THE CLEVELAND ELECTRIC ILLUMINATING COMPANY

PERRY NUCLEAR POWER PLANT OPERATIONS MANUAL

Chemistry Equipment Instruction

TITLE: MULTI-CHANNEL ANALYZER, CANBERRA, SERIES 85 _____

_____

REVISION: ___0___ EFFECTIVE DATE: _____

PRELIMINARY

DATE

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PORC MEETING NO.:			
APPROVED:			

Multi-Channel Analyzer, Canberra, Series 85

CHI-12

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SCOPE OF REVISION:

MULTI-CHANNEL ANALYZER, CANBERRA, SERIES 85

1.0 PURPOSE

This instruction is to cover the calibration and operation of the Canberra Series 85 Multichannel Analyzer (MCA) in a stand-alone mode.

2.0 DESCRIPTION

The series 85 MCA with its associated detector is used to analyze for gamma activity. The MCA in its stand-alone mode has a very limited capacity when compared to the MCA in its computer assisted mode. The series 85 MCA has an internal library used for isotope identification and an independent gamma energy calibration capability.

3.0 EQUIPMENT SPECIFICATIONS

1. High Purity Germanium (HPGE) Detector

   a. Electrical Power Requirements: Varies with detector.
   b. Equipment Range: 50 keV to   10 MeV.
   c. Equipment Accuracy: See Reference 1.

2. Nuclear Instrumentation Module (NIM) Cabinet

   a. Electrical Power Requirements: 100 - 130 volts AC 50 - 60 Hz.
   b. Equipment Range: Regulated DC 96 Watt output.

3. High Voltage Power Supply

   a. Electrical Power Requirements: Regulated DC 96 Watt (NIM)
   b. Equipment Range: 0 to ± 5000 volts DC 0 to 100 uA.
   c. Equipment Accuracy: See Reference 5.

4. Liquid Nitrogen (LN_2) Monitor

   a. Electrical Power Requirements: 110-120 volts AC 50 - 60 Hz.
   b. Equipment Range: 0 - 99 pounds.
   c. Equipment Accuracy: ± 1 pound.

5. Spectroscopy Amplifier 2020

    a. Electrical Power Requirements:

        +24 Vdc   –   110 mA
        –24 Vdc   –   150 mA
        +12 Vdc   –   180 mA
        –12 Vdc   –   75 mA

    b. For equipment ranges and accuracies, see reference 4.

6. Series 85 MCA

    a. Electrical Power Requirements: 105 to 125 volts AC 50–65 Hz.
    b. Equipment Range and Accuracy varies with connected equipment.

4.0 FREQUENCY OF CALIBRATION

4.1 Energy/Efficiency Calibration: prior to initial use as stand-alone unit, monthly

4.2 Energy Calibration Check: daily when in use

5.0 MATERIALS NEEDED

5.1 Materials Needed for Calibration

1. Mixed gamma source, in the selected geometry, with at least 3 prominent peaks in calibration range.

2. Source calibration sheet for mixed gamma source.

3. Mixed gamma point source.

5.2 Materials Needed for Operation

Container for sample in the same geometry as the calibration standard.

6.0 PRECAUTIONS

1. High voltage to the detector should be applied slowly to avoid damage to the HPGE detector.

2. Do not collect data while filling dewar with LN_2.

3. Wait 1 hour after inital power up to allow warm up and stabilization of components.

4. Samples must be counted in the same geometry as the calibration standard.

5. An 8 hour soak period must be observed when initially cooling down a detector before applying voltage.

6. Do not reset High Voltage on LN_2 monitor with high voltage applied to detector.

7.0 CALIBRATION

7.1 Energy/Efficiency Calibration

Report all data for the individual step on the Chemistry Equipment Calibration Log Sheet (Attachment 1).

1. Setup

    a. Ensure power is available to MCA components by checking that NIM POWER switch in ON.
    b. Ensure power is applied to the MCA by checking that the power switch located on the rear of the MCA is in the ON position.
    c. Turn on the LN_2 monitor, if not already energized, by placing the power switch to the ON position.
    d. Check that dewar weight is above the low level setting and that the potentiometer for the high voltage is at zero. Reset the High Voltage on the LN_2 Monitor by pressing the reset button.
    e. Set up the components of the MCA as per Attachment 1.
    f. Place the H.V. POWER SUPPLY switch to ON. Very slowly increase the high voltage to the required setting (50 volts every 5 seconds for the first 500 volts then 100 volts every 5 seconds thereafter).

        NOTE: Use the scale on the potentiometer not the meter. The meter is not accurate and should be used for indication only.

    g. Check the most recent completed Attachment 1 for FINE GAIN setting. Record actual reading on Attachment 1.

h. Check the date and time displayed on MCA. If date and
time need to be changed, turn FUNCTION switch to STATUS
and press SELECT. If date and time displayed are correct,
go to step 1.

i. Press No. This will move the flashing "*" at the top of
the MCA screen to the time position. Enter the correct
time in the form XX-XX and press STORE. (Ex. 16-57)

j. Press NO again to change the date. This will move the
flashing "*" to the date positon. Enter the correct date
in the form day-month-year and press STORE. (Ex. 1-12-82)

k. Press YES.

l. The display at the top of the MCA screen immediately after
the Task # should be blank. If there is a "R" there, turn
the FUNCTION switch to ADC and press SELECT. Press NO.
Press YES three times. Press NO.

2. Turn FUNCTION switch to PRESET. Press SELECT.

3. Press NO. Enter 2000 and press STORE. Press YES two times.

4. Place calibration source in the desired geometry for samples
to be counted and close shield. Record geometry and shelf
position on Attachment 1.

5. Press COLLECT. Check that the TIME display at the top of
the MCA screen is counting the time. The left cursor should
be moving upward slowly.

6. After the count has stopped, press PEAK. The display should
show a flashing SEARCHING. When the disp   changes to a
flashing FINISHED, press PEAK again.

7. Peaks used for calibration should have at least 10,000 counts.
To check peaks, press LEFT CURSOR and then press the direc-
tional arrows to move the cursor to the selected peak. The
counts will be the bottom number on the lower left of the MCA
screen. Press HOME and LEFT CURSOR after examining peaks.

    NOTE: A minimum of three peaks must be used for the cali-
             bration equation. Inadequate count rates may be
             improved by selecting a large count time.

8. Press ENERGY CALIB. Press NO. Press YES three times.

9. Press INDEX until the cursors bracket the lowest energy
peak to be used for calibration. Press YES. Wait for peak
to be found.

10. Enter the nuclide's energy for that peak by pressing the approriate numbers on the key pad and then press STORE Press YES.

11. Press INDEX until the cursors bracket the next higher energy peak to be used for calibration. Press YES. Wait for peak to be found.

12. Enter the nuclide's energy for that peak by pressing the appropriate numbers on the key pad and then press 'STORE'. Press YES.

13. Repeat steps 10 and 11 until all calibration peaks have been entered. Press NO.

14. Press ENERGY CALIB. two times. The calibration energy equation will be displayed at the top of the MCA screen. There should be at least 5 orders of magnitude difference between the first term and the second. The second term should be approximately .5 KEV/CH ± .05 KEV/CH. Record first and second terms on Attachment 1.

15. If the equation is satisfactory press YES two times. If the equation is not satisfactory reperform Section 7.1. If equation is not satisfactory the second time inform the Chemistry Unit Supervisor.

16. Press FFF CALIB. Press YES.

17. Press NO until the flashing "*" is next to the dimensional units desired. If the dimensional unit is EACH, press YES.

18. If the dimensional unit selected in step 16 was not EACH, use the keypad to enter the sample size for the units selected (maximum 999.99). Press STORE. Press YES.

19. Press INDEX until the cursors bracket the lowest energy peak to be used for calibration. Press YES. Wait for peak to be found.

20. Using the keypad, enter the nuclide's activity in gammas per second from the source calibration sheet. Press STORE.

21. Press *. Enter the isotope half-life in days by using the keypad. Press STORE.

22. Press *. Enter the reference source age in days from the source calibration sheet by using the keypad. Press STORE. Press YES two times.

23. Press INDEX until the cursors bracket the next higher energy peak to be used for calibration. Press YES. Wait for peak to be found.

24. Repeat steps 20 through 23 until all calibration peaks have been entered. Press NO.

    NOTE: An incorrect entry can be erased when the asterisk prompt is at G/SEC or at EFFNCY by pressing NO.

25. After satisfactory calibration, affix a calibration sticker to the Jupiter cabinet with the following information.

    a. Date calibrated
    b. Date next calibration due
    c. Initials of person performing calibration

7.2 Energy Calibration Check

Report all data for the individual step on the Chemistry Equipment Log Sheet (Attachment 2).

1. Ensure the MCA has been calibrated by checking the light over the ENERGY CALB pad. If the light is out, indicating no energy calibraton, check the calibration memory by pressing ENERGY CALIB. If an energy equation appears, check the equation with the most recent calibration record (Attachment 1). If the equation does not match Attachment 1 or no equation appears, calibrate the MCA using Section 7.1. If the equation matches Attachment 1, press YES two times. Check all other settings for MCA per most recent Attachment 1.

2. Turn FUNCTION switch to PRESET. Press SELECT.

3. Press NO. Enter 600 and press STORE. Press YES two times.

4. Press ENTER FACTOR.

5. Press NO twice. Press YES.

6. Press NO. Press YES three times.

7. Place Mixed gamma point source in shield.

8. Press CLEAR and DATA at the same time. Press YES.

9. Press HOME. Press CLEAR ROI.

10. If light over INTENS pad is lit, press INTENS.

11. Press COLLECT.

12. When collect is finished press PEAK. When FINISHED flashes on top portion of MCA screen press PEAK again.

13. Press INDEX. Press PEAK. Compare peak energy to that listed on Attachment 2 and record full with half maximum (FWHM) in space provided.

