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1000-MWe LMFBR ACCIDENT ANALYSIS
AND SAFETY SYSTEM DESIGN STUDY

— Topical Report —

Candidate Secondary Containment
Support Systems

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PREFACE

This report was originally prepared as a technical note to document the work performed in a specific contract activity as soon as the work was completed. The technical editing was limited in order to meet the objective of timely reporting. The report was issued for USAEC-ANL use only, and the intent was to update and consolidate the information from all technical notes in a comprehensive phase report before final publication for public distribution at the end of Phase II.

This plan was changed when the contract was terminated in October 1970 for the convenience of the government. Instead, a final summary report will be prepared, and the previously issued technical notes will be published as formal topical reports. In accordance with the modified plan, this technical note is being published in its original form without further editing or modification except for minor technical corrections and changes in the title and date of issue. Even without updating and technical editing, the report provides detailed information that should be helpful in evaluating and resolving LMFBR safety questions in related areas.

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Safety System Design Study
— Candidate Secondary Containment
Support Systems —

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ABSTRACT

This report describes the work performed to complete Activity 244 (Review and Identify Candidate Secondary Containment Support Systems) of the 1000-MWe LMFBR Accident Analysis and Safety System Design Study. Resultant temperature and pressure effects of spray fires and pool fires were investigated to determine features and systems that might be required to protect the public. A literature survey on reactor containments was conducted to determine the minimum practical leak rate to be expected from the containment building. Environmental calculations were then made using this leak rate as a means of determining the maximum allowable concentration of fission products, sodium-24, and plutonium in the containment building. Suggested features and systems are presented as possible candidates.

CONTENTS

	Page
1. INTRODUCTION.	1-1
1.1. Background.	1-1
1.2. Objective.	1-1
1.3. Reference Design.	1-2
2. SUMMARY.	2-1
2.1. General.	2-1
2.2. Assumptions.	2-1
2.3. Containment Survey.	2-2
2.4. Sodium Pool Fires.	2-3
2.5. Sodium Spray Fires.	2-3
2.6. Environmental Calculations.	2-4
2.7. Candidate Systems.	2-4
3. DESCRIPTION OF WORK.	3-1
3.1. Survey of Containment Philosophy.	3-1
3.1.1. Fast Breeder Reactor Follow-On Studies.	3-1
3.1.2. Containment Leakage Rates.	3-3
3.1.3. Fast Breeder Reactor Containments.	3-4
3.1.4. Inert Containment.	3-7
3.1.5. Observations.	3-7
3.2. Analytical Studies.	3-9
3.2.1. General.	3-9
3.2.2. Sodium Expulsion.	3-10
3.2.3. Spray Characteristics.	3-16
3.2.4. Sodium Fire.	3-25
3.2.5. Containment Environmental Studies.	3-33
3.3. Preliminary Candidate Containment Requirements.	3-40
3.3.1. Atmosphere.	3-40
3.3.2. Leakage.	3-40
3.3.3. Design Pressure.	3-40
3.3.4. Design Temperature.	3-40
3.3.5. Heat Removal Capability.	3-40
3.3.6. Filters.	3-41
3.3.7. Purging Requirements.	3-41
3.3.8. Isolation Equipment.	3-41
3.3.9. Missile Protection.	3-41
3.3.10. Intermediate and Decay Heat Coolant Lines.	3-42

CONTENTS (Cont'd)

	Page
3.4. Candidate Secondary Support Systems	3-43
3.4.1. Oxygen Depletion Systems	3-43
3.4.2. Containment Filter System	3-45
3.4.3. Containment	3-45
3.4.4. Double Containment System	3-46
3.4.5. Drainage Systems	3-47
3.4.6. Miscellaneous Features	3-47
4. CONCLUSIONS AND RECOMMENDATIONS	4-1
APPENDIXES	
A. Sodium Expulsion	A-1
B. Spray Characteristics	B-1
C. Spray Burning.	C-1
D. Pool Fire Sensitivity Studies	D-1
E. Post-Spray Fire Conditions.	E-1
F. Environmental Safety Calculations	F-1

List of Tables

Table	
3-1	Reactor Containment Comparisons 3-2
3-2	EBR-II and Fermi Containments 3-5
3-3	Cases Considered. 3-15
3-4	Pertinent Results 3-15
3-5	Values of W_{oij} and R_{oij} 3-23
3-6	Values of W_{oij} and R_{oij} 3-24
3-7	Case 1 Results. 3-31
3-8	Case 2 Results. 3-32
3-9	Bone Burdens 3-36
3-10	Pu and Na in Core After Equilibrium Fuel Cycle 3-37
3-11	Maximum Amounts of Isotopes Available for Leakage. 3-38
3-12	Maximum Fractions of Core Plutonium Inventory and Primary Sodium Coolant Available for Leakage 3-38
B-1	Particle Size Groupings. B-7
E-1	Program Temp (Input, Output) E-12

List of Figures

Figure		Page
3-1.	Expelled Sodium Vs Selected Parameters.	3-18
3-2.	Sodium Expulsion, Standard Case Calculations	3-19
3-3.	Sodium Expulsion, Case 2 Calculations	3-20
B-1.	Cumulative Mass Factor Vs U	B-5
D-1.	Maximum Pressure Vs Initial Oxygen Concentration in Containment	D-7
D-2.	Maximum Temperature Vs Initial Oxygen Concentration in Containment.	D-8
D-3.	Containment Temperature Vs Selected Parameters . . .	D-11
E-1.	Air Temperature Vs Time, (Case 1).	E-5
E-2.	Building Pressure Vs Time, (Case 1).	E-6
E-3.	Wall Liner Temperature Vs Time, (Case 1).	E-7
E-4.	Air Temperature Vs Time, (Case 2).	E-8
E-5.	Building Pressure Vs Time, (Case 2).	E-9
E-6.	Wall Liner Temperature Vs Time, (Case 2).	E-10

1.3. Reference Design

The reactor building structure is a reinforced concrete cylinder, 108 feet in outside diameter and 187 feet high; the cylinder and its hemispherical head are 4 feet thick. A carbon steel liner (3/8-inch thick for the dome and wall and 1/4-inch thick for the base) within the structure provides an airtight seal. The structure's design pressure is 10 psig at 200 F. The reactor operating floor level (or charge face level) is at an elevation of 57 feet, at which a personnel air lock, a personnel emergency hatch, and an equipment penetration hatch are provided. The reactor building contains the reactor vessel with its internal equipment, the argon coolers, reactor building air-conditioning coolers, three argon holdup tanks, a sodium tank, and various handling and cooling equipment. The containment air-conditioning and ventilation system has two 50%-capacity containment coolers, which circulate a total of 118,000 cfm of air, maintaining an ambient temperature at 100 F. Outside air is brought into the containment through filters, coolers, or heaters at a rate of 1750cfm and is exhausted from the containment through filters. The containment penetration for the purged-air system is designed to close in the event of a slight rise in pressure. The containment supply fan and the exhaust booster fan for the containment purged-air system are regulated to maintain a slight negative pressure within the containment. The concrete used for biological shielding is normal reinforced concrete.

It has always been recognized that the secondary containment plays a vital role in the safety of nuclear plants. It constitutes the last barrier between the plant and the public and, therefore, should receive special emphasis. Considerations pertinent to the design of the containment are complex and diverse, being closely tied to the type of plant, its operating requirements, DBA considerations, plant siting, economics, and precedents. The selection of candidate support systems for this activity did not consider economics, since it would be premature to rule out any systems or features on this basis before generating the functional requirements of the containment.

The candidate support systems were developed on the basis of anticipated functional requirements that might be applied to the reference plant. In the logical development of the effort, the designers first

sought to establish systems that would not interfere with the advantageous plant features developed in the Follow-On Study. The most important of these features was unencumbered access to the containment during plant operation.

The principal requirement for access to the B&W plant is derived from the refueling sequence that was adopted. This requirement is necessary in order to take full advantage of the under-the-plug refueling scheme. In this scheme, manual contact preparation is required for both refueling and transfer operations. Refueling operations are carried out while the reactor is down, but the time-consuming operation of transferring fuel to and from the rotating storage drum is completed while the plant is operating. The air atmosphere in the containment eliminates the need for remotely operated manipulating equipment or inert gas suits for plant personnel.

Plant access is also desirable, if not necessary, for inspecting and maintaining operating equipment. This is true regardless of the type of plant and pays dividends by increasing the plant availability. Maintaining an air atmosphere in the containment presents two major obstacles that must be overcome: It must be shown that (1) the containment cannot be compromised as a result of a sodium-air reaction, and (2) the leakage of radio-active material due to increased pressure will not exceed permissible limits. To this end, the support systems and features that were generated include alternatives to an air-filled containment.

2. SUMMARY

2.1. General

The study was directed primarily toward defining support systems that would enhance the integrity of the secondary containment. To perform this task, it was necessary to (1) establish a range of accident conditions to which the containment might be subjected, (2) establish major assumptions, and (3) survey what others have done to meet the objective.

2.2. Assumptions

The following major assumptions were made:

1. All sodium contributing to a Na-Air reaction is primary sodium. The logic for this assumption was based on the probable ability to armor and render inert all other lines carrying liquid metal.
2. A core disturbance due to the mixing of molten fuel forces all the sodium above the core and within the upper thermal shields to impact on the underside of the cover plug.
3. Leakage of the sodium into the secondary containment is through the clearances between the rotating plugs and through the openings provided for 25 control rods.
4. Emerging sodium behaves as a conical spray, and the particle size distribution of the sodium droplets follows the upper limit equation.
5. The burning rate of the particle is directly proportional to its surface; a value of 10 lb Na/h-ft^2 was selected for this study. The oxygen concentration in the building's atmosphere remains constant, and no secondary dispersion mechanisms were considered.

6. The maximum containment temperatures are based on the specific heat of air at constant volume and an instantaneous heat release rate. The heats of formation for the products of combustion were taken at 4500 Btu/lb.

7. The maximum containment pressure is based on the application of the perfect gas law.

8. The maximum permissible bone burden is the controlling factor for exposure to plutonium isotopes. The values used are one-tenth of those listed in ICRP Publication II, Table I.*

9. A 0.1% per day containment leakage rate is used in the environmental calculations.

2.3. Containment Survey

Containments in general—and fast reactor containments in particular—were surveyed. The major highlights of the results are as follows:

1. The implied basis for selecting the containment atmosphere is that no major Na-Air reaction could be considered. The following list is presented for illustration:

- a. Westinghouse Follow-On—Complete inert containment.
- b. AI Follow-On—Machinery dome.
- c. GE Follow-On—No accident.
- d. Fermi—Machinery dome.
- e. FFTF - Machinery dome

The exception to this list is EBR II—a fire analysis led to the conclusion that the integrity of the containment would not be endangered. However, it must be remembered that EBR II is a test reactor, designed and licensed a number of years ago at a remote site, and that the core contains no plutonium. In contrast to the foregoing examples, B&W's reference design has an air-filled containment and essentially follows the EBR II reasoning that a limited Na-Air reaction could be contained.

- - - - -
* Use reference 20.

2. The consensus on attainable leakage rates for containments is 0.1% per day based on the capability to measure such rates.

2.4. Sodium Pool Fires

Sensitivity studies using the modified SOFIRE I-B code indicate that prohibitive temperatures in the containment are possible and that the temperature depends primarily on the amount of sodium burned. An examination of the reference design and potential DBA conditions revealed no mechanisms for the existence of large pools of burning sodium. The results of the pool fire investigation indicate that the surface area of a pool fire is the most sensitive parameter to a release of energy. This conclusion led to the proposed drainage provisions to accommodate any unburned sodium resulting from a spray fire. (See Figure D-3).

2.5. Sodium Spray Fires

The investigation of sodium spray fires was conducted as a parametric study in which the parameters were selected to span the values expected from the accident analysis studies. The results of the study yielded maximum temperatures and pressures and containment-liner temperatures. Nine separate cases were investigated for the injection of varying amounts of sodium into the containment. Two of these cases—100 and 200 fps—were examined in detail for spray fire effects. The spray fires were based on a conservative model, which assumed that the ejected sodium formed conical sprays. The release of energy was based on 60% of the reaction going to the peroxide and 40% to the oxide, giving a total heat of formation of 4500 Btu/lb. The results of these two cases are tabulated below:

<u>Impacting Velocity, fps</u>	<u>Na expelled, lb</u>	<u>Na burned, lb</u>	<u>Max. con- tainment pressure, psia</u>	<u>Max con- tainment temp, F</u>	<u>Max con- tainment liner temp, F</u>
100	1490	397	19	185	120
200	4425	2064	32	626	283

2.6. Environmental Calculations

Environmental calculations for the hypothetical site were made to determine the maximum tolerable concentrations of radioactive material within the containment that could be available for leakage after a fire. These concentrations were based on a 0.1% per day leak rate. Under the most conservative site and the meteorological conditions assumed, 0.015% (about 0.7 kg) of the core and blanket's plutonium inventory and 0.133% (about 3300 lb) of the primary sodium could be released to the secondary containment. Again, these limits assume that all radioactive material entering the containment is available for leakage.

2.7. Candidate Systems

The following candidate systems resulted from this study:

1. Oxygen depletion systems, including partially inert systems (such as machinery domes and reduced containment pressure systems) and fully inert systems.
2. A containment filter system for atmospheric cleanup after a fire.
3. A system for adding NaCl to the atmosphere to act as an additional heat sink and fire extinguishing agent.
4. A double-containment system with pump-back capability to ensure zero leakage after a fire.
5. A sodium drainage system to prevent pool fires.

3. DESCRIPTION OF WORK

3.1. Survey of Containment Philosophy

3.1.1. Fast Breeder Reactor Follow-On Studies

The containment designs explored in the Follow-On Studies take two general paths: One is unique in that the reactor building is not a pressure vessel. The other design is closer to the conventional approach, wherein the building is designed for a given accident and must withstand the resultant pressure.

General Electric's reactor building is a rectangular structure of steel and reinforced concrete. The structure is not designed to contain a major accident; its design pressure is 0 psig. A concrete wall covering the lower portion would protect the structure from tornado-generated missiles. The cells having sodium-containing equipment are made inert with nitrogen; the main portion of the reactor building has an air atmosphere. Sodium fire considerations are not the major design requirement for the reactor building.^{1,2}

The more conventional approach was taken by Westinghouse and Atomics International, who have chosen inert containments to minimize the sodium leakage-sodium air fire problem. A few of the characteristics for each of their containments are compared in Table 3-1. Even though both have inert containments, the inert gas, the method, and the rationale used are different. In Westinghouse's design the entire space (reactor hot cell) above the reactor vessel is inert (argon), and nitrogen is used as the inert gas in other equipment rooms below the operating floor. A manned access system provides access to these inerted areas. Westinghouse's containment building is a double-barrier structure consisting of a reinforced concrete outer barrier separated from the inner steel liner by an air space. The leakage criterion for the inner vessel is 0.1%/day at design pressure.^{3,4} They use an open hot cell refueling scheme.

Table 3-1. Reactor Containment Comparisons

<u>Characteristic</u>	<u>Westinghouse</u>	<u>Atomics International</u>
Structure type	Double barrier, steel and concrete	Reinforced concrete, inside steel liner
Inert gas	Argon—reactor hot cell; Nitrogen—equipment vaults	2% O ₂ (max) in dome; cells containing primary Na
Design basis accident definition	Core meltdown — 10,800 MWs	TNT-type explosion or Na fire
Design conditions	30 psig, 500 F	10 psig, outer vessel ^(a) ; 40 psig, dome ^(a)
Maximum permissible leakage rate	0.1% /day at 30 psig, inner steel vessel	0.1% /day at 10 psig, outer shell; 10% /day at 20 psig, dome
Refueling scheme	Open hot cell	Under-the-plug, in-vessel fuel storage
Fission products and Pu release		100% noble gases, 100% halogens as aerosols, 19% nonvolatile as aerosols, Unspecified amount of Na
Safety features and support systems considered	Inert gas, post-accident atmosphere cleanup, missile protection	

(a) Implied.

Atomic International's design has a reinforced concrete containment vessel with an inside steel liner. The leakage criterion for this vessel is 0.1% /day at design pressure. There is a top shield containment dome in which the inside oxygen concentration is maintained below 2%. All cells containing primary sodium equipment within the reactor building are maintained under an inert atmosphere to prevent a sodium air fire in case of a leak. The refueling scheme is an under-the-plug arrangement.⁵

3.1.2. Containment Leakage Rates

The containment can be leak-tested by two methods: the absolute method and the reference-vessel method.^{6,7} Both have been used on reactor containments and found to be equally effective.

Examination of a number of containment leak specifications for U.S. light water reactors has shown that the leakage criterion ranges from 0.1 to 0.5% per day. Many plants now scheduled for operation early in 1970 consider a leakage rate of 0.2% per day. In general, the boiling water reactor plants are at the upper end of this range. The B&W Follow-On study specified a maximum permissible leakage rate of 0.1% per day.

