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Test Plan for the Irradiation of Nonmetallic Materials

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TEST PLAN FOR THE IRRADIATION OF NONMETALLIC MATERIALS

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ABSTRACT

A comprehensive test program to evaluate nonmetallic materials use in the Hanford tank farms is described in detail. This test program determines the effects of simultaneous multiple stressors at reasonable conditions on in-service configuration components by engineering performance testing.

Key words: hose-in-hose transfer lines, HIHTL, test plan, nonmetallic materials, irradiation, EPDM, HIHTL life extension, Teflon O-rings

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ACRONYMS AND ABBREVIATIONS

α	Ionizing radiation consisting of alpha particles (two protons and two neutrons with a charge of 2+) emitted from the nucleus of a decaying radionuclide
β	ionizing radiation consisting of beta particles (electrons) emitted from the nucleus of a decaying radionuclide
γ	ionizing radiation consisting of gamma rays (high-energy, short-wavelength photons) emitted from the nucleus of a decaying radionuclide
Al(OH) ₃	aluminum hydroxide
ASME	American Society of Mechanical Engineers
ASTM	ASTM International (ASTM is a registered trademark of American Society for Testing and Materials Corporation, West Conshohocken, Pennsylvania)
Ba, ^{137m} Ba	barium, a metastable radioactive isotope of barium with an atomic mass of 137 amu
Cl ⁻	Chloride ion
Co, ⁶⁰ Co	cobalt, a radioactive isotope of Co with an atomic mass of 60 amu
CO ₃ or CO ₃ ²⁻	inorganic carbon as carbonate group in solids or carbonate ion in aqueous solutions
Cs, ¹³⁷ Cs	cesium, a radioactive isotope of cesium with an atomic mass of 137 amu
CSR	compression stress-relaxation
DLO	diffusion-limited oxidation
DNFSB	Defense Nuclear Facilities Safety Board
DOE	U.S. Department of Energy
DST	double-shell tank
EPDM	ethylene propylene diene monomer, a synthetic rubber
ES&H	environmental, safety and health
F, F ⁻	fluoride, fluoride ion
GIF	(SNL's) Gamma Irradiation Facility
H, H ₂ , H ⁺	hydrogen, diatomic hydrogen, hydrogen ion
Hg	mercury
HIHTL	hose-in-hose transfer line
HLW	high-level waste
ID	inner diameter
K, ⁴⁰ K	potassium, a radioactive isotope of potassium with an atomic mass of 40 amu
KNO ₃	potassium nitrate
Kr, ⁸⁵ Kr	krypton, a radioactive isotope of krypton with an atomic mass of 85 amu
N	north
Na ₂ CO ₃	sodium carbonate
Na ₂ SO ₄	sodium sulfate
Na ₃ PO ₄	sodium phosphate
NaCl	sodium chloride
NaNO ₂	sodium nitrite

NaNO ₃	sodium nitrate
NaOH	sodium hydroxide
O, O ₂	oxygen, diatomic oxygen
OD	outer diameter
ORP	Office of River Protection
OUO	Official Use Only
P	pressure
PEEK	polyether ether ketone
pH	the negative, common logarithm of the activity of H ⁺
QA	quality assurance
R&A	review and approval
River Bend	River Bend Transfer Systems, LLC
SNL	Sandia National Laboratories
Sr, ⁹⁰ Sr	strontium, a radioactive isotope of strontium with an atomic mass of 90 amu
SST	single-shell tank
T	temperature
TWINS	Tank Waste Information Network System
VTR	vapor transport rate
WRPS	Washington River Protection Solutions, LLC
Y, ⁹⁰ Y	yttrium, a radioactive isotope of yttrium with an atomic mass of 90 amu

Units

%	percent
°	degree
°C	degrees Centigrade
°F	degrees Fahrenheit
amu	atomic mass unit
bar	bar
cm	centimeter
eV, MeV	electron volts, megaelectron volts
ft	foot
g	gram
gal	gallon
Gy	Gray
hr	hour
in	inch
kL	kiloliter
krad	kilorad, a unit of dose of ionizing radiation
M	Molar
mbar	millibar, a unit of pressure
mCi	millicurie
MeV	megaelectron volt
ml, mL	milliliter
mm	millimeter

MPa	megapascal
mol	mole
nm	nanometer
psi	pounds per square inch
psig	pounds per square inch (gauge pressure)
R	Roentgen, a unit of exposure to ionizing radiation
rad	rad, a unit of dose of ionizing radiation
s	second
STP	standard temperature and pressure
μCi	microcurie
wt, wt%	weight, weight %
yr	year

TEST PLAN FOR THE IRRADIATION OF NONMETALLIC MATERIALS

1. ABSTRACT

This test plan proposes a study of the possible synergistic effects of simultaneous exposure of nonmetallic materials to radiation and other stressors, and the effects of exposure to these multiple stressors on their performance and properties. The nonmetallic materials are used by Washington River Protection Solutions, LLC, (WRPS) in the Hanford tank farms in the waste transfer system. These materials include the primary (inner) hoses in hose-in-hose transfer lines (HIHTLs), Teflon¹ gaskets, ethylene propylene diene monomer (EPDM, a synthetic rubber) O-rings, and (perhaps) other nonmetallic materials. The stressors include β and γ radiation; elevated temperatures; a nonradioactive, caustic (high-pH) supernatant high-level waste (HLW) simulant of the tank farms; and elevated pressures.

The study described in this test plan will include at least three features that will be unique, or at least atypical of, previous studies of radiation effects. First, it will emphasize the irradiation of nonmetallic materials in their in-service configurations, not just the irradiation of coupons. Second, this study will simulate in-service exposure of these nonmetallic materials to simultaneous multiple stressors (i.e., radiation, elevated temperatures, nonradioactive caustic solutions, and elevated pressures). Third, it will emphasize postexposure mechanical performance testing to quantify the synergistic effects of simultaneous exposure to multiple stressors.

This test plan considers two options: a multiphase baseline test program to perform comprehensive testing on hoses, gaskets and O-rings and an alternative option with reduced cost and schedule that performs comprehensive testing on hoses with a reduced scope, proofing-type test on gaskets and O-rings. The baseline program will comprise four phases, testing HIHTLs, Teflon gaskets and EPDM O-rings concurrently. Phase 1 will compare the effects of simultaneous β and γ irradiation of nonmetallic materials to those from γ only. Phase 1 of this study must be carried out at ambient laboratory temperatures and pressures and in the absence of caustic solutions, because the sealed β sources to be used for this phase can only be used under ambient conditions to avoid seal rupture. Phase 2 will determine the effects of simultaneous exposure of nonmetallic materials to γ irradiation and elevated temperatures (up to 180 °F for hoses and up to 200 °F for other components). Phase 3 will investigate the effects of simultaneous exposure of these materials to γ irradiation, elevated temperatures, and nonradioactive caustic solutions. Finally, Phase 4 will quantify the effects of simultaneous exposure of nonmetallic materials to γ irradiation; elevated temperatures; a chemical simulant; and elevated pressures (400 or 425 psig). The reduced cost option would eliminate Phase 1

¹ Teflon and Tefzel are registered trademarks of E. I. Du Pont de Nemours and Company, Wilmington, Delaware.

(the β - γ comparison tests); perform Phase 2, 3, and 4 testing on hoses; and only Phase 3 testing on Teflon gaskets and EPDM O-rings.

Most of Phase 1 and all of Phases 2, 3, and 4 will be carried out in Sandia National Laboratories' (SNL's) Gamma Irradiation Facility (GIF) pool. These tests will use γ irradiation requiring the shielding provided by the GIF pool. Part of Phase 1 (β irradiation only or unirradiated controls) will be conducted in the GIF but outside the pool (probably in the high bay). The β exposure rate will be 100 R/hr, the γ exposure rates will be 100 or 1000 R/hr for Phase 1, and 1000 R/hr for Phases 2, 3, and 4. Sealed line sources containing ^{85}Kr will be used for β irradiation during Phase 1. Sealed source pins containing ^{60}Co will be used for γ irradiation in Phases 1, 2, 3 and 4.

Annular stainless steel vessels will be used to contain the specimens of nonmetallic materials for these tests. Each vessel will have an outer diameter of approximately 2.5 ft, a length of about 4 or 5 ft, and a central cavity with a diameter of about 1 ft that is open to the GIF pool. The β irradiations for Phase 1 will be carried out by inserting the sealed ^{85}Kr line sources inside the primary hoses and other materials, and placing these materials inside the enclosed, annular portions of these containers that surround the central cavities. The γ irradiations for Phases 1, 2, 3 and 4 will be conducted by placing sealed ^{60}Co source pins in the central cavities. A total of 18 containers will be required for the entire baseline program; a total of 12 would be needed for the reduced cost option.

Preliminary calculations were carried out to determine the required activity of each sealed ^{60}Co source pin and the total number of source pins needed to maintain a γ exposure rate of 1000 R/hr for the nonmetallic materials proposed for this study. However, additional calculations will be necessary for the final test design and prior to the start of irradiation tests. These follow-on calculations will provide more robust definitions of the final test configurations, the number of ^{60}Co sources required, and the cost of these sources.

A test control and monitoring system will be developed and deployed for all 18 or 12 of the vessels, respectively, in the proposed baseline test program or reduced cost option. One or more of the following test variables will be controlled in all four phases of the baseline program or the reduced cost option: (1) the β and/or γ exposure rates, (2) temperatures; (3) pressures, (4) the flow rate(s) of compressed air through the vessels to maintain ambient concentrations of O_2 in the vessels. The values of the following test variables will be monitored and recorded for all of the vessels: (1) total β and/or γ exposure, (2) temperature, (3) pressure, (4) the flow rate(s) of compressed air, and (5) the concentrations of O_2 . All of these control and monitoring instruments will be calibrated according to the quality assurance (QA) requirements that are being developed for this study.

The schedule for the baseline test program, shown in Figure 1, includes a year for preparations (October 2013 through September 2014). These preparations include final test-configuration calculations, design and fabrication of test components, procurement of test specimens and sealed sources, safety approvals, and verification testing. Phases 1 and 2 would be placed in the GIF pool from October through December 2014 and from January through March 2015, respectively. They would be removed from the pool from October through December 2016 and from January through March 2017, respectively. Phases 3 and 4 would be placed in the GIF pool

from October through December 2016 and from January through March 2017, respectively. They would be removed from the pool from October through December 2018 and from January through March 2019, respectively. The proposed baseline schedule also includes posttest analysis and data reports for each of these phases. A final report on the entire program would be completed by September 2019. This schedule is based on three crucial assumptions: First, it is assumed that the funding for the first year of the baseline test program (preparations) will arrive at SNL at the beginning of October 2013. Earlier or later arrival of funding would result in commensurate changes for Phases 1, 2, 3, and 4. Second, it is assumed that all 14 vessels required for Phases 1 and 2, and all 12 required for Phases 3 and 4 can be placed in the GIF pool simultaneously. Third, it is assumed that all 14 vessels required for Phases 1 and 2 can be placed in the pool from October 2014 through March 2015; and that all 12 required for Phases 3 and 4 can be placed in the pool while those used for Phases 1 and 2 are being removed.

Activity Name	Start	Finish	FY2014	FY2015	FY2016	FY2017	FY2018	FY2019
<i>Preparations, Fabrication, Procurement and Sandia Approvals</i>	02-Oct-2013*	30-Sep-2014						
<i>Phase 1 - Beta/Gamma Comparison Study</i>	01-Oct-2014	31-Mar-2017						
<i>Phase 2 - Gamma and Elevated Temperatures</i>	05-Jan-2015*	05-Jun-2017						
<i>Phase 3 - Gamma, Elevated Temperature, and Chemical Simulant</i>	03-Oct-2016*	29-Mar-2019						
<i>Phase 4 - Gamma, Elevated Temperature, Chemical Simulant, and Elevated Pressure</i>	03-Jan-2017*	28-Jun-2019						
<i>Issue Final Cumulative Report</i>	01-Jul-2019	26-Sep-2019						

Figure 1. Project Schedule for Baseline Test Program.