14. Press ISO ID. Check nuclide name to the associated energy level on Attachment 2.

15. Press ISO ID twice.

16. Repeat Steps 13 through 15 until all peaks have been recorded. Remove Mixed gamma point source from shield, return source to proper storage location.

17. Press ENTER FACTOR.

18. Press NO twice. Press YEARS four times.

19. On the calibration calendar (see FIGURE 1) attached to the Jupiter cabinet, record the initials of the individual performing the Energy Calibration Check.

8.0 OPERATION

1. Connect the LA 120 to the MCA as follows:

   a. Disconnect Terminal Interface Cable from LA-120.
   b. Connect VT-100 jumper from LA-120 to EIA-J115 connection on the MCA rear panel.
   c. Press and hold SETUP. Press BAUD until 300 is displayed on the digital readout.

      NOTE: The LA 120 must be reconnected to the Terminal Interface Cable prior to Booting up the Computer. Reset BAUD to 9600 per Step 1.c.

2. Ensure MCA has been calibrated by checking the light over the ENERGY CALIB pad. If the light is out, indicating no energy calibration, check the calibration memory by pressing ENERGY CALIB. If an energy equation appears, check the equation with the most recent calibration record (Attachment 1). If the equation does not match the record or no equation appears, calibrate the MCA using Section 7.1. If the equation matches Attachment 1, press YES two times.

3. Press CLEAR and DATA at the same time. Press YES.

4. Press HOME. Press CLEAR ROI. Press INTENS.

5. Place sample in shield.

   NOTE: Only geometry and shelf listed on Attachment 1 can be used for operation if ISO QUAN is required.

6. If the count time needs to be changed turn the FUNCTION switch to PRESET. Go to Step 7 if there is no count time change. Press SELECT. Press NO.

7. Enter the count time listed in Attachment 4 for the calibrated geometry to be used. Press YES two times.

8. Press COLLECT.

9. Press ENTER FACTOR. Press NO three times. Press YES.

10. Enter the decay time in days by using the keypad. Press STORE. If no decay correction is desired enter zero and press STORE. Press YES two times.

11. When collect is finished press PEAK. When FINISHED flashes on top portion of MCA screen press PEAK again.

12. Press READ OUT.

13. Press NO. Press 2, press STORE.

14. Press NO. Press YES six times.

15. Press No. Press YES.

16. After printout is complete remove sample from shield.

9.0 REFERENCES

1. Canberra 81-82 Product Catalog.

2. Canberra Operations Manual, Series 85 MCA.

3. Applied Physical Technology, Inc. Liquid Nitrogen Level Monitor Operator's Manual.

4. Canberra Spectroscopy Amplifier Model 2020 Instruction Manual, Rev. B-C.

5. Canberra High Voltage Power Supply, Model 3105, Instruction Manual.

6. Canberra Operator's Manual, Model 2000 Bin/Power Supply.

10.0 ATTACHMENTS

10.1 Attachment 1 - Form: OM12C: CHI-12-1 (Sheets a-c), Multi-Channel Analyzer, Canberra Series 85, Energy/Efficiency Calibration.

10.2 Attachment 2 - Form: OM12C: CHI-12-2 (Sheets a-b), Multi-Channel Analyzer, Canberra Series 85, Energy Calibration Check.

10.3 Attachment 3 - Figure 1, Form #5197, Calibration Calendar.

Perry Nuclear Power Plant

Chemistry Equipment Calibration Log Sheet

<u>Multi-Channel Analyzer, Canberra Series 85, Energy/Efficiency Calibration</u>

MPL Number _____

Frequency <u>Prior to use as stand-alone unit, monthly</u>

OM12C: CHI- <u>12</u>　　　Section <u>7.0</u>　　　Subsection <u>7.1</u>

Date Done _____　　　Date Next Due _____　　　Standard Use _____

	Parameter	Setting	Conformance	Nonconformance	As Found	As Left
Step 1e	COARSE GAIN	30				
	INPUT POLARITY	+				
	SHAPING MULTIPLIER	x1				
	SHAPING TIME	4				
	RESTORER RATE	AUTO				
	RESTORER MODE	ASYM				

<u>Remarks:</u>　　　　　　　　　　Performed By: _____

　　　　　　　　　　　　　　　Reviewed By: _____

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Attachment 1
Form: OM12C: CHI-12-1a
Sheets a-c

Perry Nuclear Power Plant

Chemistry Equipment Calibration Log Sheet

<u>Multi-Channel Analyzer, Canberra Series 85, Energy/Efficiency Calibration</u>

MPL Number _____

Frequency <u>Prior to use as stand-alone unit, monthly</u>

OM12C: CHI- <u>12</u>   Section <u>7.0</u>   Subsection <u>7.1</u>

Date Done _____   Date Next Due _____   Standard Use _____

	Parameter	Setting	Conformance	Nonconformance	As Found	As Left
	THRESHOLD	AUTO				
	PUR	ON				
	ADC/SCA ULD	10.0				
	ADC/SCA LLD	0.10				
	ADC GATE	ANTI				
	VERTICAL RANGE	AUTO, LOG				

<u>Remarks:</u>

Performed By: _____

Reviewed By: _____

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Attachment 1 (Cont.)
Form: OM12C: CHI-12-1b

Perry Nuclear Power Plant

Chemistry Equipment Calibration Log Sheet

<u>Multi-Channel Analyzer, Canberra Series 85, Energy/Efficiency Calibration</u>

MPL Number _____

Frequency <u>Prior to use as stand-alone unit, monthly</u>

OM12C: CHI- <u>12</u>   Section <u>7.0</u>   Subsection <u>7.1</u>

Date Done _____   Date Next Due _____   Standard Use _____

	Conformance	Nonconformance	As Found	As Left
Step 1f - Hight Voltage setting (NOTE 1)				
Step 1g - FINE GAIN (NOTE 2)				
Step 4 - Geometry	NA	NA	NA	
SHELF POSITION	NA	NA	NA	
Step 14 - First term/Second term			NA	

<u>Remarks:</u>   Performed By: _____

                                         Reviewed By: _____

NOTE 1:   High Voltage required setting is posted for the current in-use detector on the front
          of the UCA cabinet, beside the 3105 High Voltage Power Supply.
NOTE 2:   Value for FINE GAIN can only be changed under direction of the Chemistry Unit Supervisor.

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Attachment 1 (Cont.)
Form: OM12C: CHI-12-1c

Perry Nuclear Power Plant

Chemistry Equipment Calibration Log Sheet

<u>Multi-Channel Analyzer, Canberra Series 85, Energy Calibration Check</u>

MPL Number _____

Frequency <u>Daily when in use</u>

OM12C: CHI- <u>12</u>   Section <u>7.0</u>   Subsection <u>7.2</u>

Date Done _____   Date Next Due _____   Standard Use _____

	KEV ±1KEV	ISOTOPE	Conformance	Nonconformance	As Found	FWHM
Step 14	88.0	CD-109				
	122.0	CO-57				
	165.8	CE-139				
	279.0	HG-203				
	391.6	SN-113				
	514.0	SR-85				

<u>Remarks:</u>

Performed By: _____

Reviewed By: _____

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Attachment 2
Form: OM12C: CHI-12-2a
Sheets a-b

Perry Nuclear Power Plant

Chemistry Equipment Calibration Log Sheet

<u>Multi-Channel Analyzer, Canberra Series 85, Energy Calibration Check</u>

MPL Number _____

Frequency ____Daily____

OM12C: CHI- __12__   Section __7.0__   Subsection __7.2__

Date Done _____   Date Next Due _____   Standard Use _____

KEV ±1KEV	ISOTOPE	Conformance	Nonconformance	As Found	FWHM
661.5	CS-137				
898.0	Y-88				
1173.0	CO-60				
1332.5	CO-60				
1836.0	Y-88				

<u>Remarks:</u>

Performed By: _____

Reviewed By: _____

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Attachment 2 (Cont.)
Form: OM12C: CHI-12-2b

Calibration Calendar

MONTH
AND
YEAR

1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

NO. 5197

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FIGURE 1

PROCEDURES FOR THE DETERMINATION OF THE EXTENT OF CORE DAMAGE UNDER ACCIDENT CONDITIONS

C. C. LIN

GENERAL ⊛ ELECTRIC

PROCEDURES FOR THE DETERMINATION OF THE
EXTENT OF CORE DAMAGE UNDER ACCIDENT CONDITIONS

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GENERAL ⚛ ELECTRIC

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CONTENTS

APPENDICES

TABLES

ILLUSTRATIONS

1. OBJECTIVE AND SCOPE

The purpose of this procedure is to determine the degree of reactor core damage from the measured fission product concentrations in either the water or gas samples taken from the primary system under accident conditions. The procedure involves calculations of fission product inventories in the core and the release of inventories into the primary system under postulated loss-of-coolant accident (LOCA) conditions. The fuel gap fission products are assumed to be released upon the rupture of fuel cladding. The majority of fission product inventories in the fuel rods would be released when the fuel is melted at higher temperatures. A BWR-6/238 with a Mark III containment is used as a reference plant in the demonstration of this procedure. Application of the procedure for any other type or size of boiling water reactor (BWR) is described.