In late 1968 and the first quarter of 1969, containment leakage rate tests were run at the Carolina-Virginia Tube Reactor (CVTR) plant. The measured leakage rates ranged from 0.09 to 0.36% per day. The CVTR tests showed that the leakage rate decreased with increasing test temperature and that simulated DBA conditions appeared to have a negligible effect on the containment's leak tightness. Some effort was made to select a particular extrapolation equation^{7,11} to show the effect of air test pressure versus DBA conditions. The leakage rate increased and decreased with test pressure as predicted. However, leakage paths and associated leakage rates were found to change during and between test runs. These tests, as other publications report, indicated that both the reference-vessel method and the absolute method for measuring leakage rates are equally effective in determining the containment vessel's leakage rate.^{8,9}

Three actual containments were analyzed for leakage rates at elevated pressures: the NS Savannah, the Agesta Nuclear

Power Station, and the ESADA Vallecitos Experimental Superheat Reactor. The actual data and the analysis showed that the leakage rates for the Savannah and Agesta fall into the laminar flow regimes and that the ESADA is characteristic of the turbulent flow-smooth passage. It is not clear why one containment exhibits one type of leakage while another correlates with a different type of flow. From the three cases examined in the subject document, the laminar leakage seemed to correspond to leakage rates above 0.2% per 24 hours, while the turbulent flow matched leakage rates of approximately 0.1% per 24 hours and under.¹¹

3.1.3. Fast Breeder Reactor Containments

The containments of two existing U.S. fast breeder plants, the Experimental Breeder Reactor-II (EBR-II) and the Enrico Fermi Atomic Power Plant are compared briefly in Table 3-2.^{7,12,13} EBR-II is situated on a national testing site in the state of Idaho and generates electric power. The Fermi plant, situated on Lake Erie 30 miles SW of Detroit, generates power which is fed into an electric utility's grid system. The two containment designs reflect the different locations and uses of these two reactors.

Table 3-2. EBR-II and Fermi Containments

Item	EBR-II	FERMI
Shape	Vertical cylinder with hemispherical top and hemi-ellipsoidal bottom, partially below grade	Same
Dimensions, ft		
Height/diameter	146/80	120/72
Free volume, ft ³	450,000	280,000
Design pressure, psig	24	32(-2)
Design temperature, F	--	460 (at building's wall)
Design leakage rate	1000 ft ³ /day @ 20 psig (0.22% /day)	0.015% /day
Leakage test pressure, psig	--	30
Strength test pressure, psig	30	40
Leak test method	--	Reference
Containment vessel		
Code	--	ASME
Material	A-201-B	A-201-B, A-300
Thickness, in.	1	1(side), 5/8 (top), 1-1/4 (bottom)
Exterior protection	Aluminum paint above grade; bitumastic below grade	Asphalt paint below grade; lightning rods
Missile protection	Wall and top and bottom closures of reactor vessel; above main floor, 14 in. concrete wall and ceiling	Concrete and steel shields in and below floor; machinery dome above floor
Basis for containment design	Ejection of 3000 lb Na with high degree of dispersion	Na-Air reaction; failure of main Na piping with coincident introduction of air in normally inert atmosphere; burning continues until 95% of O ₂ is consumed

Table 3-2. (Cont'd)

<u>Item</u>	<u>EBR-II</u>	<u>FERMI</u>
Na Coolant properties at accident conditions		
Quantity, lb	640,000	400,000
Temperature (inlet/outlet), F	700/900	550/800
Fission product release		
Operation assumed before accident	60 MWt, 135 days	200 MWt, long-term
Released to contain- ment	1% of all fission products	100% of noble gases 50% of halogens 5% of solids
Released from building	25% per day of all fission products	100% of noble gases 25% of halogens 5% of solids
Doses from release		
Direct radiation dose at exclusion distance	11 r, 1 h at building surface	0.051 Rem, 2 h 5.6 Rem, 1 y
Cloud	3.19 r, 2 h	0.94 Rem, 2 h 2 Rem, 1 y
Thyroid	69 rad, 2 h	88 Rem, 2 h
Bone	--	5.7 Rem, 1 y
Dispersion conditions assumed leakage		0.15% /day for first 2 h; 0.10% /day for remainder of 1 year
Meteorological conditions		Inversion
Wind speed, m/s		1
Dispersion parameters		n = 0.55, Cz = 0.08

EBR-II and Fermi began operating in the 1960's; both are licensed and have operated at power. The most recent fast breeder plant committed to design and near-term construction is the Fast Flux Test Facility (FFTF), which will be built near Richland, Washington. The approach taken for the FFTF reactor is a double-barrier steel containment. The outer barrier, a large, spherical-shaped vessel, is approximately 200 feet in diameter. The inner barrier, a 30-foot-diameter machinery dome, is positioned over the reactor vessel's cover during reactor operation. During shutdown the dome is removed for maintenance and refueling operations. Both of these vessels have an air atmosphere. The reactor cavity vault, housing the reactor vessel and shield, has inert argon atmosphere to minimize the possibility of a sodium-air reaction.^{14,15}

3.1.4. Inert Containment

The containments of some operating thermal reactors are rendered inert to prevent fires; for example, the NS Savannah inerts to prevent oil fires due to hydraulic oil leakage from the control rod drives, and Peach Bottom HTGR inerts to prevent combustion of the graphite moderator. However, GE states that inert containments are not warranted for their BWR plants and are judged to be detrimental to overall plant safety.¹⁶

Inert containments can be provided in two ways: (1) reducing the total air pressure by pulling a vacuum to reduce the oxygen available for combustion; (2) diluting the air with another gas such as nitrogen or argon (the more conventional method).

3.1.5. Observations

3.1.5.1. Follow-On Studies Containment

The containment designs of all the contractors vary widely in design philosophy. It is obvious that the various contractors have not established definite FBR containment designs. Their approaches are too different not to expect them to change. For example, one doesn't consider the sodium-air fire in his design, but another provides inert gas in all spaces having sodium-containing equipment. It can be concluded that more work is required to establish the best overall approach to the containment design. B&W's present approach is as

reasonable as the other contractors' approaches, but additional work is required.

3.1.5.2. Containment Atmosphere

Any reactor plant that requires a partial or total inert containment atmosphere increases the capital and operational costs of the plant. In addition, it complicates access requirements, and this is also reflected in the operational costs. Most designers and utility operators agree that there is an incentive to perform inspections and preventive maintenance on selected portions of the plant during operation.

For the facilities reviewed, it is evident that the conflicting factors of decreasing the capital cost, providing access to the containment, and mitigating the effects of a sodium fire in the containment were all considered. However, the general conclusion seems to be that a fire in the containment cannot be tolerated. This conclusion is understandable because it eliminates an area of unknowns; namely, a definition of the size of the fire and the effects on the containment and the environment. The EBR-II, however, was analyzed for sodium fires, and the results were acceptable for a remote site and a uranium core.

B&W's design does not utilize a machinery dome or an inert containment. Access is required to facilitate refueling operations—a requirement above and beyond inspection and preventive maintenance. A thorough investigation is required to prove this approach.

3.1.5.3. Leakage Rates

It is generally agreed that containments can be designed to attain a leakage rate as low as 0.1% per day under design pressures. The reference-vessel and absolute methods are equally effective in determining leakage rates for the containment vessel.

3.2. Analytical Studies

3.2.1. General

The major effort has been to consider the effects of a sodium fire in the secondary containment, particularly the severe temperatures and pressures imposed on the containment vessel. The objectives of the analysis are summarized below:

1. Determine the quantity of sodium expelled through the cover structure.
2. Determine the form of the sodium expelled. The severity of the fire depends on whether the sodium is in the form of a spray or a pool.
3. Determine the containment pressure and temperature conditions resulting from the sodium fire.
4. Using the minimum leakage rate and the hypothetical site, determine the maximum permissible concentrations of the governing isotopes that may be available for leakage from the containment to the environment.

The results will aid in specifying the most stringent design conditions for the secondary containment. The containment vessel is the final barrier of the plant to contain or minimize the leakage of radioactive materials released during all postulated accident conditions. Therefore, this accident is most important in establishing the design basis of the secondary containment.

The initiating mechanism for the sodium fire is a major core disturbance. The postulated accident releases fuel into the sodium coolant, and the energy generated forces a column of sodium up against the reactor vessel's cover plug, which is subjected to this impacting force. The cover plug, a large structure covering the reactor vessel, is held in place by holddown bolts. The structure contains many sealed openings, including rotating plugs, rotating shafts, control rod drives, and replaceable plugs. Following the impact of the sodium, leakage through these openings could result in a sodium fire and spreading of core meltdown products into the secondary containment. (The design pressure of the vessel will be based on the fire.) The fission products

and plutonium in the containment would then be available for leakage through the vessel to the ambient air. From the leakage of radioactive material, the dose rates can be determined for the public and the plant personnel. The doses must be consistent with the regulations of 10 CFR 100.

These studies were performed with a view to applying the reasoning, methods, and results later, when the functional requirements resulting from the accident analysis become available. To proceed with the effort, functional requirements were generated based on the best information available. Therefore, the requirements associated with the resultant candidate systems must be substantiated before they can be included in the containment system.

The assumptions made in this study fall into three categories: (1) those used instead of input information; (2) those used instead of design information; (3) those used instead of experimental information.

Category 1 includes assumptions made to determine the magnitude of the accident, i.e., the sodium impact velocity, the inelastic collision, etc. These assumptions are perhaps the strongest, not only because they have a high degree of conservatism, but primarily because they can be modified as the accident analysis results become available.

Category 2 includes assumptions based on the ability to design structures to withstand the initiating conditions, such as the capability to hold down the cover plug, to design against intermediate sodium leaks, to prevent missile damage, etc.

Category 3 includes assumptions made to model the spray and pool fires and to perform the environmental safety calculations. These assumptions are perhaps the weakest of all the others because, to a large extent, they lack conclusive experimental verification.

3.2.2. Sodium Expulsion

3.2.2.1. Introduction

The possibility and the consequences of sodium leaking through the cover structure must be considered in designing the secondary containment. As long as there is air in the containment, a

sodium leak could lead to a sodium-air fire. A method was developed to determine a range of quantities of sodium that might be expelled through the cover plug following an assumed core accident. In addition to determining the amount of sodium leaking into the secondary containment, it is necessary to determine the character of the leak.

The severity of a sodium fire depends on whether the sodium leaks through as a fine spray, a fountain, or pours out into a pool. The form of the leak will affect the rate at which the sodium burns.

Again, it is emphasized that the subsequent approach is meant to determine the amount and characteristics of the sodium entering the containment; it is not meant to be an analysis of a structural holddown arrangement.

3.2.2.2. Approach

The calculational approach involved the force balances on the cover structure and the impacting sodium slug. The input to the problem is a given velocity for a sodium slug impacting against the lower surface of the cover plug. This sodium velocity results from a core disturbance accident; a range of from 50 to 200 fps was chosen (FFTF reports 410 fps for their reactor).¹⁴

The cover plug, a large structure covering the reactor vessel, is assumed to be held in place by holddown bolts near the periphery of the structure. The structure has many openings containing rotating plugs, rotating shafts, control rod drives, etc. The seals, which prevent normal leakage of the cover gas around these plugs and shafts into the containment space, are potential paths of leakage for sodium following the collision of a sodium slug. The smaller-diameter openings, such as the control rod drive penetrations, were assumed to be completely voided for sodium leakage during the accident. The impacting sodium slug was allowed to collide with the underside of the cover structure, producing a force on the structure. This force, applied across a portion of the plug's cross-sectional area, would then push sodium out through the voided passageways.

Force-balance equations based on Newton's second law of motion were written for both the cover structure and the

impacting sodium slug. These equations describe the dynamic response of these bodies following the collision. The force acting at the interface of the two bodies couples these relations into a single dynamic equation. Assuming an inelastic collision for simplicity, the coordinates become common, since their velocities are equivalent after the collision. The force relation reduces to an expression for the acceleration of the plug and the sodium slug. The solution gives the velocity and the displacement as a function of time.

The restraining force of the holddown bolts takes two different forms: one for the elastic elongation region, and another for the plastic deformation region. The dynamic equation is solved in the elastic region until the elongation of the bolts increases the stress to the allowable yield stress. The distance and the time for the elastic limit were then determined. The dynamic relation was solved again, using a different holddown bolt force for the plastic elongation region. In this region the impulse time period is over when the velocity of the plug and the sodium decreases to zero, stopping the movement. The work done during this time period equals the kinetic energy immediately after the collision. The time, elongation, force, and pressure were determined for each of these regions. Using the resultant pressure drop, the flow was calculated from a standard pressure drop-flow relation, which included the flow inertia-pressure drop effect. The flow rate is integrated relative to time during the impulse time for both elastic and plastic regions to determine the amount of sodium leaking out into the secondary containment.

The initiating function for this determination is the impact velocity of the sodium slug resulting from the interaction of molten fuel and sodium. The following assumptions are included in the sodium expulsion calculation:

1. The cover structure and the sodium slug are represented as free bodies.
2. The collision between the sodium slug and the cover structure is inelastic.
3. The force required to drive the sodium out through the leakage passages is neglected in the force-balance relations.
4. Movement of the cover shield plug does not change the cross-sectional areas of the leakage paths.

The calculations are divided into the two regions of holddown bolt deformation: elastic and plastic elongation regions. Similar methods are used for both regions. The calculational procedure, given in Appendix A, is summarized as follows:

1. Determine the coupled force balance for the cover plug and the sodium slug.
2. Apply the holddown bolt force for the elastic limit region to the coupled force relation.
3. Evaluate the initial velocity after collision.
4. Integrate the force relation for the velocity and displacement of the plug and the sodium slug.
5. Evaluate the displacement to exceed the elastic limit of the holddown bolt material.
6. Find the time of the elastic limit region.
7. Find the pressure drop exerted across the cover plug for the elastic region.
8. Apply the holddown bolt force for the plastic elongation region.
9. Evaluate the initial velocity for this region.
10. Integrate the coupled force relation for the velocity.
11. Find the time (for the plastic region) when the velocity reduces to zero.
12. Integrate the velocity relation for the displacement of the plastic region.
13. Find the pressure drop exerted across the cover plug for the plastic region.
14. Check the work done in the elastic and plastic regions, and the kinetic energy after impact.
15. Apply the pressure drop for the elastic region to the leakage-flow rate relation, integrate with time to determine the flow

rate, and integrate the flow rate for the elastic region's time period. The integral of the flow is the amount of sodium expelled during the elastic region.

16. Apply the pressure drop for the plastic region to the leakage-flow rate relation, integrate with time to determine the flow rate, and integrate the flow rate for the plastic region's time period. The integral of the flow is the amount of sodium expelled during the plastic region.

17. The flow rate and the amount of sodium expelled as a function of time are tabulated from 15 and 16, above, placing the plastic region after the elastic region. The MIMIC code was used to accomplish these integrations.

3.2.2.3. Results and Discussion

A calculation was established to set up a standard, whose results could be compared with those determined when important parameters are varied. This standard reference calculation does not necessarily represent the reference design LMFBR plant. The standard consisted of the following set parameters:

Sodium impacting velocity (v_1) = 100 fps

Leakage cross-sectional area (A_h) = 10.2 ft²

Holddown bolt cross-sectional area (A_b) = 5 ft²
[100 3-in. -dia bolts]

Holddown bolt length (L_b) = 20 ft

Other input to the calculation, all of which was maintained constant for this investigation, is listed in Appendix A.

The cross-sectional area of the leak (10.2 ft²) includes leakage areas around the large rotating plug, the intermediate plug, the small plug, two refueling ports, and 25 control rod drive ports. The wetted perimeter for this area is 417.2 ft, yielding a hydraulic diameter of 1.2 inches. The geometries of these leak paths are given in Appendix A.

The cross-sectional area of the bolts (5 ft²) is equivalent to 100 three-inch-diameter bolts. The two other variations

of this parameter are for 100 five-inch- and 100 seven-inch-diameter bolts.

The four parameters of the standard established the standard case. The new cases were established by holding three of these parameters constant and varying the remaining one. Table 3-3 lists the nine cases considered, and Table 3-4 gives pertinent results from these cases. The values noted in Table 3-3 indicate the parameter being varied.

Table 3-3. Cases Considered

<u>Case</u>	<u>v_1, fps</u>	<u>A_h, ft</u>	<u>A_b, ft²</u>	<u>L_b, ft</u>
1 (std)	100	10.2	5	20
2	<u>200</u>	10.2	5	20
3	<u>50</u>	10.2	5	20
4	100	10.2	<u>13.6</u>	20
5	100	10.2	<u>26.7</u>	20
6	100	10.2	5	<u>10</u>
7	100	10.2	5	<u>30</u>
8	100	<u>8</u>	5	20
9	100	<u>12</u>	5	20

Table 3-4. Pertinent Results

<u>Case</u>	<u>Elast limit reg</u>		<u>Perm elong reg</u>		<u>Tot. impulse time, s</u>	<u>Max Na lkg flow rate, lb/s</u>	<u>Tot. Na expel to, secd cont, lb</u>
	<u>Displ, ft</u>	<u>Impulse time, s</u>	<u>Displ, ft</u>	<u>Impulse time, s</u>			
1 (std)	0.02	0.00251	0.2132	0.0544	0.0569	45,880	1490
2 ($v_1 = 200$ fps)	0.02	0.00124	0.8894	0.1110	0.1123	55,900	4425
3 ($v_1 = 50$ fps)	0.02	0.00520	0.0441	0.0247	0.0299	28,660	422
4 ($A_b = 13.6$ ft ²)	0.02	0.00254	0.0855	0.0225	0.0250	54,010	698
5 ($A_b = 26.7$ ft ²)	0.02	0.00258	0.04216	0.0117	0.01430	54,840	406
6 ($L_b = 10$ ft)	0.01	0.00126	0.2193	0.0551	0.05640	15,880	1492
7 ($L_b = 30$ ft)	0.03	0.00378	0.2071	0.0536	0.0574	45,870	1493
8 ($A_h = 8$ ft ²)	0.02	0.00251	0.2132	0.0544	0.0569	34,610	1145
9 ($A_h = 12$ ft ²)	0.02	0.00261	0.2132	0.0544	0.0569	55,200	1777

Figure 3-1, a plot of these results, indicates that the impact velocity has the greatest effect on the total weight of sodium expelled, and that the leakage area has the next greatest effect. To reduce sodium expulsion effectively, considerable attention must be given to these parameters.

