results are based on preliminary MARCH analyses performed under the Severe Accident Sequence Analysis (SASA) program. Figure B2 also indicates the slow rate at which heat would be conducted through the concrete walls during a severe accident.

Loads Calculated for Watts Bar – Ice Condenser PWR

As part of the Severe Accident Sequence Analysis (SASA) program, the failure pressure for the Watts Bar containment has been estimated as between 120 and 140 psig. Any accident approaching such pressure over a prolonged period of time would require all of the ice in containment to melt plus the failure of containment heat-removal systems. The containment atmosphere would become steam saturated in such accidents. As for Bellefonte, the upper bound temperature to which containment penetrations could be continuously exposed would be ~350°F. Again, some time would be required to achieve this temperature. Figure B3 indicated the containment response to an S1CG accident. The S1CG accident is initiated by a small LOCA resulting from a 6-in.-dia break (S1) and involves a failure of both the containment spray-injection system (C) and the containment heat-removal system (G). This sequence was selected to approximate the maximum continuous pressure-temperature buildup in the Watts Bar containment. In contrast to a concrete containment, heat is transferred rapidly through the steel shell of the Watts Bar containment.

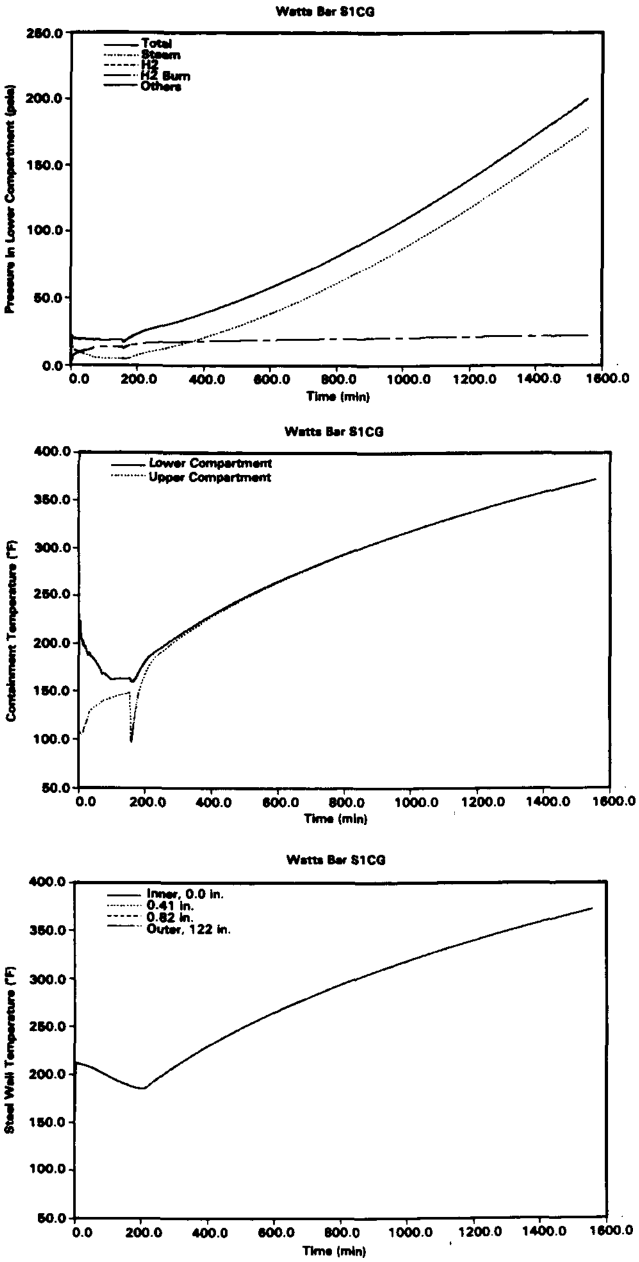


Figure B3. Preliminary Results for the S1CG Accident Progression in Watts Bar

Load Calculations for Browns Ferry 1 – Mark I BWR

The containment pressures and temperatures following a degraded core accident in Browns Ferry 1 have been calculated.[2] The accident sequences studied consists of eight BWR accident sequences that are among those identified in the Reactor Safety Study (WASH-1400) as being dominant contributers to public risk at a BWR nuclear plant. The eight sequences and time to failure can be found in Table B1. Brief descriptions of the eight sequences are also shown and the time to failure is based on a temperature and pressure failure criteria. The sequences were calculated using an updated version of the MARCH code; i.e., MARCH1.4B.