2. PROCEDURES FOR DETERMINATIONS OF CORE DAMAGE

2.1 REFERENCE PLANT (BWR-6/238, MARK III)

2.1.1 Reference Plant Parameters

The pertinent plant parameters for the reference plant are given below:

Rated reactor thermal power	3579 MWt
Number of fuel bundles	748 bundles
Total primary coolant mass (reactor water plus suppression pool water)	3.92×10^9 g
Total containment and drywell gas space volume	4.0×10^{10} cc

The fission product inventories in the core are calculated based on three years (1095 days) of continuous operation at 3651 MWt, or 102% of rated power, by using a computer code developed at Los Alamos and adapted to the GE computer system.[1] The inventories of some major fission products in the core at the time of reactor shutdown are given in Table 1.

2.1.2 Procedure

Either the gas or water samples taken from the post accident sampling system are analyzed for major fission product concentrations by gamma ray spectrometry. If the concentration of a fission product in reactor water or drywell, corrected the decay to the time of reactor shutdown, is measured to be higher than the baseline concentration shown in Table 2 (see Section 3.1 for details), the extent of fuel or cladding damage can be determined directly from Figures 1 through 4 based on isotopes I-131, Cs-137, Xe-, , and Kr-85. Measurements of Cs-137 and Kr-85 activities are not very likely until the reactor has been shut down for longer than a few weeks and most of the shorter-lived isotopes have decayed.

Table 1

CORE INVENTORY OF MAJOR FISSION PRODUCTS IN A REFERENCE PLANT OPERATED AT 3651 MWt FOR THREE YEARS

Chemical Group	Isotope*	Half-Life	Inventory** 10^6 Ci	Major Gamma Ray Energy (Intensity) KeV (γ/d)
Noble gases	Kr-85m	4.48h	24.6	151(0.753)
	Kr-85	10.72y	1.1	514(0.0044)
	Kr-87	76.3m	47.1	403(0.495)
	Kr-88	2.84h	66.8	196(0.26),1530(0.109)
	Xe-133	5.25d	202.0	81(0.365)
	Xe-135	9.11h	26.1	250(0.899)
Halogens	I-131	8.04d	96.0	364(0.812)
	I-132	2.3h	140	668(0.99,773(0.762)
	I.133	20.8h	201	530(0.86)
	I-134	52.6m	221	847(0.954),884(0.653)
	I-135	6.61h	189	1132(0.225),1260(0.286)
Alkali Metals	Cs-134	2.06y	19.6	605(0.98),796(0.85)
	Cs-137	30.17y	12.1	662(0.85)
	Cs-138	32.2m	178.0	463(0.307),1436(0.76)
Tellurium Group	Te-132	78.2h	138	228(0.88)
Noble Metals	Mo-99	66.02h	183	740(0.128)
	Ru-103	39.4d	155	497(0.89)
Alkaline Earths	Sr-91	9.5h	115	750(0.23),1024(0.325)
	Sr-92	2.71h	123	1388(0.9)
	Ba-140	12.8d	173	537(0.254)
Rare Earths	Y-92	3.54h	124	934(0.139)
	La-140	40.2h	184	487(0.455),1597(0.955)
	Ce-141	32.5d	161	145(0.48)
	Ce-144	284.3d	129	134(0.108
Refractories	Zr-95	64.0d	161	724(0.437),757(0.553)
	Zr-97	16.9h	166	743(0.928)

*Only the representative isotopes which have relatively large inventory and considered to be easy to measure are listed here.

**At the time of reactor shutdown.

Table 2

FISSION PRODUCT CONCENTRATIONS IN REACTOR WATER
AND DRYWELL GAS SPACE DURING REACTOR SHUTDOWN UNDER NORMAL CONDITIONS

Isotope	Reactor Water, μCi/g		Drywell Gas (μCi/cc)	
	Upper Limit	Nominal	Upper Limit	Nominal
I-131	29	0.7	---	---
Cs-137[c]	0.3[a]	0.03[b]	---	---
Xe-133	---	---	10^{-4}[a]	10^{-5}[b]
Kr-85	---	---	4×10^{-5}[a]	4×10^{-6}[b]

[a] Observed experimentally, in an operating BWR-3 with MK I containment, data obtained from GE unpublished document, DRF 268-DEV-0003.

[b] Assuming 10% of the upper limit values.

[c] Release of Cs-137 activity would strongly depend on the core inventory which is a function of fuel burnup.
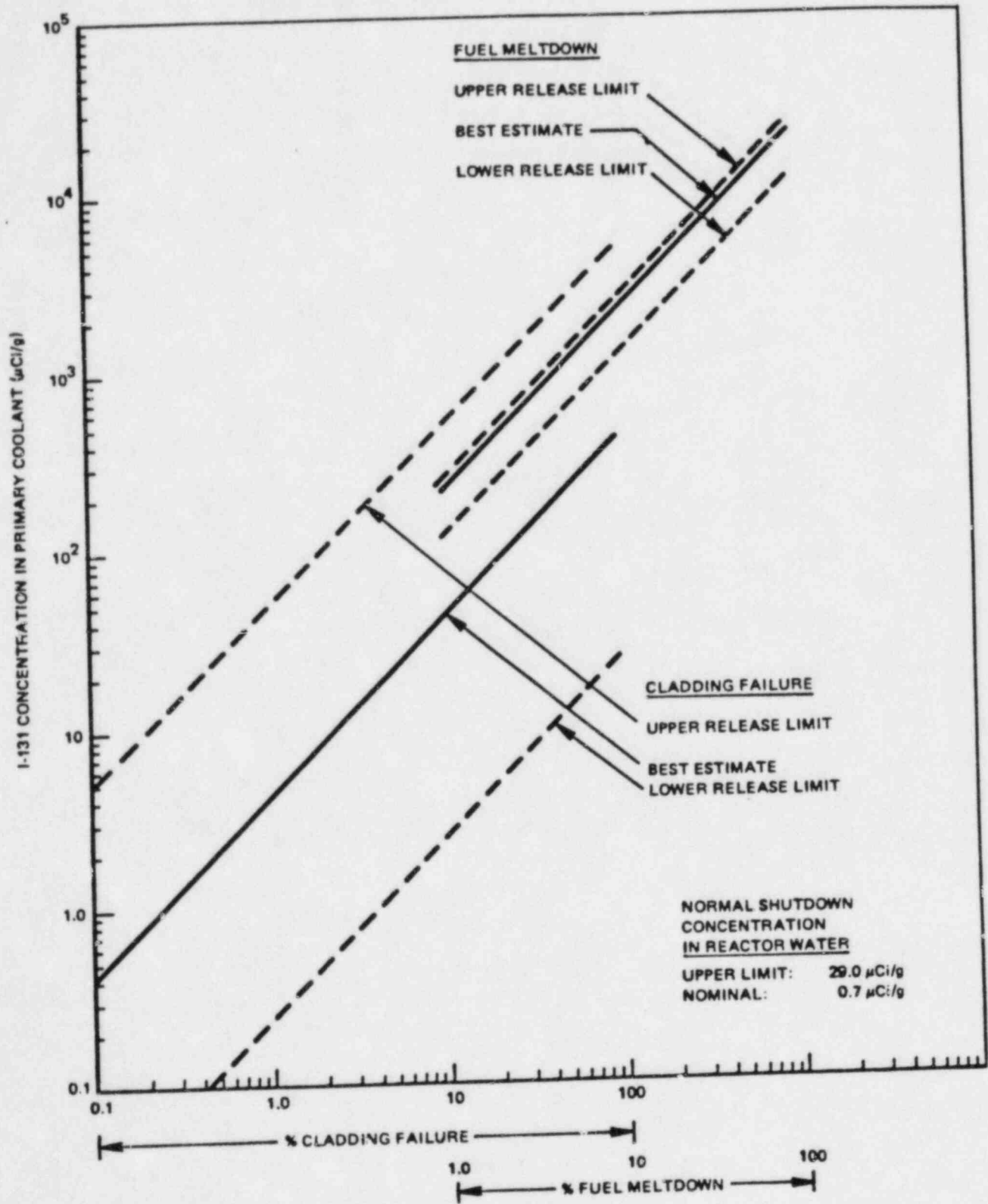
Figure 1. Relationship Between I-131 Concentration in the Primary Coolant (Reactor Water + Pool Water) and the Extent of Core Damage in Reference Plant
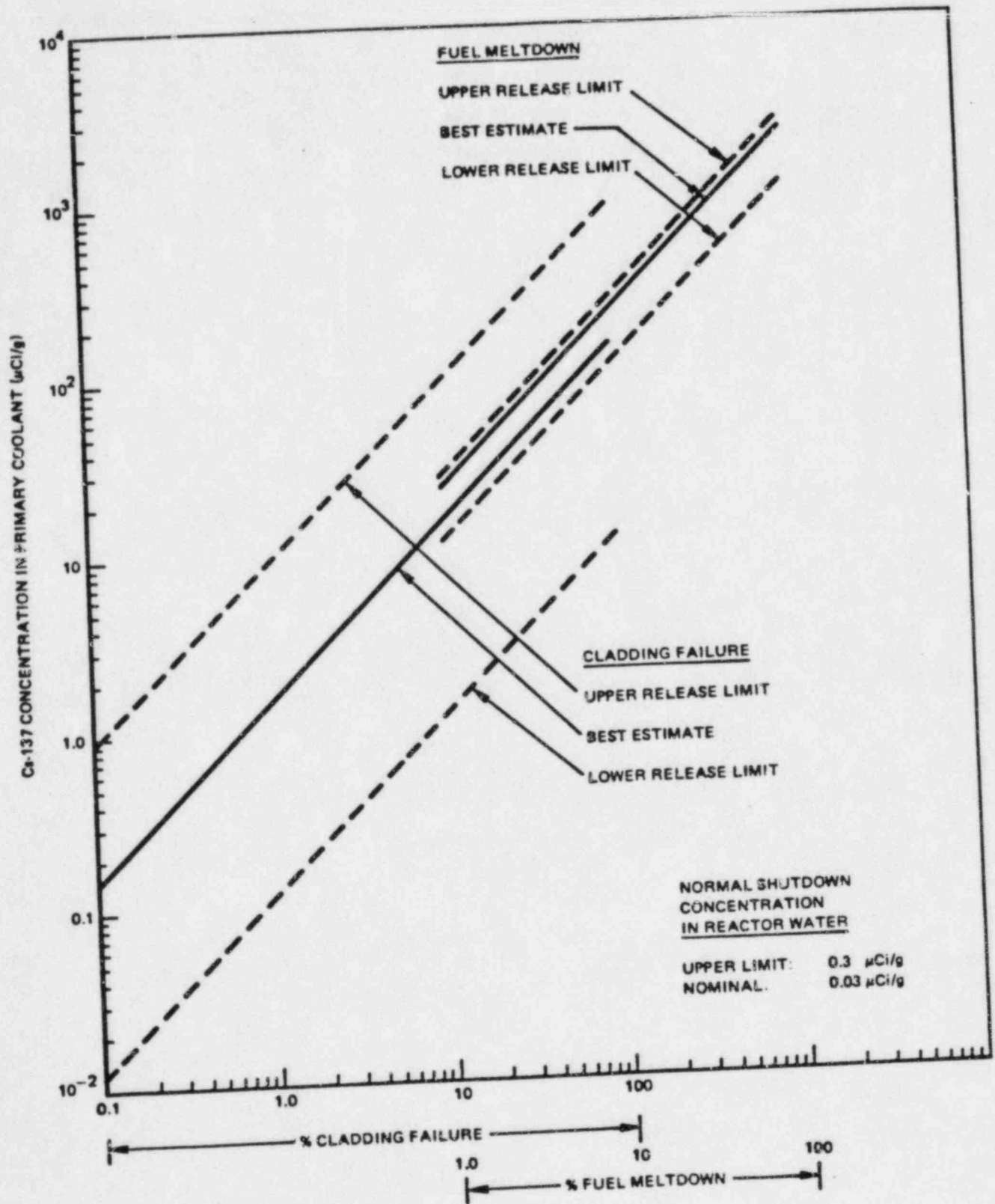
Figure 2. Relationship Between Cs-137 Concentration in the Primary Coolant (Reactor Water + Pool Water) and the Extent of Core Damage in Reference Plant