The data also indicate that the elastic limit region makes up only a small percentage of the impulse time for each case. Most of the leakage occurs in the plastic elongation region. The total weight of sodium leakage is more a function of the total impulse time than of the total displacement or the maximum flow rate. Both mild steel (low carbon content) and stainless steel are adequate for the holddown bolts based on the energy-absorbing requirements determined in these studies. The yield stresses range from 30,000 to 75,000 psi, and elongation characteristics up to 35 or 40% are available for materials of this type. These properties are dependent upon the specific type of materials and the processes used in their manufacture.

Figure 3-2 shows the impulse time response for leakage through the cover structure for the standard calculation (case 1). The flow of the sodium expelled and the time integral of this flow are shown as a function of time. The total impulse time is 0.0569 second, of which 0.0544 second is for the plastic deformation region and 0.0025 second for the elastic region. The maximum flow rate at the end of this time period is 45,880 lb/s. The total weight of sodium expelled is 1490 pounds. In all the cases considered, leakage ranged from 406 to 4425 pounds.

Figure 3-3 is similar to Figure 3-2 but represents the flow and leakage for case 2. It is presented because both cases 1 and 2 will subsequently be analyzed for fire consequences.

3.2.3. Spray Characteristics

3.2.3.1. Introduction

In order to investigate the consequences of the sodium-air reaction that would occur following the entry of sodium into the secondary containment, it was necessary to describe the geometry of the sodium. The energy release rate from the sodium-air reaction depends to a large extent on the surface area of the sodium exposed to

the air. It is common knowledge that the explosive injection of sodium into an oxygen-bearing atmosphere is one of the worst situations, primarily because intimate mixing of sodium and air can result from this mechanism. The rate of energy release and the total energy release are two important parameters to be considered in the investigation of any sodium fire. For the case in hand, which postulates that sodium is ejected into the air-filled secondary containment, these parameters must be evaluated, since the conditions imposed on the containment by the energy release may well form the basis for the design of the secondary containment's structure and related supporting safety systems. Based on the results of the preceding section, a method was developed to describe the geometry of the sodium expelled.

3. 2. 3. 2. Method Description and Discussion

The most conservative approach to this problem is to assume that the sodium mixes intimately and completely with the air in the containment building and instantaneously yields the total heat of combustion associated with the mass of sodium. This approach is felt to be overly conservative because intimate mixing will not occur over the entire volume of the building; instead, some of the sodium expelled will return to the floor of the containment building before combustion is complete.

The following method was developed to calculate the fraction of expelled sodium that burns during the in-flight time, and the fraction that returns to the floor, which may or may not contribute further energy release through a pool burning process.

The previous sections have shown that the leakage path through the cover structure is actually a composite of leakage paths that could exist around the rotating plugs, rotating shafts, control rod drives, etc.. Therefore, the geometry of the emerging sodium cannot be precisely defined. It was assumed that the leak paths behave as spray cones, which lead to a conical annulus of emerging sodium that immediately begins to break up into small particles. Reference 17 suggests that for a given relative velocity between the liquid and the gas, a maximum drop size exists. A drop that is larger than the critical maximum will shatter into smaller drops.

Figure 3-1. Expelled Sodium Vs Selected Parameters

Figure 3-2. Sodium Expulsion, Standard Case Calculations

Figure 3-3. Sodium Expulsion, Case 2 Calculations

It was further assumed that the droplet size distribution below the maximum size follows a relationship called the upper limit equation.¹⁷ It is based on a differential equation for the "normal" distribution, where the quantity distributed is a logarithmic function of the droplet's diameter. The upper limit equation has been applied to a variety of experimental data on sprays, and it fits the data accurately. Mugele and Evans¹⁸ would use the upper limit equation as a standard for describing droplet size distributions in sprays.

Based on these two assumptions, it is possible to describe the particle size distribution for a given expulsion velocity. Using the methods described in section 3.2.2, one can calculate the mass flow rate versus time for the expulsion of sodium through the cover structure. Knowing the density of the sodium and the area of the flow path, the expulsion velocity can be calculated as a function of time. The geometry of the sodium expelled was described by calculating the mass and average velocity of the sodium expelled over a small time increment: Hence, the expelled sodium was broken up into mass increments, each of which was composed of assumed spherical particles with a known size distribution and initial velocity. This information was used as input for the fire calculations presented in section 3.2.4. The appropriate equations are presented in Appendix B.

3.2.3.3. Results and Discussion

The sodium expulsion accidents referred to as cases 1 (standard case) and 2 in section 3.3.2 were selected for evaluation. Case 1 considered a slug of sodium impacting on the cover plug with a velocity of 100 ft/s at the time of impact. Case 2 considered an impact velocity of 200 ft/s. Of the accidents listed, case 2 should lead to the worst consequences because of the larger mass of sodium ejected through the cover plug.

The methods described in section 3.2.3.2 and in Appendix B were used to describe the geometry and initial conditions of the ejected sodium for both cases 1 and 2. The results are as follows:

Case 1

Total expulsion time, s: 0.05687.

Total sodium expelled, lb: 1490.

The expulsion time was divided into three equal time increments, Δt_i , where

$$\Delta t_i = \frac{0.05687}{3} = 0.01895 \text{ s.}$$

The amount of sodium ejected during each time increment, W_{oi} , was calculated from equation B-1 of Appendix B:

$$W_{o1} = 180 \text{ lb.}$$

$$W_{o2} = 530 \text{ lb.}$$

$$W_{o3} = 780 \text{ lb.}$$

The average initial velocity of each W_{oi} was calculated from equation B-2 of Appendix B:

$$V_{o1} = 556.56 \text{ cm/s.}$$

$$V_{o2} = 1638.60 \text{ cm/s.}$$

$$V_{o3} = 2411.88 \text{ cm/s.}$$

The maximum critical radius corresponding to each initial velocity was calculated using equation B-4 of Appendix B:

$$R_{m1} = 4.5783 \text{ cm.}$$

$$R_{m2} = 0.5282 \text{ cm.}$$

$$R_{m3} = 0.2438 \text{ cm.}$$

The particle size distribution was calculated for each i group ($i = 1, 2, 3$) based on R_{mi} , V_{oi} , and W_{oi} . Using Figure B-1 of Appendix B, the mass fraction and average radius were found for each of 13 increments according to particle radius. The mass fractions

were multiplied by the total mass W_{oi} in group i to obtain the mass increments W_{oij} . These results are shown in Table 3-5.

Table 3-5. Values of W_{oij} and R_{oij}

<u>j</u>	<u>R_{oij}, cm</u>	<u>W_{oij}, lb</u>	<u>R_{ozj}, cm</u>	<u>W_{ozj}, lb</u>	<u>R_{o3j}, cm</u>	<u>W_{o3j}, lb</u>
1	3.2407	1.80	0.3739	5.30	0.1726	7.80
2	2.6074	7.20	0.3009	21.20	0.1389	31.20
3	2.2404	9.00	0.2585	26.50	0.1193	39.00
4	1.9535	18.00	0.2254	53.00	0.1040	78.00
5	1.6947	18.00	0.1956	53.00	0.0903	78.00
6	1.5034	18.00	0.1735	53.00	0.0801	78.00
7	1.3408	18.00	0.1547	53.00	0.0714	78.00
8	1.1984	18.00	0.1383	53.00	0.0638	78.00
9	1.0688	18.00	0.1233	53.00	0.0569	78.00
10	0.9288	18.00	0.1072	53.00	0.0495	78.00
11	0.7657	18.00	0.0884	53.00	0.0408	78.00
12	0.5607	14.40	0.0647	42.40	0.0299	63.40
13	0.4312	3.60	0.0498	10.60	0.0230	15.60

These numbers were used as input to the burning calculations for case 1.

Case 2

Total expulsion time, s: 0.11228.

Total sodium expelled, lb: 4425.

The expulsion time was divided into three equal time increments, Δt_i , where

$$\Delta t_i = \frac{0.11228}{3} = 0.03742 \text{ s.}$$

Results of the calculations, performed exactly as for case 1, are as follows:

$$W_{o1} = 700 \text{ lb.}$$

$$W_{o2} = 1650 \text{ lb.}$$

$$W_{o3} = 2075 \text{ lb.}$$

$$V_{o1} = 1096.06 \text{ cm/s.}$$

$$V_{o2} = 2583.48 \text{ cm/s.}$$

$$V_{o3} = 3249.17 \text{ cm/s.}$$

$$R_{m1} = 1.1805 \text{ cm.}$$

$$R_{m2} = 0.2125 \text{ cm.}$$

$$R_{m3} = 0.1343 \text{ cm.}$$

Table 3-6 shows the values of W_{oij} and R_{oij} , which were calculated as before.

Table 3-6. Values of W_{oij} and R_{oij}

<u>j</u>	<u>R_{o1j}, cm</u>	<u>W_{o1j}, lb</u>	<u>R_{o2j}, cm</u>	<u>W_{o2j}, lb</u>	<u>R_{o3j}, cm</u>	<u>W_{o3j}, lb</u>
1	0.8356	7.00	0.1504	16.50	0.0951	20.75
2	0.6723	28.00	0.1210	66.00	0.0765	83.00
3	0.5777	35.00	0.0950	82.50	0.0657	103.75
4	0.5037	70.00	0.0907	165.00	0.0573	207.50
5	0.4370	70.00	0.0787	165.00	0.0497	207.50
6	0.3877	70.00	0.0698	165.00	0.0441	207.50
7	0.3458	70.00	0.0622	165.00	0.0394	207.50
8	0.3090	70.00	0.0556	165.00	0.0352	207.50
9	0.2756	70.00	0.0496	165.00	0.0314	207.50
10	0.2395	70.00	0.0431	165.00	0.0273	207.50
11	0.1974	70.00	0.0355	165.00	0.0225	207.50
12	0.1446	56.00	0.0260	132.00	0.0165	166.00
13	0.1112	14.00	0.0200	33.00	0.0127	41.50

These values were used as input to the burning calculations for case 2.

3.2.4. Sodium Fire

3.2.4.1. Introduction

The expulsion of sodium from the primary vessel into the secondary containment building will result in a sodium fire as the sodium undergoes an exothermic chemical reaction with the oxygen in the atmosphere. For noninert atmospheres the oxygen content is high, and large quantities of heat energy may be released depending on the amount of sodium expelled. The energy released will increase the temperatures and pressure in the secondary containment building. In an accident of this kind, the sodium itself is radioactive because of its previous residence in the high-neutron-flux core region, and will contain fission products and possibly plutonium. Since the secondary containment is the final barrier to prevent release of these radioactive materials, its integrity must be guaranteed. Thus, in the safety analysis of sodium-cooled reactor concepts, this type of accident must be considered.

The previous sections have considered the amounts of sodium that might be expelled during accident conditions and have presented a conservative description of the sodium's geometry upon expulsion. The remaining task is to describe quantitatively the subsequent behavior of the expelled sodium and to relate the energy release to functional requirements of the secondary containment building. Specifically, we must calculate the pressure that the building will be subjected to and the temperature time history of the building and its components. These calculations will provide part of the information needed to define the secondary containment building's design requirements and to determine whether support systems are required.

3.2.4.2. Method Description and Discussion

The physical model assumed for the burning sodium is straightforward: Immediately upon leaving the surface of the cover structure, the ejected sodium breaks up into a collection of spherical particles whose size distribution can be calculated. Each particle has a known initial velocity and size. The momentum of a particle carries it up into the air, and the particle burns at a rate proportional to

its surface area. The forces acting on the particle change as the velocity and the size of the particle change. Each particle rises to some maximum height and falls back through the air. Burning of each particle ends whenever it burns itself up or comes into contact with the floor, whichever occurs first. Each initial particle is accounted for by a group-averaging calculation. The amount of sodium burned during flight is calculated for each particle group and then summed to yield the total amount burned as a spray for the accident. The energy released through this mechanism is calculated according to the amount of sodium burned, and the release is assumed to be instantaneous. It should be pointed out that the only reason for calculating the time-dependent burning of the particles is to determine the fraction burned during the trajectory before the particles hit the floor. It makes little difference whether the energy release is assumed to occur over a time period of a few seconds or is assumed to occur instantaneously. Based on the present model, it is assumed that the sodium that burns as a spray releases its energy instantaneously, and that equilibrium temperature and pressure of the containment building's atmosphere are reached instantaneously. These are good approximations because all the spray burning occurs within several seconds from the time of expulsion.

The following discussion is divided into two sections corresponding to spray burning and pool burning, since the rate of energy release may be considerably different for each situation.

Spray Fire Analysis

In the past, several methods have been used to analyze the burning of sodium in air. The most conservative method is to assume that the sodium mixes intimately with all the oxygen available and instantaneously yields the total heat of combustion to the system for the particular amount of sodium. This method is insensitive to accident parameters other than the relative amounts of sodium and oxygen involved. Therefore, it is unsuitable for application except to provide an upper theoretical limit for comparison.

Another method, known as the free-energy minimization technique, is based on the principle that regardless of

the burning mechanism, the pressures and temperatures are limited by the thermodynamic properties of the system. This method has been developed into a computer program, and calculations have been carried out for equilibrium conditions in sodium-air mixtures.¹⁹ The method yields results that are less severe than those of the theoretical maximum calculation described above, but it, too, is not suitable for application to specific accidents other than those for which the relative amounts of sodium and oxygen are used. However, this method is more realistic and less conservative.

Experimental results may also be applied to the sodium fire analyses. This method was previously used in the FIRE code for spray fire analyses. The method is extremely simple since the experimental results are extrapolated directly to the system of concern. The data of Humphreys were previously used.²⁰ Curve fits of pressure and temperature versus the sodium-to-oxygen molar ratio were constructed from Humphreys' data. For a given amount of sodium and oxygen, the resultant atmospheric pressure and temperature could be obtained directly from the curve fits. In a later method, only the pressure curve fit was used, since this is the only measured data, and the corresponding temperature was calculated from the ideal gas law. Humphreys' data were chosen because it yielded higher pressures than did other available data. The experimental pressures obtained by Humphreys are all below the theoretical pressures calculated by the free-energy minimization technique. However, theoretical pressures approaching maximum were obtained in some cases, so that use of the experimental data was felt to be conservative. It was realized, however, that the sodium-burning experiments were designed to achieve the high degree of sodium dispersion required to reach ideal burning conditions. Much experimental data have been reported in which the pressures obtained were much lower than those theoretically possible. This pointed out the need for a model that would still be conservative when applied to specific accident conditions, but not so conservative as to assume ideal burning conditions for every accident.

Much experimental work and model development are being carried out—notably at Atomics International. Unfortunately, no analytical methods have been released for common use

in the industry; such methods should allow a realistic analysis of specific reactor accidents involving the burning of sodium that has been explosively injected into non-inert containment building atmospheres.

The current model that has been developed to suit these needs has been discussed. The appropriate equations and values for numerical constants are given in Appendix C.

The calculation is summarized as follows:

1. The expelled sodium is broken down into a collection of spherical drops immediately after expulsion, as described in section 3.2.3. Each particle or group of similar particles is characterized by an initial velocity and size.
2. The particles are allowed to burn as they move through the air, and their one-dimensional trajectories are calculated.
3. The particles are allowed to continue to burn until they impinge on the floor or burn completely, whichever occurs first.
4. The contribution of sodium burned for each group of similar particles is summed to determine the total amount of sodium burned.
5. The energy release is obtained by considering the heat of formation for the appropriate chemical reactions.
6. The entire energy release is assumed to contribute to heating up the air, and the appropriate pressure and temperature are calculated.

This model is based on several assumptions, most of which are conservative. The appropriate assumptions that are inherent in the model are listed below:

1. The particle size distribution is the distribution that would be obtained if the leakage path were a conical spray nozzle. This is a conservative assumption since the flow paths are annuli, cylinders, etc. It would be extremely difficult to relate the actual, irregular geometry of the flow paths to the corresponding particle size distribution.

2. The burning rate is directly proportional to the surface area of a particle and is independent of temperature. This may or may not be conservative depending on the value of burning rate per unit surface area used: 10 lb Na/h-ft². This value is conservative based on average burning rates for hot sodium in an air atmosphere as reported in the literature. For example, from reference 21 a burning rate of about 9 lb Na/h-ft² was reported for an experiment in which fresh air was allowed to flow across the sodium's surface. The average burning rate for the 33-hour fire was 6.2 lb/h-ft².

3. The oxygen concentration of the building's atmosphere remains constant. No credit is taken for oxygen depletion.

4. No secondary dispersion mechanisms are considered. No attempt is made to calculate air currents and their effect on the particle's trajectory. Also, no calculations were performed to account for agglomeration of particles into larger particles.

Pool Fire Analysis

Work on pool fire analyses has utilized the FIRE code, which is a modified version of the SOFIRE I-B code developed at Atomics International.²² Various pool fire situations were investigated and the results are given in Appendix D. It should be pointed out that the calculations in Appendix D were performed before the sodium expulsion calculations listed in section 3.2.2 were. Consequently, the amounts of sodium involved are significantly different. No mechanisms have been found that could lead to the introduction of such large masses of sodium into the secondary containment as were considered in the earlier work. Nevertheless, it was considered appropriate to include the results in this report because they lend some insight into methods for limiting the consequences of such large-scale pool fires. These are discussed in Appendix D.

