TECHNICAL EVALUATION REPORT

CONTAINMENT LEAKAGE RATE TESTING

JERSEY CENTRAL POWER AND LIGHT COMPANY
OYSTER CREEK NUCLEAR GENERATING STATION

NRC DOCKET NO. 50-219

NRC TAC NO. 08678

NRC CONTRACT NO. NRC-03-79-118

FRC PROJECT C5257

FRC TASK 36

Prepared by

Franklin Research Center
The Parkway at Twentieth Street
Philadelphia, PA 19103

Author: I. H. Sargent

FRC Group Leader: T. J. DelGaizo

Prepared for

Nuclear Regulatory Commission
Washington, D.C. 20555

Lead NRC Engineer: Y. S. Huang

May 21, 1981

Franklin Research Center
A Division of The Franklin Institute
The Benjamin Franklin Parkway, Phila., Pa. 19103 (215) 448-1000

CONTENTS

CONTENTS

1. BACKGROUND

On August 7, 1975 [1], the NRC requested Jersey Central Power and Light Company (JCPL) to review the containment leakage testing program for Oyster Creek Nuclear Generating Station (Oyster Creek) and to provide a plan for achieving full compliance with the requirements of 10CFR50, Appendix J, including appropriate design modifications, changes to technical specifications, or request for exemption from the requirements pursuant to 10CFR50.12, where necessary.

JCPL responded on December 24, 1975 [2] stating that the containment leakage testing program at Oyster Creek compared favorably with the Types A and B testing of Appendix J but differed considerably with the requirements for Type C testing. In a subsequent letter dated August 12, 1976 [3], JCPL requested certain exemptions from the requirements of Appendix J and also forwarded Technical Specification Change Request No. 48 to incorporate the requested exemptions into the technical specifications.

On February 24, 1977, a meeting was held between NRC and JCPL personnel in which the requested exemptions of Reference 3 were discussed. Subsequently, in a letter dated November 22, 1978 [4], JCPL submitted a modified set of requests for exemption from the requirements of Appendix J. JCPL stated that proposed revisions to the technical specifications would be withheld pending NRC action on the latest requested exemptions.

The purpose of this report is to conduct technical evaluations on all outstanding issues regarding the implementation of 10CFR50, Appendix J, at Oyster Creek. Accordingly, technical evaluations are provided for the requests for exemption from the requirements of Appendix J submitted by Reference 4. The technical specification change request of Reference 3 has not been evaluated since JCPL intends to submit revised technical specification changes upon receipt of NRC action on the exemption requests.

2. EVALUATION CRITERIA

Code of Federal Regulations, Title 10, Part 50 (10CFR50), Appendix J, Containment Leakage Testing, provided the criteria used in conducting the technical evaluations. Where applied to the following evaluations, the criteria are either referenced or briefly stated, where necessary, in support of the results of the evaluations. Furthermore, in recognition of the plant-specific conditions which could lead to requests for exemption not explicitly covered by the regulations, the NRC directed that the technical reviews constantly emphasize the basic intent of 10CFR50, Appendix J, that potential containment atmospheric leakage paths be identified, monitored, and maintained below established limits.

3. TECHNICAL EVALUATION

3.1 REQUESTS FOR EXEMPTION FROM THE REQUIREMENTS OF 10CFR50, APPENDIX J

Requests for exemption from the requirements of 10CFR50, Appendix J were submitted by JCPL as Tables 1, 2, and 3 of Reference 4 for Type A, B, and C testing, respectively. A technical evaluation of each of these requests for exemption is included in the following sections.

3.1.1 Request for Exemption from Draining and Venting Several Systems During Type A Testing

Table 1, Item 1 of Reference 4, identifies several systems, portions of which are part of the reactor coolant pressure boundary and may be open directly to the containment atmosphere under post-accident conditions, which JCPL does not intend to open or vent to atmosphere and drain during Type A testing. JCPL's bases for not opening and draining these systems during the Type A test can be categorized into four groups, each of which is evaluated separately below.

3.1.1.1 System with Reactor Vessel Penetrations Below the Water Level Required While Fuel is in the Vessel

JCPL stated that three systems having reactor vessel penetrations below the water level required while fuel is in the vessel would not be opened or vented to atmosphere and drained. These systems are:

Emergency condenser system condensate return

Reactor sample line

Reactor cleanup system.