Figure 3. Relationship Between Xe-133 Concentration in the Containment Gas (Drywell + Torus Gas) and the Extent of Core Damage in Reference Plant

Figure 4. Relationship Between Kr-85 Concentration in the Containment Gas (Drywell + Torus Gas) and the Extent of Core Damage in Reference Plant
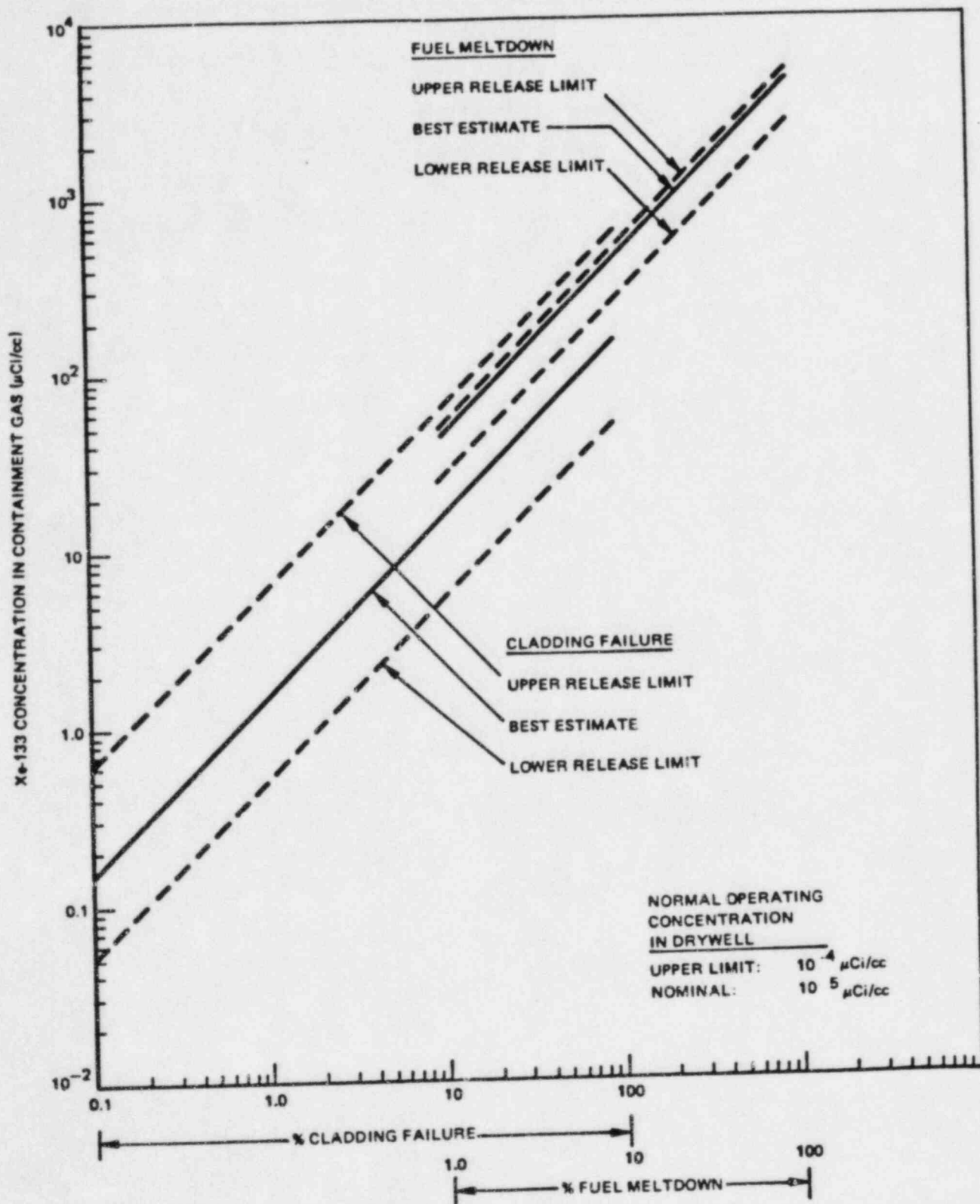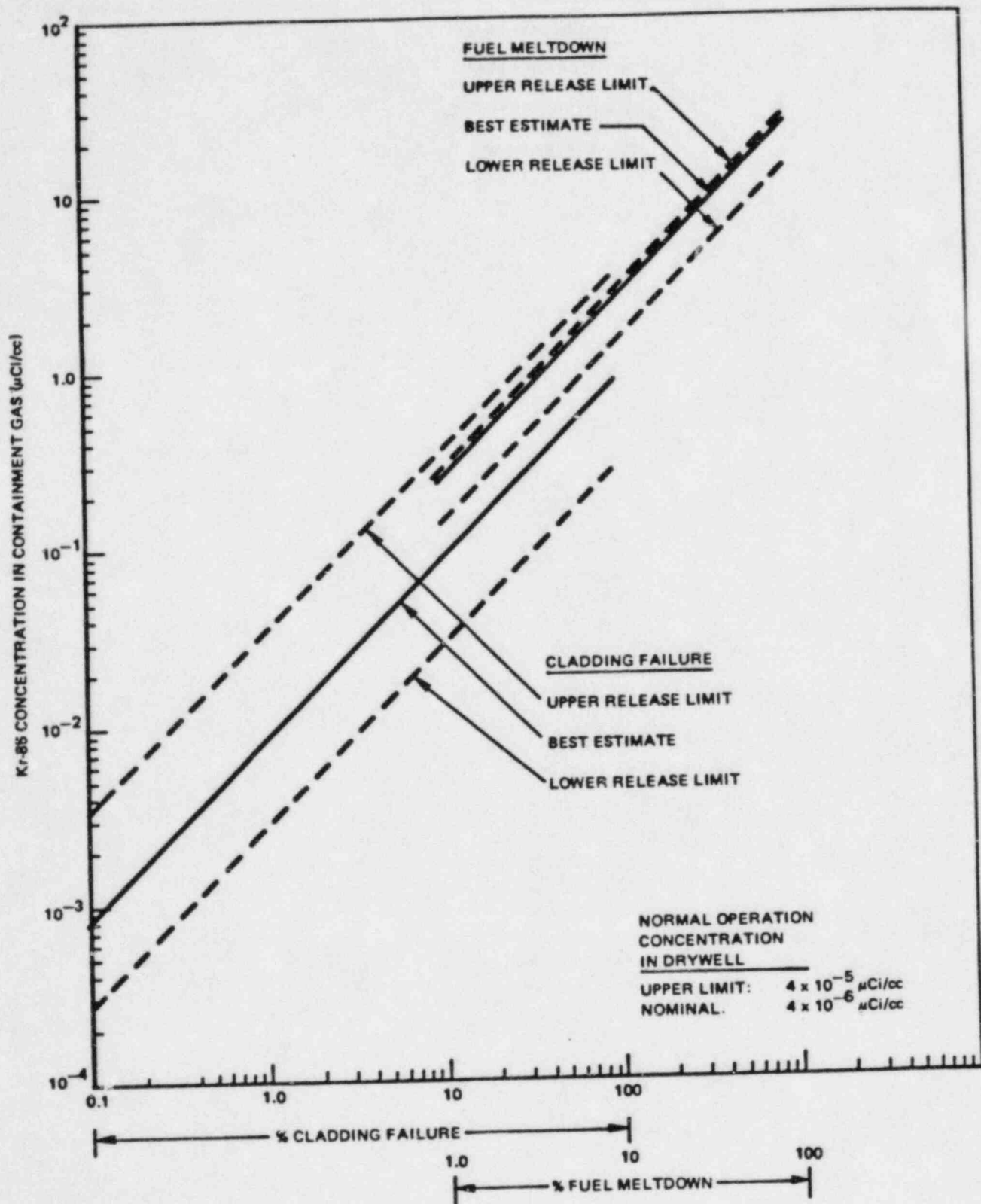
If the concentration falls into the range where release of the fission product from the fuel gap or the molten fuel cannot be definitively determined, additional data may be needed to determine the source of fission product release (see below).