The most uncertainty exists for cases in which moderately small amounts of sodium ($\approx$ several thousand pounds) are spilled on the containment building's floor. A thin pool with a thickness of an inch or less would be formed. Under these conditions, heat is rapidly transferred from the hot sodium to the much cooler floor of the building or to the upper surface of the cover plug. This leads to a

severe temperature drop of the sodium and may even induce freezing of the sodium. The pool-fire model in FIRE breaks down under these circumstances. In any event, it is felt that this sodium can be controlled because it will burn much more slowly with the use of chemical extinguishing methods.

As previously discussed, in accidents where sodium is violently expelled through the cover plug, the sodium that falls back onto the floor should not contribute significantly to the overall energy release to the system. However, more work needs to be done in this area.

3.2.4.3. Results and Discussion

Sodium-burning calculations were performed for cases 1 and 2, which are described in section 3.2.2.3. The input for each case consisted of the weights of sodium, the initial velocities, and the average particle radii listed in section 3.2.3.3. The results for each case are listed and discussed in following paragraphs.

Case 1

The expelled sodium was characterized by three mass increments, W_{oi} ($i = 1, 2, 3$), each having an average initial velocity V_{oi} . Each increment W_{oi} comprised subincrements W_{oij} , where each W_{oij} pounds of sodium consisted of particles with an average radius R_{oij} . Calculations were performed to determine how much of each W_{oij} pounds burned in flight. These burned quantities, W_{Bij} , were summed over all the j increments and then over each of the i groups to obtain the total amount burned. The results are listed in Table 3-7.

Table 3-7. Case 1 Results

<u>j</u>	<u>W_{o1j}, lb</u>	<u>W_{B1j}, lb</u>	<u>W_{o2j}, lb</u>	<u>W_{B2j}, lb</u>	<u>W_{o3j}, lb</u>	<u>W_{B3j}, lb</u>
1	1.80	0.00	5.30	0.27	7.80	1.15
2	7.20	0.02	21.20	1.36	31.20	5.75
3	9.00	0.02	26.50	2.02	39.00	8.42
4	18.00	0.05	53.00	4.70	78.00	19.39
5	18.00	0.06	53.00	5.53	78.00	22.35
6	18.00	0.07	53.00	6.33	78.00	25.11
7	18.00	0.08	53.00	7.21	78.00	28.01
8	18.00	0.09	53.00	8.18	78.00	31.00
9	18.00	0.10	53.00	9.32	78.00	34.12
10	18.00	0.11	53.00	10.89	78.00	37.93
11	18.00	0.13	53.00	13.49	78.00	43.28
12	14.40	0.16	42.40	14.80	62.40	39.79
13	<u>3.60</u>	<u>0.05</u>	<u>10.60</u>	<u>4.56</u>	<u>15.60</u>	<u>11.50</u>
	180.00	0.94	530.00	88.66	780.00	307.80

The amount of sodium burned for each group was found by summing the columns:

$$W_{B1} = 0.94 \text{ lb.}$$

$$W_{B2} = 88.66 \text{ lb.}$$

$$W_{B3} = 307.80 \text{ lb.}$$

The total amount of sodium burned was then

$$W_{BT} = \sum_{i=1}^{i=3} W_{Bi} = 307.80 + 88.66 + 0.94,$$

$$W_{BT} = 397.40 \text{ lb.}$$

Using the energy-release equations in Appendix C, the total energy released to the building's atmosphere was $Q = (2960)(397.40) = 1,176,304$ Btu.

The temperature of the building's atmosphere rose to a value of $T_F = 185$ F, with a corresponding pressure of $P = 19.16$ psia.

Case 2

The results for the case 2 calculations are as follows:

Table 3-8. Case 2 Results

<u>j</u>	<u>W_{o1j}, lb</u>	<u>W_{B1j}, lb</u>	<u>W_{o2j}, lb</u>	<u>W_{B2j}, lb</u>	<u>W_{o3j}, lb</u>	<u>W_{Bsj}, lb</u>
1	7.00	0.10	16.50	2.88	20.75	6.12
2	28.00	0.50	66.00	14.37	83.00	30.02
3	35.00	0.74	82.50	22.95	103.75	42.83
4	70.00	1.74	165.00	48.06	207.50	95.74
5	70.00	2.06	165.00	55.14	207.50	106.49
6	70.00	2.38	165.00	61.60	207.50	115.49
7	70.00	2.71	165.00	68.11	207.50	124.05
8	70.00	3.11	165.00	74.65	207.50	132.37
9	70.00	3.55	165.00	81.28	207.50	140.52
10	70.00	4.23	165.00	89.56	207.50	150.11
11	70.00	5.36	165.00	100.39	207.50	158.13
12	56.00	6.30	132.00	90.04	166.00	149.13
13	<u>14.00</u>	<u>2.18</u>	<u>33.00</u>	<u>27.02</u>	<u>41.50</u>	<u>41.46</u>
	700.00	34.96	1,650.00	736.05	2,075.00	1,292.46

The amount of sodium burned from each mass group was:

$$W_{B1} = 34.96 \text{ lb.}$$

$$W_{B2} = 736.05 \text{ lb.}$$

$$W_{B3} = 1292.46 \text{ lb.}$$

The total amount of sodium burned was $W_{BT} = 2063.47 \text{ lb.}$ This led to an energy release of $Q = 6,107,871 \text{ Btu}$, with a corresponding temperature and pressure of: $T_F = 626.18 \text{ F}$; $P = 32.26 \text{ psia}$.

3.2.5. Containment Environmental Studies

3.2.5.1. Introduction

Protection of personnel and the general public from excessive radiation exposure is a required function of any reactor plant. Accident conditions that might exist during the lifetime of the plant must be analyzed, and the resultant release, if any, of the radioactive materials must be controlled. This section presents a consideration of the environmental safety associated with B&W's accident studies of the integral-pot LMFBR concept as discussed in the preceding sections.

3.2.5.2. Discussion

In general, environmental safety studies are performed as a prerequisite for obtaining an operating license for a particular nuclear steam system. The calculations are performed to assess the consequences of accident situations relative to the exposure of personnel and the general public to radioactive materials. The reactor site may often be selected so that governmental regulations can be met without altering the plant design. Based on a preselected maximum accident, site parameters such as the exclusion radius may be chosen to minimize risk to the public. In a study such as this the plant design is somewhat flexible, and no design basis accident has been selected yet. Therefore, the accident conditions, including the possible release of fission products, radioactive sodium and plutonium, are not well defined. Furthermore, no particular site has been selected since

the study is conceptual and no actual construction is foreseen. These factors, along with the vagueness of the radioactive material released from the core, the arbitrary nature of the siting parameters, and no well defined meteorological conditions, lend difficulty to the analyses. Much work has been done and standard procedures and assumptions have been developed in conjunction with the light-water reactor program; however, the inherent differences of the LMFBR concept quite often require departure from traditional techniques. The general purpose of environmental safety calculations at this time would be to make initial investigations of problems that are peculiar to the LMFBR concept. This philosophy was adopted and led to the particular calculations presented here.

Specifically, the presence of radioactive sodium and large quantities of plutonium leads to radiation hazards not normally associated with light-water reactors. Sodium is generally not present at water reactor sites in any appreciable quantity. Although plutonium is present in significant quantities in light-water reactor cores, it does not seem to have created many problems, largely because of lack of a mechanism for its release to the reactor building. However, for a sodium-cooled reactor, it is possible for plutonium to be carried along into an airborne state through the mechanism of sodium combustion. At this time, we cannot analytically describe the chain of events leading from a possible core excursion to the release of plutonium to the secondary containment building. It would be speculative, indeed to assign plutonium and fission product core release fractions, the amount of mixing that occurs with the sodium coolant, and the subsequent disposition of the mixture. More experimental data and related modeling will be required to place these events in a more definitive status.

In lieu of a direct analytical technique for describing the behavior of the radioactive materials after a core disturbance, the following approach for plutonium and sodium hazards was taken:

1. The maximum permissible body burdens for sodium-24 and the isotopes of plutonium-239, -240, -241, and -242 were determined, according to governmental regulations.

2. A site with its associated physical dimensions was selected.

3. Two independent sets of meteorological conditions were postulated. One set results in very poor atmospheric dispersion and the other in very good atmospheric dispersion.

4. Based on items 2 and 3, and using a standard calculational technique, the leakage source from the containment building that would result in the maximum permissible body burdens for persons at the exclusion boundary was calculated.

The maximum amounts of sodium-24 and plutonium in a state available for leakage were thus determined and compared with the total amounts present in the primary system. It was hoped that an approach of this type might result in a better understanding of the overall feasibility of the plant concept.

The choices made for the maximum permissible body burdens (MPBB), the site dimensions, the meteorological conditions and the calculational technique are discussed below.

MPBBs

The maximum permissible bone burden was taken to be the controlling factor for exposure to the plutonium isotopes. For the sodium-24 isotope, the total body burden was considered as well as the external gamma dose from the passing cloud containing the isotopes. The values, given in Table 3-9, represent one-tenth of the values listed in ICRP Publication 2, Table 1.²³ The one-tenth reduction factor was included to account for non-occupational exposure. The two-hour external gamma dose selected for use is 25 Rem at the exclusion area boundary, a value recommended for site selection in 10 CFR 100.

Table 3-9. Bone Burdens

<u>Isotope</u>	<u>Maximum permissible bone burden, μCi</u>
^{239}Pu	0.004
^{240}Pu	0.004
^{241}Pu	0.090
^{242}Pu	0.005
^{24}Na	0.700 (whole body)

Site Dimension

The calculations were repeated for exclusion area radii of 600, 1100, and 1609 meters (1 mile). These values represent a range of sites that are realistic and should give an indication of future siting requirements that might be imposed on LMFBR plants.

Meteorological Conditions

The assumed meteorological conditions play an important role in the calculations. Two different sets of conditions were used for these calculations. One set represents a stable situation resulting in poor atmospheric dispersion of the radioactive materials released. This set is characterized as condition-F by Pasquill as reported by Mead.²⁴ The other set is considerably more liberal and leads to improved atmospheric dispersion. These conditions will be referred to for convenience as condition-A, although they do not correspond exactly to Pasquill's condition-A.

Calculational Technique

The calculations are explained in detail in Appendix F and are not discussed here.

3.2.5.3. Results

The source terms, Q_{oi} , were calculated for each of the plutonium isotopes and ^{24}Na for condition-F and condition-A meteorological conditions, and for three different values of the exclusion

area radius. The meaning of the Q_{oi} source values should be emphasized. These values represent the amounts of the particular isotopes which, if available in an airborne state for leakage from the secondary containment building, would lead to the accumulation of the maximum permissible bone burden in an individual at the exclusion area radius during the first 24 hours after the accident. These values are listed in Appendix F in units of grams and microcuries of activity. Table 3-10 gives the amounts of plutonium isotopes present in the core at the end of an equilibrium fuel cycle, and the amount of ^{24}Na at equilibrium conditions in the primary sodium.

Table 3-10. Pu and Na in Core After
Equilibrium Fuel Cycle

<u>Isotope</u>	<u>Amount in core</u>
^{239}Pu	3292 kg
^{240}Pu	1061 kg
^{241}Pu	194 kg
^{242}Pu	79 kg
^{24}Na	1.96 grams

Based on these core inventory values and the Q_o values listed in Appendix F, the maximum amounts of these isotopes that could be allowed to be available for leakage, expressed in percentage of core inventory, have been calculated (Table 3-11).

It can be seen from Table 3-11 that ^{241}Pu is the controlling isotope in every case. A smaller fraction of this isotope can be released than for the other plutonium isotopes. Therefore, the maximum acceptable core fraction that can be made available for leakage from the secondary containment corresponds to the ^{241}Pu fraction. Table 3-12 lists the maximum fraction (%) of the core plutonium inventory that could be made available for leakage at the design leak rate and not exceed the maximum permissible bone burdens for the plutonium isotopes. It also lists the maximum fraction (%) of the primary sodium coolant that could be made available for leakage at the

design leak rate and not exceed the maximum permissible body burden for sodium-24.

Table 3-11. Maximum Amounts of Isotopes Available for Leakage

Isotope	Q _o , %		
	600 m from source	1100 m from source	1609 m from source
<u>Condition-F</u>			
²³⁹ Pu	0.063	0.114	0.149
²⁴⁰ Pu	0.053	0.095	0.125
²⁴¹ Pu	0.015	0.026	0.031
²⁴² Pu	52.456	99.418	≈100.00
²⁴ Na	0.133	0.240	0.311
<u>Condition-A</u>			
²³⁹ Pu	1.679	2.377	2.852
²⁴⁰ Pu	1.409	1.995	2.394
²⁴¹ Pu	0.351	0.495	0.593
²⁴² Pu	≈100.00	≈100.00	≈100.00
²⁴ Na	3.510	4.969	5.980

Table 3-12. Maximum Fractions of Core Plutonium Inventory and Primary Sodium Coolant Available for Leakage

Material	Fraction, %		
	600 m from source	1100 m from source	1609 m from source
<u>Condition-F</u>			
Plutonium	0.015	0.026	0.031
Primary Na	0.133	0.240	0.311
<u>Condition-A</u>			
Plutonium	0.351	0.495	0.593
Primary Na	3.510	4.969	5.980

It has been shown that the site dimensions and meteorological conditions play an important role in the calculation of acceptable radioactive materials released to the environment. It is realized that this study is far from complete and that many other things need to be known to guarantee the public's safety. This analysis has shown that reasonable siting can be accomplished for plants whose maximum accident conditions lead to core releases of the amounts shown in Table 3-12.

Within the framework of the assumptions made, it was shown that under the worst meteorological and site conditions, 0.015% of the core plutonium inventory and 0.133% of the primary sodium could be released to the secondary containment. At the best conditions, these fractions are 0.593 and 5.980%, respectively. These values represent conservative bounds when interpreted as maximum release fractions to the secondary containment, since not all of the material released to the containment is available for leakage. A complete study would include agglomeration, settle-out and plate-out of material in the secondary containment building. This calculation has also conservatively assumed that the building leaks at its design leak rate over the entire 24-hour period.

Also, it is noted that, since there are about 2.5×10^6 pounds of primary sodium in the primary system, the ejection of 3325 pounds and 150,000 pounds of sodium from the primary system to the secondary system could be tolerated under the worst and best site and meteorological conditions, respectively, as far as radiation hazards to the public are concerned and assuming that the secondary containment building's integrity is maintained.

3.3. Preliminary Candidate Containment Requirements

Reference containment support systems and features in Activity 254 will be selected on the basis of a fully developed set of requirements. Since the overall objective is to identify candidate systems and features, it follows that the identifications must be based on "candidate" requirements. This section, then, points out the possible requirements as they exist at this time; later, the necessary selections will be based primarily on the results of Activities 222 and 223.

3.3.1. Atmosphere

1. Air, Basis: (a) Accident analysis indicates that the amount of sodium expelled is not prohibitive. (b) Machinery dome required because of other considerations.

2. Nitrogen, Basis: No effective means can be found to prevent an intolerable sodium fire.

3.3.2. Leakage

1. 0.1%/24 h, Basis: Ground release.

2. 0.1%/24 h, Basis: Stack release.

3. Zero leakage, Basis: No release for first 24 hours.

3.3.3. Design Pressure

1. 35 psia, Basis: This value, the result of the analysis reported in section 3.5.4, will probably be attainable with the design as described in the B&W 1000-MWe Follow-On Studies.

3.3.4. Design Temperature

1. 300 F, Basis: This value, the result of the analysis reported in section 3.5.4, will require a redesign of the 1000-MWe reference design.

3.3.5. Heat Removal Capability

1. Normal Operation, 5×10^6 Btu/h, Basis: B&W 1000-MWe Follow-On Studies. No change in this value is expected during normal operation.

2. Post Accident, 5×10^6 Btu/h, Basis: Studies indicate that a heat removal system will not aid in reducing peak temperatures, but once the fire is out, this system will aid in maintaining the containment temperature at a low level.

3.3.6. Filters

1. Roughing, Absolute and Charcoal, Basis: To be included with the heat removal coolers as a bypass system if an air atmosphere is used; the purpose is cleanup. No credit can be claimed for these filters as an instrument for reducing the environmental hazards.

3.3.7. Purging Requirements

1. If the containment is air filled, then the requirements for human habitation will remain as given in the 1000-MWe Follow-On Studies, i.e., 1750 cfm, Dehumidification, etc.

2. If the containment is to be inert (nitrogen) then no purging is required during plant operation. Requirements for obtaining and holding an inert atmosphere have not been developed.

3.3.8. Isolation Equipment

Basis: Air-filled containment —

1. All gas-carrying lines or ducts are to be double-valved (one inside the containment and one outside). These valves will be closed automatically when a rise in containment pressure is detected.

2. All ducts going to or coming from the air coolers and filters will be closed and the fans secured when a containment fire is detected.

3.3.9. Missile Protection

Basis: Air- or nitrogen-filled containment —

1. All coolers, filters, isolation valves instrumentation and other vital equipment will be placed so that they are protected from damage by missiles.

3.3.10. Intermediate and Decay Heat Coolant Lines

Basis: Air-filled containment —

1. All lines carrying coolant other than primary sodium, freon, and gas are to be within an inert atmosphere and surrounded by steel-reinforced concrete. The concrete chases will be designed to withstand the maximum impact loads that might be expected due to missiles, crane accidents, or other equipment failure. The line protection features will be designed to provide for thermal growth, cooling, cover plug movement, instrumentation and insulation while the plant is in operation; visual inspection and maintenance will be provided when the plant is shut down.