JCPL stated that modifications would be made to the reactor sample line and the reactor cleanup system so that local leak rate testing could be performed on the isolation valves. The local leak results would be added to the result of the integrated leak rate test (ILRT). JCPL requested exemption from the requirement to vent and drain the emergency condenser system condensate return lines because having these lines water-filled will not affect the test results.

Evaluation. Section III.A.1.(d) of Appendix J does not require venting and draining of systems which are part of the reactor coolant pressure boundary and may be opened to containment atmosphere after an accident if the system is required to maintain the plant in a safe condition during the Type A test. Section III.A.1.(d) further requires that the containment isolation valves of these systems be local leak rate tested. The results of the local leak rate tests are then added to the results of the ILRT (Type A test).

Venting and draining of systems with reactor vessel penetrations below the water level required while fuel is in the vessel, therefore, is not required by Section III.A.1.(d) since to do so would place the plant in an unsafe condition. Furthermore, JCPL has committed itself to performing Type C tests of the containment isolation valves of the reactor sample line and the reactor cleanup systems. In Section 3.1.4.2 of this report, FRC has determined that the isolation valves of the emergency condenser system condensate return lines do not require Type C testing because they are not relied upon to perform a containment isolation function as defined in Section II.B of Appendix J with regard to the leakage of containment atmosphere. Therefore, the three systems of this category need not be vented and drained during the Type A test and no exemptions from the requirements of Appendix J are necessary because all Appendix J requirements will be met.

3.1.1.2 Systems with Reactor Vessel Penetrations Below the Water Level in the Vessel During the Test

JCPL stated that five systems having reactor vessel penetrations below the level in the vessel during the Type A test would not be opened or vented to atmosphere and drained. These systems are:

- Feedwater system
- Control rod driveline (CRD) hydraulic return to reactor
- Liquid poison
- Core spray to reactor
- Reactor coolant instruments.

JCPL stated that modifications would be made to the feedwater system, CRD hydraulic return to reactor, and liquid poison system so that local leak rate testing of isolation valves could be performed. Local leakage results would be added to the results of the ILRT. JCPL requested exemption from the requirements of Appendix J to vent and drain the core spray to reactor lines and the reactor coolant instruments since these lines are not considered to be sources of post-accident containment atmospheric leakage.

Evaluation. Section III.A.1(d) of Appendix J does not require venting and draining of systems which are part of the reactor coolant pressure boundary and may be opened to containment atmosphere after an accident if the system is required to maintain the plant in a safe condition during the Type A test. Section III.A.1.(d) further requires that the containment isolation valves of these systems be local leak rate tested. The results of the local leak rate tests are then added to the results of the ILRT (Type A test).

FRC infers from JCPL's statement that the systems in this category have penetrations below the water level in the vessel during the Type A test and that this level is the level necessary to maintain the plant in a safe condition throughout the Type A test. If this were not the case, the water level would be lowered to that level necessary to expose the isolation valves of these systems to the differential pressure of the Type A test and there would be no need for an exemption request.

Provided that the water level maintained in the vessel during the Type A test is the level which JCPL has determined to be required to maintain the plant in a safe condition, these systems need not be vented and drained prior to and during the Type A test. In the case of the feedwater system, CRD hydraulic return, and liquid poison system, JCPL's commitment to perform local leakage rate tests on the containment isolation valves in these systems and to add to the measured leakage to the ILRT results meets all requirements of Appendix J and no exemption is needed for these systems.

The core spray system is designed to function throughout the post-accident period. It has sufficient redundancy to ensure that the system

will be pressurized to pressures greater than the peak calculated containment accident pressure (Pa) regardless of a possible single active failure to the system. Consequently, the isolation valves of this system are not relied upon to perform an isolation function to prevent leakage of containment atmosphere at any time throughout the post-accident period. Consequently, these valves are not containment isolation valves as defined by Section II.B of Appendix J and therefore they need not be tested. The core spray system need not be vented and drained during the Type A test and the isolation valves need not be local leak rate tested because Appendix J does not require this testing. No exemption from Appendix J is needed.

