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Preliminary Failure Mode Predictions for the SSMRP Reference Plant (Zion 1)

Seismic Safety Margins Research Program

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ABSTRACT

This report presents a review of safety related equipment and structures in the SSMRP reference plant. Preliminary determinations of failure modes for these components and structures were made based on a review of seismic design requirements, design calculations and engineering judgment. This review and preliminary failure mode evaluation will serve as the basis of developing generic probabilistic failure criteria (fragility curves) for all identified components.

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1. INTRODUCTION

A preliminary determination of failure modes for safety related equipment and major structures in the SSMRP reference plant was made. The preliminary predictions were made using engineering judgement as a review of seismic qualification requirements, design calculations and test results was not conducted in support of this activity.

The SSMRP fragility project will entail effort to gather seismic qualification and fragility information and will include a review of component subsystem and structural design specifications and review of design reports.

Chapter 2 of this report addresses failure modes of safety related equipment. Most equipment is treated generically although some plant unique equipment is isolated for separate consideration. Chapter 3 discusses methods to determine progressive failure of the reference plant structures and some of the failure modes that could exist in the major structures of the reference plant.

2. PRELIMINARY FAILURE MODES OF SAFETY RELATED EQUIPMENT IN THE ZION 1 & 2 NUCLEAR POWER PLANT

As a preliminary exercise in the overall fragility project of the SSMRP, a tabulation of safety related specific and generic components in the ZION 1 & 2 reference plant was made and estimates were made as to the most likely failure modes in the event of a major seismic event. Table 2-1 presents the list of specific and generic components, significant information characterizing the components and the estimated failure modes. The failure modes were determined on the basis of individual experience in the design and analysis of nuclear power plant components and a review of the performance of conventional power plant, refinery and chemical pocess plant equipment performance during major earthquakes, Refs. 1-5. A review of ZION equipment specifications and seismic qualification reports was not conducted in this preliminary failure mode determination. In the next phase of the fragility program, representative design specifications and reports will be reviewed and fragility information and test data will be gathered such that the failure modes and generic component groupings can be substantially refined. Generic equipment types were identified by reviewing Westinghouse System Summary publication, Ref. 6 and the ZION plant layout and P&I diagrams, Ref. 7.

Some important points and assumptions to be emphasized in this preliminary summary of failure modes are presented such that the informaton presented in Table 1 will not be misleading.

First, no effort was made to rank the primary failure modes of different generic components in order of criticality. In general, active electro-mechanical equipment will be more critical during a seismic event that passive mechanical equipment. Actual fragility levels for specific and generic equipment will, however, be determined in a later phase of the fragility project and at that time a criticality ranking can be constructed.

Failure modes include a condition that results in a loss of coolant or the loss of a function necessary for the safe shutdown of the reactor. Incipient failure modes that might be caused by a seismic event are not considered as it is assumed that after a major seismic event a thorough plant inspection would be performed and such incipient failures detected.

Specific and generic components include their supports to the point of interface with the building structure. Electro-mechanical or active mechanical devices such as motor operated valves, pneumatic and hydraulic operated valves and motor, turbine and diesel driven pumps include the complete assemblies normally furnished by the component suppliers. Thus, valve operators, pump motors and ancillary equipment for cooling and lubrication are included as part of the component category. External control systems, power supplies and connecting electrical cables are not included as part of the component and are considered in separate generic categories.

The governing codes and standards first listed in Table 1 are those in existance at the time of the ZION design that generally were applied to components of that vintage. Those listed second are current codes and standards. Frequently, for more critical mechanical components the older codes and standards were supplemented with design philosophy from ASME Section III, which, at the time, only covered nuclear vessels. Since a review of the ZION component design specifications has not, as yet, been conducted, it is not known when supplemental criteria may have been applied. Most of the equipment was qualified for seismic service in about the 1969 to 1970 period. This was a period where piping, pumps and valves were not covered specifically by ASME but codes were being drafted. Also, IEEE did not, at that time, have standards for seismic testing of Class 1E electrical equipment. Other areas not covered were core support structures and component supports which are now addressed by Section III of the ASME Code. Hence, much of the seismic design and qualification criteria were not specifically addressed by the non-nuclear codes and standards applied to ZION. Consequently, the NSSS and A/E frequently supplemented the non-nuclear criteria with more specific seismic design and qualification criteria.

The failure mode and susceptibility of a structural element to seismic loading is a strong function of the ductility of the element and the portion of the allowable stress or load used up by normal loading as opposed to seimsic loading. The factor of safety against seismic failure in any design can be expressed as:

$$F.S. = \frac{\frac{Su}{Sd} - \frac{Sn}{Sd}}{\frac{Sa}{Sd} - \frac{Sn}{Sd}} \qquad \text{where:}$$

Su is the ultimate strength capacity, Sd is the allowable design stress level, capacity, Sa is the applied stress or load including seismic and Sn is the non-seismic (normal) part of the stress or load. Thus, it can be seen that as the normal portion of the stress, Sn, increases toward the allowable stress, Sd, the seismic factor of safety increases. This is due to the fact that, if the normal stress comprises most of the design allowable stress, the seismic contribution to the total stress must, by definition, be small and seismic events significantly greater than the safe shutdown earthquake can be accommodated without exceeding the ultimate capacity. Consequently, if structural elements are stressed to the design limit (Sa = Sd), those with no significant normal load (Sn = 0) are the most vulnerable to seismic overload conditions. Thus, seismic supports might be more critical in general than high pressure components if they are designed to their allowable stress limit.

Following is a discussion of each of the categories and failure modes of equipment contained in Table 2-1.

2.1 REACTOR CORE ASSEMBLY INCLUDING THE CORE SUPPORT STRUCTURE, FUEL ASSEMBLIES AND CONTROL ROD ASSEMBLIES

The most sensitive part of the ZION reactor vessel internals during a seismic event are the spring clip grid spacer assemblies. These devices maintain fuel rod spacing and support the long slender fuel rods laterally. Crushing of the grid assemblies during a seismic event could result in local restricted flow through the core and misalignment between the control rod guide tubes and the control rods. A second failure mode might be bending of the control rod assemblies above the reactor vessel top head such that rod insertion could be prevented. There is a support frame to provide lateral support of the control rod assemblies, thus, deformation of the support frame or the control rod assemblies might both result in binding of the control rods with a failure of the rods to drop on command.

A third failure mode of much less likelihood of occurrance would be failure of mechanical fasteners in the core support structure at points where fatigue cracks might have been initiated by flow induced vibration and thermal stress. Such failures may or may not be a serious hindrance to safe shutdown.

2.2 REACTOR COOLANT SYSTEM VESSELS

This category includes the reactor pressure vessel, steam generators and the pressurizer. The vessels are of heavy wall construction to contain the high pressure in the primary system. Seismic loading on the vessels themselves is generally not a governing loading condition since a good portion of the primary stress limits are used up by pressure loading. The most likely failure mode is considered to be failure of one of the nozzle to pipe weld joints. This failure mode could occur in the presence of a large flaw in the weld joint and would result in a LOCA.