The important parameters for the EPA study are the high temperatures encountered in the dry well. Four of these sequences were selected to represent the maximum temperatures and pressures (Figure B4). Figure B4 shows the dry-well gas temperature and pressure, in addition to the containment wall temperature. The containment wall temperature is designated as node (1).

Table B1. Comparison of Containment Failure Times[2]

Sequence	Containment Failure Time (min) Over-temperature*	Overpressure (WASH-1400)**	Decrease of Failure Time (%)
TW	—	1018	—
TC	692	961	28
TQUV	193	288	33
AE	17	183	91
S_1E	40	200	80
S_2E	45	210	79
S_2I	—	1533	—
S_2J	—	1632	—

Brief Definition of Sequences are as follows:

TW – Anticipated transient followed by loss of decay heat removal; offsite and onsite AC power assumed available; initiating event assumed a loss of main condenser vacuum.

TC – Anticipated transient without scram; manual rod insertion and standby liquid control systems unavailable.

TQUV – Anticipated transient combined with failure of high pressure coolant injection, reactor core isolation, and low pressure.

AE – Large LOCA with failure of emergency coolant injection.

S_1E – Small LOCA with failure of HPCI and low-pressure ECCS.

S_2E – Small LOCA with failure of HPCI, RCIC, and low-pressure ECCS.

S_2I – Small LOCA with failure of low-pressure coolant recirculation system.

S_2J – Small LOCA with failure of residual heat-removal service-water system for cooling RHR heat exchangers; LPCI mode of RHR system is available for suppression cooling.

*Dry-well electric-penetration assembly seal failure at ambient temperature above 500°F.