The reduced cost option would eliminate the Phase 1 β - γ comparison tests. The issue of relative damage from β versus γ radiation would be studied using alternative means. Hoses will still be tested at the varying levels of the four primary stressors as described in Phases 2, 3, and 4, allowing a better service life prediction model to be developed. PUREX connector gaskets and O-rings will only be tested as described in Phase 3, with chemical stimulant, varying temperature and varying radiation exposure up to two years total. This will demonstrate gasket acceptability in a “proofing” sense and give insight into the effect of increasing radiation levels to the gasket material in the confined geometry of the PUREX connector.

The primary advantages for the reduced-scope program are significant cost reductions and reduction of the schedule. Cost saving come from elimination of the high-cost β sources, reduction in the number of test vessels, test hoses, gaskets, and coupons, less postexposure testing and analysis, and a reduced number of test, instrument, and control loops. Most significantly, this option also reduces the space requirements such that all test vessels required can fit into the GIF pool at the same time, allowing Phase 2, 3 and 4 to run simultaneously. The preparation time is similar, but this option would cut two years off the total schedule.

This document does not include an estimate of the cost for execution of this test plan. Instead, the cost estimate is found in a separate document, RPP-PLAN-54568_rev1 (see Section 8 below for complete information on this and other references included in this test plan). RPP-PLAN-54568_rev1 includes the cost of the baseline test program and the reduced cost option. This cost estimate is SNL Proprietary Information.

Finally, WRPS issued this test plan as RPP-PLAN-50529_rev1. This SAND report is essentially identical to RPP-PLAN-50529_rev0, except that: (1) these reports are formatted differently; (2)

some minor editorial changes have been made in this version and some typos have been corrected; and (3) the starting date for Phase 2 in Figure 1 (see above) was corrected from October 1, 2014, to January 5, 2015.

2. INTRODUCTION

2.1 Objectives

This test plan proposes a study of the possible synergistic effects of simultaneous exposure of nonmetallic materials to radiation and other stressors, and the effects of exposure to these multiple stressors on their performance and properties. The nonmetallic materials are used by WRPS in the Hanford tank farms waste transfer system. They include the primary (inner) hose of the HIHTLs (hereafter referred to as “hoses”), Teflon gaskets, and ethylene propylene diene monomer (EPDM) O-rings used in the tank farms. The stressors include radiation (both β and γ); elevated temperatures; a nonradioactive, caustic, supernatant HLW simulant of the tank farms; and elevated pressures.

This test plan originates from a Defense Nuclear Facilities Safety Board (DNFSB) recommendation (Winokur, 2011) to the U.S. Department of Energy (DOE) to conduct postservice examination of HIHTLs and Teflon gaskets to improve the existing technical basis. The U.S. DOE’s Office of River Protection (ORP) responded that it recognized the value in enhancing the technical basis of HIHTLs and other nonmetallic materials, but stated that concerns regarding worker exposure outweighed the potential benefits of posttest examinations (Huizenga, 2011). In a subsequent letter (Bechtol and Samuelson, 2011), the U.S. DOE’s ORP directed WRPS to provide a cost and schedule for development of this test plan and to identify the test plan in the Documented Safety Analysis as a planned improvement.

The study described in this test plan will include at least three features that will be unique, or at least atypical of, previous studies of radiation effects. First, it will emphasize the irradiation of nonmetallic materials in their in-service configurations (see Subsection 2.2), not just the irradiation of coupons. Second, this study will simulate in-service exposure of these nonmetallic materials to simultaneous multiple stressors (i.e., various combinations of β and γ irradiation; elevated temperatures; the presence of a nonradioactive, caustic, a chemical simulant; and elevated pressures). (Subsections 2.3 and 2.4 describe these stressors in more detail.) Third, it will emphasize postexposure mechanical performance testing (e.g., burst tests and leak tests), independent of mechanical properties testing, to quantify the synergistic effects of simultaneous exposure to multiple stressors. Implementation of performance-based testing will allow WRPS to use the results directly in the safety basis required to complete its tank farms mission. (Subsection 2.5 discusses the difference between mechanical performance and properties testing; Subsection 2.6 explains the unique or atypical features of this test program in more detail.)

This test plan considers two options: the baseline test program and alternative reduced cost option. The baseline program will be comprised of four phases, testing hoses, Teflon gaskets and EPDM O-rings concurrently. Phase 1 (Paths 1, 2.1, 2.2, 3.1, and 3.2) will compare the effects of simultaneous β and γ irradiation of hoses and Teflon gaskets to those from γ only. Path 4 of Phase 1 will comprise the control samples for the baseline program (see Subsection 3.1 and Figure 9 below). Phase 2 will determine the effects of simultaneous exposure of hoses, Teflon gaskets, and EPDM O-rings to γ irradiation and elevated temperatures. Phase 3 will investigate the effects of simultaneous exposure of the same materials used in Phase 2 to γ irradiation, elevated temperatures, and a chemical simulant. Finally, Phase 4 will quantify the

effects of simultaneous exposure of the same materials used in Phases 2 and 3 to γ irradiation, elevated temperatures, the chemical simulant, and elevated pressures. This phased approach was established during a meeting of WRPS, SNL, and other personnel held July 31-August 1, 2012, in Richland, Washington. This baseline program will allow for testing of the three highest-priority materials using the space available in SNL's irradiation facility to the maximum extent possible. Other nonmetallic materials are not included in the baseline test program because of the space and time required to complete this option with the three highest-priority materials. However, the baseline could be expanded, at the discretion of WRPS, by adding more materials or different combinations of stressors (see below).

Figure 2 illustrates the logic of the proposed four-phase baseline test program. Table 1 identifies the test variables and their values for each of the four phases of this baseline program. This four-phase sequence will provide WRPS with the most important information needed to address the questions posed by the DNFSB as soon as possible. Furthermore, it reflects the anticipated time required to obtain environmental, safety and health (ES&H) approvals for each phase of the baseline program, listed from the shortest to the longest expected approval process.

The radiation to which nonmetallic materials are exposed in the Hanford tank farms include both β from ^{90}Sr and ^{90}Y , which are associated mainly with the solids in the tanks; and γ from ^{137}Cs and $^{137\text{m}}\text{Ba}$, associated mainly with the supernatant solutions (TFC-ENG-STD-34, Attachment E).

Sealed β sources will be used to avoid contamination of the irradiated samples of nonmetallic materials (see Section 3.0). The disadvantages of worker exposure resulting from testing contaminated samples would outweigh the benefits of the data obtained. Furthermore, the use of sealed sources will greatly simplify the postexposure mechanical testing that will be used to quantify the effects of β , γ , and simultaneous β and γ irradiation on these samples. However, the sealed β sources identified for this test plan can only be used at ambient laboratory pressures and temperatures, and only in the absence of the chemical simulant to avoid breaching the thin walls of these sealed β sources (see Subsection 3.3).

The effects of β and γ irradiation must be determined under ambient laboratory conditions without the simulated supernatant solution by comparing the effects of simultaneous β and γ irradiation to those from γ only. This comparison will provide a " β enhancement factor" or " β factor" to reflect how much additional damage, if any, results from simultaneous irradiation with β and γ relative to that from γ only. (Subsection 3.1 explains the establishment of the β factor in detail). This factor will be used to correct the results obtained from simultaneous exposure to γ irradiation and one or more additional stressors (elevated temperatures, simulated supernatant solutions, and elevated pressures). It is practical to combine γ irradiation and these other stressors because the γ radiation from sealed sources outside the stainless steel vessels will penetrate the vessels (and in some of the tests) the chemical simulant without contaminating the nonmetallic test materials.

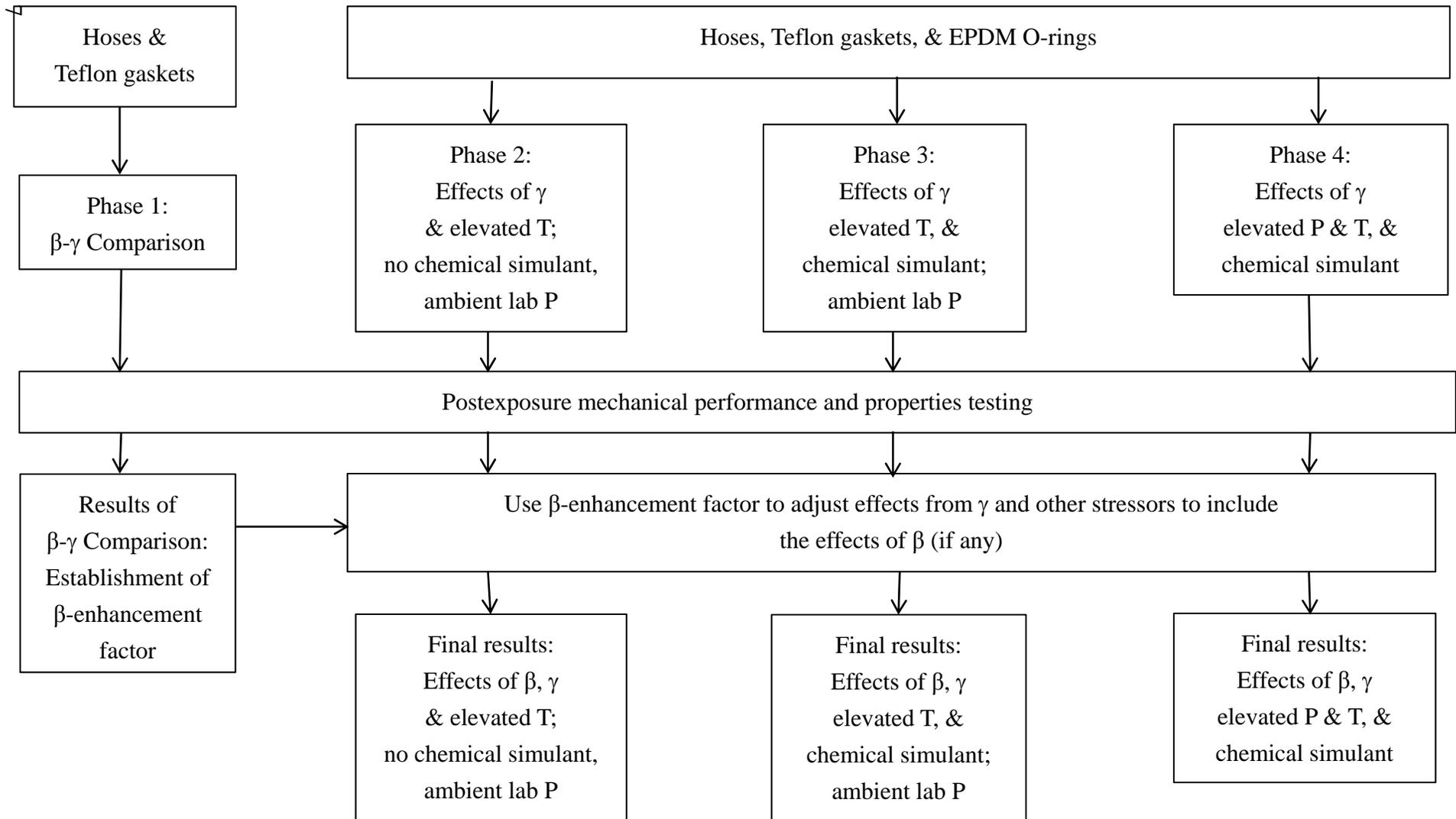


Figure 2. Logic for the Proposed Baseline Test Program Proposed for the Irradiation of Nonmetallic Materials.

Table 1. Identification of the Baseline Experimental Variables and Values for the Irradiation of Nonmetallic Materials.