Reactor coolant instrument lines do not require Type C testing unless they provide a direct connection between inside and outside containment atmospheres as required by Section II.H.1 of Appendix J. In the case of these lines, a passive failure of the instrument line outside containment is required in order for there to be a leakage path. In addition, since the lines penetrate the reactor vessel below the minimum water line, there is no possibility for leakage of containment atmosphere even with a passive failure. Consequently, these lines do not need to be vented and drained during the Type A test nor do they require Type C testing in accordance with Appendix J. No exemption from Appendix J is necessary.

3.1.1.3 System Required to be In Service to Maintain the Plant in a Safe Shutdown Condition During the Test

JCPL stated that two systems required to be in service to maintain the plant in a safe shutdown condition during the Type A test would not be opened or vented to atmosphere and drained. These systems are:

Shutdown cooling system

Reactor building closed cooling water system.

JCPL stated that modifications would be made to the reactor building closed cooling water system to permit local leakage rate testing of this system. The measured leakage from these local leak tests would be added to

the results of the ILRT. JCPL requested exemption from the requirements of Appendix J with regard to venting and draining the shutdown cooling system during the Type A test since this system does not contribute to post-accident containment atmospheric leakage.

Evaluation. Section III.A.1.(d) does not require venting and draining of systems which are part of the reactor coolant pressure boundary and/or may be opened to containment atmosphere after an accident if the system is required to remain in operation during the test to maintain the plant in a safe condition. This section, however, requires that the containment isolation valves in these systems be Type C tested.

Since the reactor building closed cooling water system isolation valves will be local leak rate tested and the measured leakage will be added to the ILRT results, this system need not be vented and drained prior to and during the Type A test and no exemption from the requirements of Appendix J is needed.

In Section 3.1.4.1 of this report, FRC determined that the isolation valves of the shutdown cooling system do not require Type C testing because they are not relied upon to perform a containment isolation function as defined in Section II.B of Appendix J with regard to leakage of containment atmosphere. Therefore, FRC finds that the shutdown cooling system need not be vented and drained for the Type A test and that no exemption from the requirements of Appendix J is necessary.

3.1.1.4 System Normally Filled with Water and Operating Under Post-Accident Conditions

JCPL stated that the CRD insert and withdraw lines are normally filled with water when operating after an accident and therefore would not be vented and drained for the Type A test. JCPL requested exemption from the requirements of Appendix J to vent and drain these lines stating that they were small lines (3/4 to 1 inch), seismically designed, and protected from damage due to pipe ruptures.

Evaluation. Section III.A.1.(d) of Appendix J requires venting and draining of systems which are part of the reactor coolant pressure boundary

and may be open to containment atmosphere under post-accident conditions. The CRD insert and withdraw lines connect to the reactor coolant pressure boundary but are not open to containment atmosphere under post-accident conditions. These lines connect to the reactor coolant system at the bottom of the reactor vessel, well below the minimum water level required to maintain the core covered. In addition, the lines are designed seismically and protected against other secondary effects of the LOCA which could cause one or several lines to rupture. Since there is no potential containment atmospheric leakage path from these lines, Appendix J does not require that they be vented and drained during the Type A test and no exemption is necessary.

3.1.2 Request for Exemption from Correcting Test Leakage Rates for Instrument Error

Table 1, Item 2B of Reference 4, identified the Licensee's intent not to add a statistically determined, root-mean-square allowance for instrument error to the "measured" leak rate. This request for exemption was combined with the requirement of Section III.A.~~2~~3.(c) of Appendix J, implying that the licensee was of the opinion that this information is relevant to the instrument error correction requirement of that section.

Evaluation. Section III.A.~~2~~3.(c) of Appendix J requires that calculated leakage rates (for both the Type A and supplemental ILRT tests) be based on the absolute value of measured parameters (i.e., containment pressure, containment temperature, water vapor pressure, etc.) corrected for errors in those instruments used to evaluate these parameters. This article creates no requirements pertaining to addition of any error factor (including a statistically determined "instrument error") to a calculated leakage rate. JCPL's request for exemption, therefore, is unnecessary since Appendix J does not require the imposition of an instrument error to the measured leakage rate. The requirements of Section III.A.~~2~~3.(c) with regard to instrument errors, as applied to the measurement of parameters, should be followed.