**Containment failure by overpressure of 160 psig, assuming no prior failure caused by overtemperature.

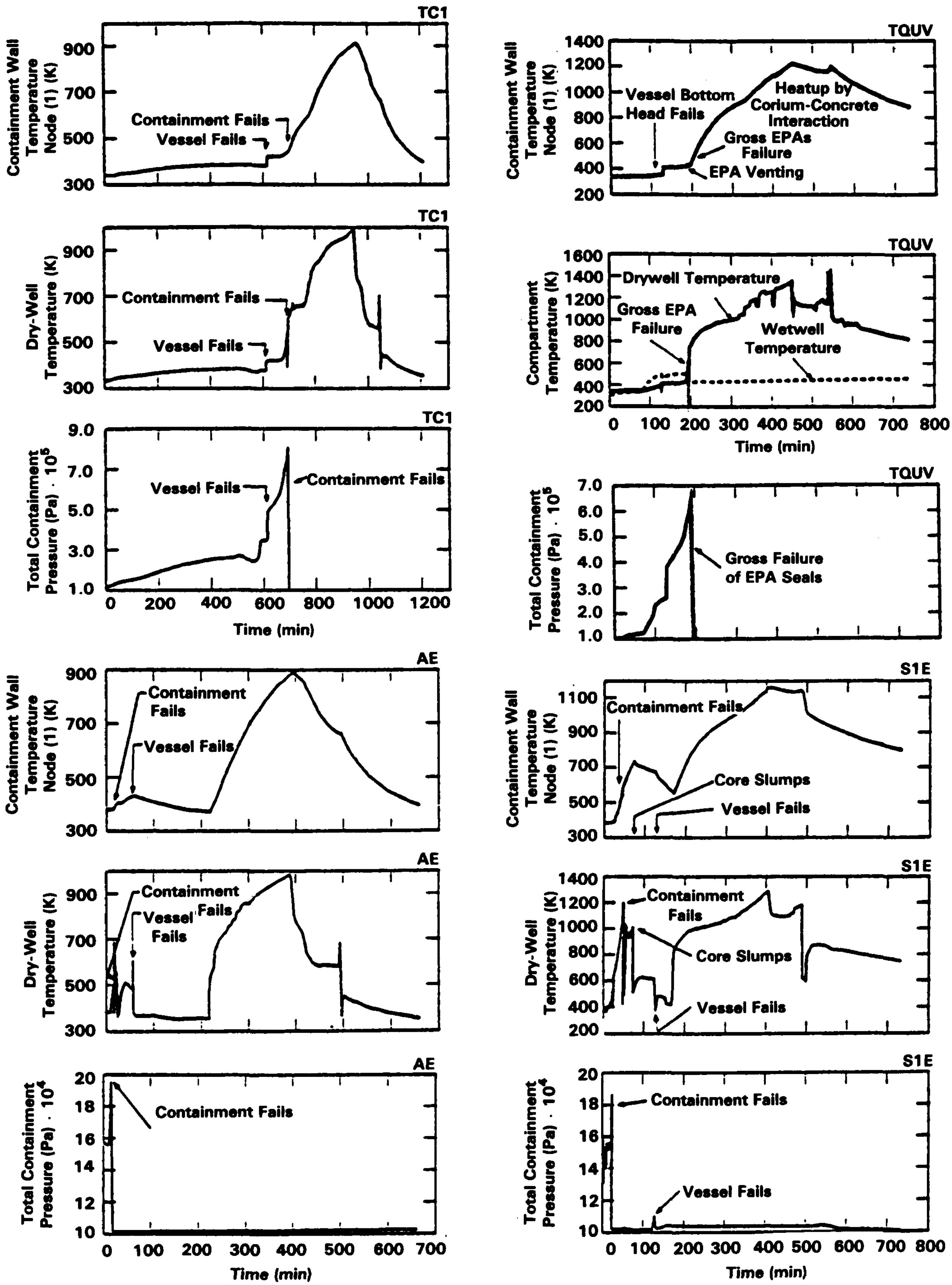


Figure B4. Accident Sequence Progression for Browns Ferry 1

APPENDIX C

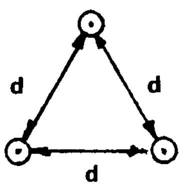
Fault Current Effects on EPA Leakage

Fault Currents

The objective of this Appendix is to outline some of the problems associated with fault currents and their effect on the physical integrity of EPAs. This section discusses the lateral loads and temperatures induced by fault currents. The induced temperatures and their relation to the seal-melting point (or limiting temperature) is significant.

Fault Current Loads

Most medium voltage penetrations are typically three-conductor assemblies, and because of the large fault current forces all have a thick triangular plate made of insulating material spanning outside the ends of each conductor. Although large lateral forces have been reported (10 000 lb/ft), these forces are between the conductors and are self-equilibrating within the assembly.[2] This means that no large net forces will exist beyond the nozzle. These large forces are only generated within the medium voltage penetrations and are of short duration (i.e., a few cycles). Under a fault current, the conductors will either repel or attract each other, depending on the phase of the current. The mechanical load can be determined from the following equation:[27]



$$F = 34.9 \frac{I^2}{d} \times 10^{-7}$$

F = Lateral Force in lb/ft
d = Conductor spacing in inches
I = Current in amps

The lateral force in the cable is similar to the force in a clothesline rope—the longer the distance between supports, the greater load at the ends. If the distance is long enough, a small load will break the rope. This can also happen inside a long penetration assembly. To minimize the clothesline effect, the support distance is made smaller. This is seen in many of EPA designs as internal support plates or structures. The support plates are spaced at approximately one sleeve diameter. The support plates are all one piece and under fault current loads; the cables push against the plates with equal and opposite loads that are in phase. The loads act internally to the support plates, so that the net external load is zero (i.e., no forces against the nozzle or sleeve). The force between parallel conductors also acts on the ends of the MVP assemblies; the triangular piece (seen in the MVP EPA, Figure A1) is added to restrain the deflection at the end of the conductors.

Fault Current Temperatures

Because the regulatory guidelines have changed over the years, the safety level in older plants has been questioned. The NRC initiated a program to reevaluate safety-related equipment in some of the older plants. This project was called the Systematic Evaluation Program (SEP) and included electrical penetrations in the assessment. Nine older plants have been studied and the results reported.[17, 28-35] The reports compare the ability of the circuit breakers and/or fuses to clear the circuits under fault current conditions before the seal melts. The time for the seal to melt is derived from the classical Onderdok formula:[28]

$$t = \frac{A}{I^2} (0.0297) \log \frac{T_2 + 234}{T_1 + 234}$$

t = time in seconds
A = conductor area in MCC (thousands of circular mils)
I = current in amps
T_2 = seal failure temperature (°C)
T_1 = starting temperature (°C)

This equation along with the seal melting or limiting temperature was used in the SEP assessment. These temperatures vary dramatically from among the various EPAs and are listed in Table C1. The values range from a low of 300° to a high of 1710°F. Some of the limiting temperatures are only for short times. This is acceptable to fault current conditions because the high amperage loads only last 5 to 10 cycles (for a 60-cycle system).