It is recommended that both the water and gas phase samples be measured in order to reduce the uncertainty in core damage estimations.

2.1.3 Supplementary Data

In addition to the longer-lived isotopes, some shorter-lived isotope concentrations may be measured in the sample. The ratios of isotopes released from either the fuel gap or the molten fuel are significantly different as shown in Table 3 (see Section 3.3 for details), thus the source (fuel or gap) of release may be identified. Furthermore, some less volatile elements in the core may also start to release as the fuel starts to melt. If the less volatile fission products, such as isotopes of Sr, Ba, La, and Ru (either soluble or insoluble), are found to have unusually high concentrations in the water sample, some degree of fuel melting may be inferred. In a mixture of fission products 2.7h Sr-92 (1.384 MeV) and 40h La-140 (1.597 MeV) should be relatively easy to identify and measure from a gamma ray spectrum. More work, however, is needed to establish the baseline concentrations for those isotopes.

2.2 SPECIFIC PLANT APPLICATION

2.2.1 Plant Parameters

The pertinent reactor parameters for selected plants currently being retrofitted with the post accident sampling system are tabulated in Table 4.[2] Similar information is available for all BWRs.

Table 3

RATIOS OF ISOTOPES IN CORE INVENTORY AND FUEL GAP

Isotope	Half-Life	Activity Ratio* in Core Inventory	Activity Ratio* in Fuel Gap
Kr-87	76.3 m	0.233	0.0234
Kr-88	2.84h	0.33	0.0495
Kr-85m	4.48h	0.122	0.023
Xe-133	5.25d	1.0*	1.0*
I-134	52.6 m	2.3	0.155
I-132	2.3 h	1.46	0.127
I-135	6.61h	1.97	0.364
I-133	20.8 h	2.09	0.685
I-131	8.04d	1.0*	1.0*

*Ratio $= \dfrac{\text{noble gas isotope concentration}}{\text{Xe-133 concentration}}$ for noble gases

$= \dfrac{\text{Iodine isotope concentration}}{\text{I-131 concentration}}$ for iodines

Table 4
PLANT PARAMETERS[2]

Plant	Reactor Type/ Containment Design	Rated Power (MWt)	Primary Coolant*		Containment Gas*	
			Reactor Water Mass $(10^8$ g)	Suppression Pool Water $(10^9$ g)	Drywell Gas Volume $(10^9$ cc)	Torus/ Containment Gas Volume $(10^9$ cc)
Standard	BWR 6/III	3579	2.46	3.67	7.77	32.5
Brunswick-1/2	BWR 4/I	2436	2.14	2.48	4.65	3.46
Chinshan-1/2	BWR 4/I	1775	1.76	1.93	3.68	2.69
Cofrentes	BWR 6/III	2894	2.04	3.14	6.91	32.43
Cooper	BWR 4/I	2380	2.00	2.48	3.75	3.03
Dresden-2/3	BWR 3/I	2527	2.61	3.18	4.48	3.30
Duane Arnold	BWR 4/I	1593	1.45	1.67	2.67	2.67
Fermi-2	BWR 4/I	3293	2.77	3.23	4.64	3.71
Fitzpatrick	BWR 4/I	2436	2.14	3.00	4.37	3.20
Hanford-2	BWR 5/II	3323	2.74	3.17	5.75	4.08
Hatch-1	BWR 4/I	2436	2.00	2.47	4.07	3.20
Hatch-2	BWR 4/I	2436	2.00	2.47	4.12	3.11
Hope Creek-1/2	BWR 4/I	3293	2.93	3.34	4.79	3.78
Kuo sheng-1/2	BWR 6/III	2894	2.04	3.74	6.74	40.50
Limerick-1/2	BWR 4/II	3293	2.93	3.63	6.66	4.23
Millstone-1	BWR 3/I	2011	2.05	2.78	4.16	3.06
Monticello	BWR 3/I	1670	1.75	1.93	3.80	2.76
NMP-1	BWR 2/I	1850	2.17	2.34	5.10	3.33
Oyster Creek	BWR 2/I	1933	2.05	2.32	5.10	3.85
Peach Bottom-2/3	BWR 4/I	3293	2.67	3.48	4.98	3.62
Pilgrim	BWR 3/I	1998	2.05	2.38	4.16	3.18
Susquehanna-1/2	BWR 4/II	3293	2.92	3.60	6.79	4.36
Vermont Yankee	BWR 4/I	1593	1.77	1.93	3.79	3.18

---

*Total Primary Coolant Mass = Reactor Water + Suppression Pool Water

Total Containment Gas Volume = Drywell Gas + Torus (or Primary Containment in Mark III gas

2.2.2 Procedure

The extent of core damage in an operating BWR can be determined by comparing the measured concentrations of major fission products in either the gas or water samples, after appropriate normalization, with the reference plant data. The following procedure is recommended.

1. Obtain the samples from the post accident sampling system, and the concentration of a fission product i (C_{wi} in water or C_{gi} in gas is determined).

2. Correct the measured concentration for decay to the time of reactor shutdown.

3. Correct the measured gaseous activity concentration for temperature and pressure difference in the sample vial and the containment (torus) gas phase (see footnote on Page 2-12).

4. Calculate the fission product inventory correction factor (Section 2.2.2.2).

5. Calculate the plant parameter correction factor (Section 2.2.2.3).

6. By using the correction factors, calculate the normalized concentration, C_{wi}^{Ref} or C_{gi}^{Ref} (Section 2.2.2.1).

7. Use Figures 1 through 4 to estimate the extent of fuel or cladding damage.

2.2.2.1 Comparison with Reference Plant Data

The extent of core damage can be estimated from the measured fission product concentrations in either the gas or water samples, as described for the reference plant. However, the measured concentration must be corrected

for the differences in operation power level, time of operation, primary coolant mass and containment gas volume.

$$C_{wi}^{Ref} = C_{wi} e^{\lambda_i t} \times F_{Ii} \times F_w$$

or

$$C_{gi}^{Ref} = C_{gi} e^{\lambda_i t} \times F_{Ii} \times F_g$$

where

C_{wi}^{Ref} = concentration of isotope i in the reference plant coolant (μCi/g)

C_{gi}^{Ref} = concentration of isotope i in the reference plant containment gas (μCi/cc)

C_{wi} = measured concentration of isotope i in the operating coolant at time, t (μCi/g)

C_{gi} = measured concentration of isotope i in the operating containment gas at time, t (μCi/cc)*

$e^{\lambda_i t}$ = decay correction to the time of reactor shutdown

λ_i = decay constant of isotope i (day^{-1})

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*The following correction for the measured concentration is needed if the temperature and pressure in the sample vial (T_1, P_1) are different from that in the containment (T_2, P_2):

$$C_{gi} = C_{gi(vial)} \times \frac{P_2 T_1}{P_1 T_2}$$

t = time between the reactor shutdown and the sample time (day)

F_{Ii} = inventory correction factor for isotope i (see Section 2.2.2.2)

F_g = containment gas volume correction factor (see Section 2.2.2.3)

F_w = primary coolant mass correction factor (see Section 2.2.2.3)

2.2.2.2 Inventory Correction Factor

$$F_{Ii} = \frac{\text{Inventory in reference plant}}{\text{Inventory in operating plant}}$$

$$= \frac{3651 \, (1-e^{-1095 \, \lambda_i})}{\sum_j \left[P_j \, (1-e^{-\lambda_i T_j}) \, e^{-\lambda_i T_j^0} \right]}$$

where

P_j = steady reactor power operated in period j (MWt)*

T_j = duration of operating period j (day)*

T_j^0 = time between the end of operating period j and time of the last reactor shutdown (day)

For a particular short-lived isotope, i, a calculation for only a period of ~6 half-lives of reactor operation time before reactor shutdown should be accurate enough. An example of calculation is illustrated in Appendix A. It should be pointed out that the computer calculation of core inventory takes into account the fuel burnup, plutonium fission and neutron capture reactors.

*In each period, the variation of steady power should be limited to ±20%.

The correction factor calculated from this equation may not be entirely accurate, but the error is insignificant in comparison to the uncertainties in the fission product release fractions (Table 5) and other assumptions (Section 3.2).