3.1.3 Request for Exemption with Respect to Type B Testing of Drywell Airlocks

Reference 4, Table 2, Items 2 and 3, requested exemptions with respect to both the frequency and pressure of drywell airlock testing. JCPL proposed that airlocks at Oyster Creek be tested at 6-month intervals at a pressure of 35 psig using strongbacks to prevent the inner door from becoming unseated. If the airlock is opened during the interval between the 6-month tests, the airlock would be tested within 72 hours of every first of a series of openings at a pressure of 10 psig, a pressure not requiring the use of stongbacks. The result of the test at 10 psig will be conservatively extrapolated to a leakage rate at 35 psig to determine the acceptability of each test.

Evaluation. Sections III.B.2 and III.D.2 of Appendix J require that containment airlocks be tested at peak calculated accident pressure (Pa) at 6 month intervals and after each opening. This requirement of more frequent testing of airlocks than other isolation barriers is based on the fact that these potentially large leakage paths are more subject to personnel error and degradation than other containment penetrations. A compilation of airlock events from Licensee Event Reports submitted since 1969 shows that airlock testing in accordance with Appendix J has been effective in prompt identification of airlock leakage, but that rigid adherence to the after-each-opening requirement may not be necessary.

Since 1969, there have been approximately 70 reported instances in which airlock testing results have exceeded allowable leakage limits. Of these events, 25% were the result of leakage other than that from improper seating of airlock door seals. These failures were generally caused by leakage past door-operating mechanism handwheel packing, door-operating cylinder shaft seals, equalizer valves, or test lines. These penetrations are not unlike other Type B or Type C containment penetrations except that they may be operated more frequently. Since airlocks are tested at a pressure of Pa every 6 months, these penetrations are tested, at a minimum, four times more frequently than typical Type B or C penetrations. The 6-month test is therefore considered to be both justified and adequate for the prompt identification of this leakage.

Improper seating of the airlock door seals, however, is not only the most frequent cause of airlock failures (the remaining 75%), but also represents the largest potential leakage path. While testing at a pressure of Pa after each opening will identify seal leakage, seal leakage can also be identified by alternative methods such as pressurizing between double-gasketed door seals (for airlocks designed with this type of seal) or pressurizing the airlock to pressures other than Pa. Furthermore, experience gained in testing airlocks since the issuance of Appendix J indicates that the use of one of these alternative methods may be preferable to the full pressure test of the entire airlock.

Reactor plants designed before the issuance of Appendix J often do not have the capability to test airlocks at Pa without the installation of strongbacks or the performance of mechanical adjustments to the operating mechanisms of the inner doors. This is because the inner doors are designed to seat with accident pressure (i.e., accident pressure on the containment side of the door), and therefore the operating mechanisms were not designed to withstand accident pressure in the opposite direction. When the airlock is pressurized for a local airlock test (i.e., pressurized between the doors), pressure is exerted on the airlock side of the inner door, causing the door to unseat and preventing the conduct of a meaningful test. The strongback or mechanical adjustments prevent the unseating of the inner door, allowing the test to proceed. The installation of strongbacks or performance of mechanical adjustments is time consuming (often taking several hours), may result in additional radiation exposure to operating personnel, and may also cause degradation to the operating mechanism of the inner door with consequential loss of reliability of the airlock. In addition, when conditions require frequent openings over a short period of time, testing at Pa after each opening becomes impractical (tests often take from 8 hours to several days) and accelerates the rate of exposure to personnel and degradation of mechanical equipment.

For these reasons, FRC concludes that the intent of Appendix J is satisfied and the undesirable effects of testing after each opening are reduced if a satisfactory test of the airlock door seals is performed within 3 days of each opening or every 72 hours during a period of frequent openings.