The next most likely and most devastating failure mode during an extreme seismic event would be failure of the vessel supports. The reactor vessel supports are designed such that failure would allow some excess motion which might induce secondary failures but the vessel itself cannot become completely dislodged with gross failure of the concrete support structure. Steam generator and pressurizer support failures could be more significant especially the steam generator supports, as a gross failure of the steam generator supports could cause a LOCA in both the primary and secondary system.

A third failure mode to consider would be fracture of an integrally reinforced nozzle in the presence of large flaws produced by fatigue. The forged nozzles are considered much less likely to fail in a seismic event than the pipe to nozzle weld joint. A primary coolant system vessel failure is considered a much less likely event than failure in more complex components. Note, that steam generator tube failure is not considered a failure mode as no external loss of coolant results and only partial loss of function could result.

2.3 PRIMARY COOLANT SYSTEM PIPING

The primary coolant system piping is characterized by its severe loading from high pressure, thermal expansion and thermal transients. Construction details of the primary coolant system piping are much more stringent than for some of the other piping systems that may only experience intermittant service. Branch connections in the primary coolant piping system are usually of the forged, integrally reinforced type and are not the potential problem of fabricated branches used in some earlier piping systems of lesser importance.

The most likely failure mode is considered to be failure of the support system which could result in subsequent failure of the piping pressure boundary due to an overload condition. Support system failure could be failure of a snubber to perform its intended function or failure of a support at a mechanical joint. The next most likely failure mode would be failure of a butt weld joint in the presence of a large undetected flaw which might be caused by fatigue and/or stress corrosion. The third and most unlikely failure mode would be the collapse of an elbow with a resulting through wall failure. Elbows and forged branch connections are very ductile and gross deformation would be necessary for a failure to occur that would result in loss of coolant containment.

2.4 LARGE DIAMETER PIPING GREATER THAN 8" IN DIAMETER

The ZION plant seismic design criteria were apparantly different for piping 8 inches in diameter and greater than for smaller piping. The criteria have not been reviewed as yet, and, as such, the detailed differences are not specifically known. It was common in the ZION design era to perform dynamic analysis for large diameter critical piping and design the smaller piping by static coefficient methods. We might then expect a difference in actual design factor of safety but this in itself would not alter the failure modes. Construction details of the larger, more critical, piping were, however, also more stringent and as such we would expect the construction details to be comparable to the primary coolant system piping and the failure modes the same. Further review of the design criteria and construction details may alter these assumptions.

2.5 INTERMEDIATE DIAMETER PIPING, 2-1/2" TO 8" INCH DIAMETER

A separate category is devised for piping between 2-1/2 and 8 inches in diameter due to the anticipated construction details that may exist in these systems. Since many of the smaller diameter systems frequently have fabricated branch connections as opposed to integrally reinforced forged branch connections, the primary failure mode is considered to be in these areas. Fabricated branch connections are often highly loaded and are not particularly ductile compared to other piping components. Component supports would run a close second to fabricated branch connections due to practice of that era to often times weld pipe supports directly to the pipe. This was frequently done on elbows. These types of joints are not very ductile and a support failure at a support/pipe interface could initiate pressure boundary failure of the pipe.

2.6 SMALL DIAMETER PIPING, 2" IN DIAMETER AND LESS

The design codes for piping allow the use of socket welds for piping 2 inches in diameter and less. Socket welds possess very little ductility and are considered the most vulnerable type of piping joint in the event of a severe seismic event. The order of failure modes for piping 2 inches in diameter and less is tnen considered to be socket welds followed by fabricated branch connections and component supports that are welded to the piping systems.

2.7 LARGE VERTICAL STORAGE VESSELS WITH FORMED HEADS

These vessels are typically low pressure, thin wall construction supported by skirts. They may have non-integrally reinforced nozzles or non-reinforced fabricated nozzles. Temperatures are usually quite low and loading on the tank supports and nozzles is predominantly from seismic events. The most critical failure mode is assumed to be tank support failure either due to buckling or anchor bolt failure. Such failure could result in sufficient tank movement to fail the pressure boundary at tank nozzles or at the support to tank interface. The second most likely failure mode would be the failure of a non-integral reinforced or non-reinforced nozzle at the tank to nozzle interface. The third and much less likely failure mode would be at a pipe to nozzle butt weld joint.

2.8 LARGE VERTICAL FLAT BOTTOM STORAGE TANKS

Large diameter vertical flat bottom storage tanks used in the non-nuclear industry have been observed to be a problem in major earthquakes. The problem arises from use of design criteria that does not adequately account for the amplified response of part of the water mass due to tank wall flexibility. The Housner approach, as recommended in TID-7024, Ref. 8, and accepted by the USNRC Standard Review Plan, Ref. 9, does not account for tank wall flexibility in determining the response of large water filled tanks. Consequently, the response is typically underestimated. As a result, non-nuclear oil and water storage tanks designed to this criterion have experienced significant damage during major earthquakes.

Flat bottom storage tanks in the nuclear industry are typically anchored to the foundation. The most predominant failure mode in such tanks would be failure of the anchor bolts which would allow uplift of the tank. The uplift would then result in buckling of the tank wall on the compression side and possible rupture of the tank wall to tank bottom joint on the tensile side.

The next most likely failure mode would be roof damage due to sloshing of the fluid. This is not considered a safety problem, however, since the coolant is still retained. The third and less likely failure mode would be nozzle failure at pipe penetrations.

2.9 LARGE HORIZONTAL VESSELS

These vessels are similar in construction to vertical vessels except for the tank support design. The order of failure modes is the same as for vertical tanks with formed heads, however, the mechanism of a support failure could be quite different. The critical stresses due to a seismic event are usually at the support to tank interface. The failure mode depends much on the details of the interface and could be a cracking of the tank wall due to excessive local deformation or could be at a nozzle induced by tank movement due to support bolt failure.

2.10 REFUELING WATER STORAGE TANKS (RWST)

The ZION RWSTs are steel lined concrete structures that are approximately triangular in shape. They resemble building structures more than vessels. The critical locations in the tanks are considered to be at the bottom to side intersection, and side to side intersection. A third critical area might be the nozzle to tank detail. Drawings of the tank construction were not reviewed and a review of the drawings, design specification and design report could significantly improve the assumed failure mode determination. It is highly improbable that the tanks would fail catastrophically. The more likely failure mode would be a leak due to gross degradation of the concrete structure under vibratory seismic motion and a resulting cracking of the steel liner at a sharp corner.

2.11 SMALL TO MEDIUM VESSELS AND HEAT EXCHANGERS

There are numerous small to medium vessels and heat exchangers in the reactor system. They are typically cylindrical in shape, although spherical vessels are occasionally used. Cylindrical vessels may be mounted horizontal or vertical. Supports are typically legs or saddles welded directly to the pressure boundary and bolted to the floor of a building. The least ductile and most likely points for failure to occur are in the supports at either the support/tank interface or support/building interface. The next most likely failure point is at a non-integral reinforced or non-reinforced nozzle followed by the buttweld joint at a nozzle to the connecting piping.