Test Phase	Description	Test Materials			Remarks
		Hoses	Teflon	EPDM O-Rings	
1	β-γ comparison at ambient high-bay or GIF-pool P and T, no chemical simulant. β = 100 R/hr. γ = 100 and 1000 R/hr.	30-in long primary (2-in ID) hoses in their in-service configuration & coupons of composite hose materials.	Gaskets confined in connectors in their in-service configurations, unconfined gaskets, & coupons.	Will not be included in β-γ comparison (will not be exposed to β radiation in their in-service configurations).	It is anticipated that the β-γ comparison will require the least amount of time for ES&H R&A, so this series of tests will probably start first.
2	Effects of γ & elevated T without chemical simulant, ambient GIF-pool P. γ = 1000 R/hr. Remove samples at 10 ⁵ , 10 ⁶ , 10 ⁷ , & > 10 ⁷ R.	Same sample configurations as above. T = 70, 130, & 180 °F (ambient, operating & design, respectively).	Same sample configurations as above. T = 70, 130, & 200 °F (ambient, operating & design, respectively).	O-rings confined in connectors in their in-service configurations, & (perhaps) unconfined O-rings & coupons. T = 70, 130, & 200 °F (ambient, operating & design, respectively).	It is anticipated that the effects of γ & elevated T will require more time for ES&H R&A than that for the β-γ comparison, so this series of tests will probably start second.

6

Test Phase	Description	Test Materials			Remarks
		Hoses	Teflon	EPDM O-Rings	
3	Effects of γ , elevated T, & chemical simulant at ambient GIF-pool P. $\gamma = 1000$ R/hr. Remove samples at 10^5 , 10^6 , 10^7 , & $> 10^7$ R.	Same sample configurations as above, same Ts as above.	Same sample configurations as above, same Ts as above.	Same sample configurations as above. Same Ts as above.	It is anticipated that the effects of γ , elevated T & chemical simulant will require more time for ES&H R&A than that for the effects of γ & elevated T, so this series of tests will probably start third.
4	Effects of γ , elevated P & T, & chemical simulant. $\gamma = 1000$ R/hr. Remove samples at 10^5 , 10^6 , 10^7 , & $> 10^7$ R (exact durations TBD).	Same sample configurations as above, P = 425 psig, same Ts as above.	Same sample configurations as above, P = 400 psig, same Ts as above.	Same sample configurations as above, P = 400 psig. Same Ts as above.	It is anticipated that the effects of γ , elevated P & T, & chemical simulant will require more time for ES&H R&A than that for the effects of γ , elevated T & chemical simulant, so this series of tests will probably start last.

Notes for Table 1:

β = beta radiation from sealed ^{85}Kr sources
 EPDM = ethylene propylene diene monomer
 ES&H = environmental safety and health
 F = Fahrenheit
 γ = γ radiation from sealed ^{60}Co sources
 GIF = SNL's Gamma Irradiation Facility

ID = inner diameter
 P = pressure
 psig = pounds per square in (gauge)
 R&A = review and approval
 P = pressure
 T = temperature

The baseline program outlined in Figure 2 and Table 1 could be expanded in two ways, at additional cost and impact to the schedule, by adding: (1) more materials to the program; and (2) different combinations of stressors. Adding more materials could be used to expand the β - γ comparison or the assessment of the combined effects of γ irradiation and elevated temperatures (Phase 2) while awaiting ES&H approval for Phase 3. Adding different combinations of stressors could be used to complete a fractional factorial matrix to identify which binary or ternary combinations of stressors produce the greatest synergistic effects (if any). The baseline program outlined in Figure 2 and Table 1 could also be modified to reduce the work scope, shorten the schedule, or alter the order in which the testing is carried out. All modifications to the baseline program are at the discretion of WRPS.

2.2 Materials

WRPS has identified the inner hoses from the HIHTLs, Teflon gaskets, and EPDM O-rings as the three highest-priority nonmetallic materials for this study. The HIHTL assembly is comprised of two hoses, the primary (inner) hose and the secondary (outer) hose. Both of the hoses are constructed similarly, however, only the primary hose will be the focus of this work. Phase 1, the β - γ comparison, will include hoses and Teflon gaskets, but not EPDM O-rings, because the O-rings are exposed to γ irradiation, but not β , in their in-service configurations in the tank farms. Phases 2, 3, and 4 will include all three of these materials.

The samples of hoses will comprise 30-in long primary (2-in nominal inner diameter, or ID) hoses in their in-service configuration, but with blank end fittings; and flat coupons of the composite hose materials provided by River Bend Transfer Systems, LLC, the manufacturer of the HIHTLs. The hose materials are nominally 3/8-in thick and consist of (1) an inner layer of EPDM rubber; (2) a layer of woven polyester; (3) a central layer of EPDM embedded with two helical steel wraps; (4) another layer of woven polyester; and (5) an outer layer of EPDM. The helical coils embedded in the central layer of EPDM consist of high-tensile-strength, 1/16-in diameter carbon steel, each with 10 ft of steel per ft of hose. The burst pressure reported for new primary hoses is typically 2800–3000 psig.



Figure 3. Sample Primary HIHTL Hose with 6-in Ruler for Scale.

River Bend personnel refer to the 30-in long primary hoses in their in-service configuration as “coupons.” In this test plan, these samples are referred to as “30-in long primary hoses,” “30-in long hoses,” or as previously stated “hoses.” “Coupons” refers to flat pieces of the five-layer

composite material (EPDM-woven polyester-EPDM embedded with two helical steel wraps-woven polyester-EPDM) described above, which will be included along with the hoses in Phases 1 through 4 of this study (see Table 1). This usage is consistent with that used in the materials-science literature.



Figure 4. EPDM O-Ring on HIHTL End Fitting.

The samples of the Teflon gaskets will consist of gaskets confined in connectors in their in-service configurations, unconfined gaskets, and coupons of the same Teflon used for the confined and unconfined gaskets. The EPDM samples will include O-rings confined in connectors in their in-service configurations, and (perhaps) unconfined O-rings & coupons.



Figure 5. Teflon Gasket in Retaining Ring and Unconfined.

2.3 Beta and Gamma Irradiation Rates

The radioactive source term to which the nonmetallic materials described in this test plan are exposed in the Hanford tank farms include mainly (1) β from ^{90}Sr and ^{90}Y , which are associated mainly with the solids in the tanks; and (2) γ from ^{137}Cs and $^{137\text{m}}\text{Ba}$, associated mainly with the supernatant solutions.

The relative proportions of β and γ radiation to which the nonmetallic materials are exposed depend on factors such as the concentrations of ^{90}Sr and ^{90}Y associated with the solids at the bottoms of the tanks, the concentrations of these solids suspended in the solutions pumped through the primary hoses, the concentrations of ^{137}Cs and $^{137\text{m}}\text{Ba}$ in the supernatant solutions, and the duration of pumping.

WRPS has specified that the primary γ irradiation rate used for this study will be 1000 R/hr². 100 R/hr will also be used during Phase 1 to determine the effects of dose rate. The 1000 R/hr irradiation rate bounds the rates provided in the histogram of estimated double-shell tank (DST) supernatant (^{137}Cs and $^{137\text{m}}\text{Ba}$) γ irradiation rates in TFC-ENG-STD-34, Figure E-1 (included herein as Figure 6). Therefore, the irradiation rate specified by WRPS is more representative than Nigrey's (2000) dose rate of 95 krad/hr. Use of this more representative irradiation rate will require longer irradiation times to achieve the exposures requested by WRPS, and thus largely eliminate the issue of limited time for O₂ diffusion into the test specimens (Burnay and Hitchon, 1985; Gillen et al., 1989; Wise et al., 1997; Gillen et al., 2003), which could bias the results in favor of reduced damage.

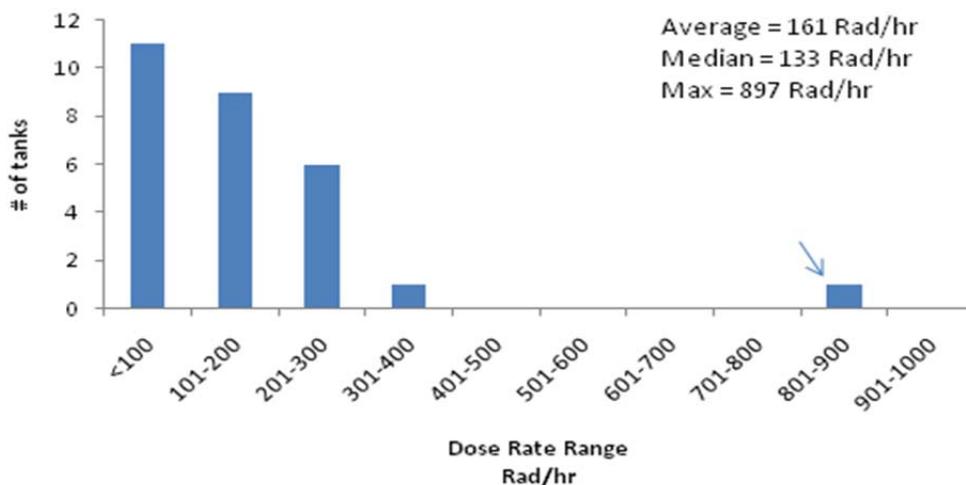


Figure 6. Histogram of DST Supernatant Estimated Dose Rates (from TFC-ENG-STD-34).

Hanford tank farms nonmetallic materials are evaluated to a nominal 250 Rad/hr based on the above histogram detailing supernatant exposure. For the purposes of this testing, a more detailed source term was developed in Section 2.7.5. Sealed β sources capable of producing an exposure rate of 100 R/hr were identified as the only β sources suitable for the β - γ comparison

² The irradiation rates specified in this test plan are in units of Roentgen for the purposes of source sizing and selection, as it is independent of the test material being exposed. The radiation unit of concern for nonmetallic material degradation is the Rad. Calculations herein assume materials exhibit absorption behavior similar to tissue, wherein 1 R approximately equals 1 Rad. As explained later, the test configuration will use shielding to adjust the radiation field produced from the sources to the desired exposure rate. This shielding approach should allow enough flexibility to account for inaccuracy, as determined in detailed radiation calculations during design, in the absorption behavior assumption.

(see Subsection 3.4). This rate is close to that established as a reasonably conservative, bounding β irradiation rate.³ Gamma irradiation rates of 100 and 1000 R/hr are proposed for the β - γ comparison (see Subsection 3.1). The WRPS-specified γ irradiation rate of 1000 R/hr will be used for Phases 2 through 4 of this study.

2.4 Values Specified for Other Stressors

This subsection describes the temperatures, the composition of the nonradioactive, caustic solution that will simulate the supernatant HLW solutions, and the pressures that will be used in the baseline test program. Table 1 summarizes the temperatures, whether a nonradioactive, caustic, supernatant HLW simulant will be present or absent, and the pressures for each of the four phases of this study.

Phase 1 of this study (see Table 1) must be carried out at ambient laboratory temperature and pressure, and in the absence of caustic solutions simulating the supernatant tank solutions (see Section 3.0). This is because the sealed β sources for this study (Subsection 3.3) can only be used under ambient conditions to avoid rupture of the thin walls of these sealed β sources (see Subsection 4.3) and contamination of the irradiated samples of nonmetallic materials. This will facilitate the postexposure mechanical testing (Section 5.0).

Phase 2 will be conducted at temperatures of 70, 130, and 180 °F for the hoses and coupons that simulate the hoses. However, the confined and unconfined Teflon gaskets and Teflon coupons; and the confined EPDM O-rings and (perhaps) the unconfined O-rings and EPDM coupons will be tested at 70, 130, and 200 °F. Phase 2 will be performed in the absence of the chemical simulant and at ambient pressure.

Phase 3 will be run at temperatures of 70, 130, and 180 °F for the hoses and coupons; and 70, 130, and 200 °F for the Teflon gaskets and coupons; and the EPDM O-rings and (perhaps) coupons. Phase 3 will include the chemical simulant, but will be performed at ambient pressure. Subsection 2.7.4.1 provides the composition of the simulant.