3.4. Candidate Secondary Support Systems

As a result of the work performed in the previous sections, a number of candidate systems are presented below. While these systems are the outgrowth of concerns which stem from major accident assumptions, and while it is the purpose of these systems to mitigate the effects of the accidents, other systems and features that also work towards this end are included in the investigations of primary containment safety features (Activity 243).

3.4.1. Oxygen Depletion Systems

These systems will limit the amount of oxygen available for reaction with sodium. They cover a range of schemes having different capabilities, and they must be matched with the functional requirements.

3.4.1.1. System A — Partially Inert Atmosphere

This system provides a machinery dome type of protection. It requires a massive cover that would form an envelope over the possible leak paths. In addition, it requires an inert gas system, a special cooling system for the inert gas, and a purging system. In the A^2S^2 study the machinery dome concept is considered as part of the primary containment; it is discussed in more detail under Activity 243.

Observations

This system has several major drawbacks, which are listed as follows:

1. It must be a sophisticated design so that it would not interfere with the refueling operations.
2. Maintenance to the control rod drives cannot be performed during plant operation.
3. Down time maintenance is increased because of inert gas requirements, purging, cover removal, etc.

This system has one advantage in that it would act as a missile barrier.

3.4.1.2. System B — Reduced Containment Pressure

This system requires a steam jet exhauster to maintain the entire containment pressure at approximately 9 psia. The studies reported in Appendix D show that an appreciable reduction in the maximum temperature and pressure of the containment can be attained. The system is rather simple and is being planned for use in some light-water reactor plants.

Observation

This scheme has a serious disadvantage: if the containment is at a lower pressure than the primary system's pressure, then radioactive material could leak into the containment during normal operation. The countermeasure of operating the primary system at a pressure equal to the containment's pressure seriously affects such items as the primary pump's available NPSH, the entire cover gas and waste gas equipment and promotes consequences that might arise from a sudden pressure differential. This system can almost be ruled out at this time.

3.4.1.3. System C — Totally Inert Containment

This system will require a gas purging provision and makeup storage. It will not require the continuous purge as with an air-filled containment, nor will it require the attendant valves and instrumentation.

Observations

Because the virtues of the present refueling scheme depend heavily on manned access and because a serious blow would be dealt to preventive maintenance, this system should be considered only when no other solution is satisfactory. Its faults are based mainly on economics. Its advantage lies in its inherent ability to protect the containment from fire under virtually all conditions; this probably enhances the chance of its being licensed above all other schemes.

3.4.2. Containment Filter System

This system would be used to clean up the containment's atmosphere after a fire.

The filtration system would operate in conjunction with the containment's coolers. The filter system would contain roughing filters, absolute filters, and charcoal filters in parallel with the air coolers. These filters would be valved off during normal operation and would be heavily protected against missiles, as are the coolers themselves.

At the first sign of a sodium fire, the coolers would be secured and isolated from the containment's atmosphere. When the fire has been extinguished and the containment's atmosphere has become relatively free of large-sized particles, the coolers, together with the filter system, would be placed in operation until the containment was free of radioactive material.

Because of the time required to clean up the containment, it is highly unlikely that this system could be given credit for reducing the maximum body burden dose outside the containment.

3.4.3. Containment Atmosphere Salt Addition System

This system was proposed on the basis that it would (1) add additional heat sink capacity to the containment, (2) serve as a possible fire extinguishing agent, and (3) serve as a possible aid in agglomerating atmospheric particles.

The system has a number of possible arrangements, of which two are discussed below:

System A

In this arrangement, bins are located in the hemispherical portion of the containment containing specially treated NaCl to prevent caking. These bins would be open to the containment atmosphere during a fire to allow a gravity discharge at some preselected rate. Opening of the bins would be performed electrically on a signal originating from either a manual or an automatic source.

System B

This system is essentially the same as system A except that in place of gravity feed, the bins are provided with blowers to discharge the salt to the atmosphere.

System A has the advantage of simplicity but may not have the controllability of system B. If the assumption that the salt reaches an equilibrium temperature with the containment's (see Appendix E) atmosphere during its trip to the floor is poor, then it may very well be necessary to exercise greater control of the salt discharge. Of course, the equilibrium temperature depends to a large extent on the grain size of the salt and consequently the heat transfer area that it presents to the atmosphere. In addition to controllability, System B has the advantage of being able to direct the flow to given areas depending on the degree of sophistication that is built into the system. Like all engineered safety systems, these systems would require periodic testing to increase their availability; this requirement would undoubtedly add complications.

3.4.4. Double-Containment System

3.4.4.1. Zero-Leakage System

This system would yield an essentially zero leakage from the containment after a sodium fire. It is proposed as a possibility only if it is not possible to prevent a greater than allowable concentration of plutonium in the secondary containment when a 0.1% per day leakage is assumed.

This system consists of a double liner with a capability of "pump back" to the containment after an accident. During normal operation the space between the liners is exhausted to a stack along with the purge air from the containment. The space between the liners is always kept below atmospheric pressure with a steam jet exhauster.

After a fire is detected, the containment is isolated, and the mechanical vacuum-compressor pumps are started. These pumps discharge back into the containment, maintaining the below-atmospheric condition between the liners.

3.4.4.2. Stack Release System

This system would permit a larger amount of radioactive release inside the secondary containment than would a single-barrier containment. The system would be identical to the zero-leakage system but would not require the pump-back capability, including inspection and reliability of this feature. Releasing through a stack lessens the dose rate of the release from distance, dilution, and mixing phenomena.

In general, systems of this type will add materially to the capital cost of the plant. An economic trade-off would be required between these systems and others, such as a partially inert or fully inert containment, before a selection could be made.

3.4.5. Drainage Systems

This system would prevent the availability of large areas of sodium surface for burning. The system consists of grated floors, floor drains, and drain tanks to accept the molten sodium. The grated floor will help shut off the oxygen.

As previously discussed in section 3.2.4.2, no mechanism could be found that would yield the large pool fires examined in Appendix D. However, the analysis on the spray fires did show that some of the sodium would reach the floor and would be available for pool burning, if no provisions were made for drainage. The value of the grated floor is questionable as a fire retardant, but it should enhance drainage.

3.4.6. Miscellaneous Features

3.4.6.1. Containment Liner Insulation

In an air-filled containment, where there is a possibility of fire, it may be necessary to insulate. Pressurized water reactors have several coats of a special paint to provide the extra temperature required for the liner. Certain manufacturers offer a silicon resin that is resistant to as much as 2000 F flame for a short time without losing flexibility. This material has a thermal conductivity of 0.09 Btu-ft/h-ft²-F, and it is claimed that its final oxidation state is

silica. Its apparent ability to bond to all materials makes it a good candidate for insulation. Its ability to cure as a rubbery compound might be beneficial to reduce containment leakage further.

3.4.6.2. Spray Baffles

This study has shown that sodium sprays constitute the major source for energy release in the event of a fire. It is, therefore, necessary to suppress a spray configuration. One possible method is through the use of baffles, which is discussed in Activity 243.

4. CONCLUSIONS AND RECOMMENDATIONS

A survey of the literature and a review of all the 1000-MWe studies indicated that:

1. A 0.1% per day leakage rate is a reasonable lower limit for a containment based on the methods available to measure leakage.
2. Primary sodium fires in the secondary containment can be avoided by both partial containment and complete inert arrangements.
3. Although it is designed for 10 psig, B&W's containment can probably withstand a pressure of from 30 to 40 psia.

As a result of the analysis performed, it was found that:

1. No mechanism can be identified that would yield a large sodium pool fire.
2. Based on the quantities of sodium that were used in analyzing the spray fires, the containment will not be endangered as a result of either temperature or pressure.
3. The incorporation of appropriate systems and/or features from the candidates listed in section 3.5 will further enhance the integrity of the containment.

It is concluded that an air-filled containment is indeed feasible and has the potential for meeting licensing requirements.

Under postaccident conditions with an assumed containment leakage rate of 0.1% per day, the MPBB received by an individual at the exclusion radius indicates that the containment's atmosphere can bear reasonable concentrations of ^{241}Pu and ^{24}Na .

To develop confidence in the results of this study, further investigations should be performed as follows:

1. Develop designs to limit the Na impact velocity on the plug, and restrict the flow passages available through the plug as are now being investigated under Activity 243.
2. Develop laboratory-substantiated mathematical models to better simulate the effects of fires resulting from gross sodium leakages than are now available.
3. Develop models to allow prediction of the release and transport of plutonium and fission products following a core disturbance involving fuel meltdown.
4. Investigate the state of radioactive materials within the secondary containment and possible mechanisms for their removal.

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APPENDIX A
Sodium Expulsion

This appendix describes the model used to determine the amount and form of the sodium leakage that follows the core disturbance accident. Symbols are defined in part 4.

1. Force Balances

The cover plug and the sodium slug are shown in the sketch. Newton's second law of motion states that the acceleration of a body is directly proportional to the net force acting on the body and inversely proportional to the mass of the body. One-dimensional force balances are written

for the dynamic response following the impact of the sodium slug on the cover structure. A force balance is written for both the plug and the sodium slug. For the plug,

$$m_2 \frac{d^2x_2}{dt^2} = -W_2 - F_b + F_i. \quad (A-1)$$

Cover Plug — Free Body Diagram

For the sodium slug,

$$m_1 \frac{d^2x_1}{dt^2} = -W_1 - F_i. \quad (A-2)$$

Sodium Slug — Free Body Diagram

Summing these equations,

$$m_2 \frac{d^2x_2}{dt^2} + m_1 \frac{d^2x_1}{dt^2} = -W_2 - (F_b + F_i) - (W_1 - F_i).$$

From the coefficient of restitution ratio and assuming an inelastic collision ($e = 0$),

$$e = \frac{\frac{dx_2}{dt} - \frac{dx_1}{dt}}{v_1 - v_2} \quad (A-3)$$

where

$$\frac{dx_2}{dt} = \frac{dx_1}{dt} \quad \text{and} \quad \frac{d^2x_2}{dt^2} = \frac{d^2x_1}{dt^2} = \frac{d^2x}{dt^2}.$$

The force equation above becomes

$$F = m_T \frac{d^2x}{dt^2} = -W_T - F_b. \quad (A-4)$$

The solution of the force equation now depends on the form of the holddown bolt's restraining force. First, let us examine the elastic region for the bolts:

1. 1. Elastic Region

$F_b = kx$; $F_b = SA_b$ and $S = Ex/L_b$; then $F_b = EA_b x/L_b$, where $k = EA_b/L_b$.

For this region the dynamic equation becomes

$$\frac{d^2x}{dt^2} = -\frac{W_T}{m_T} - \frac{k}{m_T} x. \quad (A-5)$$

Define

$$\omega \equiv \sqrt{k/m_T},$$

whose solution is

$$x_e = A \sin \omega t + B \cos \omega t - (W_T/k)$$

and

$$\frac{dx_e}{dt} = A\omega \cos \omega t - B\omega \sin \omega t.$$

A and B are determined from the following boundary conditions: at $t = 0$, $x(0) = 0$, and $dx/dt = \dot{x}(0)$,

$$A = \dot{x}(0)/\omega \quad \text{and} \quad B = W_T/k.$$

Then,

$$x_e = \frac{\dot{x}(0)}{\omega} \sin \omega t + W_T/k \cos \omega t - W_T/k.$$

From the momentum balance (before and after the collision),

$$m_1 v_1 + m_2 v_2 = m_1(dx_1/dt) + m_2(dx_2/dt), \quad (A-6)$$

where

$$v_2 = 0,$$

$$dx_1/dt = dx_2/dt = dx/dt,$$

$$dx/dt = \dot{x}(0) = \frac{m_1}{m_1 + m_2} v_1.$$

The elastic limit is exceeded when the stress developed in the holddown bolts exceeds the yield stress of the bolt material. Determine the displacement where the stress equals the yield stress. From $S = Ex_e/L_b$,

$$x_e = SL_b/E.$$

Substitute this x_e into the solution for equation A-5 and determine by trial and error the time t_e . Also determine the dx/dt at this time. These will become the initial conditions for the plastic region.

To determine the pressure drop (ΔP) exerted across the plug, divide the force by the plug area of interest. (The force is given by equation A-4.)

$$F_e = \frac{\int_0^x F dx}{\int_0^x dx} = \frac{-\int_0^x (kx + W_T) dx}{\int_0^x dx}.$$

$$\Delta P = F_e / A_p \quad (A-7)$$

Now determine the flow from the pressure drop equation—this includes friction, entrance and exit losses, and the flow inertia effects:

$$\Delta P = \left(\frac{3600^2 f L P_w}{48 \times 10^{10} \rho A_h^3} + \frac{K}{288 g \rho A_h^2} \right) w^2 + \frac{L}{144 g A_h} \frac{dw}{dt}.$$

Solve this for dw/dt :

$$\frac{dw}{dt} = \frac{144 g A_h}{L} \Delta P - \frac{144 g A_h}{L} \left(\frac{3600^2 f L P_w}{48 \times 10^{10} \rho A_h^3} + \frac{K}{288 g \rho A_h^2} \right) w^2. \quad (A-8)$$

The solution of this equation with pressure drop from equation A-7 yields the flow rate. Integrate the flow rate versus time, yielding the weight of sodium leaking through the cover structure:

$$W = \int_0^t w dt. \quad (A-9)$$

1.2. Plastic Region

The plastic deformation force for the holddown bolts is constant: $F_b = S A_b$. Equation A-3 becomes

$$m_T \frac{d^2 x}{dt^2} = -(S A_b + W_T). \quad (A-10)$$

defining

$$U \equiv \frac{SA_b + W_T}{m_T},$$

the dynamic equation becomes

$$\frac{d^2x}{dt^2} = -U. \quad (A-11)$$

With boundary conditions from the elastic region and at $t = 0$, $x(0) = 0$, and $dx/dt =$ the time derivative when x_e reaches its elastic limit, the velocity of the plug and sodium becomes

$$\frac{dx}{dt} = -Ut + \dot{x}(t_e). \quad (A-12)$$

Determine t_p when $dx/dt = 0$; this will be the time required to decelerate the plug and sodium and stop the movement. This also allows the holddown bolts to absorb the kinetic energy after collision in the form of work or potential energy. The distance moved is given by equation A-13:

$$x_p = \frac{-Ut^2}{2} + \dot{x}(t_e)t. \quad (A-13)$$

Depending on the bolt material, the x_p has an upper limit past which the material will break. The desired target percentage of elongation here is about 20%.

The pressure drop across the plug is calculated in much the same way as for the elastic region—by dividing the force from equation A-10 by the area. This pressure drop is applied to equation A-8, and the flow and leakage weight are determined for the time period t_p .

2. Energy Checks

From the momentum equation (A-6) and the coefficient of restitution (e), relation (A-3), it can be proved that the kinetic energy after impact does not equal the kinetic energy before impact when the

coefficient of restitution is less than one. For our case, with e equal to zero for an inelastic collision and v_2 equal to zero, the kinetic energy after impact is

$$KE_{ai} = \frac{m_1 v_1}{2} \frac{dx_1}{dt}. \quad (A-14)$$

The kinetic energy after impact is equivalent to the work done in the elastic region plus that done in the plastic-deformation region.

$$KE_{ai} = F_e x_e + F_p x_p. \quad (A-15)$$

Input

Reference case calculation:

$$v_1 = 100 \text{ fps}$$

$$A_h = 10.2 \text{ ft}^2 \text{ (over core tank)}$$

$$A_b = 5 \text{ ft}^2 \text{ (one hundred 3-in. -dia bolts)}$$

$$L_b = 20 \text{ ft}$$

Constants:

$$A_p = 808.4 \text{ ft}^2$$

$$E = 30 \times 10^6 \text{ psi}$$

$$e = 0$$

$$f = 0.02$$

$$g = 32.174 \text{ ft/s}^2$$

$$K = 1.5$$

$$L = 10 \text{ ft}$$

$$P_w = 417.2 \text{ ft}$$

$$S = 30,000 \text{ psi}$$

$$W_1 = 0.5 \times 10^6 \text{ lb}$$

$$W_2 = 5.7 \times 10^6 \text{ lb}$$

$$\rho = 50.554 \text{ lb/ft}^3$$

3. Cover Plug Leak Area

The passages that could be available for the expulsion of sodium after a core disturbance are delineated in part 3. The area includes the annular areas around three plug sections, two refueling parts, and all 25 control rod drive apertures. Dimensions of the plug and port are given below, and the annular areas are assumed to be 1/2-inch in width. The leakage areas and the wetted perimeters for these openings are given in the tabulation.

<u>Aperture No.</u>	<u>Shape</u>	<u>Diameter, ft-in.</u>	<u>Area, ft²</u>	<u>Wetted perimeter, ft</u>
Large rotating plug (1)	Annular	32-1	4.20	201.6
Intermediate plug (1)	Annular	22-6	2.95	141.4
Small plug (1)	Annular	7-8	1.00	48.2
Refueling part (2)	Circular	0-6	0.39	3.1
Control rod drive (25)	Circular	0-3.5	1.67	22.9
Total			10.21	417.2

4. Nomenclature

- A Constant, ft.
- A_b Holddown bolt cross-sectional area, ft².
- A_h Cover plug leak area, ft².
- A_p Plug area where impact force is applied, ft².
- B Constant, ft.
- E Young's modulus of elasticity, psi.
- e Coefficient of restitution.
- F Force, lb.
- F_b Force of holddown bolts, lb.
- F_e Holddown bolt force in elastic limit region, lb.