Furthermore, these tests, conducted between 6-month full pressure (Pa) tests, may be conducted at a pressure less than Pa which does not require the installation of strongbacks or performance of other mechanical adjustments. However, leakage determined from such tests must be conservatively extrapolated to an equivalent leakage rate at Pa to determine acceptability. Acceptable methods for extrapolation of leakage rates are given in Appendix A to this report. As can be seen in Appendix A, a conservative correlation between the measured leakage rate at pressure Pt ($\dot{m}t$) and the theoretical leakage rate at pressure Pa ($\dot{m}a$) is given by (where Pat = atmospheric pressure):

$$\frac{\dot{m}a}{\dot{m}t} = \frac{(Pa + Pat)^2 - (Pat)^2}{(Pt + Pat)^2 - (Pat)^2}$$

In summary, JCPL's proposed drywell airlock testing is acceptable, provided the results of testing at 10 psig are conservatively extrapolated to 35 psig. An exemption from the requirements of Appendix J is not required because the proposed testing is in conformance with Section III.D.2, as revised on October 22, 1980. The Licensee should ensure that it complies with all provisions of the revised Section III.D.2.

3.1.4 Request for Exemption from Type C Testing Requirements

Table 3 of Reference 4 identifies 10 isolation valves for which JCPL has requested exemption from the Type C testing requirements of Appendix J. These valves are associated with two systems, the shutdown cooling system (2 valves) and the emergency condenser system (8 valves). The request for exemption for each system is evaluated separately below.

3.1.4.1 Request for Exemption from Type C Testing of Shutdown Cooling System Valves V-17-19 and V-17-54

JCPL requested an exemption from the Type C testing requirements for shut-down cooling system valves V-17-19 and V-17-54 on the basis that the

system is not expected to be a source of post-accident leakage. The valves are closed during power operation. The system is closed outside containment, is seismically designed, and is protected from the effect of pipe rupture.

Evaluation. Valves V-17-19 and V-17-54 are normally shut valves which remain shut in the post-accident condition. Since the shutdown cooling system connects to the reactor coolant pressure boundary through the reactor recirculation system, these valves will remain water-covered throughout the post-accident period by the water level in the reactor vessel (the recirculation nozzles penetrate the reactor vessel well below the level necessary to maintain the core covered). Consequently, there is no path for containment atmospheric leakage to penetrate the containment boundary through these two valves.

Section III.A.1.(d) requires that containment isolation valves in systems that are open to containment atmosphere after an accident be tested by Type C testing procedures. Section II.B defines containment isolation valves as those valves relied upon to perform a containment isolation function. Since valves V-17-19 and V-17-54 are not relied upon to perform a containment isolation function against potential leakage of containment air, Appendix J does not require that they be tested. FRC finds that these valves need not be tested and that no exemption from Type C testing requirements of Appendix J is necessary.

3.1.4.2 Request for Exemption from Type C Testing of Emergency Condenser System Valves V-14-30 Through V-14-37

JCPL requested an exemption from the Type C testing requirements for emergency condenser system valves V-14-30, V-14-31, V-14-32, and V-14-33 (10-inch motor-operated steam line isolation gate valves) and V-14-34, V-14-35, V-14-36, and V-14-37 (10-inch motor-operated condensate return isolation gate valves). JCPL's basis for this request is that the emergency condenser system is designed to be operable following an accident and acts as an extension of the containment boundary. It is not a source of leakage during the post-accident period. It is isolated automatically only on high flow, or manually on high radiation in the condenser shell.

Evaluation. Section III.A.1.(d) requires Type C testing of containment isolation valves which are connected to the reactor coolant pressure boundary. Section II.B, however, defines containment isolation valves as those valves relied upon to perform a containment isolation function.

Steam supply isolation valves (V-14-30 through V-14-33) are normally open valves, and therefore the closed-loop emergency condenser piping outside containment is constantly pressurized to reactor coolant system pressure. JCPL has stated that this piping is an extension of the containment boundary. The isolation valves are shut only on high flow or high radiation in the condenser shell, neither of which results from a LOCA inside containment. Consequently, it is clear that the emergency condenser system isolation valves (V-14-30 through V-14-37) are not relied upon to perform a containment isolation function following a LOCA, and therefore Type C testing is not required. No exemption from Appendix J is required.

4. CONCLUSIONS

Requests for exemption from the requirements of 10CFR50, Appendix J, submitted by JCPL in Reference 4 were technically evaluated. The following conclusions are submitted:

- The following systems or portions of systems do not require venting and draining prior to and during the Type A test (Section III.A.1.(d) of Appendix J). No exemptions from the requirements are needed.