The degraded core conditions have time scales of minutes and hours; therefore, the limiting temperature for fault current loads can be much higher. Furthermore, in considering degraded core environments, another portion of the barrier could have a lower temperature capability. As an example, the brass packing ring in the LaCrosse EPAs has a temperature limit of 1710°F; however, if the packing ring is mounted to a plate that is in turn bolted to the nozzle, then the O-ring gasket could be affected by the degraded core temperature rise before the brass packing ring is affected. The purpose of this example is to point out the necessity of knowing the design details of each EPA as well as the physical properties of the materials.

Table C1. Melting Temperature of Cable or Conductor Seals

Plant	EPA[a] Type	Melting Temp (°F)	Remarks
Big Rock Point	MVP	307	Penetration same as Dresden 1 and EPAs tested to 307°F
	LVP	307	Field manufactured
	DCP	307	
Dresden 1	MVP	307	Based on tests by utility
	LVP	302	MP[b] of sealant
	DCP	307	Based on tests
			Field manufactured
Dresden 2	MVP	622[c] (4 s)	Temperature limits
	LVP	340 (6 h)	Based on testing (epoxy seal)
	DCP		GE FO1 Series canister
Ginna	MVP	1100	MP of silver braze
	LVP	361	MP of solder
	DCP	361	MP of solder
			Manufactured by Crouse-Hinds
Haddam Neck	MVP	490	Kerite insulation temperature limit
	LVP	800	Extrapolated from tests (short time capability)
	DCP	700	Supplied by Conax
LaCrosse	MVP	1710	Brass Packing Gland
	LVP	1710	MP of hermatic seal
	DCP	1710	Manufactured by General Cable
Palisades	MVP	1200	Ceramic bushings
	LVP	575 (400 h)[d]	Qualification test temperature of penetration
	DCP	575 (400 h)[d]	Viking canister type
San Onofre 1	MVP	842	MP of seal
	LVP	400	MP of seal
	DCP	300	MP of seal
			No manufacturer mentioned (could be Viking)
Yankee Rowe	MVP	392	Buna rubber melting temperature
	LVP	1652	Temperature limit of brass ring
	DCP	1652	Temperature limit of brass ring
			All field manufactured

[a]MVP = Medium voltage power (>1000 V)
LVP = Low voltage power (0 to 1000 V)
DCP = Direct current power (0 to 1000 V)

[b]MP = Melting Point of material

[c]Temperature shown is applicable for very short time durations

[d]This is a qualification test conducted on Viking EPAs. Actual temperature capability is much higher (~1000°F).

APPENDIX D

Thermal Response of EPAs in Browns Ferry 1 to Severe Environments

Introduction

The purpose of the thermal modeling is to provide refinement and additional details in determining the thermal response of EPA seals. The containment failure times assumed in Reference 2 are based on only the dry-well gas and steam temperatures. This assumption does not make allowances for the thermal mass of the EPAs or geometric configurations. Some important considerations in the thermal response are based on the temperature capability of the sealant, the nozzle length, the location of the seals, the flow restrictions in the interior of the EPA, and the ability to reject heat at the outboard end. The study in References 36 and 37 includes these additions, where appropriate. A similar analysis and test was described in References 38 and 39 with comparable results.

The developed thermal model represents the GE modular design (Series 100) installed in Browns Ferry 1 and 2. Each module has a double seal that is located at the outboard end of the nozzle (see Figure 5). Three modes of heat transfer were studied, and each is treated separately to evaluate the effect of each mode. Radiant heat was not considered as a source of energy into the seals because the outboard end is shielded by numerous conductors, support plates, and a junction box on the inboard end. The modes of heat transfer considered are conductive, mass diffusion, and convection.