F_i	Force at impact interface, lb.
F_p	Holddown force in permanent elongation region, lb.
f	Friction factor.
g	Acceleration due to earth's gravity, ft/s^2 .
K	Entrance and exit velocity head pressure loss.
KE_{ai}	Kinetic energy of plug and sodium after impact, ft-lb.
k	Constant, lb/ft .
L	Plug height or leakage flow path length, ft.
m_1	Mass of impact sodium, lbm.
m_2	Mass of cover plug structure, lbm.
m_T	Total mass of sodium and plug, lbm.
P_w	Leakage-wetted perimeter, ft.
S	Yield stress in holddown bolts, psi.
t	Time, seconds.
t_e	Impulse time in elastic limit region, seconds.
t_p	Impulse time in permanent elongation region, seconds.
U	Definition, $(SA_b + W_T)/m_T$, ft/s^2 .
v_1	Initial velocity of impacting sodium slug, fps.
v_2	Initial velocity of cover plug, fps.
W	Weight of sodium leakage into secondary containment, lb.
W_1	Weight of impacting sodium, lb.
W_2	Weight of cover plug, lb.
W_T	Total weight of sodium and plug, lb.
w	Sodium leakage flow rate, lb/s .
x	Displacement of sodium and plug after impact, ft.
x_1	Displacement of sodium after impact, ft.
x_2	Displacement of plug after impact, ft.

- $x(0)$ Displacement at time zero, ft.
- $\dot{x}(0)$ Velocity at time zero, ft/s.
- x_e Displacement x in elastic limit region, ft.
- x_p Displacement x in permanent elongation region, ft.
- ΔP Pressure drop exerted across cover structure following collision impact, psi.
- ω Definition, $(k/m_T)^{1/2}$, s^{-1} .
- ρ Sodium density, lb/ft³.

APPENDIX B
Spray Characteristics

This appendix presents the equations and techniques for calculating the geometry of the sodium after it exits the cover structure.

1. Mass Grouping and Initial Velocity

Let w be the flow rate of sodium through the cover structure as derived in Appendix A. Then,

$$W_{oi} = \int_{t_i}^{t_{i+1}} w dt, \quad (B-1)$$

where W_{oi} is the total amount of sodium ejected during the time interval from t_i to t_{i+1} . If ρ is the density of the sodium and A_h is the flow area, then

$$V_{oi} = \frac{W_{oi}}{\rho A_h (t_{i+1} - t_i)} \quad (B-2)$$

is the average velocity of ejection for the mass increment W_{oi} . If W_{oT} is the total sodium ejected during the accident, then

$$W_{oT} = \sum_{i=0}^I W_{oi}, \quad (B-3)$$

where I is the number of mass increments.

2. Critical Radius

The critical maximum droplet radius is given by

$$R_{mi} = \frac{10\sigma_s}{\rho_g V_{oi}^2}, \quad (B-4)$$

where

σ = surface tension = 156 dynes at 1100 F,

ρ_g = air density = 0.0011 g/cm³,

V_{oi} = relative velocity between the sodium droplet and the air.

3. Size Distribution

The upper limit analysis of droplet size distributions in sprays is discussed in detail by Muegle and Evans.* The volume distribution equation is written as

$$\frac{dv}{dy} = \frac{\delta}{\sqrt{\pi}} \exp(-\delta^2 y^2), \quad (\text{B-5})$$

where $y = \ln \frac{ax}{x_m - x},$ (B-6)

x = drop diameter,

x_m = maximum drop diameter,

a = dimensionless constant,

δ = parameter that determines the degree of dispersion of the distribution.

δ is related to the standard deviation, σ , by

$$\delta = \frac{1}{\sigma \sqrt{2}}. \quad (\text{B-7})$$

The numerical values of δ and a used in this analysis were chosen from reference 18 as being typical for atomized sprays.

The cumulative volume fraction v can be obtained by integrating the volume distribution equation

$$v = \int_{-\infty}^y \frac{\delta}{\sqrt{\pi}} \exp(-\delta^2 y^2) dy. \quad (\text{B-8})$$

This equation can be rewritten as

$$v = \int_{-\infty}^{\delta y} \frac{1}{\sqrt{\pi}} \exp(-u^2) du, \quad (\text{B-9})$$

where $u = \delta y = \frac{y}{\sqrt{\pi} \sigma},$

$$u^2 = \frac{y^2}{2\sigma^2}$$

* R. A. Muegle and H. D. Evans, "Droplet Size Distribution in Sprays", Ind and Eng Chem 43, 46, p 1317.

Equation B-9 is recognized as being of the form of the standard normal distribution equation, and the value of the integral is tabulated in many reference books.

Using the equations above, it is possible to calculate the distribution of the mass according to particle radius, for each mass increment ejected. Figure B-1 shows a plot of $R/R_m - R$ versus the cumulative mass fraction (v) in percent. The figure was constructed on logarithmic-probability paper and thus yields a straight line. It is noted that the volume fraction and the mass fraction are equivalent, and thus, the terms may be used interchangeably.

Based on the plot shown in Figure B-1, the information listed in Table B-1 was generated. This information was common to all the calculations. The information is discussed below according to the column number in the table.

Column 1

Each initial sodium mass, W_{oi} , was broken into 13 increments, W_{oij} , where $j = 1 \rightarrow 13$.

Column 2

The cumulative mass fraction that forms the abscissa of Figure B-1 was broken up as listed in column 2.

Column 3

The individual mass fractions, Δv_j , were found by subtracting the cumulative mass fractions that bracket the increment.

Column 4

The U values which, according to Figure B-1, correspond to the v values chosen were read from the figure.

Column 5

Knowing that, in general, $U = R/R_m - R$, it can be seen that

$$R = \frac{U}{1+U} R_m. \quad (B-10)$$

Figure B-1. Cumulative Mass Fraction Vs U

For a particular i group then,

$$R_{oi} = \frac{U}{1+U} R_{mi}.$$

or

$$\frac{R_{oi}}{R_{mi}} = \frac{U}{1+U}.$$

(B-11)

These values are listed in column 5.

Column 6

In order to obtain the average radius, R_{oij} , to represent the jth mass increment, an average value of the R_{oi} 's that bracket the increment was calculated:

Let R'_{oi} be the radius corresponding to the upper side of the increment and R''_{oi} the radius of the lower side. Then, R_{oij} , the linear average of the two, is given by equation B-12:

$$R_{oij} = \frac{1}{2}(R'_{oi} + R''_{oi})$$

$$R_{oij} = \frac{1}{2} \left(\frac{U'}{1+U'} + \frac{U''}{1+U''} \right) R_{mi} \quad (B-12)$$

$$\frac{R_{oij}}{R_{mi}} = \frac{1}{2} \left(\frac{U'}{1+U'} + \frac{U''}{1+U''} \right).$$

For example, $\frac{R_{oi3}}{R_{mi}} = \frac{1}{2} (0.519 + 0.459) = 0.489;$

hence, $R_{oi3} = 0.489 R_{mi}.$

Therefore, using the information in Table B-1 and knowing W_{oi} and R_{mi} for each i group, the increments W_{oij} were calculated from equation B-13:

$$W_{oij} = W_{oi} (\Delta V_j), \quad (B-13)$$

and the average particle radius for each W_{oij} was calculated using equation B-14,

$$R_{oij} = \frac{R_{oij}}{R_{mi}} R_{mi}, \quad (B-14)$$

and the numerical values for R_{oij}/R_{mi} listed in column 6 of Table B-1.

Table B-1. Particle Size Groupings

(1) j	(2) v	(3) Δv_j	(4) U	(5) $\frac{R_{oi}}{R_{mi}}$	(6) $\frac{R_{oij}}{R_{mi}}$
	0.9999		3.90	0.796	
1		0.0099			0.708
	0.9900		1.63	0.620	
2		0.04			0.570
	0.9500		1.08	0.519	
3		0.05			0.489
	0.9000		0.85	0.459	
4		0.10			0.427
	0.8000		0.65	0.394	
5		0.10			0.370
	0.7000		0.53	0.346	
6		0.10			0.328
	0.6000		0.45	0.310	
7		0.10			0.293
	0.5000		0.38	0.275	
8		0.10			0.262
	0.4000		0.33	0.248	
9		0.10			0.234
	0.3000		0.28	0.219	
10		0.10			0.203
	0.2000		0.23	0.187	
11		0.10			0.167
	0.1000		0.173	0.147	
12		0.08			0.122
	0.0200		0.108	0.097	
13		0.02			0.094
	0.0200	--	0.10	0.091	
		1.00			

It is noted that $\sum_j \Delta v_j = 1.00$

4. Nomenclature

A_h	Sodium Flow area, ft^2 .
a	Constant, dimensionless, in this study $a = 2.62$.
I	Total number of W_{oi} .
R	Particle radius, ft.
R_{mi}	Critical maximum drop radius for the i th particle group, cm.
R''_{oi}	Radius of drop corresponding to lower side of j th mass increment.
R_{oi}	Radius of drop for W_{oi} as related to R_{mi} by $R_{oi} = (U/1+U)R_{mi}$.
R'_{oi}	Radius of drop corresponding to upper side of j th mass increment.
R_{oij}	Average radius of particle for subincrement, ft.
t_i	i th time interval, seconds.
U	$R_{oi} / (R_{mi} - R_{oi})$.
U'	$R'_{oi} / (R_{mi} - R'_{oi})$.
U''	$R''_{oi} / (R_{mi} - R''_{oi})$.
u	Product of δ and y , dimensionless.
V_{oi}	Average ejection velocity for W_{oi} , fps.
v	Cumulative volume or mass fraction.
W	Mass of particle, lb.
W_{oi}	Mass of increment of sodium for t_i , lb ($i = \text{first, second, or third time increment}$).
W_{oij}	Subincrement of W_{oi} composed of R_{oij} particles, lb ($j = 1$ through 13).
W_{oT}	Total amount of sodium ejected to containment, lb.
w	Sodium flow rate, lb/s.
x	Drop diameter, ft or cm.
x_m	Maximum drop diameter, ft or cm.
y	$\ln \frac{ax}{x_m - x}$.
Δv_j	Individual mass fraction for the j th subincrement.
δ	Parameter that determines the degree of dispersion of distribution, dimensionless in this study, $\delta = 1.131$.

- ρ Sodium density, 50.8 lb/ft³.
 ρ_g Air density, g/cm³ or lb/ft³.
 σ_s Sodium surface tension, dynes.

APPENDIX C
Spray Burning

This appendix presents the equations that were solved to yield the amount of sodium burned during the in-flight time period of the collection of particles, the associated energy release, and the associated rise in the pressure and temperature of the containment building's atmosphere.

1. Amount Burned

For a single unrestrained particle moving under the influence of gravity, Newton's law of motion can be applied:

$$F = \frac{d}{dt} (mV). \quad (C-1)$$

Here F is the sum of the forces acting on the particle, and the right-hand side of the equation is the time rate of change of momentum. For this analysis, only one dimension is considered—the vertical dimension represented by the X coordinate, where $X=0$ lies on the upper surface of the cover plug.

Equation C-1 may be expanded as

$$F = m \frac{dV}{dt} + V \frac{dm}{dt}, \quad (C-2)$$

where the second term on the right is nonzero, since the particle is burning and giving up mass. V is the particle velocity and is positive or negative for particle motion up and down, respectively.

Within the framework of the model, there are only two external forces on the particle: the gravitational force and the drag force due to motion through the air. Thus, equation C-2 can be written as

$$-mg - f\rho_1 A \frac{V|V|}{2} = m \frac{dv}{dt} + V \frac{dm}{dt} \quad (C-3)$$

or

$$-g - f\rho_1 A \frac{V|V|}{2m} = \frac{dV}{dt} + \frac{V}{m} \frac{dm}{dt} \quad (C-4)$$

Using the relations

$$m = \rho_2 \frac{4}{3} \pi R^3,$$

$$\frac{dm}{dt} = 4\rho_2 \pi R^2 \frac{dR}{dt},$$

$$A = \pi R^2,$$

equation C-4 becomes

$$-g - f \frac{\rho_1}{\rho_2} \frac{3}{8} \frac{V|V|}{R} = \frac{dV}{dt} + \frac{3V}{R} \frac{dR}{dt}. \quad (C-5)$$

The drag force term was developed in the manner of Bird.* The friction factor, f , is a function of Reynolds number, Re , which in turn is a function of the particle velocity, V . Hence,

$$f = f(Re) \quad (C-6)$$

where

$$Re = \frac{2RV\rho_1}{\mu} \quad (C-7)$$

and μ = gas (air) viscosity.

The functional form of the friction factor is given in reference (*) as

$$f = \frac{24}{Re} \quad \text{for} \quad Re \leq 0.90, \quad (C-8)$$

$$f = \frac{18.5}{Re^{0.6}} \quad \text{for} \quad 0.90 < Re \leq 900, \quad (C-9)$$

$$f = 0.44 \quad \text{for} \quad 900 < Re \leq 2 \times 10^5. \quad (C-10)$$

Recognizing also that R is a function of time,

$$R = R(t). \quad (C-11)$$

* R. B. Bird, W. E. Stewart, and E. N. Lightfoot, Transport Phenomena, Chapter 6, John Wiley & Sons, Inc., New York (1966).

Equation C-5 can be rewritten as

$$-g - f(Re) \frac{\rho_1}{\rho_2} \frac{3}{8} \frac{V|V|}{R(t)} = \frac{dV}{dt} + \frac{3V}{R(t)} \frac{dR(t)}{dt}. \quad (C-12)$$

An equation for the time-dependent particle radius can be derived as follows:

We have assumed that the burning rate is directly proportional to the surface area of the particle; hence

$$\frac{dW}{dt} = -(BR)A \quad (C-13)$$

where

$$\begin{aligned} A &= \text{particle surface area,} \\ W &= \text{particle mass (lb),} \\ (BR) &= \text{burning rate constant,} \\ dW &= -(BR)Adt. \end{aligned} \quad (C-14)$$

Since

$$\begin{aligned} W &= \rho_2 \frac{4}{3} \pi R^3 \\ dW &= \rho_2 4\pi R^2 dR \\ dW &= \rho_2 AdR \end{aligned} \quad (C-15)$$

Combining equation C-14 and C-15 yields

$$-(BR)Adt = \rho_2 AdR$$

or

$$-(BR)dt = \rho_2 dR,$$

which may be integrated to yield

$$R(t) = R_o - \frac{(BR)t}{\rho_2} \quad (C-16)$$

where R_o = initial particle radius.

The weight of sodium burned, W_B , can be found as a function of time as

$$\begin{aligned}
 W_b(t) &= \rho_2 \frac{4}{3} \pi R_o^3 - \rho_2 \frac{4}{3} \pi R^3(t) \\
 W_b(t) &= W_o - \rho_2 \frac{4}{3} \pi \frac{R_o^3}{R_o^3} R^3(t) \\
 W_b(t) &= W_o - W_o \frac{1}{R_o^3} R^3(t) \\
 W_b(t) &= W_o \left[1 - \frac{1}{R_o^3} \left(R_o - \frac{BR}{\rho_2} t \right)^3 \right]
 \end{aligned} \tag{C-17}$$

where W_o = initial particle weight.

The term in brackets in equation C-17 represents the fraction of the particle that burned. Therefore, the equation holds for an assembly of N identical particles if we redefine W_o and W_b as

$$\begin{aligned}
 W_o &= \text{initial weight of the } N \text{ identical particles,} \\
 W_b(t) &= \text{weight burned from the particles.}
 \end{aligned}$$

From equation C-16 it is seen that

$$\frac{dR(t)}{dt} = - \frac{BR}{\rho_2} \tag{C-18}$$

Substitution of equation C-16 and C-18 into equation C-12 yields

$$-g - f(Re) \frac{\rho_1}{\rho_2} \frac{3}{8} \frac{V|V|}{R_o - \frac{BR}{\rho_2} t} = \frac{dV}{dt} - \frac{3(BR)V}{\rho_2 \left(R_o - \frac{BR}{\rho_2} t \right)} \tag{C-19}$$

Also,

$$V = \frac{dx}{dt} \tag{C-20}$$

Equations C-19 and C-20, along with equations C-7, -8, -9, and 10, can be solved numerically to describe the trajectory of a particle with an initial radius R_o and an initial velocity V_o . These equations, along with equation C-17, were programmed on the CDC-6600 computer using an existing code, MIMIC, which is a general-purpose program for the numerical solution of differential equations.

The input for each case consisted of the initial weight, W_{oij} , the initial velocity, V_{oij} , and the average initial radius, R_{oij} , for each particle group as defined in Appendix B. Each case terminated when the particle burned completely or impinged onto the surface of the cover structure. The amount burned at this time, W_{bij} , was summed over the J groups as

$$W_{bi} = \sum_{j=1}^J W_{bij} \quad (C-21)$$

The total amount of sodium burned as a spray for the entire incident was then calculated as

$$W_{bt} = \sum_{i=1}^I W_{bi} \quad (C-22)$$

2. Energy Release

The two principal chemical reactions that occur are shown below along with the heat of formation for each as given in the documents cited below.*

$$\Delta H' = \text{heat of formation of } Na_2O = 3900 \text{ Btu/lb} \quad (C-24)$$

$$\Delta H'' = \text{heat of formation of } Na_2O_2 = 4500 \text{ Btu/lb} \quad (C-26)$$

- - - - -
- * 1. Quarterly Technical Progress Report LMFBR Safety Programs, Jan-Mar 1969, Atoms International, AI-AEC-12816, May 1969.
2. Annual Technical Progress Report LMFBR Safety Programs, GFY 1969, Atoms International AI-AEC 12858, Nov 1969.