Finally, Phase 4 will be carried out at the same temperatures used for Phases 2 and 3 with the chemical simulant. However, a pressure of 425 psig will be used for the hoses and coupons; and 400 psig will be used for the Teflon gaskets and coupons; and the EPDM O-rings and (perhaps) coupons.

WRPS specified all of these material-specific temperatures and pressures for the test program. These values are generally defined as ambient, normal operating and design conditions.

It must be emphasized that the simulated supernatant solution described in Subsection 2.7.4.1 will not contain any of the radionuclides present in HLW; rather, this chemical simulant will be nonradioactive, except for very low concentrations of naturally occurring radioisotopes in

³ In this test plan, “bounding” is used to describe a reasonable upper limit. The exact cause of greater damage at lower dose rates is not completely resolved within literature. It is assumed that eliminating diffusion-limited oxidation effects minimizes concern around evidence of lower dose rates causing greater levels of damage on accumulated basis.

the reagent-grade chemicals used to synthesize the simulant (e.g., naturally occurring ^{40}K in the reagent-grade K-bearing compounds).

2.5 Postexposure Testing

Postexposure mechanical testing will provide the results used to compare the effects of β and γ irradiation of nonmetallic materials, and to quantify the possible synergistic effects of simultaneous exposure of these materials to the four stressors described above.

Postexposure testing will include quantification of both mechanical performance and mechanical properties. For the purposes of this test plan, postexposure mechanical performance testing refers to measurements that are directly applicable to the primary hoses, Teflon gaskets, and EPDM O-rings as used by WRPS in the tank farms (i.e., in their in-service configurations). Examples include measurements of the pressure required to burst the hoses, or the torque required to prevent leakage of Teflon gaskets and leak rate of EPDM O-rings in their confined configurations. Postexposure mechanical properties testing, on the other hand, refers to standardized procedures such as the ASTM⁴ International (ASTM) test for compression set or elongation at rupture. ASTM procedures will be used for coupons of the composite hose materials, Teflon, or EPDM. Section 5.0 of this test plan describes these procedures in detail.

2.6 Relation of this Test Plan to Other Studies

The study described in this test plan will include at least three features that will be unique, or at least atypical of, the approaches used in other studies of radiation effects. First, this study will emphasize the irradiation of nonmetallic materials in their in-service configurations, not just the irradiation of coupons (see Subsection 2.2). This feature will facilitate the direct application of the results of postexposure mechanical testing to the performance of these materials in the Hanford tank farms. Second, this study will simulate in-service exposure of these nonmetallic materials to simultaneous multiple stressors (i.e., various combinations of β and γ irradiation; elevated temperatures; the presence of a nonradioactive, synthetic solution representative of the supernatant solutions in the single-shell tanks (SSTs) and DSTs; and elevated pressures). Third, this study will emphasize postexposure mechanical performance testing, not just mechanical properties testing, to quantify the synergistic effects of simultaneous exposure to multiple stressors. Subsection 2.5 explains the difference between mechanical performance and mechanical properties testing.

2.7 Technical Justifications

This test plan is designed to address technical questions about the use of nonmetallic materials with Hanford tank farms using representative conditions to simulate exposure. Justifications of the conditions selected are presented herein.

⁴ ASTM is a registered trademark of American Society for Testing and Materials Corporation, West Conshohocken, Pennsylvania.

2.7.1 Materials

The materials identified in this test plan were selected based on their application within the Hanford waste transfer system and for the added value in addressing regarding the longevity. This value is manifested in an improved safety basis for operating safety-significant equipment, beneficial cost and schedule gains due to potentially increased service lives, and reduced risk to the cost and schedule baseline by developing a service-life basis which may be used for improved run/repair/replace decisions. Collectively, materials evaluated for inclusion in this test plan are listed in TFC-ENG-STD-34. Of this list of materials, testing for three of these materials is initially included in this test plan. After review of the extent of testing required to address technical issues and the durations required, the focus of the test plan was narrowed to HIHTLs, Teflon gaskets, and EPDM O-rings. The methodology developed herein can be extended to the remaining materials with appropriate postexposure tests selected, during or after the six-year schedule if necessary.

Discussed in Section 2.1, the primary focus of the test plan are the primary hoses of the HIHTL assemblies. HIHTLs are currently used within waste retrieval systems due to the extensive cost savings provided over the use of pipe-in-pipe systems. HIHTLs provide flexibility to support multiple tank retrievals without requiring extensive excavation and removal that a piped system requires and minimizes the space required to support retrieval transfers compared to piped systems. The EPDM hoses are also used in flexible jumpers in the DST transfer system.

HIHTLs are a composite rubber hose, consisting of an inner and outer layer of EPDM, two intermediate layers of polyester fibers surrounding central dual helical steel wire reinforcement with EPDM filler. Swaged stainless steel threaded connectors are fitted on the ends of the hose. In general, the EPDM layers protect the hose from environmental exposure, the polyester fibers provide axial strength, and the steel wire reinforcement provides radial strength. The swaged fittings have performed exceptionally and have not been a known point of failure in any previous testing or operating experience.

Teflon gaskets used in PUREX connectors are the secondary focus of the test plan, primarily due to the discrepancy with the exemplary service record at Hanford compared to the poor radiation tolerance of Teflon⁵. PUREX connectors have a unique confining geometry that may limit factors contributing to the damaging mechanism. PUREX connectors are used to make remote connections to minimize worker exposure in waste transfer pits and boxes. The Teflon gasket is the sealing surface between the connection points.

EPDM O-rings are a common sealing material within pressure boundary components, found as backup rings in valve seats and in the HIHTL end fittings. Their inclusion in this set of testing is relatively simple and does not require a significant amount of space. Additionally, the inclusion of an EPDM-only component may provide general qualitative evidence of the performance of the EPDM component in HIHTLs.

⁵ Teflon radiation tolerance is frequently cited at approximately 10^4 Rad. Usage of Teflon at Hanford suggests this critical dose has been exceeded routinely with no noted failures.

Of the remaining TFC-ENG-STD-34 materials, two major component types can be identified. Tefzel¹, Kynar⁶, and Ultra-High Molecular Weight Polyethylene (UHMWPE) are employed as valve seat materials. Two specific flat gasket materials, Garlock⁷ Blue-Gard⁷ 3000 and 3700, are identified. The valve seat materials would require similar space and confined geometry considerations as the Teflon gaskets, yet these materials do not have the outstanding conflict between literature radiation data and operating experience of Teflon use at Hanford. The flat gasket materials would require greater space than the EPDM O-rings, are less prevalent and do not provide additional insight into HIHTL durability as the O-rings potentially do. Other materials listed in TFC-ENG-STD-34 find more specialized applications (i.e., are much less prevalent in use) requiring either explicit test specificities that reduce the potential value if other applications are later employed, or generalizations that reduce the direct applicability. Either option is less ideal than prioritizing testing the materials identified above. The methodology described in this test plan can be implemented into testing for these materials with relatively little additional effort. It was determined to be prudent to focus on the specified materials, while ensuring the applicability of the remaining materials.

2.7.1.1 In-Service Configurations

Testing components in their in-service configurations is an essential component of this test plan. Testing ‘coupons,’ or small samples, of material are useful for making comparative, mechanistic, or modeling determinations. The goal of this test plan is to develop a technical basis for an expected service life of nonmetallic components. In order for this to be achieved, the testing must be as representative of the in-service exposure as possible. The efforts to achieve representative conditions with regard to configuration are discussed herein.

Significant physical geometry will be preserved to the maximum extent possible. This includes metallic components as part of the assembly containing metallic materials, the directional source of radiation, chemical attack, and thermal exposure. Using Teflon PUREX gaskets as an example, the retaining ring geometry will be entirely preserved, while the sealing surfaces and immediate surrounding surface of the connector block and of the nozzle will be preserved. An alternative clamping/compression mechanism may be selected and the remainder of the assembly form may be adjusted to minimize space and maximize penetration from an external radiation source. The HIHTL primary hoses will have their configuration conserved in their entirety. EPDM O-rings may be contained in the hose assembly on the end fittings.

All components will be internally exposed to a simulated supernatant liquid solution to represent the chemical environment during waste transfers. Components will be connected or compressed in the same manner as in field deployment or in a representative manner resulting in similar physical force applied.

2.7.2 Temperature

Temperature is well known as a critical parameter in the degradation of polymers. Temperature not only drives the rate of degrading chemical reactions, but also can result in property changes

⁶ Kynar is a registered trademark of Arkema, Inc., King of Prussia, Pennsylvania.

⁷ Garlock and Blue-Gard are registered trademarks of Garlock Sealing Technologies LLC, Palmyra New York.

of the polymer material affecting transport of reactants and breakdown or leeching of additives. Additionally, mechanical properties are often temperature sensitive; therefore, any synergistic effects based on mechanical stresses may also have a temperature contribution. The effects of temperature on polymer degradation have been the explicit focus for a number of accelerated aging studies to examine time-temperature superposition, solely to account for and predict the significant effect temperature has on degradation.

Test temperatures are specified to be at realistic conditions. In doing so, the need for extrapolation from elevated test temperatures to field exposure conditions is eliminated. Interpolation within the test temperature range is less likely to produce erroneous results that result from changes in the degradation regime, and is more likely to exhibit known and predictable polymer degradation behavior as evidenced by the applicability of time-temperature superposition in some materials. Temperatures selected in Table 2 will nominally represent ambient or low-end operating conditions, intermediate or heat-traced conditions, and design temperatures. There is some evidence that increased levels of degradation may occur at intermediate temperatures, as evidenced by Gillen et al. (1994). This phenomenon is known as the inverse temperature effect. This has been demonstrated for polyolefins in the above paper, however it supports maintaining an intermediate temperature in case this phenomena exists for other materials as well.

Table 2. Specified Test Temperatures for Nominal Conditions.

Material	Ambient	Intermediate	Design
HIHTL	70 °F	130 °F	180 °F
Other			200 °F

2.7.3 Pressure

Pressure will exist in two forms during testing: internal fluid pressure and applied compression force to sealing components. Applied compression forces will be imposed by using representative in-service configurations. Internal fluid pressure will be applied at design conditions, 425 psig for HIHTL and 400 psig for other materials. There will be some cyclic pressurization due to replenishment of the chemical simulant. Generally, internal fluid pressure is expected to have only a minor contribution to material degradation, based on previous work detailed in RPP-6711, Appendix L. It should be noted that the testing reported in Appendix L of RPP-6711 was a static pressurization and did not include any pressure cycling. However, compressive and stress relaxation properties may be significant for sealing components.

Cyclic mechanical stress effects are a relatively well-understood phenomenon. Polymers, specifically elastomers, generally exhibit elastic behavior, recovering completely from applied stress. Over time as the polymer degrades, it may become fatigued or embrittled and begin to take on a compression set for repeated or consistently applied stress. It is expected that a component degraded from other exposure will take on mechanical changes such as compression set earlier than a nonexposed component subjected to similar mechanical stress.

Additionally, if flaws develop in a component, such as a small crack, it would be expected that applied pressure would result in a concentration of stress at the crack, potentially resulting in a worsening of the flaw. However, literature searches have yielded little information on enhancing synergistic degrading effects in nonmetallic materials. While other conditions may have been necessary for development of the flaw, the worsening of the flaw may be primarily dependent on mechanical pressure. Although mechanical stress may or may not possess synergistic qualities with respect to the other stressors, its effects may contribute to material degradation and will be included to properly represent conditions during waste transfers and retrieval.