2.12 BURIED PIPE

The service water pipe exits the crib house below grade and runs to the auxiliary building. Buried pipe is typically and conservatively assumed to have the same strain as the surrounding soil. Straight pipe sections are generally not critical unless there are large soil strains or actual faults across the pipe run. Branch connections in a buried pipeline can, however, be critical due to the high concentration of loading on the branch as the soil strains and bears against the pipe. Failure of a branch connection would be the most likely failure mode. Another possible failure mode would be at the pipe to equipment interface. Relative motion between the soil surrounding the pipe and the building housing the equipment could result in inexcessive deformation being concentrated at a pipe anchor point such as a termination point at a pump or vessel. Another possible failure point would be at a buttweld joint at the small end of a reducer. This is another point of strain concentration in buried pipe.

2.13 MAIN COOLANT PUMPS

Pumps themselves are quite rugged and have performed well in non-nuclear applications in major earthquakes, Ref. 1-5. The main coolant pumps have ancillary equipment for lubricating and cooling bearings and seals. Due to the complexity of this ancilliary equipment it is considered the most likely part of the pump to fail first. Such a failure would require the shutdown of the affected pump. Failure of pump supports is considered to be the next most critical failure mode. Support elements, though rugged, possess limited ductility at complex joints and are considered more vulnerable than the pump pressure boundary. This is the only really critical failure mode listed as it is the only one that could result in a LOCA. The third failure mode is considered to be distortion induced vibration. A seismic event greater than that for which the pump was designed could produce inelastic response of critical elements of the motor-pump structure, causing misalignment which could, in turn, result in vibration and ultimate bearing failure.

2.14 LARGE VERTICAL CENTRIFUGAL PUMPS WITH ELECTRIC MOTOR AND DIESEL DRIVES

These types of pumps are found in the Crib House and are used as service water pumps and fire pumps. They typically are supported at a flange at the motor-pump interface and have lengths several times the pump diameter such that they respond to seismic excitation as a flexible cantilever beam. They are generally quite flexible and as such, the most common failure mode is considered to be distortion induced vibration which could ultimately result in bearing failure and seizure. The drive motors are considered to be the next most likely failure mode. Diesel drive motors used on fire pumps are not, in themselves, particularly sensitive to seismic excitation but the ancilliary equipment for the diesels may be susceptible due to its complexity. Electric motor drives are fairly rugged and failure of a motor would most likely be due to vibration caused by permanent deformation and misalignment in the motor-pump assembly during a seismic event. A third and less likely failure mode would be the failure of a pump nozzle/pipe joint.

2.15 HORIZONTAL MOTOR, TURBINE AND DIESEL DRIVEN PUMPS AND COMPRESSORS OF ALL SIZES

Pumps and compressors have an excellent history of operation during major earthquakes, thus, data on failure is essentially non-existant. The horizontal pump-motor combinations are floor mounted, compact and quite rigid assemblies. Consequently, distortion induced vibration would not be expected to be a principal failure mode. The more likely failure mode would be support failure due to a combination of inertia loading and pipe reaction loading. Support failure or partial failure could then cause misalignment between the pump and motor drive resulting in vibration and a required shutdown. A less likely failure mode would be a structural failure of a pump nozzle/pipe interface.

2.16 LARGE MOTOR OPERATED VALVES

Large motor operated isolation and control valves are characterized by their very rugged body with an extended yoke structure that supports a motor-gearbox operator assembly. The valves are line mounted and can undergo significant seismic acceleration and displacement such that the motor operator and its connecting electrical leads can experience quite high seismic excitation. It is anticipated that the principal mode of failure would be binding due to permanent deformation of the yoke-neck-stem assemblies resulting in full or partial failure to actuate. The next most likely failure mode would be an electrical failure of the operator assembly. The operator motor may, itself, fail due to a combination of service degradation of insulation and seismic induced vibration or the electrical cable to operator interface may be a failure point. A third and much less likely failure mode would be fracture of the pipe to valve nozzle joint. Valve bodies, by code requirements, are designed to be much stronger than the connecting pipe and are not a failure mode of concern.

2.17 LARGE RELIEF AND CHECK VALVES

These types of valves are compact, rugged assemblies that should not be as susceptible to seismic loading as the extended motor operator type of valve. The most predominant, but unlikely, failure mode would be an electrical failure of the power actuator if an electrical powered actuator is incorporated. Degradation of insulation coupled with severe seismic excitation could cause a breakdown in electrical continuity.

Binding of check or relief valve mechanical parts could occur during a severe seismic event but, due to the compactness of the designs, the mechanical parts are relatively immune to seismic inertial force damage. Pipe to valve nozzle joint fracture is a lower probability failure mode and would only occur in the presence of large undetected flaws.

2.18 MISCELLANEOUS VALVES LESS THAN 8 INCHES IN DIAMETER

The size break of eight inches is chosen to coincide with the piping size break, however, the most significant difference between large and small valves would be to consider the fact that, for very small motor operated valves, the extended operator problem is much more severe than for larger valves. Small motor operated valves are considered to be the most vulnerable of all valves with the predominent failure mode being binding due to deformation of the yoke-neck-stem assemblies between the valve body and operator. The next and much less likely failure mode would be electrical breakdown of a motor operator. A third failure mode would be failure of pneumatic or hydraulic operators at the pneumatic/hydraulic power line/operator interface.

2.19 LARGE COOLING FANS, MOTOR-GENERATORS AND ELECTRIC MOTORS

Large capacity horizontal and vertical electric drive motors used for cooling fans and equipment drives and motor-generator sets are characterized as rigid, compact rotating electrical machinery. The most likely failure mode during a severe seismic event would be distortion in the motor casing or shaft to the extent that resulting vibration from misalignment would ultimately damage the bearings or windings, necessitating a shutdown. A secondary failure mode is considered to be the motor supports at the motor/structure interface. Support damage or failure would result in misalignment with the driven component and severe vibration and bearing damage. A third mode of failure would be bearing failure and immediate seizure. Immediate bearing seizure is a much less probable event though than slower bearing deterioration caused by distortion and misalignment.

2.20 EMERGENCY AC POWER UNITS (DIESEL GENERATORS)

Diesel generator units are complex systems that could have many failure modes. The diesel engines and alternators are of rugged construction and are not considered to be very susceptible to seismic damage. The most probable failure mode in the event of a severe earthquake would be failure of some of the ancillary equipment necessary for the diesel generator to operate. Items such as air supply, fuel and oil lines, filter brackets, starter motor, local controls and instrumentation would be the predominant candidates for failure. Secondly, the fuel supply day tank component supports might be a source of seismic induced failure. The third and much more unlikely mode of failure would be ultimate failure of the alternator caused by vibration which was in turn caused by severe distortion induced misalignment.