It is not known exactly in what proportion these reactions occur, but recent experimental data (*) have indicated that approximately 60% of the reaction goes to the peroxide according to equation (C-25) and that the remaining 40% goes to the oxide as in equation (C-23).

The heat input to the containment building's atmosphere is then calculated as

$$Q = W_{bT}(0.60 \Delta H'' + 0.40 \Delta H') - Q_L,$$

where Q_L is the latent heat of vaporization of the sodium. A value of 1300 Btu/lb was chosen for Q_L . Therefore,

$$Q(\text{Btu}) = 2960 * W_{bT}. \quad (\text{C-27})$$

3. Pressure and Temperature

The maximum temperature of the containment building's atmosphere is calculated from the equation

$$Q = m_a C_v (T_F - 80), \quad (\text{C-28})$$

where

Q = heat input, Btu,

m_a = mass of air in the building,

C_v = specific heat of the air,

T_F = max air temperature, °F,

80 = initial air temperature, °F.

The mass of air is given by

$$m_a = \rho_1 (\text{vol}),$$

where

ρ_1 = air density,

vol = free volume of the containment building.

Even though the specific heat at constant volume for air is a function of temperature, an average value was chosen for the assumed temperature range. The values used for the constants are:

$$\rho_1 = 0.0796 \text{ lb/ft}^3.$$

$$\text{vol} = 814,420 \text{ ft}^3.$$

$$C_v = 0.1275 \text{ Btu/lb-}^\circ\text{F}.$$

Inserting these values into equation (C-28) and solving for T_F yields

$$T_F (^\circ\text{F}) = 80 + \frac{Q}{11,182.8}. \quad (\text{C-29})$$

The corresponding pressure can be calculated from the equation

$$P_F = \frac{nR T_f}{\text{vol}},$$

where n = number of moles of gas,
 Rg = gas constant.

Taking no credit for the oxygen depletion due to burning, the number of moles of air is then approximately 2254. Therefore,

$$P_F = 0.0297 (T_F + 460) \text{ psia}. \quad (\text{C-30})$$

4. Nomenclature

A	Cross-sectional area of particle normal to direction of motion ($A=\pi R^2$), ft^2 .
BR	Burning rate of sodium, lb/h-ft^2 .
C_v	Specific heat of air, $0.1275 \text{ Btu/lb-}^\circ\text{F}$.
F	Force.
f	Friction factor, dimensionless.
g	Acceleration of gravity, 32.2 ft/s^2 .
J	Total number of W_{bij} groups.
m	Mass of particle, lb .

m_a	Mass of containment air, 64,828 lb.
n	Moles of air in containment (2254).
P_F	Maximum containment atmosphere temp, °F.
O	Energy released to building atmosphere, Btu.
O_L	Latent heat of vaporization, 1300 Btu/lb.
R	Particle radius, ft.
Re	Reynolds number
R_g	Gas constant, $\text{ft}^3/\text{in.}^2 \cdot ^\circ\text{R}$.
R_o	Initial particle radius, ft.
R_{oij}	Average radius of particle for subincrement, ft.
T_F	Maximum containment atmosphere temp, F.
t	Time, seconds.
V	Sodium velocity.
V_{oij}	Velocity of W_{oij} .
v	Cumulative volume or mass fraction.
vol	Containment free volume, 814,420 ft^3 .
W	Mass of particle, lb.
W_{bi}	Amount of W_{oi} that burns, lb.
W_{bij}	Amount of W_{oij} that burns, lb.
$W_b(t)$	Weight of sodium burned, lb (function of time).
W_{bT}	Total amount of sodium burned for all the i time increments, lb.
W_o	Initial particle weight, lb.
W_{oij}	Subincrement of W_{oi} composed of R_{oij} .
X	Vertical dimension in containment where $X=0$ is upper surface of cover plug, ft.
$\Delta H'$	Heat of formation of Na_2O , 3900 Btu/lb.
$\Delta H''$	Heat of formation of Na_2O_2 , 4500 Btu/lb.
μ	Viscosity of air, 1.90×10^{-4} .
ρ_1	Air density, 0.0796 lb/ ft^3 .
ρ_2	Particle density, 50 lb/ ft^3 ($\rho_2 = \frac{4}{3} \pi R^3$).

APPENDIX D
Pool Fire Sensitivity
Studies

1. Introduction

The FIRE code has been used to conduct a preliminary investigation of accidents whereby liquid sodium is released into the upper containment building of an LMFBR. The reference model is the B&W design described in the Follow-On Study reports. Sensitivity studies were made to determine the effects of variations in parameters on the consequences of such accidents. The reference values used for each of these parameters are as follows:

<u>Variable, units</u>	<u>Symbol</u>	<u>Reference Value</u>	
Sodium pool depth, ft	ZS	0.5	
Sodium pool surface, ft ²	AO	7,854	
Building's heat sink mass, lb	AM3	13,661,500	
Initial gas pressure, psia	PI	14.7	
Initial O ₂ conc., lb/ft ³	C2I	0.0168	
Burning rate/O ₂ conc., lb Na-ft/lb O ₂ -h	HC	595.2	
Heat removal system, Btu/h	Q70	0	0

In each calculation, where one parameter was varied the other parameters were assigned values corresponding to those tabulated. The selected value of AO represents the entire area of the containment building floor. The reference value assigned to AM3 was determined by an estimate, which considered the mass, surface area and volume of the fuel-transfer machine, intermediate heat exchangers, primary pumps, large-component valve box, inner steel wall liner, polar crane, and fuel-transfer gantry. The estimated values were lumped together and considered to possess the thermal characteristics of steel. The initial oxygen concentration (C2I) used is that of normal air at PI equal to 1 atmosphere and at 80 F.

Input for the FIRE code requires many parameters other than those listed above. In all cases these parameters were held constant at values that represent the best available data and follow the geometry of B&W's LMFBR containment building design.

2. Discussion and Results

The peak pressure and peak temperature of the atmosphere in the containment building during a sodium-fire accident were used as criteria for determining the severity of the accident. In a detailed analysis, however, many other consequences could be of importance, such as the temperature gradient across the containment building's wall. The following tabulations list only the maximum pressure ($P_{\max}$) and temperature ($T_{\max}$) as a function of the varied parameter.

2.1. Sodium Pool Depth (ZS)

A sensitivity analysis of the sodium pool thickness was performed. The thicknesses considered ranged from about 100,000 to 800,000 pounds of sodium over the containment building's floor. The results, tabulated below, indicate that $P_{\max}$ and $T_{\max}$ are weak functions of the pool's depth.

<u>ZS, ft</u>	<u>$P_{\max}$, psig</u>	<u>$T_{\max}$, F</u>
2.0	17.41	753
1.5	17.39	752
1.0	17.35	751
0.5	17.26	747
0.3	17.10	740

2.2. Sodium Pool Surface (AO)

The heat generation rate is a linear function of the surface area of sodium exposed to the atmosphere. The effects of varying the surface area on the maximum pressure and temperature reached during a pool fire situation are as follows:

<u>Burning area, ft²</u>	<u>P_{max}, psig</u>	<u>T_{max}, F</u>
7854	17.26	747
7000	16.32	712
6000	15.12	664
5000	13.78	610
4000	12.19	548
2734	9.71	451
2000	7.92	380
1000	4.73	255

These results show that the severity of the accident as reflected by the maximum pressures and temperatures is a sensitive function of the pool's burning area, indicating that a strong incentive exists for minimizing burning areas.

2.3. Building Heat Sink Mass (AM3)

The pressure and temperature within the containment building during a sodium-fire accident can be reduced by using materials that act as a heat sink. The containment building used as a reference model does contain miscellaneous materials and equipment. The effect of this material on the course of the fire was determined. The amount of material was also varied by +50% to determine whether the use of extra material could be of benefit. The results are as follows:

<u>AM3, lb</u>	<u>A3, ft²</u>	<u>V3, ft³</u>	<u>P_{max}, psig</u>	<u>T_{max}, F</u>
0	0	0	24.76	1040
680,750	24,150	6,527	20.16	860
1,361,500	48,305	13,054	17.26	747
2,042,250	72,450	19,581	15.19	666

The value of AM3 = 1,361,500 pounds represents an estimate of the mass of material in the containment. The other values were calculated arbitrarily, keeping the surface-to-mass ratio constant.

2.4. Initial Gas Pressure and O₂ Concentration (PI and C2I)

It has long been recognized that one significant way to reduce the severity of a sodium fire is to reduce the amount of oxygen with which it can react. Two methods of reducing the amount of oxygen in the containment building were considered: Reduce the total amount of gas in the building by operating at reduced pressure; remove quantities of air and replenish with nitrogen, hence diluting the oxygen and operating at 1 atmosphere of pressure. These methods are discussed below.

For these calculations, the initial pressure, air density, and oxygen concentration were varied consistent with each other to represent a range of initial operating pressures of from 9.0 to 14.7 psia. The results are as follows:

<u>PI, psia</u>	<u>C2I, lb O₂/ft³</u>	<u>P_{max}, psig</u>	<u>T_{max}, F</u>
14.7	0.01680	17.26	747
14.0	0.01600	15.06	733
13.0	0.01486	12.95	713
12.0	0.01371	10.46	691
11.0	0.01257	8.07	666
10.0	0.01143	5.70	642
9.0	0.01029	3.36	614

Since it may be undesirable to operate the reactor with a reduced containment building pressure, calculations were made to observe the effects of reducing the oxygen concentration by removing air and replacing it with nitrogen. The total containment volume, 814,423 ft³, was divided in each case between oxygen and nitrogen, which was then mixed together to yield an average initial oxygen concentration and gas density while maintaining an initial gas pressure of 1 atmosphere. The results are as follows:

<u>Vol of air at 1 atm, ft³</u>	<u>Vol of N₂ at 1 atm, ft³</u>	<u>C21, lb O₂/ft³</u>	<u>P_{max}, psig</u>	<u>T_{max}, F</u>
814,423	0	0.01680	17.26	747
700,000	114,423	0.01444	16.82	730
600,000	214,423	0.01238	15.42	680
500,000	314,423	0.01031	13.92	622
400,000	414,423	0.00825	12.25	557
200,000	614,423	0.00412	8.02	398

The data from these two tabulations corresponding to the two methods of oxygen reduction are plotted in Figures D-1 and D-2. The two methods cannot be compared directly from the tables since the data points do not occur at the same oxygen concentration.

2.5. Burning Rate/O₂ Concentration (HC)

The FIRE code assumes that the burning of the sodium pool is proportional to the volume-averaged oxygen concentration at any point in time. The proportionality constant, HC, is determined by observing experimental data for the burning rate of sodium in normal air. Burning rates have been reported over the range from 6 to 15 lb Na/h-ft². The current value being used is about 10 lb Na/h-ft². Because of the uncertainty that exists in choosing this value, a sensitivity analysis was performed. The results are listed below.

<u>HC</u>	<u>Burning rate, lb-Na/h-ft²</u>	<u>P_{max}, psig</u>	<u>T_{max}, F</u>
357.7	6	13.51	602
476.2	8	15.52	680
595.2	10	17.26	747
714.3	12	18.65	805
833.3	14	20.02	857
952.4	16	21.18	899

Figure D-1. Maximum Pressure Vs Initial Oxygen Concentration in Containment

Figure D-2. Maximum Temperature Vs Initial Oxygen Concentration in Containment

2.6. Heat Removal System (Q70)

It was desired to determine what influence an external heat removal system would have in mitigating the results of a sodium fire. The parameter Q70 represents the capacity of the system in Btu/h. The results of varying this parameter are shown below. All other parameters are the same as tabulated in 3.2.4, with the initial burning rate set at 10.

<u>Q70, Btu/h $\times 10^6$</u>	<u>P_{max}, psig</u>	<u>T_{max}, F</u>
0	17.26	747
2	17.17	744
5	17.05	739
10	16.83	731
20	16.38	715
50	14.92	662
75	13.65	613
100	12.94	588

It can be seen that the peak pressure and temperature reached during the accident can be reduced by using an external heat removal system, but not significantly unless very large units are used. However, the use of a heat removal system would reduce the pressure and temperature within the containment building much sooner as a function of time. For no external heat removal, the containment building's pressure returns to 1 atmosphere 3.5 hours after the start of the fire, whereas with Q70 equal to 5,000,000 Btu/h, 1 atmosphere pressure is attained after 2.4 hours.

3. General Conclusions

The sensitivity studies have pointed out at least three parameters worthy of further study in attempting to reduce the severity of sodium fires: the exposed surface area of the sodium pool, the initial operating pressure, and the initial oxygen concentration.

The initial pressure and the oxygen concentration certainly play an important role in the accidents. Drastic reductions in severity can be achieved by proper handling of these parameters. Figure D-3 shows the relative importance of each of the parameters discussed previously as functions of temperature.

Figure D-3. Containment Temperature Vs Selected Parameters

APPENDIX E
Post-Spray-Fire Conditions

1. Introduction

An analysis was performed to investigate conditions within the secondary containment building following the spray fire accident. The specific parameters investigated were the time-dependent behavior of the atmospheric pressure and temperature, and the temperature of the wall liner in the containment building.

2. Method Description

A simple model was developed in which the system initially consists of only three components: the air, the steel wall liner, and a lumped mass representing the collection of miscellaneous equipment within the containment building. A fourth component can be added at a constant rate. The time-dependent addition of a fourth component was used to represent an addition of sodium chloride to the system, which would act as a heat sink, and would help extinguish any sodium that might be on the floor of the building.

The energy released from combustion of the sodium spray was assumed to be transferred to the atmosphere instantaneously, after which heat was transferred in a time-dependent fashion from the atmosphere to the other components. The model is graphically shown in the following sketch.

The assumptions are as follows:

1. The system is adiabatic. There is no net gain or loss of energy for the system.
2. At time zero, the air contains the energy released from sodium combustion. The wall liner and other materials are initially at the normal operating temperature (≈ 80 F).
3. Heat is transferred from the air to the wall liner and to miscellaneous material by convection only. Radiative heat transfer is neglected.
4. The NaCl is added at a constant rate. The amount added during a calculation time step, Δt , is assumed to reach instantaneous temperature equilibrium with the air temperature at that time.
5. Each of the components, i.e., the wall liner, the miscellaneous material, the air, and the NaCl, is treated as a single node. Conduction within each component is characterized by its average temperature.
6. No heat transfer is allowed from the wall liner to the concrete wall.

Under the restrictions of these assumptions, it is felt that the calculation yields relevant results. The equations and numerical constants are given in this appendix.

3. Results and Discussion

The sodium fire accidents previously referred to as cases 1 and 2 were investigated. For case 1, the sodium combustion led to an instantaneous atmospheric temperature of 185 F and to a pressure of 19.16 psia. The subsequent time behavior of these quantities is shown in Figures E-1 and E-2. In the analyses of cases 1 and 2, separate calculations were made for no NaCl addition to the containment's atmosphere and for the addition of NaCl to the system. In the latter cases, NaCl was added at a rate of 100 lb/s for the first 660 seconds, making a total addition of 66,000 pounds. These results are shown in the figures.

Figure E-3 shows the behavior of the wall liner's temperature with time. For no NaCl addition, the temperature reaches a maximum of about 120 F. When NaCl was added, the peak temperature of the wall liner was reduced to about 102 F.

The case 2 results are shown in Figures E-4 through E-6. The addition of NaCl reduced the maximum temperature of the wall liner from 283 F to 197 F. In this case, the initial atmospheric temperature was 626 F and the pressure was 32.3 psia.

Figure E-1. Air Temperature Vs Time (Case 1)

Figure E-2. Building Pressure Vs Time (Case 1)

Figure E-3. Wall Liner Temperature Vs Time (Case 1)

Figure E-4. Air Temperature Vs Time (Case 2)

Figure E-5. Building Pressure Vs Time (Case 2)

Figure E-6. Wall Liner Temperature Vs Time (Case 2)

4. Calculation of Atmospheric Pressure and Temperature and Wall Liner Temperature

This section describes the equations used to calculate the building's atmospheric pressure and temperature and the wall liner's temperature as a function of time after the sodium spray burning occurred.

Each temperature is held constant for the time period TST. The amount of heat transferred is calculated for the i th time step as follows:

$$\text{DELQ1} = H1(A1)(T1 - T2)\text{TST}. \quad (\text{E-1})$$

$$\text{DELQ2} = H2(A2)(T1 - T3)\text{TST}. \quad (\text{E-2})$$

$$\text{DELQ3} = \text{rate}(\text{CP4})(T1 - 80.0)\text{TST}. \quad (\text{E-3})$$

The temperatures are then adjusted for the next time step as:

$$T1_{i+1} = T1_i - \frac{\text{DELQ1} + \text{DELQ2} + \text{DELQ3}}{\text{FM1}(\text{CP1})}. \quad (\text{E-4})$$

$$T2_{i+1} = T2_i + \frac{\text{DELQ1}}{\text{FM2}(\text{CP2})}. \quad (\text{E-5})$$

$$T3_{i+1} = T3_i + \frac{\text{DELQ2}}{\text{FM3}(\text{CP3})}. \quad (\text{E-6})$$

It is assumed that the NaCl added during a time step reaches equilibrium temperature with the air at that time step. The calculation is extended out in time using this technique until equilibrium temperatures are reached.

A small program called TEMP was written for use on the CDC-6600 computer to solve the foregoing equations. The program is listed in Table E-1.