2.7.4 Chemistry

Chemical exposure will be provided using a nonradioactive, caustic, supernatant HLW simulant of the Hanford tank farms. The chemical simulant will approximate the exposure conditions created during waste retrieval. This simulant will expose components to its constituents, radiolysis-generated reactive products, and leach mobile products out of the polymer. In order to maintain a consistent chemical environment, the simulant will be replaced approximately every two months. Expected potentially reactive species include, but are not limited to nitrates, nitrites, oxygen (O₂), hydroxide, peroxides, free radicals, and various intermediate products. Of these, O₂ is the most attributed and studied component to polymer degradation.

Organic chemicals are also well known to be degrading to polymeric materials. However, the resistance to degradation from organic chemicals is highly specific to the organic chemical and polymer exposed. Selection of a representative organic component has been determined to be unfeasible since it is believed that no organic simulant could be both inclusive of a significant number of possible organic chemicals of concern and remain representative of the majority of waste. It is recommended that organic chemicals of concern be evaluated for compatibility on a case-by-case basis.

Stress corrosion cracking has been observed in a few polymers in case studies, predominantly acetals, in acidic environments (Wright, 2006). Stress corrosion cracking is caused by hydrolysis of susceptible functional groups, including ester, amide, imide, and carbonate groups. Other chemically aggressive species such as condensed halogens or their acids have been identified as responsible in case studies, notably PVDF. Such conditions are not expected on wetted surfaces in the Hanford waste transfer system. Polyethylene terephthalate, commonly called polyester, exists as the fiber reinforcement within the HIHTL hose. Polyester is known to be subject to stress corrosion cracking with exposure to NaOH, however the polyester within the hose assembly is not in direct contact with the process fluid, separated by a layer of EPDM. Generally, materials in contact with process fluid are suitably resistant, as evaluated in TFC-ENG-STD-34. However, evolution of polymer degradation products may concentrate within a constrained geometry to create a microenvironment conducive to crevice or stress corrosion cracking of either the polymer material or the surrounding steel components. Such a mechanism has not been observed at Hanford, however examinations of equipment removed from service are generally not conducted due to the extent of contamination.

2.7.4.1 Chemical Simulant

Testing will utilize a reasonably bounding chemical source term developed in TFC-ENG-STD-34, shown in Table 3. This source term was developed using the Tank Waste Information Network System (TWINS) database for inclusion of 95% by mass of DST supernatant analytes, with inclusion of Cl^- , F^- , and PO_4^{3-} because of material or process sensitivities, resulting in a cumulative wt% of 97%. Total inorganic C is assumed to be Na_2CO_3 .

There is no existing procedure for synthesizing a simulant of this composition; thus, one will need to be developed. The approach taken for development of an AN-107 simulant in WTP-RPT-115 may be useful, wherein two solutions were prepared such that ideal mixing would result in the target composition after addition of nonreactive salts. Precipitates were allowed to form and drop out of solution.

Table 3. Chemical Simulant Composition (from TFC-ENG-STD-34).

Compound	Concentration (wt %)	Concentration (M)
KNO_3	1.31	0.17
NaNO_3	11.41	1.7
NaNO_2	7.38	1.4
Na_2CO_3	3.99	0.5
NaOH	4.61	1.5
$\text{Al}(\text{OH})_3$	1.93	0.55
Na_2SO_4	0.64	0.06
NaCl	0.47	0.11
Na_3PO_4	0.49	0.04
NaF	0.10	0.03
Balance of Na^+	1.19	

No solid particulate matter will be included in the simulant, as erosion is not being considered within this test plan. The existing erosion basis will continue to apply to nonmetallic material usage. Specifically for HIHTL hoses, in RPP-6711, EPDM rubber is cited for its resistance to abrasive erosion due to its ability to deform elastically under impact and its common applications in tires and pumps. Furthermore, a meaningful test program for erosion requires extensive test controls over a wide variety of parameters, resulting in the extensive complication of delivering uniform erosive conditions to a hundred or more samples within an underwater radiation environment. Including erosive material would also have significant design challenges and complicate the safety review and approval process.

2.7.4.2 Oxygen Concentrations

Oxygen plays a vital role in degradation mechanisms of nonmetallic materials. The sources and transport of O₂ needs to be understood to ensure it is accounted for properly during testing for unconstrained geometries such as HIHTL hoses. For constrained geometries, diffusion limited oxidation (DLO) effects are suspected in service due to the lack of replenishment of O₂. During waste transfers, HIHTLs are expected to be full of the pumped fluid due to minimum flow requirements practiced to prevent settling of solids during transfer. The O₂ content of waste is explored further in this section. While installed, the hose-in-hose geometry connects the annulus space between the primary and secondary hose to be exposed to the air space in the tanks. It is expected that this allows for a source of O₂ replenishment for the exterior of the primary hose, and assumes that the surface hose is exposed to a chemically ambient air.

Oxygen generation and depletion in Hanford wastes has been a topic of study within the past two decades as part of the safety-related effort in determining (H₂) gas evolution rates to protect against flammable gas and buoyant gas displacement events. Radiolysis caused by water being present in a radiation field results in the generation of H₂ and O₂. While H₂ was the primary focus of these studies, O₂ plays a role in flammable gas mixtures and it has been found that the presence of an O₂ atmosphere increases the H₂ generation rate of Hanford wastes, especially those containing organic material. This work is summarized in WTP-RPT-115.

WTP-RPT-115 concluded that O₂ is depleted by actual tank wastes and in simulants for both high organic content and no organic content. The results from WTP-RPT-115 are shown in Table 4 with the simulant composition shown in Table 4, compared to the specified TFC-ENG-STD-34 simulant. The depletion of O₂ matches process knowledge that quiescent tanks contain O₂-depleted supernatant.

Table 4. O₂ Depletion Rates for Actual and Simulated Wastes (from WTP-RPT-115).

Tank Type	Cover Gas, 20% O ₂ in Ne		
	O ₂ depletion, mol/kg/day	Standard Deviation	TOC (minus oxalate), wt%
AN-102	-1.83×10^{-2}	1.19×10^{-2}	1.99
AN-106	-4.23×10^{-3}	1.41×10^{-3}	0.02
AN-107	-2.90×10^{-2}	1.82×10^{-2}	2.86
AW-101	-3.13×10^{-3}	1.26×10^{-3}	0.14
U-106	-2.30×10^{-2}	1.58×10^{-2}	2.70
AN-107 simulant	-1.18×10^{-2}	4.44×10^{-3}	1.37
AN-107 simulant (no organics)	-1.94×10^{-3}	3.25×10^{-4}	0

Mechanisms presented in WTP-RPT-115 are generally H₂ focused. Mechanisms focusing on O₂ depletion all used degradation of organics to explain O₂ consumption, with no inorganic mechanisms postured. Appendix C of WTP-RPT-115 discusses possible mechanisms that would

be responsible for increasing H₂ generations rates due to O₂; however, they are deemed insignificant to degradation of organics. This makes it difficult to understand mechanistically what is responsible for the observed O₂ depletion organic-free AN-107 simulant, AN-106 waste and perhaps AW-101 waste, as shown in Table 4. However, the O₂ depletion of the AN-107 simulant without organics provides confidence that the TFC-ENG-STD-34 specified simulant will also be O₂ depleting under irradiation.

Thus, for primary hoses, the external surface is exposed to atmospheric O₂, while the internal surface is not exposed during waste transfers. The test configuration for test Phases 3 and 4 including chemical exposure via simulant will model this environment well. However, it must be determined that the O₂ exposure and dose rate specified within Subsection 2.7.5, 1,000 R/hr γ , will not create diffusion-limited oxidation (DLO) effects. A method for determining when DLO effects occur, developed by A.V. Cunliffe and A. Davis (Clegg and Collyer, 1991) will be applied to determine if DLO effects will be present for HIHTL irradiation at 1000 Rad/hr. Cunliffe and Davis' criterion is presented below, where values greater than eight indicate DLO effects are present.⁸

$$\frac{L^2 \Phi}{P_{ox} p} \geq 8$$

Where: L = sample thickness (cm)
 Φ = O₂ consumption rate (ml STP/ml/s)
 P_{ox} = O₂ permeation rate (ml STP/cm/cm Hg/s)
 p = partial pressure of atmospheric O₂ (cm Hg)

Φ can be determined by multiplying a G(-O₂) value (ml STP/ml/Gy) by the dose rate (units of Gy/s, by dimensional analysis). A quantitative test of the Cunliffe-Davis theory is discussed wherein P_{ox} was found to be 7.3×10^{-9} ml STP/cm/cm Hg/s at 70 °C and G(-O₂) was found to be 5.8×10^{-10} mol O₂/ml/Gy for a commercial EPDM rubber. Application of the ideal gas law at STP converts G(-O₂) to 1.3×10^{-5} ml STP/ml/Gy. While not explicitly stated, it is assumed this criterion assumes atmospheric O₂ diffusion in two dimensions on a sample of thickness L. In our application, O₂ diffusion is available in only one direction; therefore, L will be twice the thickness of HIHTL hose (3/8 in), plus an additional 1/16 in to account for EPDM tape used to apply heat trace, equaling 7/8 in or 2.2 cm. 1000 Rad/hr corresponds to 2.78×10^{-3} Gy/s. Partial pressure of O₂ at SNL is approximately 13.2 cm Hg.

$$\frac{(2.2cm)^2 * \left(1.3 * 10^{-5} \frac{ml\ STP}{ml * Gy}\right) * \left(2.78 * 10^{-3} \frac{Gy}{s}\right)}{\left(7.3 * 10^{-9} \frac{ml\ STP}{cm * cm\ Hg * s}\right) * 13.2cm\ Hg} = 1.82 < 8$$

⁸ The following analysis and corresponding values used are found in Clegg and Collyer (1991).

The Cunliffe-Davis criterion indicates that there will not be DLO effects for irradiation of HIHTL filled with chemical simulant at 1000 Rad/hr.

2.7.5 Radiation

Degradation caused by irradiation of nonmetallic materials is a growing concern in both the commercial and defense nuclear industries. Commercially, nuclear power plants seeking to extend their license beyond their original design life are evaluating degradation of insulating cables and other materials. These plants are evaluating the remaining service life as well as the remaining ability to withstand loss of coolant accidents after years of exposure. The defense sector work includes this test plan, as well as degradation of sealing materials in packaging and shipping containers.

This test plan, to our knowledge, is unique in delivering low dose rate exposure over a significant period of time with simultaneous exposure to a chemical solution, elevated temperatures and pressures. This approach will allow for the study of synergistic effects that may accelerate or mitigate known degradation mechanisms. These mechanisms will be covered briefly herein; extensive detail of these mechanisms is available in literature.

Radiation-induced damage of polymeric materials can be generalized as a change in the polymeric structure, usually predominated by the long carbon chain backbone. This chain can undergo scission and cross-linking; changes which are generally understood and modeled as a chemical system by the generation, propagation, and termination of radicals. Free radicals are highly reactive, especially in the presence of O₂, as reflected by its prevalence in reactive pathway studies and kinetic models. Changes in material properties can be generally attributed to either chain scission or cross-linking, such as increased hardness, strength, brittleness and reduced flexibility and elasticity for cross-linking polymers. However, changes in material properties, desirable or not, are the consequence of a dynamic environment wherein the competition between chain scission and cross-linking can change. The nonlinear behavior of material properties as a function of dose rate was discussed in Wilski (1986), while Nigrey (2000) demonstrated the nonlinear behavior of material properties as a function of absorbed dose. In short, the half-value dose may suggest a final cross-linked or scissioned state, but the path to that state may have local maxima in either direction for both mechanism and properties.

Possible synergistic effects of radiation-induced damage are based on interactions with the O₂-radical pathways. Reaction rates of these degradation pathways may be temperature sensitive, whether it be from increased diffusion and transport of O₂, Arrhenius behavior of initiating, intermediate, and termination reactions, promotion of competing intermediate reactions, or increased radical mobility resulting in changes in observed oxidation reaction rates. The presence of a chemical solution may make available a number of additional reactive and oxidative chemicals, including nitrates and nitrites, or radiolysis products such as peroxides. Mechanical stress, in the form of internal pressure, or compression in the case of sealing materials, may change mass transfer via altered micropore structure, physical alterations of the polymer chain configuration from stretching, straining, or otherwise, resulting in possible changes in energy absorption properties, relative physical relocation of existing radicals, and changes in the apparent activation energy of scission or cross-linking reactions.