Conduction Thermal Response

The conductive model consists of the 12-in.-dia nozzle with the header plate welded to the outboard end. The nozzle length is 84 in. and the header plate and weld attachment is 4.5 in. long. Since the nozzle is structural steel, the conductive heat-transfer coefficient is based on a mild steel. A portion of the nozzle was insulated; this was extended in the conductive model to the length of the nozzle. This basically assumes that the nozzle and the outboard end are adiabatic. An adiabatic boundary condition is equivalent to an insulated surface in which no heat is lost. The thermal input to the models uses the temperature profiles in Appendix B, Figure B4. These profiles are used as thermal inputs at the junction of the nozzle and steel containment shell. The calculations were carried out to times greater than the pressure failure times based on WASH-1400 analysis. Table D1 provides an indication of the effect of heat conduction into the EPA seals at the pressure failure times.

Table D1. Outboard Seal Temperature Rise Due to Conduction (pressure of 160 psig at containment failure)

	Containment Failure[2] Times (min)		
Sequence	Inboard Seal	Overpressure (160 psig)	Temperature Rise at Outboard Seal (°F)
TC	692	961	40
TQUV	193	288	2
AE	17	183	0
S_1E	40	200	0

Mass Diffusion/ Condensation Thermal Response

A second thermal model studies mass diffusion/condensation as a mode of heat transfer. Although the EPAs contain a number of obstacles in the center of the EPAs, the paths are not leaktight and gases from the dry well can diffuse towards the outboard end. This diffusion of gases can transmit the thermal energy contained in the gases. In particular, when steam diffuses towards the cooler end of the nozzle, it will condense yielding thermal energy in the process. The time response depends on the amount of gas flow, the latent heat of vaporization, and the temperature at the outboard end of the EPA. As steam condenses, the latent heat is transmitted to the header plate. The steam at the header plate is in a saturated steam state that provides an upper bound to the temperature (~350°F). The time it takes to reach 350°F is dependent on the steam flow rate. Since steam has a high specific volume, it takes a large volume to produce one pound of water. The flow rate can be high but not much thermal energy will be transmitted. A reasonable estimate of a flow rate was calculated in Reference 37 and is ~0.06 lbm/h. With this flow rate, in 10 h there will be 0.6 lbs of steam, which will increase the EPA seal temperature ~220°F.

Another aspect of the mass diffusion/condensation is quite important since it provides a limiting condition for the seal temperatures. While the steam is condensing on the outboard header plate, the temperature is limited by the liquid water state and the pressure in the containment. At a pressure of 175 psia, the temperature is ~360°F. To go above this temperature requires an additional source of heat to revaporize the liquid water (which in turn absorbs a significant amount of energy) and delays heating up the seals.

Convective Heat Transfer

Convective heat transfer is another mode of heat transfer that is probably more complex then the other modes discussed. Transfer of heat by convection is not easily treated analytically; however, several experimental studies[40 41] were found and applied to this study. The heat transfer is dependent on the Nusselt number, which is between 10 and 25 for the conditions in the EPAs for Browns Ferry 1. The higher Nusselt number results in an effective heat-transfer rate to the header plate from the 1200°F dry-well air of 3.7 Btu/h. This causes a temperature change in the header plate of ~0.9°F/h.[37]

Conclusions on Heat-Transfer Modes

The modes of transfer considered in Reference 37 suggest that it is unlikely the seals will reach failure temperatures in 30 h after the accident is initiated. It would require ~10 h to reach 360°F and an additional 20 h to go from 360° to 400°F.

Other information that also supports these conclusions can be obtained from References 38 and 39. Reference 38 is an analytical evaluation of the heat transfer of a module in an LMFBR severe accident environment. The heat-transfer mode was by conduction and provided results similar to Reference 36. Reference 39 is equally important because it was a demonstration of the conductive and convective modes of heat transfer. Reference 39 is a high-temperature test conducted at one end of 1-in.-dia by 33-in.-long module (described in the main body of this report). A portion of the test sequence was conducted at steady-state conditions of 800°F for 140 h. The outboard end of the module stabilized at 152°F. It is believed that the conductive mode of heat transfer would provide most of the increase in temperature at the outboard end. The convective heat-transfer mode, although present, would contribute very little of this increase.

The test conducted in Reference 39 was conducted in hot dry air, so that one important heat-transfer mechanism was not present. The mass diffusion/condensation mode was not present and could conceivably have resulted in a higher outboard temperature. The upper limit would still be ~360°F, which is 20°F above its useable temperature.

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