  Emergency condenser system condensate return
  Reactor sample line
  Reactor cleanup system
  Feedwater system
  CRD hydraulic return to reactor
  Liquid poison
  Core spray to reactor
  Reactor coolant instruments
  Shutdown cooling
  Reactor building closed cooling water
  CRD insert and withdraw lines.

- The addition of a statistically determined instrument error to the Type A or supplemental test is not required by Appendix J. The requirement of Section III.A.3.(c) to calculate leakage rates based upon absolute values corrected for instrument errors in the instruments used to measure the parameters should be followed.

- JCPL's proposal to test drywell airlocks at 6-month intervals at a pressure of Pa (35 psig) and within 72 hours of every first of a series of openings at 10 psig in the interim between 6-month tests is acceptable. No exemption is required because of the revision to Section III.D.2 of Appendix J, effective October 22, 1980.

- Shutdown cooling system valves V-17-19 and V-17-54 do not require Type C testing and no exemption is required because Appendix J does not require that these valves be tested.

- Emergency condenser isolation valves V-14-30 through V-14-37 need not be Type C tested and no exemption is required because Appendix J does not require that these valves be tested.

5. REFERENCES

1. NRC, Generic letter to JCPL regarding implementation of 10CFR50, Appendix J at Oyster Creek
07-Aug-75

2. V. R. Finfrock, Jr. (JCPL)
Letter to K. R. Goller (NRC)
24-Dec-75
(GD-75-020)

3. V. R. Finfrock, Jr. (JCPL)
Letter to Secretary, USNRC
12-Aug-76
(EA-76-781)

4. V. R. Finfrock, Jr. (JCPL)
Letter to Director, NRR
22-Nov-78

APPENDIX A

CONVERSION OF REDUCED PRESSURE AIR LEAKAGE MEASUREMENTS TO EQUIVALENT FULL PRESSURE AIR LEAKAGE

JULY 17, 1980

Dr. G. P. Wachtell

Franklin Research Center

APPENDIX A. AIR TO AIR LEAKAGE CONVERSION

In pneumatic leakage testing in which application of Pa psig is called for by Appendix J, it is sometimes necessary to request an exemption that permits pneumatic testing at a lower pressure, Pt psig. The leakage rate, Lt, measured under test conditions must then be converted mathematically to the leakage rate, La, that would occur if the pressure were equal to Pa. It is essential that the conversion be conservative. That is, the calculated value of La must not be lower than the actual leakage rate at Pa would be. On the other hand, the conversion should not be more conservative than necessary in the light of available data, because excessive conservatism could frequently result in the interpretation that a given leak exceeds its maximum allowable limit when in fact it would not exceed that limit if Pa were actually applied.

The meaning of the expression "if Pa were actually applied" should be carefully considered. The assumption is made that the geometry and dimensions of the leakage path would be the same with Pa applied as with Pt applied, or that any changes in geometry would not increase the leakage rate. In the case of airlock doors in which Pt is applied in the reverse direction, opposite to the direction in which Pa would be applied under function conditions, the use of the reverse direction of application of pressure is expected to tend to open the seal and increase the leakage rate. Under function conditions, in which pressure is applied in the forward direction, the seal should be improved if it changes at all. The expression "if Pa were actually applied" in this case means "if Pa were actually applied in the forward (normal for function) direction." In the case of valves and other penetrations, it is essential that increasing the applied pressure from Pt to Pa not change the geometry so as to increase the leakage rate. For example, increasing the pressure on a closed valve should tend to improve its sealing at the surfaces that provide the seal, and also in any other

potential leakage paths such as valve stem or packing that may have a connection to the applied pressure. Such other potential leakage paths are of course absent in valve designs in which the stem and packing have a connection only to the downstream side of the valve.

Reference 1, which is ASME Code, Section XI, paragraph IWV-3423 (e), states the following rule for tests at less than function differential pressure:

> "Leakage tests involving pressure differentials lower than function pressure differentials are permitted in those types of valves in which service pressure will tend to diminish the overall leakage channel opening, as by pressing the disk into or onto the seat with greater force. Gate valves, check valves, and globe-type valves having function pressure differential applied over the seat, are examples of valve applications satisfying this requirement. When leakage tests are made in such cases using pressures lower than function maximum pressure differential, the observed leakage shall be adjusted to function maximum pressure differential value. This adjustment shall be made by calculation appropriate to the test media and the ratio between test and function pressure differential, assuming leakage to be directly proportional to the pressure differential to the one-half power."