The objective of this test plan is to expose materials to a dose as representative as possible while achieving results in a reasonable time frame, yet improving on past irradiation experiments. To this end, exposure rates of 100 or 1000 R/hr of β irradiation and 1000 R/hr of γ have been specified. This will improve upon previous irradiation-only experiments at exposure rates on the order of 10^5 - 10^7 Rad/hr.

2.7.5.1 Radiation Type

This test plan must align the types of radiation from Hanford wastes with suitable test sources capable of surviving the test environment. Both topics are addressed here.

Hanford wastes are a product of plutonium production from the 1940s up to 1985, and the separations processes continued up to 1988. Alpha, β , and γ emitters are all present in Hanford wastes in varying quantities. However, since reactor production ceased in 1985, the majority of remaining Hanford waste radioactivity are attributed to the approximately 30-yr half-life fission products of ^{137}Cs and ^{90}Sr , and their respective daughter products $^{137\text{m}}\text{Ba}$ and ^{90}Y . Various α emitters are present; however, their exclusion in the test plan is a consequence of the progeny and scope of the test plan. Postservice examination of components were considered prior to direction to develop this test plan, but not deemed worth the cost of worker exposure in handling the contaminated materials (Huizenga, 2011). Alpha sources are too fragile to withstand the environments to be produced during testing and working directly with an α -emitting solution resulting in contaminated equipment undermines the inherent direction of the test plan scope.

Testing will be carried out with sealed β and γ sources. An ^{85}Kr line source capable of producing the required β exposure rate in the desired configuration has been identified. High β -exposure rates are typically generated in beams, in relatively fragile packing to allow transmission, or with small windows that do not provide the desired coverage. For γ irradiation, ^{60}Co line sources are readily available, which is an advantage relative to potentially available ^{137}Cs sources that would provide the most appropriate radiological energy spectrum. Subsection 4.3 provides additional information on these sources.

An important element of this test plan is focused on potentially different effects of β versus γ irradiation. The existing information on the radiation resistance of nonmetallic materials is based on accelerated testing using high rates of γ irradiation only. A series of reports from a joint U.S. and French research program that examined the comparative effects of β and γ irradiation concluded that the effects can be correlated on the basis of absorbed dose (Wyant et al., 1986; Buckalew et al., 1987; 1989). However, these tests generally used thin specimens. It is not clear, due to the different energy deposition properties of β and γ radiation, if they will have the same effect on a bulk component, such as HIHTL hoses.

Beta irradiation, compared to γ , has a strong interaction with matter owing to its charge. Electrons essentially continuously interact, and deposit energy, to the surrounding matter. These interactions occasionally cause secondary electrons to be emitted from the path of the primary electron resulting in a branched pattern of energy deposition in a short range in dense matter. Beta radiation from a ^{90}Sr source will deposit approximately 90% of its energy in 4 mm of water.

Gamma irradiation is modeled as a particle that does not continuously interact with the matter around it. Instead, it is modeled as having a particular chance to ‘collide’ with matter it passes through. Several feet of water is often used as shielding in pool irradiator facilities. For the photon energies of concern, Compton scattering is the dominant phenomenon upon interaction in matter. In Compton scattering, a photon interacts with an outer electron, ejecting it and producing a photon of lesser energy in a random direction, hence scattering. This effect leads to the phenomenon that the absorbed dose of a material subject to γ irradiation is higher slightly under the surface of the material than at the surface. The decay of γ irradiation dose deposition generally follows the Beer-Lambert law, with mass attenuation coefficients unique to individual materials. One cm of water will absorb less than 10% of the dose rate from the ^{137m}Ba photon emission.

2.7.5.2 Irradiation Dose Rate

Dose rate selection must consider multiple factors: expected radionuclide content of Hanford waste streams, test durations to reach critical doses, facility capabilities, and DLO effects. In order to make this determination, irradiation of HIHTL hoses will be used as a basis given their importance in the test plan and on their lack of confined geometry. DLO effects are discussed in Section 2.8.4.2. Additionally, the capabilities of SNL’s GIF and associated facilities far exceed the requirements of this test plan.

Hanford waste is stored in 177 underground storage tanks containing 56 million gallons of liquid and solid waste. The waste was produced from multiple reactors and several processing and postprocessing plants and methods, leading to a considerable variety in radionuclide content. Waste transfer operations may involve pumping supernatant liquid only or solids suspended in water or supernatant liquid. Due to the fact that ^{137}Cs and ^{90}Sr are highly partitioned to the liquid phase and solid phase, respectively, the slurry stream of waste solids suspended in supernatant liquid produces the largest amount of energy deposited in an HIHTL and most conservative to use as a basis. Based on volumetric material balances, averaged solids loading during retrieval are typically 5% solids or less; with one retrieval approaching 10% solids (RPP-RPT-50852). Accounting for the possibility of more efficient retrieval technologies, 15% solids will be used as a conservative basis.

Radionuclide loadings are tracked at Hanford as part of the TWINS. The information is segregated into many parameters, including tank, waste layer designation, volume, and constituent concentration. The relevant parameters listed below with respective units/descriptions.

- Waste Phase
 - Sludge
 - Saltcake
 - Supernatant
- Analyte
 - ^{137}Cs
 - ^{90}Sr
- Inventory
 - Ci

- Volume
 - kL
- Component Density
 - g/mL
- Adjusted Concentration
 - $\mu\text{Ci/mL}$ (for liquids)
 - $\mu\text{Ci/g}$ (for solids)

The waste phase designation for sludge and saltcake layers carries several different variations (e.g., 'Sludge [Liquid & Solid]' and 'Sludge Solid'); however, no phase shares a descriptor as both saltcake and sludge. Any variation of sludge was designated as sludge, and so forth. All SSTs and DSTs were included. Data were retrieved on June 4, 2012, for analytes ^{90}Sr and ^{137}Cs with a decay date of November 11, 2008. The data were processed using simple arithmetic as follows:

1. Solids concentrations were adjusted to volumetric basis by multiplication with the component density.
2. Radionuclide inventory and waste volume values were summed for total values.
3. Segregated data by waste phase and analyte.
4. Sorted data from smallest to largest concentration.
5. Calculated waste volume and radionuclide inventory as a percentage of total volume or inventory for each waste layer.
6. Calculated percent cumulative waste volume and radionuclide inventory in ascending order with ascending concentration.

Matching process knowledge, it was found that sludge solids contribute to dose more than saltcake; therefore, sludge waste is used as the basis for solid radionuclide contribution. Plotting cumulative volume and radionuclide inventory versus analyte concentration for ^{137}Cs in supernatant and ^{90}Sr in sludge results in Figures 7 and 8.

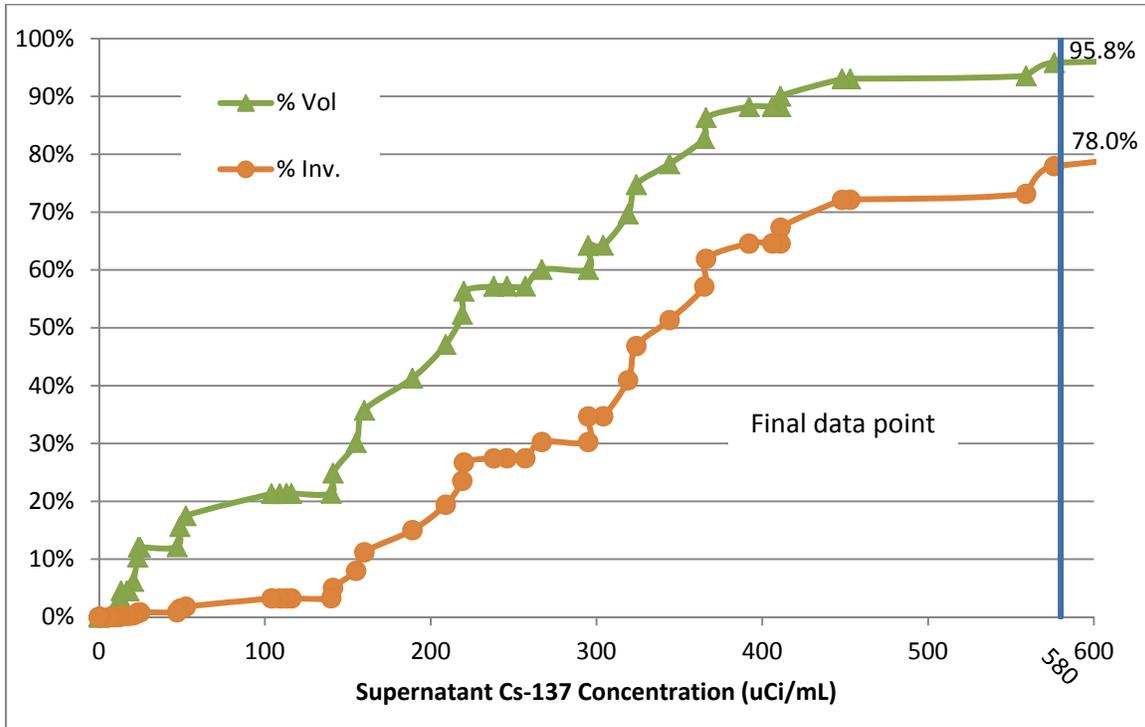


Figure 7. Cesium-137 Supernatant Concentrations versus Cumulative Waste Volume and Radionuclide Inventory.

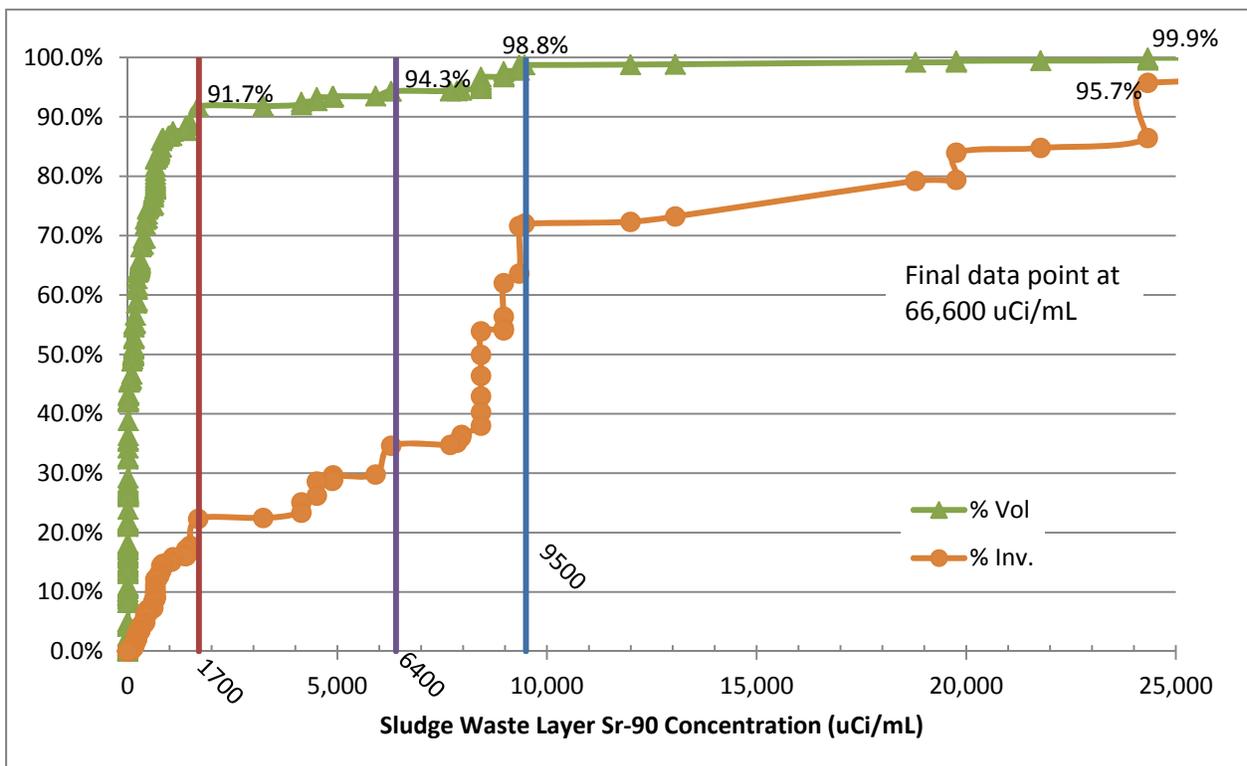


Figure 8. Strontium-90 Sludge Waste Layer Concentrations versus Cumulative Waste Volume and Radionuclide Inventory.