2.21 DC POWER (BATTERIES AND STATIC CHARGES)

The batteries and chargers are compact units that in themselves are quite rugged. Batteries have proven very reliable when subjected to severe shock loading during underground nuclear tests at the Nevada Test Site. Batteries are mounted in steel framed racks which are fastened to the floor of the surrounding building. The most likely initial failure point would be the rack to building interface since this is the least ductile part of the rack structure. Resulting uplift or shifting could sever the electrical connections. The next mode of failure to be considered is failure of the electrical connections due to excessive motion of the racks. With properly designed electrical connectors and sufficient slack in the leads to accommodate motion, this failure mode should not occur. A third possibility of failure is the structural failure of components of the batteries and chargers themselves.

2.22 SWITCH GEAR

Switchgear that handles emergency AC power are complex electrical assemblies that possess many failure modes. The electrical components are housed in structural cabinets which are bolted to the building floor. The first mode of failure is considered to be equipment supports, either at the switchgear to building interface or the switchgear transformer supports. The second mode of failure is considered to be the transformers themselves. This is considered a possibility since long term usage may degrade the transformer insulation to a point that severe vibratory motion in a seismic event could cause a failure in the insulated windings. The third failure mode would likely be a failure to function for active electrical components of the switchgear, i.e., relays and breakers.

2.23 MISCELLANEOUS MOTOR CONTROL CENTERS, INSTRUMENT RACKS, H&V&AC CONTROLS, AUXILIARY RELAY CABINETS, BREAKER PANELS AND LOCAL INSTRUMENTS

This category of electrical instrumentation and control equipment is characterized as light weight active and passive electrical equipment mounted in panels and racks. Due to the large number of individual items within a rack or panel the most likely failure mode would be failure to function of an electrical control device or instrument. Actual individual comnponent fragility varies considerably from item to item and by manufacturer such that the specific functional failure cannot readily be predicted. A second failure mode would be a structural failure of the supporting rack or panel itself. The failure could be at the hold down bolts at the interface of the rack and building structure or could be local wherein a critical instrument or control device would not be properly supported. A third failure mode could be the electrical leads at the interface point with the racks.

2.24 INVERTORS

Invertors are passive electrical devices that convert 125V AC power to DC. They should be fairly rugged units and not particularly sensitive to seismic loading. The first failure mode is considered to be a structural failure of internal supports with the second failure mode being a failure of external supports at the invertor-building interface. The third failure mode is considered to be failure of the electrical connections in or out of the invertors.

2.25 CABLE TRAYS

Cable trays are usually supported for seismic loading via struts and threaded rods. Cable trays are generally conservatively designed as the seismic analysis performed usually does not account for the large degree of damping offered by the cable bundles. Large amounts of deformation should be able to be accommodated without serious consequences to function.

The first mode of failure is considered to be a structural failure of a tray support at a threaded connection (typically threaded rods are used as supports). A second and less likely mode of failure would be in the miscellaneous steel (unistruts) which serves as an interface between the building structure and the cable tray supports. A third mode of failure is considered to be cable damage at termination points due to excessive motion of the cable trays relative to electrical equipment or junction boxes.

2.26 DUCTING

Ducting for critical cooling air, exhaust, etc., is considered to possess much lower susceptibility to seismic damage than other more massive passive structural elements. Ducting is light in weight and inertial loading from a seismic event is consequently small. Relative motion between the ducting supports and the equipment with which the ducting interfaces could cause joint leakage. Such leakage might be introduced due to buckling of the thin wall ducts or pulling apart of the joints. The second failure mode to be postulated is local support failure due to excessive motion of the building structure. A third failure mode would be total severence of a ducting joint. This would require considerable motion of the ducting system.

TABLE 2-1

GENERIC COMPONENT FAILURE MODES

GENERIC COMPONENT OR SUBSYSTEM	LOCATION IN PLANT	FUNCTION	GOVERNING CODE OR STANDARD	SEISMIC QUALIFICATION METHOD	SIZE/SHAPE OF EQUIPMENT	PRIMARY FAILURE MODE	SECONDARY FAILURE MODE	TERTIARY FAILURE MODE
Reactor core assembly including core supports, fuel and control rod assemblies.	Containment building.	Heat power source	NSSS Criteria ASME Sec. III for support, NSSS criteria for fuel & control rods.	Analysis plus test of fuel assemblies.	Cylindrical assembly of fuel rods & control rods surrounded by core support structure.	Crushing of fuel pin grid spacers.	Binding of control rod drives.	Core support structure fasteners.
Reactor coolant system vessels (RPV, SG and pressurizer).	Containment building.	Containment of coolant.	ASME Sec. III.	Analysis.	Large, vertical, cylindrical, heavy wall.	Nozzle/pipe weld in presence of flaw.	Vessel supports.	Nozzle with flaws.
Primary coolant system piping.	Containment.	Coolant boundary.	ANSI B31.1 ASME Sec. III.	Analysis.	Continuous 3D beam.	Component supports.	Butt welds in presence of flaws.	Elbow collapse.
Large diameter piping, 8" and greater.	Containment, auxillary and turbine bldg.	Coolant boundary.	ANSI B31.1 ASME Sec. III.	Analysis.	Continuous 3D beam.	Component supports.	Butt welds in presence of flaws.	Elbow collapse.
Intermediate diameter piping 2½" - 8".	Containment and auxillary building.	Coolant boundary.	ANSI B31.1 ASME Sec. III.	Analysis.	Continuous 3D beam.	Fabricated branch connections.	Component supports (welded to piping).	Butt welds in presence of flaws.
Small diameter piping, 2" and less.	Containment and auxillary building.	Coolant boundary.	ANSI B31.1 ASME Sec. III.	Analysis.	Continuous 3D beam.	Socket welds.	Fabricated branch connections.	Component supports (welded to piping).

TABLE 2-1

GENERIC COMPONENT FAILURE MODES (continued)

GENERIC COMPONENT OR SUBSYSTEM	LOCATION IN PLANT	FUNCTION	GOVERNING CODE OR STANDARD	SEISMIC QUALIFICATION METHOD	SIZE/SHAPE OF EQUIPMENT	PRIMARY FAILURE MODE	SECONDARY FAILURE MODE	TERTIARY FAILURE MODE
DC power (batteries and static chargers).	Auxillary building.	Emergency DC power source.	None IEEE 323 & 344.	Test.	Rack-mounted units.	Rack/building interface.	Electrical connection.	Battery or charger failure.
Switch gear.	Auxillary building.	Emergency AC power control to ESF systems.	None IEEE 323 & 344.	Analysis and test.	Transformers, relays, breakers, etc., mounted in racks or consoles.	Equipment supports.	Transformers.	Miscellaneous electrical equipment failure.
Miscellaneous motor control centers, instrument racks, H & V and AC controls, aux. relay cabinets, breaker panels, local instruments.	All buildings except crib house.	Elect. control and instrumentation for ESF systems.	None IEEE 323 & 344.	Analysis and test.	Primarily rack mounted electrical equipment.	Failure of electrical function.	Rack failure (local or at rack/building interface).	Electrical connections.
Invertors.	Auxillary building.	AC-DC power conversion.	None IEEE 323 & 344.	Test.	Compact, rigid.	Internal supports.	External support.	Electrical connections.
Cable trays.	All buildings.	Support of power and instrument cables.	AISC AISC	Analysis.	Beam-like structures.	Local supports.	Miscellaneous steel.	Cable damage due to excessive motion.
Ducting.	Containment, auxillary and turbine bldgs.	Channel vital ventilation and cooling air.	AISC AISC	Analysis.	Beam-like structures with thin walls.	Joint leakage.	Support failure.	Joint severance.