In the discussion below, it is shown that if (a) the test medium is air, (b) Pa is appreciable compared to one atmosphere, and (c) the leakage path is such as to produce laminar viscous flow (i.e., capillary-like rather than orifice-like), the calculation appropriate to this test medium yields a substantially higher calculated value of Pa than would be obtained by assuming leakage to be directly proportional to the pressure differential to the one-half power.

For air flow through an orifice, assuming uniform flow velocity over the orifice area, the mass flow rate per unit orifice area is ρv, where ρ is the density of air in the orifice and v is velocity in the orifice. Assuming that the discharge pressure is Pat = 1 atmosphere and the source pressure is Po, where Po and Pat are both absolute pressures, ρv is given by

$$(\rho v)^2 = \frac{2\gamma g}{\gamma-1} \frac{Pat^2}{R_o T} \left(\frac{Po}{Pat} - 1 \right) G \qquad \text{(A-1)}$$

where γ = 1.4 is the specific heat ratio for air, g = 32.2 ft/sec^2 is the acceleration of gravity, T is source (upstream, at Po) temperature (°R), $\dot{P}$ is absolute pressure (psf), R_o = 53.26 ft-lb/lb°F is the gas constant for air and G is given by

$$G = \left(\frac{Pe}{Pat}\right)^2 \frac{x^{\frac{\gamma-1}{\gamma}} \cdot \left(x^{\frac{\gamma-1}{\gamma}} - 1\right)}{\left(\frac{Po}{Pat} - 1\right)} \qquad \text{(A-2)}$$

$$x = \frac{Po}{Pe}$$

Pe = Pat for subsonic flow

Pe = 0.5283 Po for choked flow

Choked flow occurs when

$$\frac{Pat}{Po} \leq \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma}{\gamma-1}} = 0.5283$$

$\sqrt{G}$ is proportional to $\rho v/\sqrt{Po-Pat}$. Values of $\sqrt{G}$ are listed in Table A-1. $\sqrt{G_o}$, the limiting value of $\sqrt{G}$ for small (Po-Pat), is $\sqrt{(\gamma-1)/\gamma}$ = 0.5345.

In Table A-1, inspection of $\sqrt{G}/\sqrt{G_o}$ shows the accuracy of the assumption that for an orifice-like leakage flow resistance, leakage mass flow rate is proportional to pressure difference to the one-half power. For example, if Po = 60 psig (Po-Pat = 60 in Table A-1), $\sqrt{G}/\sqrt{G_o}$ = 1.210. Extrapolation of mass flow rate measured with Pt = 15 psig to mass flow rate predicted for Pa = 60 psig will underestimate the mass flow rate by the factor 0.968/1.210 = 0.80, or 20%.

The foregoing argument tacitly assumes that the orifice coefficient is = 1.0. However, the same conclusion concerning extrapolation from low values of Pt to high values of Po can be drawn if the orifice coefficient is assumed to be constant, i.e., independent of Po. Consequently,

Table A-1. $\sqrt{G}$ for Various Values of Po - Pat for Orifice. (Pat taken = 15 psia.)

Po - Pat (psi)	$\sqrt{G}$	$\sqrt{G}/\sqrt{G_0}$
0.01	0.5345	1.000
1	0.5332	0.998
5	0.5282	0.988
13.3	0.5185	0.970
13.4*	0.5184	0.970
15 *	0.5176	0.968
20 *	0.5230	0.978
25 *	0.5346	1.000
30 *	0.5490	1.027
35 *	0.5648	1.057
40 *	0.5811	1.087
45 *	0.5977	1.118
50 *	0.6143	1.149
55 *	0.6307	1.180
60 *	0.6470	1.210

*Choked flow

for leakage paths that are known to be entirely orifice-like, the assumption that leakage mass flow rate is proportional to pressure difference to the one-half power gives a reasonably accurate correlation, underestimating the leakage mass flow rate by at most 20% for Pa $\leq$ 60 psig. To correct the underestimate, the factor $(\sqrt{G}/\sqrt{G_0})_a/(\sqrt{G}/\sqrt{G_0})_t$ has to be applied, where a and t mean Po = Pa and Pt, respectively. References 2, 3, and 4 discuss the conversion formulas to be applied for various fluids (e.g., air and water) for various types of leakage path. For viscous flow of a gas, the mass flow rate from a source at absolute inlet pressure P_1 to absolute outlet pressure P_2 is proportional to $(P_1^2 - P_2^2)$. The proportionality factor is $C/\mu T$, where C is a function of geometry, T is absolute temperature, and μ is viscosity (which is a function only of temperature).