Figure 7 displays the range of ^{137}Cs concentrations existing in Hanford tank farms supernatant waste. From this graph, a reasonably bounding ^{137}Cs concentration can be identified to provide context for selection of a testing dose rate. Over 90% of supernatant waste by volume has a ^{137}Cs concentration of about 450 $\mu\text{Ci/mL}$ or less. An approximate 25% increase to 580 $\mu\text{Ci/mL}$ bounds two additional supernatant concentrations and an additional 5-6% of total ^{137}Cs inventory. A single supernatant composition is not bounded by 580 $\mu\text{Ci/mL}$, which at 1470 $\mu\text{Ci/mL}$ represents a 250% increase over the selected basis of 580 $\mu\text{Ci/mL}$. This value is bounding for 95.8% of all supernatant waste, excluding only Tank 241-AZ-101 supernatant.

Figure 8 displays the range of ^{90}Sr concentrations existing in Hanford tank farms sludge waste layers. From this graph, a reasonably bounding ^{90}Sr concentration can be identified to provide context for selection of a testing dose rate. Over 90% of supernatant waste by volume has a ^{90}Sr concentration of 1700 $\mu\text{Ci/mL}$ or less. Increasing the bounding value beyond this point returns little additional bounded volume for a large increase in concentration. The next plateau in the graph occurs at 6400 $\mu\text{Ci/mL}$, representing an increase of over 350% to bound an additional 2.6% of sludge waste. At a total volume of 42,000 kL, or 1.11 million gal, the 8.3% not bounded by the 1700 $\mu\text{Ci/mL}$ value represents ~92,000 gal of sludge waste or less than 1% of the total of 56 million gal of Hanford tank farms waste. Furthermore, sludge conservatively bounds the ^{90}Sr content of saltcake layers.

Collectively, use of 580 $\mu\text{Ci/mL}$ ^{137}Cs supernatant and 1700 $\mu\text{Ci/mL}$ ^{90}Sr sludge as a basis for a slurry transfer bounds all possible transfers, excluding AZ-101 supernatant and 92,000 gal of sludge. These source concentrations can be used to calculate a dose rate produced from a reasonably bounding 15% by volume sludge slurry transfer. By assuming the ^{137}Cs contribution from the sludge is insignificant relative to the supernatant and the ^{90}Sr contribution from the supernatant is insignificant relative to the sludge, a slurry source term is calculated by simple multiplication by 85% and 15%, respectively, resulting in 493 $\mu\text{Ci/mL}$ ^{137}Cs and 255 $\mu\text{Ci/mL}$ ^{90}Sr .

Both $^{137\text{m}}\text{Ba}$ and ^{90}Y exhibit secular equilibrium with their parent radionuclides. Approximately 95% of ^{137}Cs decays result in $^{137\text{m}}\text{Ba}$, with the remaining 5% going directly to the stable ^{137}Ba . ^{90}Sr decays directly to ^{90}Y . The resulting concentrations of $^{137\text{m}}\text{Ba}$ and ^{90}Y are 468.4 $\mu\text{Ci/mL}$ and 255 $\mu\text{Ci/mL}$, respectively. A summary of the radionuclide concentrations, and their respective emission energies are shown in Table 5.

To apply this source term to determine a dose rate, a rule of thumb from Shleien and Terpilak (1992) will be applied. This rule of thumb is listed in the same form for both β and γ sources; however, their applicability varies due to the nature of the radiation type. The rule of thumb is to determine dose rate for tissue immersed in an infinite solution of uniform radionuclide concentration. The rule of thumb can be modified by a factor of 0.5 to calculate the dose rate at the surface of an infinite solution. Because no input parameters are based on the object being irradiated, including density and thickness, and the infinite field assumption, the rule of thumb calculates a maximum possible dose rate for a given concentration. Given the penetration depth of the β energies of concern, the diameter and thickness of the HIHTL hose, the infinite solution

assumption is valid. For γ irradiation, the penetration depth is much greater than the thickness and diameter of HIHTL hose, meaning that the rule of thumb is very conservative. Furthermore, it is assumed for this calculation that the f-factor for dose deposition in tissue compared to nonmetallic materials is 1.

$$Dose\ Rate\ \left(\frac{Rad}{hr}\right) = \sum_i 0.5 * 2.12 * \frac{E_i * C_i}{\rho}$$

Where: E_i = Emission energy for radionuclide i (MeV)

C_i = Concentration of radionuclide i (μ Ci/mL)

ρ = Density of solution (g/mL)

Application of the rule of thumb results in the values listed in Table 5. A density of 1.25 g/mL will be conservatively used for a 20% by volume sludge slurry solution, as a lower density value results in a higher dose rate.

Table 5. Application of Rule of Thumb (Shleien and Terpilak, 1992)

Radionuclide	Type of Emission	Energy (MeV)	Concentration $\mu\text{Ci/mL}$	Dose Rate to Tissue (Rad/hr)	Total Dose Rate to Tissue (Rad/hr)
^{137}Cs	β	0.174	493	74.1	γ
$^{137\text{m}}\text{Ba}$	γ	0.662	468.4	267.7	267.7
^{90}Sr	β	0.196	255	43.2	β
^{90}Y	β	0.934	255	205.7	322.9

For γ irradiation of tissue, the conversion from Roentgen to rad is approximately a factor of 1. It must be reemphasized that these values are determined by applying a rule of thumb rather than a rigorous calculation, with simplifying assumptions to determine a slurry stream composition, with bounding source term values and a conservative solids loading. However, this estimation provides much needed context for a reasonably bounding dose rate for test plan implementation. This calculation is not intended to be directly comparable to existing dose rate estimation practices employed for Hanford tank farms.

Radiation resistance of materials is often presented in literature in the form of critical dose, which is typically defined as the amount of dosage required to cause a 50% reduction in a specific material property, usually tensile strength. Most materials have a cited critical dose on the order of 5×10^6 to 5×10^7 Rad, with notable exceptions of Teflon at 10^4 and polyether ether ketone (PEEK) at 10^8 or higher. EPDM and polyethylene, components of HIHTL hose, are commonly cited at around $1\text{--}2 \times 10^7$ Rad. Usually these critical doses are determined at dose rates on the order of 10,000–100,000 Rad/hr (100–1000 Gy/hr), resulting in irradiation times of 3 days to 12 weeks. Extremely thin samples are required to prevent DLO effects at these rates. However, as previously discussed, this test plan is designed to improve upon these bases by using a more realistic dose rate on actual components to simulate actual exposure conditions. If the combined dose rate of 590.6 Rad/hr developed above was used to obtain 2×10^7 Rad, the total irradiation time is approximately 4 yr. For comparison, dose rates calculated using the same rule of thumb in RPP-6711, Appendix T, for retrievals of C-103, C-106, C-108, C-109 had a maximum of 34 Rad/hr, while retrieval of S-112 calculated 365 Rad/hr. These two dose rates result in considerably longer exposure times, which are impractical. Due to space restrictions, cost concerns, and the desire for data after a reasonable time, a slightly higher dose rate is selected. However, this dose rate must not be so high as to introduce DLO effects in the unconstrained HIHTL hose. It is suspected that DLO effects are observed in field configurations due to limited access to O_2 replenishment from the constrained geometry. The γ -exposure rate for the majority of testing is specified to be 1000 R/hr. Assuming the energy absorption of EPDM is roughly similar to tissue, the specified dose rate is roughly 1000 Rad/hr. This rate of exposure results in an integrated dose of 8.8×10^6 Rad after 1 yr, 1.31×10^7 Rad after 1.5 yr, and 1.75×10^7 Rad after 2 yr.

To investigate the effects of exposure rate and type, Phase 1 will use exposure rates 100 R/hr of β irradiation (the upper limit of β line sources) and 100 or 1000 R/hr of γ .

2.7.5.3 Exposure

Recreating reasonable testing radiation conditions is largely dependent on geometry. Since using a radioactive simulant solution is not practical for this test plan, no configuration will be able to mimic radiation source geometry perfectly, which affects dose uniformity and dose deposition profiles.

Hanford waste transfers can be assumed to produce a uniform concentration of radionuclides. Any significant nonuniformity would be present due to a stratification of suspended solids, which would result in a significant disparity of ^{90}Sr concentration. Of tank waste layers that have been analyzed for ^{90}Sr particle size distributions, observed particle sizes in sludge have been less than 200 nm (Wells et al., 2011), matching process knowledge that strontium's insolubility results in early precipitation of fine particles. Particles of this size will be easily suspended during transfers. Incorporation of these fine particles into aggregates could result in association with larger particle sizes; however, such aggregation would also provide a degree of shielding. Regardless, limitations in source selection have bounded the maximum β dose rate available. The mineral nastrophite ($\text{NaSrPO}_4 \cdot 9\text{H}_2\text{O}$) has been observed in saltcake layers as particles as large as 200 μm ; however, saltcake wastes have significantly lower ^{90}Sr concentrations.

Line sources will be used to approximate a pipe or hose filled with an approximately uniform radionuclide concentration. This configuration provides the same 360° coverage and uniform dosage if placed in the center of the pipe or hose, for an isolated system. For β irradiation, this configuration will be used, due to the penetration characteristics of β exposure. Achieving a uniform field with β sources using an array to irradiate multiple samples would be bulky. Furthermore, the dose-deposition profile would vary drastically from the field condition it is intended to represent, with approximately zero dose on the inner surface of the component if an external array were used. In regards to β irradiation, each hose can be treated as an isolated system with an internal source.

In contrast with β irradiation, the penetration of γ irradiation requires neighboring sources to be considered and permits having an external source produce an approximately uniform dose to all sides of a component. To maximize the radiation field generated from a γ source, an annular vessel with the sources in the center will be deployed. This approach will minimize the number of sources required. If significant dosage differences are expected for the component facing towards the sources versus away from the sources, then a method of periodic rotations could be deployed to ensure an even cumulative dose. Using external γ sources does result in an inverted dose deposition profile, albeit to a much lesser degree than compared to β irradiation.

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3. PHASE 1: COMPARISON OF BETA AND GAMMA IRRADIATION OF NONMETALLIC MATERIALS

3.1 Objectives and Strategy

The nonmetallic materials used in the Hanford tank farms are exposed to both β and γ radiation. The sources of β radiation are mainly ^{90}Sr and ^{90}Y , which are associated with the solids in the tanks. The sources of γ are mainly ^{137}Cs and $^{137\text{m}}\text{Ba}$ and are associated with the supernatant solutions.

It is not practical to use a β source dispersed in an aqueous or gaseous medium in direct contact with the insides of the hoses, Teflon gaskets, or EPDM O-rings for the β - γ comparison. Rather, it is highly desirable that sealed β sources be used to avoid contamination of the irradiated nonmetallic materials. This will greatly simplify the postexposure mechanical testing to be used to quantify the effects of β , γ , and simultaneous β and γ irradiation on these materials. However, the sealed β sources identified for this test plan can only be used at ambient laboratory temperatures and pressures, and only in the absence of caustic solutions simulating the supernatant tank solutions.