2.2.2.3 Plant Parameter Correction Factors

$$F_w = \frac{\text{operating plant coolant mass (g)}}{\text{reference plant coolant mass } (3.92 \times 10^9 \text{ g})}$$

$$F_g = \frac{\text{operating plant containment gas volume (cc)}}{\text{reference plant containment gas volume } (4 \times 10^{10} \text{ cc})}$$

In case the fission product concentrations are measured separately for the reactor water and suppression pool water or the drywell gas and the torus gas, the measured concentrations C_{wi} or C_{gi} would be averaged from the separate measurements:

$$C_{wi} = \frac{(\text{conc. in Rx water}) \times (\text{Rx water mass}) + (\text{conc. in pool}) \times (\text{pool water mass})}{\text{Reactor water mass + pool water}}$$

$$C_{gi} = \frac{(\text{conc. in drywell}) \times (\text{drywell gas vol}) + (\text{conc. in torus}) \times (\text{torus gas vol})}{\text{drywell gas volume + torus gas volume}}$$

Table 5
BEST-ESTIMATE FISSION PRODUCT RELEASE FRACTIONS[7,8]

	Gap Release			Meltdown Release			Oxidation Release			Vaporization Release		
	Nominal	Lower Limit	Upper Limit	Nominal	Lower Limit	Upper Limit	Nominal	Lower Limit	Upper Limit	Nominal	Lower Limit	Upper Limit
Noble Gases (Xe,Kr)	0.030	0.010	0.12	0.873	0.485	0.970	0.087	0.078	0.097	0.010	0.010	0.010
Halogens (I,Br)	0.017	0.001	0.20	0.885	0.492	0.983	0.088	0.078	0.098	0.010	0.010	0.010
Alkali Metals (Cs,Rb)	0.050	0.004	0.30	0.760	0.380	0.855	---	---	---	0.190	0.190	0.190
Tellurium Group (Te,Se,Sb)	0.0001	3×10^{-7}	0.04	0.150	0.05	0.250	0.510	0.340	0.680	0.340	0.340	0.340
Noble Metals (Ru,Rh,Pd,Mo,Tc)	---	---	---	0.030	0.01	0.10	0.873	0.776	0.970	0.005	0.001	0.024
Alkaline Earths (Sr,Ba)	1×10^{-6}	3×10^{-9}	0.0004	0.100	0.02	0.20	---	---	---	0.009	0.002	0.045
Rare Earths (Y,La,Ce,Nd,Pr, Eu,Pm,Sm,Np,Pu)	---	---	---	0.003	0.001	0.01	---	---	---	0.010	0.002	0.050
Refractories (Zr,Nb)	---	---	---	0.003	0.001	0.01	---	---	---	---	---	---

3. TECHNICAL BASIS

3.1 FISSION PRODUCT CONCENTRATIONS IN THE PRIMARY SYSTEM DURING REACTOR SHUTDOWN UNDER NORMAL OPERATION CONDITIONS

3.1.1 Fission Product Concentrations in Reactor Water

It is well known that some volatile and water soluble fission products, mainly iodine and cesium isotopes, will be released (called spiking) from defect fuel rods when the reactor is shutdown and depressurized. Based on Pasedag of NRC,[3] the maximum I-131 release would be 10 Ci per each μCi/sec release rate during normal power operation (see Appendix B). According to the GE design basis of I-131 release rate at 700 μCi/sec[4] a maximum of 7000 Ci of I-131 may be released during reactor shutdown, and the concentration in reactor water would be 29 μCi/g.

An analytical model to predict the magnitude of I-131 spiking following reactor shutdown in operating BWRs has been reported by Brutschy et al[5]. The "best estimate" concentration for I-131 has to be calculated based on the analytical mode[5] for the individual reactor according to its fuel condition (see Appendix C). However, if one adopts a standard I-131 concentration of 5×10^{-3} μCi/g or ~18 μCi/sec) as proposed by ANS[6], the nominal I-131 spiking is estimated to be ~0.7 μCi/g in the reference plant water. This concentration is consistent with an average spiking concentration observed experimentally (see Appendix C, Figure C-1).[5] The results of these estimations, including the Cs-137 concentration, have been summarized in Table 2.

Potential future research in this area will be discussed in Section 4.

3.1.2 Noble Gas Concentrations in Drywell and Torus Gas Phase

Similar to the spiking magnitude, the noble gas activities in the drywell and the torus gas may vary significantly from reactor to reactor, mainly depending on the fuel condition and the steam leakage rate. In an operating BWR when the Xe-133 release rate measured at the steam jet air ejector (SJAE)

was 1.5×10^4 μCi/sec* (compared to design basis release rate at 8200 μCi/sec), the noble gas concentrations in the drywell were determined to be $\sim 10^{-4}$ μCi/cc for Xe-133 and $\sim 4 \times 10^{-5}$ μCi/cc for Kr-85. These data may be considered as the upper limit values.

3.2 FISSION PRODUCT RELEASE SOURCE TERMS UNDER ACCIDENT CONDITIONS

The source terms for the damaged core under accident conditions have been proposed by several investigators.[7,8] The "best estimate" release source terms for different chemical groups of fission products are summarized in Table 5.

The release of fission products from the damage core has been estimated to be a function of temperature,[9] and time after the loss-of-coolant accident.[7] In the present procedure, the fraction of fission product release from the core is assumed to be proportional to the fraction of core damage as suggested by Malinauskas, et. al.[9] It is further assumed that the core is homogeneous so that each fuel rod has an identical exposure history. The fuel cladding rupture has been assumed to occur over the temperature range from about 780° to 1100°C,[9] and the entire fission product noble gas inventory in the fuel gap would be released. All other fission products in the fuel gap, which may be present in a condensed phase, or as vapor in equilibrium with a condensed phase, will not be released as quickly as noble gases until the temperature is further increased. According to a model calculation,[7] portions of the fuel may start to melt before the cladding is totally destroyed.

3.3 ISOTOPIC DISTRIBUTION IN FUEL GAP

Diffusion equations predict that the fractional release of radioactive isotopes from the fuel to the plenum and void spaces should be inversely proportional to the square root of the decay constant for isotope reaching production-decay equilibrium.[10,11] This prediction has been substantiated by experimental data reported by several investigators.[12-17] A comparison of

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*Data obtained from GE unpublished document, DRF 268-DEV00009. The fission product release pattern was found to be mostly "recoil."

isotopic distributions in the total fuel inventory and the predicted distribution for some major fission products has been shown in Table 3. Thus, by measuring the ratios of fission product activities in either the gas or water samples, the source of fission product release may be semi-quantitatively determined (see more discussion in Section 4).

3.4 ANTICIPATED CHEMICAL BEHAVIOR OF IODINE AND COOLANT CHEMISTRY UNDER ACCIDENT CONDITIONS

The results of measurements of Three Mile Island-2 (TMI-2)[18,19] indicate that the airborne radioiodine release was much lower when compared to the noble gas activity release (by a factor of $\sim 10^6$). Extensive investigations at the Oak Ridge National Laboratory (ORNL) on the nature and quantity of fission product release from the over-heated fuel have concluded that cesium iodide CsI (B.P. = 1280°C) is the primary volatile species released from the fuel at elevated temperatures.[20] The behavior of iodine under loss-of-coolant accident (LOCA) conditions has been evaluated by Lin[21] and Campbell et. al.[22]

For iodine at a concentration of a few ppm in aqueous solutions, the redox reactions should be more predictable and formations of anomalous or organic species should be much smaller than that at very low concentrations as generally assumed for radioiodine release. If iodine is released as CsI, it would stay in water as the I^- ion in a slightly basic solution (mainly due to Cs ions which may be released as elemental Cs or Cs oxides in addition to CsI). Air oxidation[23] or radiation-induced oxidation of I^- to I_2[24] is not very likely to occur in a basic solution. In addition to the reducing nature of zirconium and iron metals in the core, the production of hydrogen from Zr steam reactions should make the chemistry environment in the primary system favorable to reducing reactions for iodine.

There are at least three known volatile forms of iodine, I_2, HIO, and organic iodine. The formation of I_2 from I^- is not very likely in basic solutions. The existence of HIO has never been chemically identified due to its low stable concentration. The airborne species called HIO is one which behaves differently from I_2 and organic iodine determined by using the iodine species

sampling method developed by Keller, et. al.[25] However, some convincing evidence has been given by Lin[26] that HIO, a product of I_2 hydrolysis, is the second volatile inorganic species in the gas phase when I_2 was initially added to water in equilibrium partitioning studies. The partition coefficient increases with decreasing iodine concentration; at very low iodine concentrations, the total iodine partition coefficients have been determined to be ~8000 at 21°C and ~1600 at 72°C.[26] It must be pointed out that since both I_2 and HIO are very reactive species, any reducing impurities in water or on construction material surfaces would reduce I_2 or HIO to I^- and significantly reduce the airborne iodine concentration.

The mechanisms of converting inorganic iodine to organic iodine, which is generally observed in gas phase at very low concentrations, are largely unknown. It is certain, however, that at least more than a stoichiometric amount of organic species (or carbon-containing compounds) should be readily available for reaction with iodine. As such organic species are limited, the results of several experiments[27] indicate that the yield of organic iodine decreases with increasing iodine concentration in the gas phase. Less than 0.1% conversion is expected when the airborne iodine concentration is 1 g/m^3 or larger.[27] The total iodine concentration could be ~3 g/m^3 in the containment free air space if all iodine is assumed to become airborne. It is also important to realize that the organic iodine, e.g., CH_3I is readily hydrolyzed in water[28] and basic solutions[29] at higher temperatures. The half-time of hydrolysis is ~20 min in water at 100°C and ~3 sec at 200°C, based on Heppolette and Robertson's data.[28]

It is obvious that the very low release of iodine activities to the atmosphere in the TMI-2 accident can be easily explained in terms of the nature of iodine released from the fuel and the subsequent stabilization in water. Water plays an important role in preventing iodine from release to the atmosphere. In the present procedure, all the iodine activities are assumed to stay in water, and the airborne activities are dominated by the noble gas fission products.