TABLE 2-1

GENERIC COMPONENT FAILURE MODES (continued)

GENERIC COMPONENT OR SUBSYSTEM	LOCATION IN PLANT	FUNCTION	GOVERNING CODE OR STANDARD	SEISMIC QUALIFICATION METHOD	SIZE/SHAPL OF EQUIPMENT	PRIMARY FAILURE MODE	SECONDARY FAILURE MODE	TERTIARY FAILURE MODE
Vertical diesel driven centrifugal pumps.	Crib house.	Fire pump.	ASME Sec. VIII ASME Sec. III	Analysis.	Vertical, cylindrical, slender.	Distortion induced vibration.	Diesel ancillary equipment.	Nozzle/pipe joint.
Horizontal motor, turbine & diesel driven pumps & compressors, all sizes.	All buildings.	Pump coolant & compressed air.	ASME Sec. VIII ASME Sections III & VIII.	Analysis.	Compact, heavy.	Supports.	Distortion induced vibrations.	Nozzle/pipe joint.
Large motor-operated valves.	Containment, auxillary and turbine bldgs.	Flow isolation and control	USAS B16.9 ASME Sec. III	Analysis.	Rigid body with extended operator.	Binding from yoke/stem deformation.	Operator failure.	Pipe/valve nozzle.
Large relief and check valves >8".	Containment, auxillary and turbine bldgs.	Flow isolation & overpressure protection.	USAS B16.9 ASME Sec. III	Analysis.	Rigid body with or without operator.	Operator failure if power actuated.	Binding due to permanent deformation.	Pipe/valve nozzle.
Miscellaneous small valves, <8".	Containment, auxillary and turbine bldgs.	Flow isolation, control & overpressure, protection.	USAS B16.9 ASME Sec. III	Analysis and test.	Rigid body with various operators.	Binding of MOV.	Operator failure, MOV most critical.	Pneumatic and hydraulic control system failures.
Large cooling fans, motor generators & electric motors.	Containment, auxillary and turbine bldgs.	Rotary power drive, DC power generation.	None IEEE 323 & 344.	Test and analysis.	Compact and rigid.	Distortion and vibration with eventual winding damage.	Supports.	Bearing seizure.
Emergency AC power units (diesel generators.	Auxillary building.	Generate AC power	None IEEE 323 & 344	Test and analysis.	Skid-mounted assembly of rigid & flexible components.	Ancillary equip. (brackets, fuel lines elect. connec., etc.)	Day tank component supports.	Distortion, misalignment, vibration & ultimate alternator failure.

TABLE 2-1

GENERIC COMPONENT FAILURE MODES (continued)

GENERIC COMPONENT OR SUBSYSTEM	LOCATION IN PLANT	FUNCTION	GOVERNING CODE OR STANDARD	SEISMIC QUALIFICATION METHOD	SIZE/SHAPE OF EQUIPMENT	PRIMARY FAILURE MODE	SECONDARY FAILURE MODE	TERTIARY FAILURE MODE
Large vertical storage vessels with formed heads.	Containment and auxiliary building.	Coolant pressure boundary.	ASME Sec. VIII ASME Sec. III.	Analysis.	Vertical, cylindrical, thin wall.	Tank supports.	Nonintegral reinforced or nonreinforced nozzles.	Pipe/nozzle joint.
Large vertical flat bottom storage tanks.	Outdoors by turbine building.	Water storage.	ASME, Sec. VIII ASME Sec. III.	Analysis.	Cylindrical, flat bottom, thin wall.	Hold down bolt failure induces tank wall failure.	Roof damage.	Nozzle failure at nonintegral or nonreinforced nozzle.
Large horizontal vessels.	Auxiliary building.	Coolant pressure boundary, Diesel Oil storage.	ASME Sec. VIII ASME Sec. III.	Analysis.	Horizontal, cylindrical, thin wall, low pressure.	Tank supports.	Nonintegral reinforced or nonreinforced nozzles.	Pipe/nozzle joint.
Refueling water storage tanks.	Between auxiliary and containment bldgs.	Coolant storage.	ACI-318 ACI-349-76	Analysis.	Triangular shaped, concrete wall, steel lined.	Bottom-side wall intersection.	Intersection of sides.	Nozzles.
Small-medium vessels and heat exchangers.	Auxiliary building.	Coolant pressure boundary	ASME Sec. VIII ASME Sec. III.	Analysis.	Horizontal and vertical cylindrical.	Tank supports.	Nonintegral reinforced or nonreinforced nozzles.	Pipe/nozzle joint.
Buried pipe.	Crib house to turbine and auxiliary bldg.	Pressure boundary.	ANSI B31.1 ASME Sec. III.	Analysis.	3D beam-like structure.	Pipe branch connections.	Pipe/equipment interface.	Pipe butt welds at reducer.
Main coolant pumps.	Containment building.	Primary coolant pump.	ASME Sec. VIII ASME Sec. III.	Analysis.	Vertical, cylindrical, slender.	Cooling or lubrication system.	Pump supports.	Distortion induced vibration.
Large vertical centrifugal pumps with motor drive.	Crib house.	Service water & fire pumps.	ASME Sec. VIII ASME Sec. III	Analysis.	Vertical, cylindrical, slender.	Distortion induced vibration.	Drive motor.	Nozzle/pipe joint.

3.0 PRELIMINARY STRUCTURAL FAILURE MODES FOR THE ZION 1 & 2 NUCLEAR POWER PLANT

INTRODUCTION

The determination of the modes of collapse and ultimate seismic capacity of a nuclear power plant is a complex undertaking involving a number of steps and detailed calculations. This effort has not as yet been completed for the ZION Nuclear Generating Station. The following discussion is, therefore, the result of a preliminary evaluation of the structures which attempts to outline some potential failure modes and areas of concern together with a brief discussion of possible methods of analysis.

The structural degradation and ultimate collapse of a building may occur as a result of collapse of the entire system due to a controlling element or detail failure. More often, it results as a sequential failure of several structural elements or details. This in turn may result from increased loads imposed on an element as the result of failure of other redundant load carrying elements in the structure, or from increasing response due to amplification as the duration of the earthquake increases, or simply from low-cycle fatique due to several cycles at essentially constant amplitude. Finally, the collapse of the structure may be virtually complete or may occur in phases, particularly when different methods of construction or design criteria are used in a single building.