Assuming that test pressure Pt psig is applied at the same temperature as that at which function pressure Pa psig is applied, and assuming

further that the downstream pressure is one atmosphere, Pat psia, then the ratio of the mass flow rates is

$$\frac{\dot{m}a}{\dot{m}t} = \frac{(Pa + Pat)^2 - (Pat)^2}{(Pt + Pat)^2 - (Pat)^2} \qquad (A-3)$$

If the temperatures are not the same, the right side of Equation (A-3) has to be multiplied by

$$\frac{\mu(Tt)\cdot Tt}{\mu(Ta)\cdot Ta} \qquad (A-4)$$

Assuming that Tt = Ta, Table A-2 shows the ratio $\dot{m}a/\dot{m}t$ for various values of Pa and Pt, along with values of $(Pa\ psig/Pt\ psig)^{1/2}$. Pat is taken to be 15 psia in calculating $\dot{m}a/\dot{m}t$.

Table A-2. $\dot{m}a/\dot{m}t$ for Various Values of Pa and Pt.

Pt (psig)	$\dot{m}a/\dot{m}t$ Pa=50 (psig)	55	60	$(Pa/Pt)^{1/2}$ 50	55	60	$(\dot{m}a/\dot{m}t)/(Pa/Pt)^{1/2}$ 50	55	60
5	22.86	26.71	30.86	3.16	3.32	3.46	7.2	8.1	8.9
15	5.93	6.93	8.00	1.83	1.91	2.00	3.2	3.6	4.0
25	2.91	3.40	3.93	1.41	1.48	1.55	2.1	2.3	2.5
35	1.76	2.05	2.37	1.20	1.25	1.31	1.5	1.6	1.8
45	1.19	1.39	1.60	1.05	1.11	1.15	1.1	1.3	1.4

In all cases, the assumption that mass flow rate is proportional to pressure differential to the one-half power is unconservative for purely viscous flow. For Pa = 60 psig and Pt = 5 psig, it is unconservative by a factor of 8.9.

RECOMMENDED PROCEDURE

Any one of the following procedures, A, B, or C should be adopted.

A. Test Program

An extensive test program, covering several components of each type for which a correlation from Pt to Pa is sought, should be performed, in which sufficient experimental data showing the relation between Pt and leakage mass flow rate are obtained to permit a conservative empirical correlation to be established. Care must be taken to ensure that experimental orifice-like leaks are not used to represent actual, potentially capillary-like or viscous leaks.

B. Conservative Theoretical Correlation

Use Equation (A-3) as the correlation formula, including the factor (A-4) if necessary.

C. Measure Leakage Characteristic

For a given penetration, several values of Pt may be applied, so that an empirical correlation can be established. A statistical analysis of the data would be required to ensure at a 95% confidence level, that the predicted value of $\dot{m}a$ is not exceeded by the actual value of $\dot{m}a$.

REFERENCES

1. ASME Code, Section XI, paragraph IWV-3423(e).

2. Amesz, J., "Conversion of Leak Flow-Rates for Various Fluids and Different Pressure Conditions," 1966, EUR 2982.e, ORGEL Program, Ispra Establishment, Italy.

3. Maccary, R.R., DiNunno, J.J., Holt, A.E., and Arlotto, G.A., "Leakage Characteristics of Steel Containment Vessels and the Analysis of Leakage Rate Determinations," May, 1964, Division of Safety Standards, AEC, TID-20583.

4. Cottrell, Wm. B., and Savolainen, A.W., editors, "U.S. Reactor Containment Technology," ORNL-NSIC-5, Aug. 1965. Chapter 10, "Performance Tests," R.F. Griffin and G.H. Dyer. Sections 10.4.5 and 10.4.6 adapted from Reference 3.