The chemistry in the primary coolant may be significantly changed under accident conditions. Mainly due to the release of cesium, the water pH may increase to $\sim$10.5[21] and the water conductivity may increase from $\sim$10 μS/cm (torus water quality specification) to as high as $\sim$170 μS/cm.

4. DISCUSSION AND SUGGESTIONS FOR FUTURE WORK

It is obvious that the uncertainty of gas release fractions for iodine and cesium are too large for an accurate calculation of the extent of core damage. While additional experimental work in fuel gap measurements is apparently needed, the lower limit release fraction for iodine may be reevaluated by examining the iodine spiking release data from defective fuel rods following normal operation shutdowns.

Although the I-131 spiking data has been well documented previously[5], the analytical model may be refined to reflect more recent experimental data. The maximum spiking release of I-131 estimated by Pasedag[3], based on pre-197. data, is obviously too high, particularly when the improved fuels which are currently used in most of the operating BWRs are considered.

The accuracy of core damage estimation may be significantly improved by measuring more than iodine, cesium, and noble gas activities. Some less volatile but easy to measure isotopes of Sr, Ba, La, and Ru may be determined in the water sample. More work, however, is needed to establish the release fractions as well as the baseline (shutdown spiking) concentrations for those isotopes. Additionally, some chemical analysis data, such as hydrogen production from water-zirconium reaction may be used to improve the estimate. The degree of core damage between fuel cladding failures and core melt, namely fuel overheating, may be determined.

As mentioned in Section 3.3, it is possible to determine the source of fission product release by measuring the activity ratios of noble gases or iodine isotopes. It must be cautioned, however, each isotope should be accurately measured. Particular care must be exercised when the Xe-133 activity is determined in a mixture of other fission products with high concentration because of its low gamma ray energy (81 keV). Additional work is required to perfect this procedure.

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Appendix A

SAMPLE CALCULATION OF FISSION PRODUCT INVENTORY CORRECTION FACTOR

$$F_{Ii} = \frac{\text{Inventory of nuclide i in reference plant}}{\text{Inventory of nuclide i in operating plant}}$$

$$= \frac{3651 \, (1 - e^{-1095 \, \lambda_i})}{\sum\limits_{j} \left[P_j \, (1 - e^{-\lambda_i T_j}) e^{-\lambda_i T_j^0} \right]}$$

where

P_j = steady reactor power operated in period j (MWt)

λ_i = decay constant of nuclide i (day^{-1})

T_j = duration of operating period j (day)

T_j^0 = time between the end of operating period j and time of last reactor shutdown (day)

3651 = ave. operation power (in MWt) for the reference plant.

1095 = continuous operation time (in day) for the reference plant.

Assuming a reactor has the following power operation history:

Operation Period	Days Since Startup	Operation Time T_j (day)	T_j^0	Average Power P_j (MWt)
1A	1 - 60	60	254	1000
1B	61 - 70	---	---	0
2A	71 - 270	270	44	2000
2B	271 - 300	---	---	0
3	301 - 314	14	0	3000

- <u>For I-131 ($\lambda = 0.0862$ day^{-1})</u>

$$F_{I(I-131)} = \frac{3651(1-e^{-0.0862 \times 1095})}{1000(1-e^{-0.0862 \times 60})e^{-0.0862 \times 254} + 2000(1-e^{-0.0862 \times 200})}$$

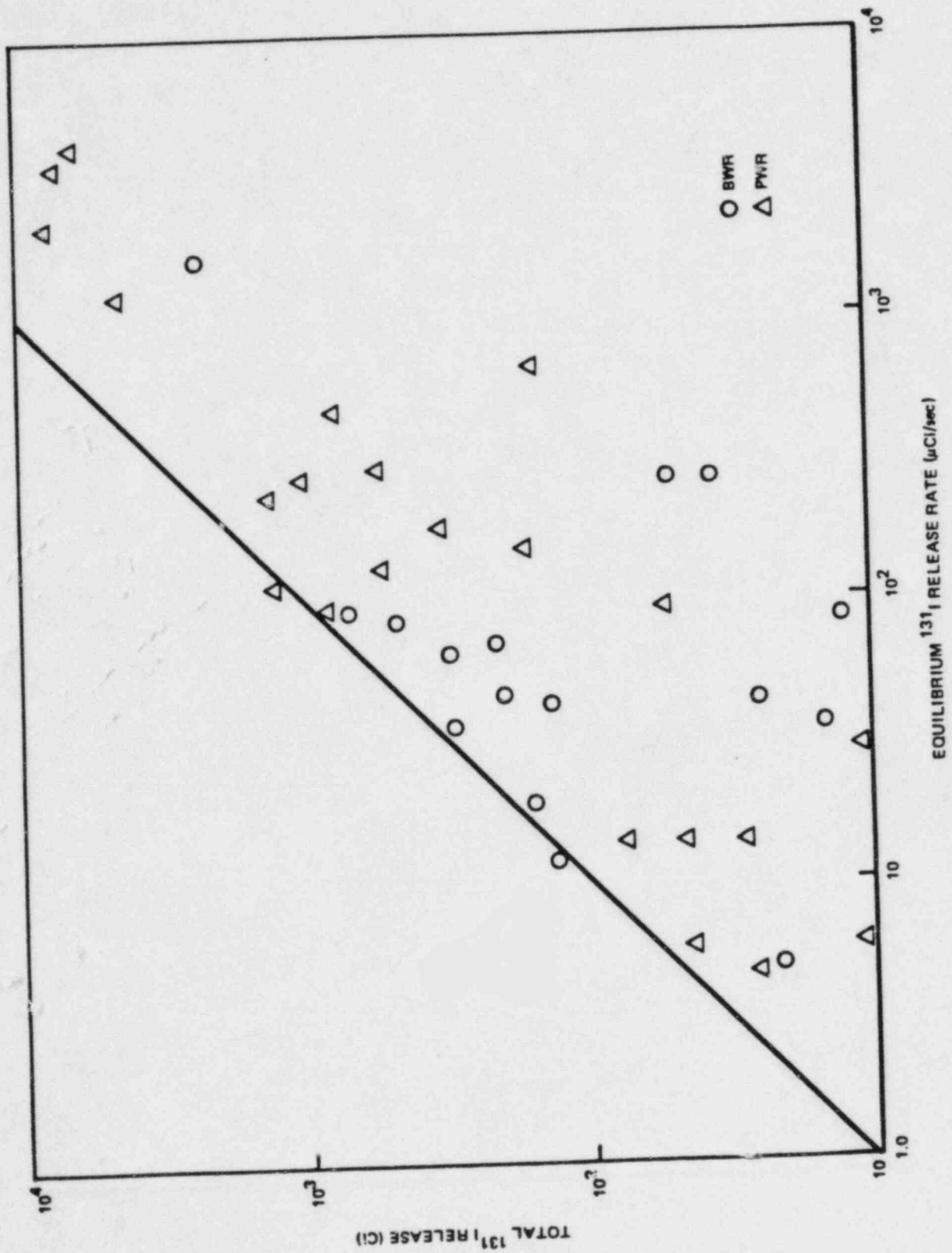$$\overline{e^{-0.0862 \times 44} + 3000(1-e^{-0.0862 \times 14})e^{-0.0862 \times 0}}$$

$$= \frac{3651}{\sim 0 + .45 + 2103} = 1.7$$

- <u>For Cs-137 ($\lambda = 6.29 \times 10^{-5}$ day^{-1})</u>

$$F_{I(Cs-137)} = \frac{3651(1-e^{-6.29 \times 10^{-5} \times 1095})}{1000(1-e^{-6.29 \times 10^{-5} \times 60})e^{-6.29 \times 10^{-5} \times 254}}$$

$$\overline{+ 2000(1-e^{-6.29 \times 10^{-5} \times 200})e^{-6.29 \times 10^{-5} \times 44}}$$

$$\overline{+ 3000(1-e^{-6.29 \times 10^{-5} \times 14})e^{-6.29 \times 10^{-5} \times 0}}$$

$$= \frac{243.16}{3.74 + 24.93 + 2.64} = 7.77$$

Appendix B
TOTAL I-131 RELEASE DURING A SPIKING SEQUENCE[4]

Appendix C

ESTIMATION OF MAXIMUM IODINE-131 SPIKE CONCENTRATION IN REACTOR WATER

The magnitude of iodine spiking in BWRs can be predicted by an empirical relationship proposed by Brutschy, et. al.[5] The data basis for the empirical relationship are shown in Figure C-1.

In order to predict the maximum I-131 concentration in reactor water (assuming no reactor water clean-up system in operation) during a shutdown spiking, the following information should be known for the reactor during steady state operation: I-131 concentration in reactor water, I-131 release source term, and the knowledge of the fission gas release characteristics.