One of the more fruitful approaches to determining the fragility levels of a structure is to evaluate the response and concurrent damage of a structure as a result of increasing levels of seismic excitation. This involves first of all an evaluation of the structural load paths for all modes of response together with the yield and ultimate strengths of the structural members and connections. Care must be taken to assure the connection details are adequate to develop the full element strength or introduce reduced levels of ductility as the result of nonductile failure modes. Several approaches concerning the strengths of the elements are possible. If a lower bound of fragility levels is desired lower bounds of material strength, element geometry, etc., can be used. In order to obtain more realistic analytical results, it is usually desirable to base fragility calculations on median values of strength with upper and lower bounds considered to define the range of damage acceleration levels.

3.1 ANALYTICAL APPROACHES

Several analytical approaches are available to determine structural response and fragility levels of structures. Almost inevitably they involve consideration of the nonlinear response inherent in the structure at close to collapse loads. For very simple structures rigorous analysis based on time history techniques together with detailed load deformation characteristics can be utilized. They require extensive prior evaluation of all the individual nonlinear elements and computer programs capable of following various load curves as the overall structure response dictates. For instance, Figure 3-1 shows the load-deformation curve for a simple diagonal brace of a braced frame system (assuming adequate connection strength exists). In order to adequately represent the load reversals occurring during a seismic event the computer must be able to define the load path from any state of stress and of course, the load deformation curves must be developed for each element. Figure 3-2 shows a typical load deflection plot for a reinforced concrete shear wall. Again, the complexity of determining the possible load path as the result of a series of load reversals at varying loads in a manner the computer can utilize is not a trivial task. In addition, it must be recognized that use of this type of analysis requires that a number of time histories at various acceleration levels must be used since the acceleration at which failure is expected is not known before hand.

For structures where only a relatively few nonlinearities can be identified at response levels of interest, techniques exist based on utilizing the linear characteristics (normal modes) of the system together with a nonlinear force correction method. In this method the structural nonlinearities are treated as a pseudo load in combination with the forcing function. It allows the treatment of complex systems by a relatively few degrees of freedom and is computationally economical. Such methods are an excellent choice where the number of nonlinearities are relatively few and they can be identified early in the analysis and described in a tractable load-deformation relationship.

Somewhat simpler methods involving incremental increases in input are readily available. Such analyses typically involve use of a linear model to determine levels where yielding and possibly even failure of a few elements occurs. For higher ground motion inputs, ductility modified response spectra or reserve energy methods can be used along with suitably modified structural models. Care must be taken in these techniques to assure the level of ductility is valid, that diaphragm and other connection strength details are accurately determined, and that p-Δ effects are included when assessing collapse capacities. Also care must be taken throughout the analysis to incorporate changes in soil characteristics as a function of input acceleration level and keep in mind any threshold levels of phenomena such as liquifaction which could completely alter the physical response.

A structural system as complex as the ZION Nuclear Station requires consideration of a very large number of potential failure modes. This includes evaluation of a great many structural elements and details to determine yield and ultimate load capacities and, in many cases, their load deformation characteristics. Adequate analysis has not yet been completed to develop this data for ZION. Among the potential failure modes of the structures are a number which have an extremely low probability of occurrence. Several are discussed in the following. However, insufficient analysis has been conducted to establish ground motion acceleration levels at which structural degradation or ultimate collapse can result or even to rank the modes in terms of relative severity.

3.2 SOIL FOUNDATON FAILURE MODES

One class of failure modes to be considered in a nuclear power station, particularly for massive structures such as the reactor containment building, involves failures resulting from the soil foundation media. The most likely of these is concerned with soil toe pressure failure under successive cycles. This is particularly important at input acceleration levels high enough to cause base slab uplift. This is shown schematically in Figure 3-3. Overturning of the structure has an extremely low probability of occurrance as a result of a single or few cycles because of the very short period of an excitation cycle compared to the time required to rotate the structure sufficiently to cause instability. However, successive cycles may degrade the soil sufficiently to allow enough rotation that relative motion between the containment and penetration building can cause pipe or conduit failure. Soil type failure modes may or may not be accompanied by structural failure.

Since the reactor containment building is embedded 26 feet to the bottom of the base slab and the sump under the reactor vessel an additional 26 feet below the base slab, the potential for sliding of the structure is very remote. Other considerations for the ZION plant include soil liquifaction and possibly even surface faulting.

3.3 REACTOR CONTAINMENT BUILDING STRUCTURE

Structural failure of the containment building can occur in the containment shell, the base slab and sump, and the concrete internal structures. Axial loads in the containment shell from flexure are distributed according to the first harmonic, at least in the linear response range. At high load conditions, cracking at maximum tension location can occur but, provided axial prestress is retained, these cracks will normally close upon load reversal and although yielding of the reinforcing steel may result, substantial inelastic deformation can be expected. In highly stressed regions of compression resulting from flexure, loss of compression can result from crushing and abrasion of the concrete. Load reversals and failure of the reinforcing steel and liner buckling and rupture can occur. The ground motion levels at which this degree of damage may be expected is determined not only by the concrete compressive strength and prestress but on whether adequate confinement of the fractured concrete is provided by the reinforcing steel as well as the number of cycles. Areas of concern which must be considered include not only the flexural loads but axial load, loads from vertical excitation and load increments such as may occur from recontact of the base slab with the soil if uplift has occurred. In establishing the axial prestress capacity, care must be given not only to the ultimate strength and elongation of the tendons, but also to the possibility of damage to tendon cap and anchor details as a result of seismic excitation. Typically, the circumferential prestress system is not heavily loaded additionally in the cylindrical portion of the structure as the result of seismic flexural loads.

The tangential shear distribution through the cylindrical shell is also distributed according to the first harmonic for elastic lateral loads. Shear "yielding" can occur in the same manner as in plane shear walls. This results in loss of aggregate interlock and reduction in dowel stiffness as the cracks widen. Of particular concern are construction joints such as the interface of the base slab and containment shell and other locations of maximum shear stress.

Other areas of concern in the containment structure include the construction joints in the base slab, especially if base slab uplift occurs, failure of a tendon gallery, which could lead to prestress tendon damage, and regions of high discontinuity stresses such as the spring line. All of these could cause or contribute to failure from concrete fracture leading to loss of prestress, liner rupture, and eventually to buckling and collapse of the structure.

In addition to the containment shell itself, the internal concrete structures must be evaluated for fragility levels. Of primary concern is the ability to support the Seismic Category I equipment and piping and load transfer capacity to the containment pressure boundary. The latter item includes possible interaction of the operating floor slab with the shell and the integrity of the base slab liner as a result of seismic loads from the internals. Finally, a fragility evaluation of the structure must include an investigation of the ultimate capacity of the polar crane hold-down devices and the effect of inpact and liner damage should the crane become dislocated under extreme seismic excitation.