Table E-1. Program Temp (Input, Output)

```

PROGRAM TEMP (INPUT, OUTPUT)
000003      READ 100, ICASE
000011      100 FORMAT (6E12.5)
000011      IC = 1.0
000013      104 READ 101, T1, T2, T3
000025      READ 101, H1, H2, A1, A2
000041      READ 101, TST, TMAX
000051      READ 101, FM1, FM2, FM3, CP1, CP2, CP3
000071      READ 101, RATE, CP4, FM4
000103      101 FORMAT (6E12.5)
000103      TIME = 0.
000104      SFM4 = 0.0
000105      1000 TIME = TIME+TST
000107      DELQ1 = H1*A1*(T1-T2)*TST
000113      DELQ2 = H2*A2*(T1-T3)*TST
000117      DELQ3 = RATE*CP4*(T1-80.0)*TST
000123      DELFM4 = RATE*TST
000124      SFM4 = SFM4+DELFM4
000125      IF(SFM4.GT.FM4) GO TO 1002
000131      GO TO 1003
000131      1002 SFM4 = SFM4 - DELFM4
000133      DELQ3 = 0.0
000134      1003 T1=T1-(DELQ1+DELQ2+DELQ3)/(FM1*CP1)
000143      T2=T2+DELQ1/(FM2*CP2)
000146      T3=T3+DELQ2/(FM3*CP3)
000152      IF(TIME.GT.TMAX) GO TO 1001
000156      PRINT 102
000161      102 FORMAT(1H, * TIME          GAS TEMP    WALL TEMP
1          MISC TEMP    SALT MASS*)
000161      PRINT 103, TIME, T1, T2, T3, SFM4
000177      103 FORMAT(5(E12.4,8X))
000177      GO TO 1000
000200      1001 IC = IC + 1
000202      IF(IC.GT.ICASE) GO TO 1004
000205      GO TO 104
000205      1004 STOP
000207      END

```

5. Nomenclature

A1	Heat transfer area of material 2 exposed to air, 40,530 ft ² .
A2	Heat transfer area of material 3 exposed to air, 7778 ft ² .
CP1	Specific heat of material 1, 0.1710 Btu/lb-F.
CP2	Specific heat of material 2, 0.1220 Btu/lb-F.
CP3	Specific heat of material 3, 0.1220 Btu/lb-F.
CP4	Specific heat of NaCl, Btu/lb-F.
DELFM4	NaCl added during TST seconds, lb.
DELQ1	Heat transferred from material 1 to material 2 during TST seconds, Btu.
DELQ2	Heat transferred from material 1 to material 3 during TST seconds, Btu.
DELQ3	Heat transferred from material 1 to material 4 during TST seconds, Btu.
FM1	Mass of material 1, 64,830 lb.
FM2	Mass of material 2, 109,600 lb.
FM3	Mass of material 3, 1,252,000 lb.
FM4	Total amount of NaCl available (variable), lb/s.
H1	Convection heat transfer coefficient, air to material 2, 0.00041 Btu/s-F-ft ² .
H2	Convection heat transfer coefficient, air to material 3, 0.00041 Btu/s-F-ft ² .
Q1	Heat transfer rate from material 0 to material 2, Btu/s.
Q2	Heat transfer rate from material 1 to material 3, Btu/s.
Q3	Heat transfer rate from material 1 to material 4, (NaCl), Btu/s.
rate	Rate of NaCl addition (variable), lb/s.
T1	Building air (material 1) temp, F.
T2	Wall liner (material 2) temp, F.
T3	Miscellaneous material (material 3) temp, F.
TST	Time step value used in calculations, 10 seconds.

APPENDIX F
Environmental Safety Calculations

This appendix presents the equations and numerical values used in performing the environmental calculations.

1. Dose Equations

The equation used for calculating the accumulated body burden (BB) for the isotopes is

$$BB = \frac{Q_{oi}(LF)t(X/Q)(BR)f}{(MPBB)_i} \quad (F-1)$$

where

BB = accumulated amount of isotope i in units of MPBB,

$(MPBB)_i$ = maximum permissible body burden for isotope i (or the maximum permissible burden for the organ of interest, i.e. the bones for Pu isotopes), μ ci.

This equation follows the standard form as suggested in TID-14844. The following sections investigate the numerical values used for these terms.

1.1. Source Term, Q_{oi}

In calculating these terms, it was desired to know the values of Q_{oi} that lead to the accumulation of 1 MPBB at the exclusion areas radius for the accident.

1.2. Leak Time, t

For the plutonium and sodium inhalation calculations, the 24-hour accumulated burdens were considered to be important. For the external gamma dose due to ^{24}Na , the 2-hour exposure was considered.

1.3. Leak Rate, LF

A value of 0.1% per day was used as the design leak rate. The building was assumed to leak at this rate over the entire 24-hour period even though it has been shown that the overpressure existing within the building following an accident is severely reduced within 3 hours (see Figure E-5 of Appendix E).

2. Atmospheric Dispersion

The technique used is commonly referred to as the Gifford wake model.* The ground-level, downwind concentration of released material is given by

$$X = \frac{Q}{(\pi \sigma_y \sigma_z + CA)u} \quad (F-2)$$

where σ_y^2, σ_z^2 = dispersion coefficients, m^2 . The grouping X/Q , a measure of the dispersion of the source material, has the physical interpretation of being the concentration per unit source.

The dispersion coefficients for the condition-F calculations were obtained from Gifford.** They are:

<u>Distance from source, meters</u>	<u>σ_y, meters</u>	<u>σ_z, meters</u>
600	22	9.5
1100	43	17
1609	60	20

The following numerical values were also used:

$$u = 1, \text{ m/s,}$$

$$C = 1 \text{ (recommended value),}$$

$$A = 1563 \text{ m}^2.$$

* F. A. Gifford, Jr., "Atmospheric Dispersion Calculations Using the Generalized Plume Model," Nuclear Safety, Vol. 2, No. 2 (1960).

** F. A. Gifford, Jr., "Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion," Nuclear Safety, Vol. 2 No. 4 (1961).

The X/Q values were calculated according to

$$X/Q = \frac{1}{(\pi \sigma_y \sigma_z + CA)u} \quad (F-3)$$

The results are as follows;

<u>Distance from source, m</u>	<u>Condition-F X/Q, s/m³</u>	<u>Condition-A X/Q, s/m³</u>
600	4.5×10^{-4}	1.7×10^{-5}
1100	2.5×10^{-4}	1.2×10^{-5}
1609	1.9×10^{-4}	1.0×10^{-5}

The values for condition-A, represent a typical site.

2.1. Breathing Rate

A value of 3.47×10^{-4} m³/s was used for the breathing rate as recommended in TID-14844.

2.2. (MPBB)_i

These values are listed and discussed in section 3. 2.5.2 of this report.

3. Retention Factor

A retention factor of 20% was used in these calculations although it is suspected of being too high. A 1966 article* indicates that perhaps only 2% of the inhaled plutonium is retained in the bones.

Equation E-1 was rearranged by setting BB = 1 and solving for Q_{oi}:

$$Q_{oi} = \frac{(MPBB)_i}{(LF)t(X/Q)(BR)f} \quad (F-4)$$

*"Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract," Health Physics, 12, pp 173 - 207 (1966).

Insertion of numerical values yields

$$Q_{oi} = 1.44 \times 10^7 \frac{(\text{MPBB})_i}{X/Q}. \quad (\text{F-5})$$

This equation was solved using the appropriate values of $(\text{MPBB})_i$ and X/Q ; the results (Q_o in microcuries) are given in the following tabulations:

Condition-F			
Isotope	Distance from source, m		
	600	1100	1609
^{239}Pu	1.28×10^8	2.30×10^8	3.02×10^8
^{240}Pu	1.28×10^8	2.30×10^8	3.02×10^8
^{241}Pu	2.88×10^9	5.18×10^9	6.80×10^9
^{242}Pu	1.60×10^8	2.88×10^8	3.78×10^8
^{24}Na	2.24×10^{10}	4.03×10^{10}	5.29×10^{10}

Condition-A			
Isotope	Distance from source, m		
	600	1100	1609
^{239}Pu	3.39×10^9	4.80×10^9	5.76×10^9
^{240}Pu	3.39×10^9	4.80×10^9	5.76×10^9
^{241}Pu	7.62×10^{10}	1.08×10^{11}	1.30×10^{11}
^{242}Pu	4.24×10^9	6.00×10^9	7.20×10^9
^{24}Na	5.93×10^{11}	8.40×10^{11}	1.01×10^{12}

The preceding source values were converted to units of kilograms to compare them with the core inventory for each isotopic. The results (Q_o in kilograms) are as follows:

Condition-F			
Isotope	Distance from source, m		
	600	1100	1609
²³⁹ Pu	2.09	3.75	4.92
²⁴⁰ Pu	0.56	1.01	1.33
²⁴¹ Pu	0.03	0.05	0.06
²⁴² Pu	41.44	74.59	97.90
²⁴ Na	0.0026 (grams)	0.0047 (grams)	0.0061 (grams)

Condition-A			
Isotope	Distance from source, m		
	600	1100	1609
²³⁹ Pu	55.26	78.24	93.89
²⁴⁰ Pu	14.95	21.17	25.40
²⁴¹ Pu	0.68	0.96	1.15
²⁴² Pu	1098.16	1554.00	1864.80
²⁴ Na	0.0688 (grams)	0.0974 (grams)	0.1172 (grams)

The equation used in evaluating the 2-hour gamma dose due to ²⁴Na is as follows:

$$D = 9.4 \times 10^{-4} E(X/Q)(Q_0)(LF)t \quad (F-6)$$

where D = dose, Rem.

This method of analysis assumes immersion in a semi-infinite cloud as suggested in WASH-740. For ²⁴Na, an equivalent gamma energy of 2.7 MeV/disintegration was used. This value was obtained from ICRP Publication 2, Table 5. The value of t = 2 h was used for all cases.

By substituting numerical values for t, LF, and E and letting D = 25, equation F-5 can be rewritten as

$$Q_0 (\mu\text{Ci}) = 4.255 \times 10^{11} / (X/Q) \quad (F-7)$$

The results of solving this equation for the different site and meteorological conditions are:

<u>Distance from source, m</u>	<u>Condition-F Q_o, μCi</u>	<u>Condition-A Q_o, μCi</u>
600	9.46×10^{14}	2.50×10^{16}
1100	1.70×10^{15}	3.55×10^{16}
1609	2.24×10^{15}	4.26×10^{16}

These source values of Q_o were converted from μCi of ^{24}Na to grams; the results are shown below:

<u>Distance from source, m</u>	<u>Condition-F Q_o, g</u>	<u>Condition-A Q_o, g</u>
600	109.7	2900.0
1100	197.2	4118.0
1609	259.8	4941.6

The conversion equation was

$$Q_o(\text{g}) = 1.16 \times 10^{-13} Q_o(\mu\text{Ci}). \quad (\text{F-8})$$

The equilibrium amount of ^{24}Na in the reactor's primary sodium system is no more than a few grams. Therefore, it was concluded that the gamma dose from released radioactive sodium is not severe and will not impose undue restrictions on plant siting. It should be mentioned here that there is considerable gamma activity, approximately 15×10^6 curies, associated with the primary sodium. However, since the amount of sodium is so great, the specific activity is not great, and a release of sodium in the amounts discussed herein would create no unusually severe problems relative to the external gamma doses.

4. Nomenclature

A	Cross-sectional area of containment building normal to wind direction, m^2 .
BB	Body burden, accumulated amount of isotope i in units of MPBBs.
BR	Breathing rate, m^3/s .
C	Constant related to turbulence caused by building.
D	dose, Rem.
E	γ ray energy, MeV/disintegration.
f	Body retention factor, fraction.
LF	Design leak rate of building, fraction of cont. volume/s.
(MPBB) _i	Maximum permissible BB for isotope i (or maximum permissible burden for the organ of interest, e.g., bones for Pu isotope), μCi .
Q	Source strength, Ci/s.
Q _o	Amount of ^{24}Na available for leakage, μCi .
Q _{oi}	Amount of isotope i available for leakage, μCi .
t	Exposure (or leak) time s; release time, h.
u	Mean wind speed, m/s.
X	Concentration, Ci/ m^3 .
X/Q	Dispersion parameter, s/ m^3 .
σ_y^2, σ_z^2	Dispersion coefficients, m^2 .

ARGONNE NATIONAL LABORATORY

February 19, 1971

PRO:K:029

Mr. Robert L. Shannon, Director
Division of Technical Information Extension
U.S. Atomic Energy Commission
P.O. Box 62
Oak Ridge, Tennessee 27830

Subject: 1000-MWe LMFBR Safety Studies -
Publication of Babcock & Wilcox Topical Reports

Reference: Letter, L. W. Fromm to R. L. Shannon, "1000-MWe LMFBR
Safety Studies - Publication of Contractors' Phase and
Topical Reports," October 16, 1970

Dear Mr. Shannon:

In the reference letter I advised you that we would be transmitting to you for publication a total of twelve Babcock & Wilcox Company Phase and Topical Reports, and possibly three reports from other contractors, generated under the AEC-sponsored 1000-MWe LMFBR Safety Analysis Studies program. With that letter I enclosed one B&W report (BAW-1344, which you have since published), and advised that the remainder would be transmitted to you for publication when received and patent-cleared.

I am enclosing herewith one copy of each of the eight B&W Topical Reports listed below, all of which are now patent-cleared and ready for publication. The covers for these reports should be that used for the previously-issued BAW-1344, except for the changes noted in the table below. The letters heading the columns of the table are keyed to the markings on the attached xerox copy of the cover for BAW-1344.

OK
PWR
2-25-71

"A"

"B"

"C"

BAW-1342	TOPICAL REPORT	Accident Analysis Methods
BAW-1349	TOPICAL REPORT	Candidate Secondary Containment Support Systems
BAW-1350	TOPICAL REPORT	Accident Initiating Conditions Part 1 - Flow Abnormalities
BAW-1351	TOPICAL REPORT	Candidate Emergency Decay Heat Removal Systems
BAW-1352	TOPICAL REPORT	Candidate Primary Containment Safety Features
BAW-1354	TOPICAL REPORT	Candidate Protective Features
BAW-1355	TOPICAL REPORT	Effects of Irradiation-Induced Metal Swelling on the Reference Design
BAW-1360	TOPICAL REPORT	Accident Initiating Conditions Part 2 - Reactivity Insertions

All other parts of the front covers for these reports should remain the same as the cover for BAW-1344.

Binding edge captions for the reports should read:

BAW-1342	1000-MWe LMFBR Safety Studies	B&W	Acc. Anal. Methods	USAEC
BAW-1349	1000-MWe LMFBR Safety Studies	B&W	Sec. Containment	USAEC
BAW-1350	1000-MWe LMFBR Safety Studies	B&W	Init. Cond. - 1. Flow	USAEC
BAW-1351	1000-MWe LMFBR Safety Studies	B&W	Decay Heat Removal	USAEC
BAW-1352	1000-MWe LMFBR Safety Studies	B&W	Pri Containment	USAEC
BAW-1354	1000-MWe LMFBR Safety Studies	B&W	Protective Features	USAEC
BAW-1355	1000-MWe LMFBR Safety Studies	B&W	Eff. of Metal Swelling	USAEC
BAW-1360	1000-MWe LMFBR Safety Studies	B&W	Init. Cond. - 2. Reactivity	USAEC

Mr. R. L. Shannon, Director
February 19, 1971

I note that for BAW-1344 you used a two-piece cover with staple binding, and the "binding edge caption" actually appeared on the back of the report. If this is to be the case with the reports enclosed, then the binding edge captions may be omitted. However, if any of the reports will actually have binding edges upon which printing can appear (and be visible with the reports on a library shelf), then the above captions should be used.

The distribution of all of these reports should be our "Distribution A" plus Category UC-80, Reactor Technology, as before. For your convenience I am enclosing another copy of the "Distribution A" list previously supplied to you.

In the reference letter I stated that there would be twelve B&W reports, and possibly three from other contractors. This has now been revised downward to eleven B&W reports and one report from Atomics International. The single remaining B&W report and the AI report will be transmitted to you when received and patent-cleared.

Thank you again for your excellent cooperation in publishing these reports. If there are any questions, please contact me on FTS extension 312/739-2971 or 312/739-4844.

Very truly yours,

L. W. Fromm, Manager
1000-MWe Studies
LMFBR Program Office

LWF:el
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EAW-1344

"A"

1000 MWe

L M F B R

Liquid Metal Fast Breeder Reactor

SAFETY ANALYSIS STUDIES

BABCOCK & WILCOX

Accident Analysis and Safety System Design Study

PHASE I REPORT

"B"

**Fault Trees and Malfunction
Catalog**

"C"

Prepared for ARGONNE NATIONAL LABORATORY

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DISTRIBUTION "A"

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In Reply Refer To: TDD:PWR

October 20, 1970

Files

PROCESSING OF 1000-MWe LMFBR SAFETY STUDIES

We have been asked by L. W. Fromm, Manager, 1000-MWe Studies LMFBR Program Office, ANL, to print and distribute subject reports as a logical continuation of our involvement in the Follow-on Study Program. A total of 12 reports have been generated by BAW. There may also be a single report from each of 3 contractors, AI, GE and Westinghouse. Each report will be cleared for publication before being sent to DTIE.

Distribution is to be as follows:

UC-80	- 225 copies
NTIS	- 25 extra cys.
Stock	- 50 copies
1000 MWe Dist.	- 165 copies
	<u>465</u> copies

Phillip W. Rosser

cc: Dreyer
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