The fission product release from the defective fuel rods in a BWR during steady operation is empirically characterized by

$$A_i (Ci/sec) = KY_i \lambda_i^{1-b}$$

or

$$R_i (fission/sec) = \frac{A_i}{Y_i \lambda_i} = K\lambda_i^{-b}$$

where

R_i = fission product release source term

K = a dimensional constant establishing the level of release

b = a dimensionless constant establishing the relative amount of each nuclide in the mixture of similar chemical groups, i.e., noble gases or iodine isotopes.
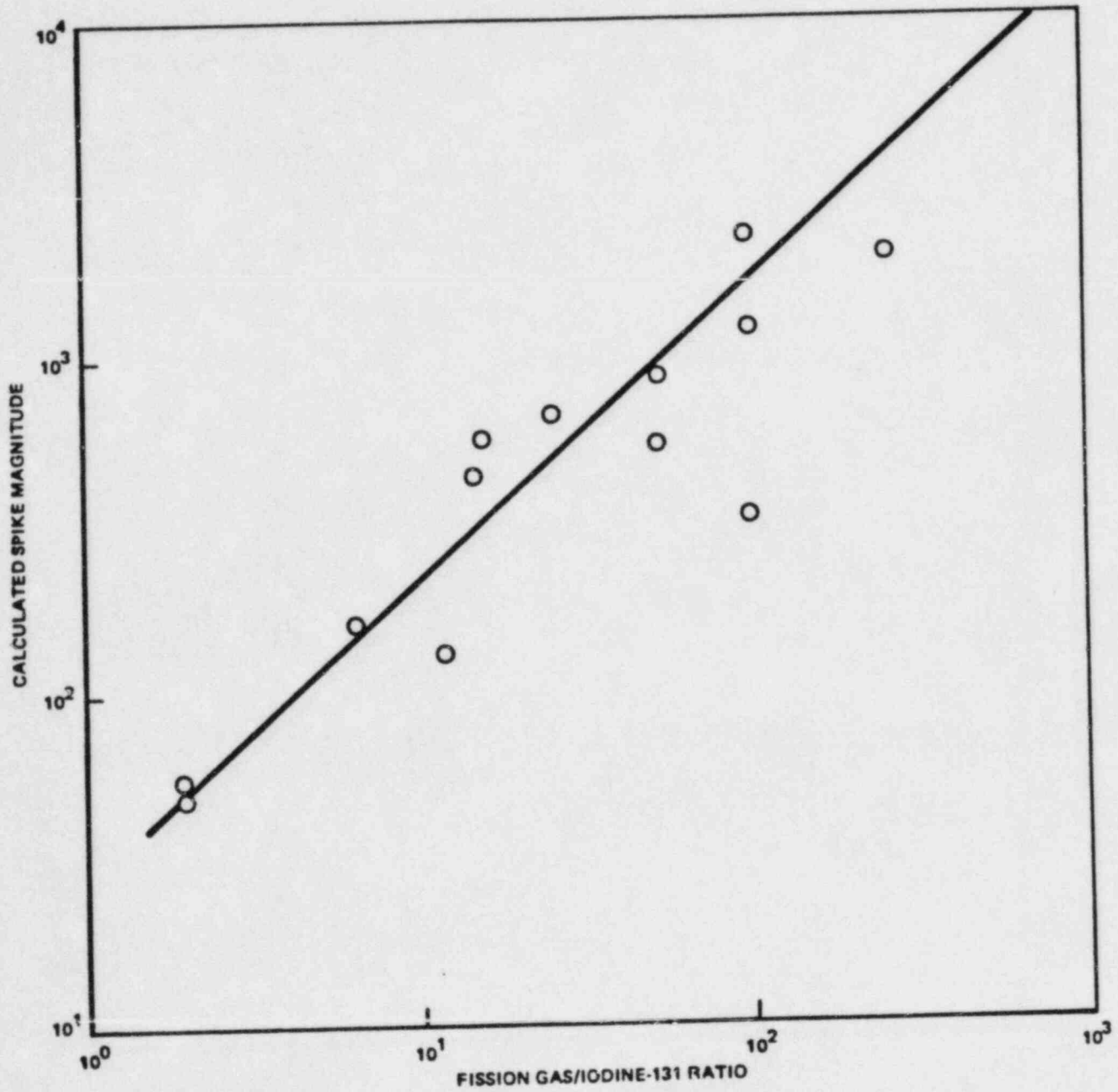
Figure C-1. Fission Gas to Iodine-131 Ratio versus Calculated Spike Magnitude[5] (Assuming one peak, and cleanup system out of service)

By plotting $A_i/Y_i\lambda_i$ against λ_i for noble gases or iodine isotopes on a log-log paper, a straight line can be obtained with a negative slope of b as demonstrated in Figure C-2.

Experimentally, the noble gas activity release rate (concentration in the offgas times offgas flow rate) is measured at the steam jet air ejector (SJAE) sample point. The measurement of iodine activity release rate is more complicated. By assuming no iodine activity is returned from the feedwater into the reactor vessel.* The release rate can be calculated by

$$A_i = C_i W(\lambda_i + \beta_c + \beta_s)$$

where

A_i = release rate to coolant from the core, $\mu Ci/sec$.

W = reactor water mass, Kg

λ_i = decay constant of species i, sec^{-1}

β_c = reactor water cleanup (RWCU) system removal time constant, sec^{-1}, which is defined as $\beta_c = f/W$, assuming $\sim100\%$ efficient.

f = RWCU flow rate, Kg/sec

β_s = steam removal time constant, sec^{-1}, which is defined as $\beta_s = \varepsilon F/W$

ε = iodine carryover, defined as the ratio of

$$\frac{\text{the concentration of species i in condensate}}{\text{the concentration of species i in reactor water}}$$

F = steam flow rate, Kg/sec

---

*This is true only for non-forward pumping plants.

The source term ratio (R_g/R_{I-131}) in Figure C-1 is defined as the ratio of the noble gas source term estimated at the λ of I-131 to the I-131 source term (see Figure C-2). By knowing R_g/R_{I-131} and the magnitude of I-131 spiking (maximum spiking concentration/steady state concentration) from Figure C-1, the maximum I-131 concentration in reactor water during a shutdown spiking can be estimated.
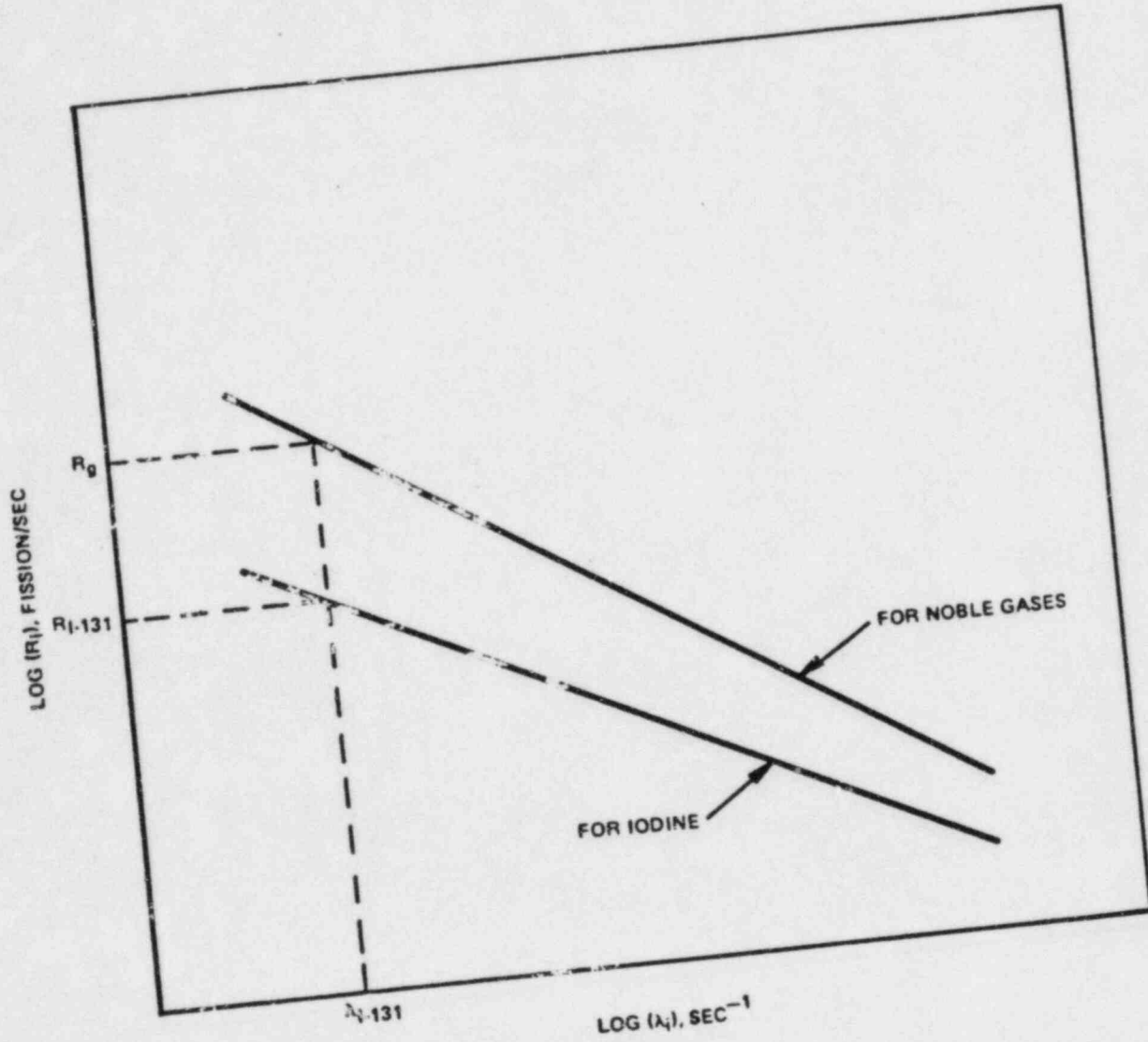
Figure C-2. Plot of Log (R_i) versus Log (λ_i)