3.4 AUXILIARY-TURBINE BUILDING STRUCTURE

The auxillary-turbine building complex consist of both concrete shear wall and braced steel frame construction. Further, it is composed of more than fourteen floor slabs and roof structures arranged with a considerable amount of nonsymmetry. Details of the roof bracing system and connection details were not available in order to determine the amount of diaphragm action expected or the acceleration levels at which failure could be expected. Although the wall bracing system was briefly reviewed, again no connection details were available in order to determine the amount of ductility which exists nor were details of the attachment methods and any resulting stiffness of the wall panels available.

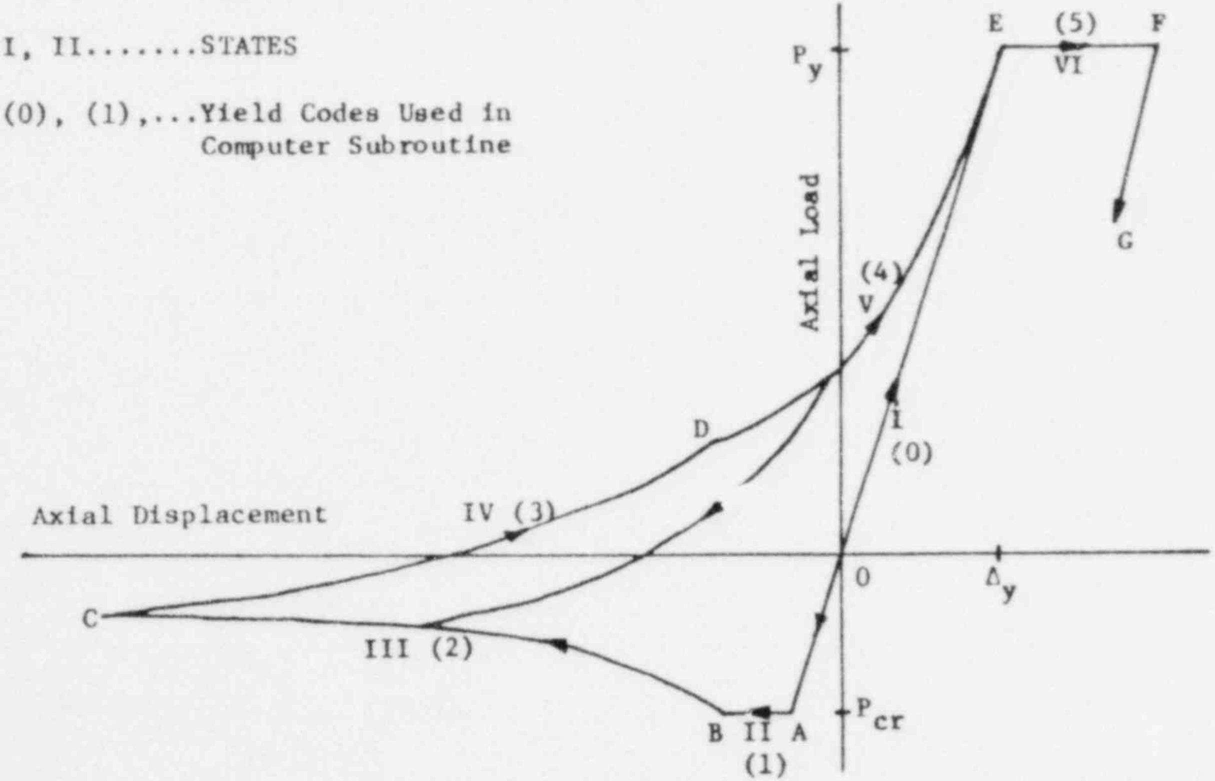
For braced frame structures such as the auxiliary-turbine building, collapse does not normally occur until loss of the roof diaphragm and failure of the lateral bracing system occurs. Then, failure mode is essentially in-place vertical collapse resulting from $P-\Delta$ effects. Buckling of lateral bracing can occur but as long as the elements can perform their function in tension after load reversal, collapse normally does not result. Also, since the system is highly redundant, failure of a single brace does not necessarily cause building failure. At high seismic acceleration levels, other effects such as concrete anchor bolt pull out and fracture, and particularly connection details must be evaluated in order to establish the level of ductility expected. Once this has been accomplished, this type of system is tractable to analysis by means of ductility modified response spectra. For a system as complex as the auxiliary-turbine building, with significant non-symmetry, several analyses at various levels of degradation are probably required in order to properly establish the system fragility level. At levels where inelastic response occurs, substantial variations in response frequency, mode shapes including amount of torsion response, and damping result and they must normally be evaluated in a progressive manner as the level of seismic input increases.

The lower elevations of the auxiliary-turbine building are constructed of reinforced concrete shear walls. For structural walls designed to ACI standards for relatively low stress levels, flexural buckling and loss of compression concrete are normally the limiting factors. A significant number of inelastic cycles can usually be withstood. Large out of plane displacement will significantly limit the inelastic capability of these walls. For reinforced concrete walls designed for high values of shear stress, shear failure is typically the limiting factor. Again, a number of inelastic cycles can usually be achieved. Other fracture and degradation can occur in places such as grade beams, footings, piers, and minor sliding at construction joints which would normally be classed as "failure" by a structural engineer. However, so long as the structure does not collapse or incur deformations which would prevent the function of Category I equipment, it may be considered to be acceptable for earthquake levels of extremely high accelerations.

3.5 CRIB HOUSE

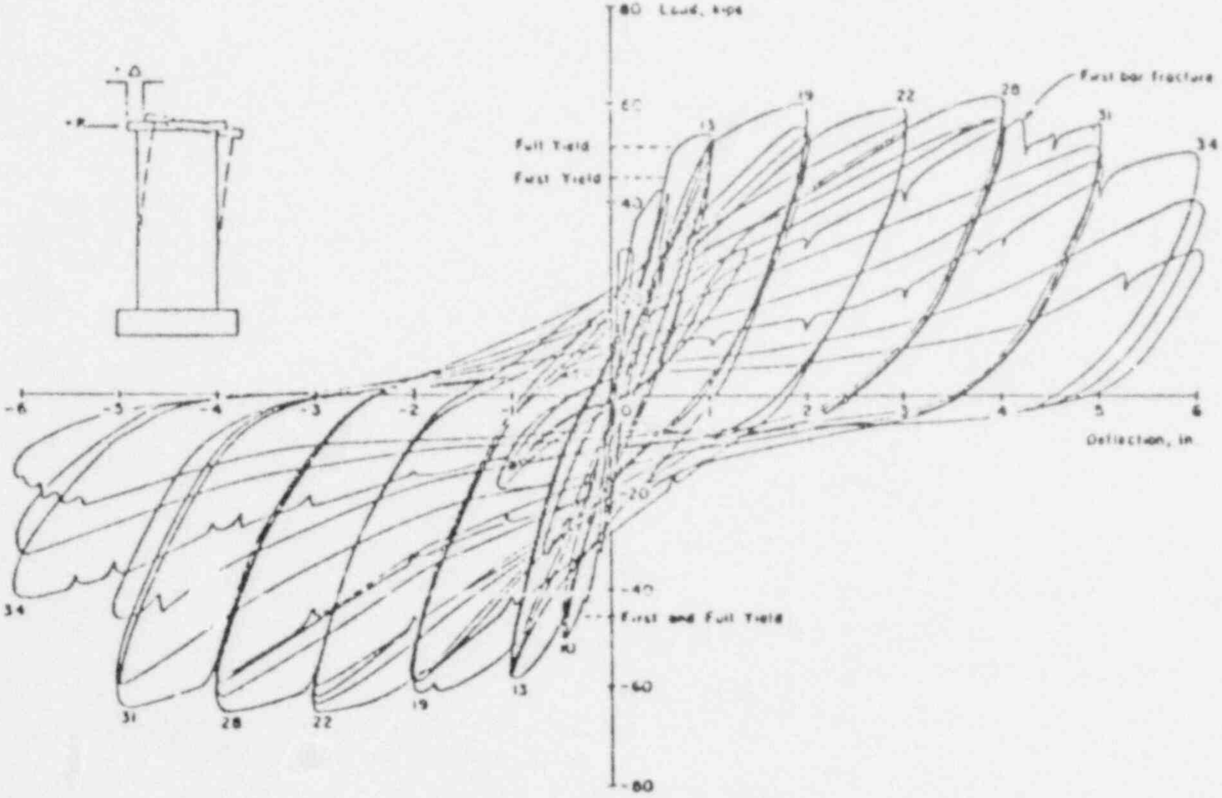
The ZION Crib House is a reinforced concrete structure consisting of the base slab and four additional slabs supported either by shear walls in the form of inlet guide vanes or essentially complete box sections for the higher elevations. Failure modes expected for this structure are expected to consist of tyical reinforced concrete shear walls fracture and buckling and subsequent vertical collapse. Relative motion between the structure and piping is of concern and the possibility of structure sliding at very high acceleration levels should be considered. Also the fluid forces must be considered both for virtual mass effects as well as convective forces.

The crib house structure is quite symmetric so that significant amounts of torsional response are not expected. Also, there is substantial frequency separation for the two principal directions for the elastic response analysis so that establishing the fragility levels for the crib house is not expected to require nearly the level of effort required for the auxiliary-turbine building.



Hysteresis Behavior of Bracing Member

FIGURE 3-1



Continuous Load-Deflection Plot

FIGURE 3-2

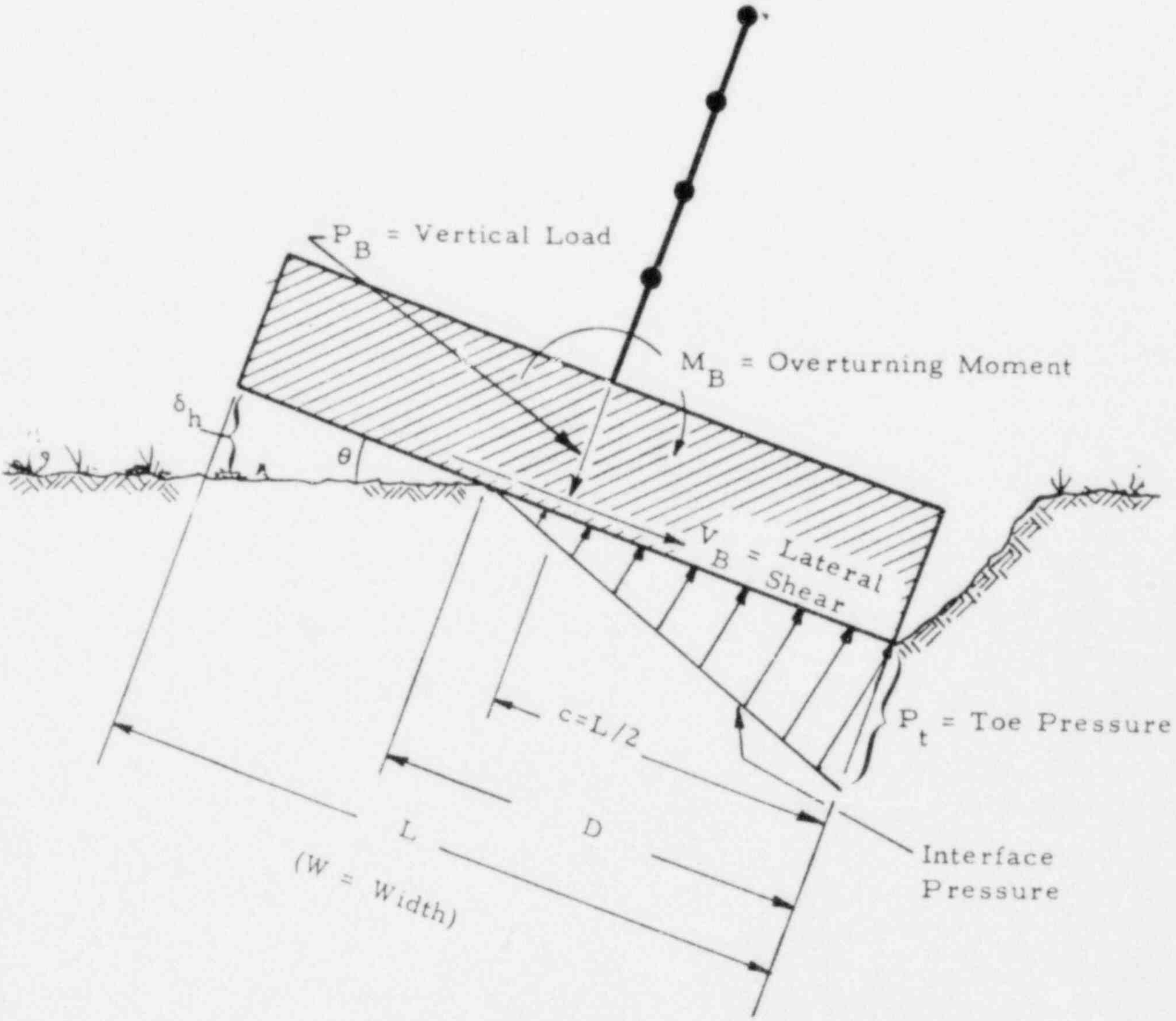


FIGURE 3-3

BASE SLAB ROCKING SHOWING UPLIFT

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A preliminary determination of failure modes for safety related equipment and major structures in the SSMRP reference plant was made. The preliminary predictions were made using engineering judgment as a review of seismic qualification requirements, design calculations and test results was not conducted in support of this activity.

The SSMRP fragility project will entail effort to gather seismic qualification and fragility information and will include a review of component subsystem and structural design specifications and review of design reports.

Chapter 2 of this report addresses failure modes of safety related equipment. Most equipment is trated generically although some plant unique equipment is isolated for separate consideration. Chapter 3 discusses methods to determine progressive failure of the reference plant structures and some of the failure modes that could exist in the major structures of the reference plant.

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