Therefore, the possible synergistic effects of simultaneous β and γ irradiation must be determined under ambient laboratory conditions without the simulated supernatant solution by comparing the effects of simultaneous β and γ irradiation to those from γ only (see below). This comparison will provide a “ β enhancement factor” or “ β factor” to reflect how much additional damage, if any, results from simultaneous irradiation with β and γ relative to that from γ only. This factor will be used to correct the results obtained from simultaneous exposure to γ irradiation and one or more additional stressors (elevated temperatures, simulated supernatant solutions, and elevated pressures). It is practical to combine γ irradiation and these stressors because the γ radiation from sealed ^{60}Co sources outside the stainless steel vessels will penetrate the vessels without contaminating the samples inside the vessels.

Figure 9 provides the baseline test matrix proposed for the β - γ comparison. Comparisons of the results measured by postexposure mechanical testing after Paths 2 and 3 of Phase 1 will provide a “ β enhancement factor” or “ β factor” to quantify how much additional damage (if any) results from irradiation with both β and γ (Path 3) relative to that from γ only (Path 2). This factor will be used to correct the results obtained from Phases 2, 3, and 4 of this study, which will use γ only, to simulate the additional effects of β . The proposed use of the β factor is illustrated in Figure 2, the waterfall diagram (see Section 2.0).

Use of this β enhancement factor to correct the results from Phases 2, 3, and 4 will necessitate the assumption that this factor is identical for the conditions used for Phase 1 (the β - γ comparison) and those used for Phases 2, 3, and 4 (effects of simultaneous exposure to multiple stressors). These other stressors include (1) elevated temperatures (Phase 2); (2) elevated temperatures and the presence of a caustic solution to simulate the supernatant liquid in the tanks (Phase 3); and (3) elevated temperatures, the caustic solution, and elevated pressures (Phase 4). Therefore, use of the β factor to correct the results from Phases 2, 3, and 4 will require

the assumption that this factor is independent of temperature, the caustic chemical conditions in the tanks, and pressure, up to temperatures of 200 °F and pressures up to 425 psig.

The proposed β irradiation rate of 100 R/hr is the maximum exposure rate achievable with commercially available line sources (Subsection 3.3). However, this exposure rate is close to the reasonably conservative, bounding β irradiation rate provided by WRPS (Subsection 2.3). WRPS has specified that the γ irradiation rate for Phases 2, 3, and 4 of this study (Section 4.0) will be 1000 R/hr (Subsection 2.3). Therefore, Path 1 of Phase 1 will be carried out at a β irradiation rate of 100 R/hr, Path 2.1 at a γ irradiation rate of 1000 R/hr, and Path 3.1 at a β irradiation rate of 100 R/hr and a γ irradiation rate of 1000 R/hr.

Paths 2.1 and 3.1 are the most important elements in the proposed baseline matrix (Figure 9), because comparison of the results of these tests will provide an estimate of the additional effects that would be observed if β irradiation were added to the results of Phases 2, 3, and 4. However, comparison of the sum of the effects of Paths 1 and Path 2.1 to those from Path 3.1 will reveal if simultaneous β and γ irradiation results in synergistic effects that cannot be predicted by adding the effects observed separately in Paths 1 and 2.1.

Furthermore, it will also be useful to conduct Path 2.2 at a γ irradiation rate of 100 R/hr, and Path 3.2 at a β irradiation rate of 100 R/hr and a γ irradiation rate of 100 R/hr. Performing Paths 2.2 and 3.2 would reveal whether the β factor depends on the γ irradiation rate. This is potentially important because, although a γ irradiation rate of 1000 R/hr is a reasonably conservative, bounding rate for the nonmetallic materials used in the tank farms, all of the observed γ irradiation rates are actually less than 1000 R/hr (TFC-ENG-STD-34, Figure E-1). In fact, the mean of the estimated DST supernatant (^{137}Cs and $^{137\text{m}}\text{Ba}$) γ exposure rates is 161 rad/hr; the median is 133 rad/hr; and the modal interval of the histogram is < 100 rad/hr (TFC-ENG-STD-34, Figure E-1). Therefore, it would be prudent to ascertain if the β factor depends on the γ irradiation rate, as well as determining the effects of varying γ dose rate.

Finally, Path 4 is proposed as a control. Path 4 will quantify the effects (if any) of shipment of the samples of hoses and Teflon to SNL and storage of these materials under ambient conditions there. It is unlikely that these operations will affect the performance of these materials. However, inclusion of control samples would be relatively easy (no additional safety approvals would be required) and hence relatively inexpensive.

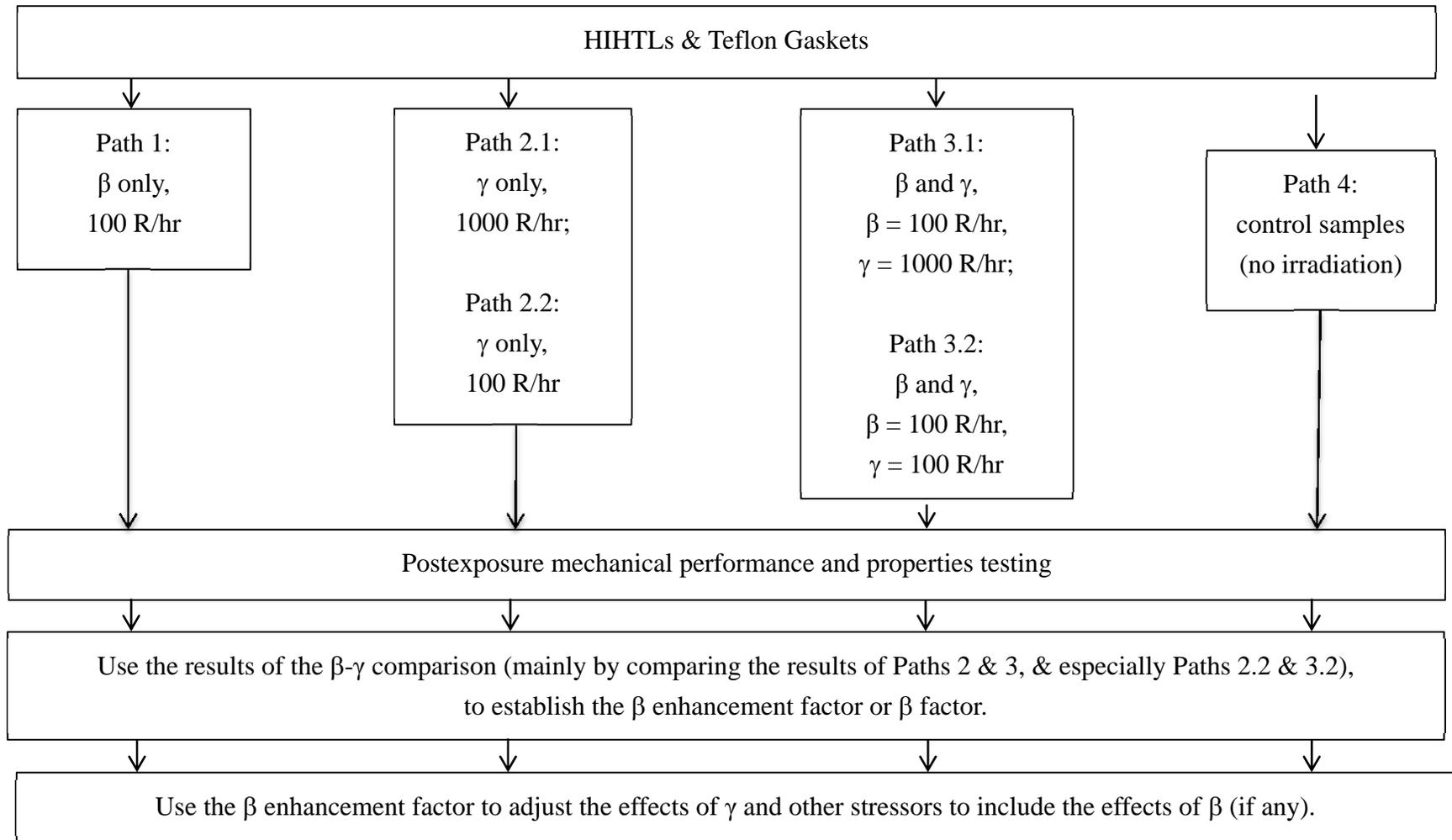


Figure 9. Baseline Test Matrix Proposed for the β - γ Comparison.

3.2 Facility, Test Vessels and Samples, and Test Conditions and Durations

Paths 1 and 4 of the β - γ comparison, which will include a β irradiation rate of 100 R/hr or no irradiation, respectively, will be carried out in a dry, shielded area of SNL's GIF outside the dry irradiation cells (probably in the high bay). The test vessels to be used for Path 4 (see below) will not — of course — require shielding, but will be colocated with those used for Path 1 to ensure that the ambient laboratory conditions for the controls are as similar as possible to those for Path 1. It would not be practical to place any control samples in the GIF pool because of the space limitations anticipated for this part of the facility. Paths 2.1, 2.2, 3.1, and 3.2 must be conducted in the GIF pool, because they will include ^{60}Co γ sources capable of irradiating the nonmetallic test materials at 100 or 1000 R/hr.

A total of 12 annular stainless steel vessels will be used to contain the specimens of nonmetallic materials for Phase 1. Each vessel will have an outer diameter (OD) of approximately 2.5 ft, a length of about 4 or 5 ft, and a central cavity with a diameter of about 1 ft that is open to the GIF pool. The β irradiations for Phase 1 will be carried out by inserting the sealed ^{85}Kr sources inside the primary hoses and other materials, and placing these materials inside the enclosed, annular portions of these containers that surround the central cavities. The γ irradiations for Phase 1 (and for Phases 2, 3 and 4) will be conducted by placing sealed ^{60}Co sources in the central cavities. The objective of using these vessels during Phase 1 will be to contain any radioactive gas (^{85}Kr) that might leak from the sealed β sources (see Subsection 3.3) during the tests. Although it is unlikely that the sealed β sources would leak, the use of leak-proof vessels will facilitate SNL's ES&H R&A process for Phase 1. The 12 vessels required for Phase 1 need only be leak-proof at the ambient temperatures and pressures of the GIF high bay (4 vessels) or GIF pool (8 vessels). Therefore, these vessels might not have to be certified for use at elevated temperatures and pressures, and for exposure to the simulated supernatant solutions, because Phase 1 will be carried out at ambient temperatures and pressures in the high bay of the GIF or in the GIF pool. However, SNL's ES&H R&A process will probably be easier to fulfill, and might even result in the requirement that the 8 vessels to be placed in the GIF pool, or even all 12 vessels to be used for Phase 1, must be identical to those used for Phases 2 through 4 (i.e., certified for use at elevated temperatures and pressures, and for exposure to the simulated supernatant solutions). Furthermore, six of the vessels used for Phase 1 could be reused for Phase 3 if these vessels were certified for elevated temperatures, for exposure to the chemical simulant, and for elevated pressures. This would obviate the need to purchase six vessels for these phases in addition to six of the leak-proof vessels for Phase 1. Therefore, it is assumed that the vessels to be used for Phase 1 will be identical to those used for Phases 2, 3, and 4.

Two vessels will be used for each path or subpath in Figure 9. One of these vessels will contain 12 primary hoses and 12 coupons of the composite hose materials. The other will hold 12 confined Teflon gaskets, 12 unconfined Teflon gaskets, and 12 Teflon coupons. The six vessels to be used for hoses will have dimensions that are identical to the six to be used for the Teflon gaskets. Figures 10, 11, and 12 illustrate these vessels.

Four of these vessels will be placed in the GIF high bay (two for Path 1 and two for Path 4). The other eight will be placed in the GIF pool.

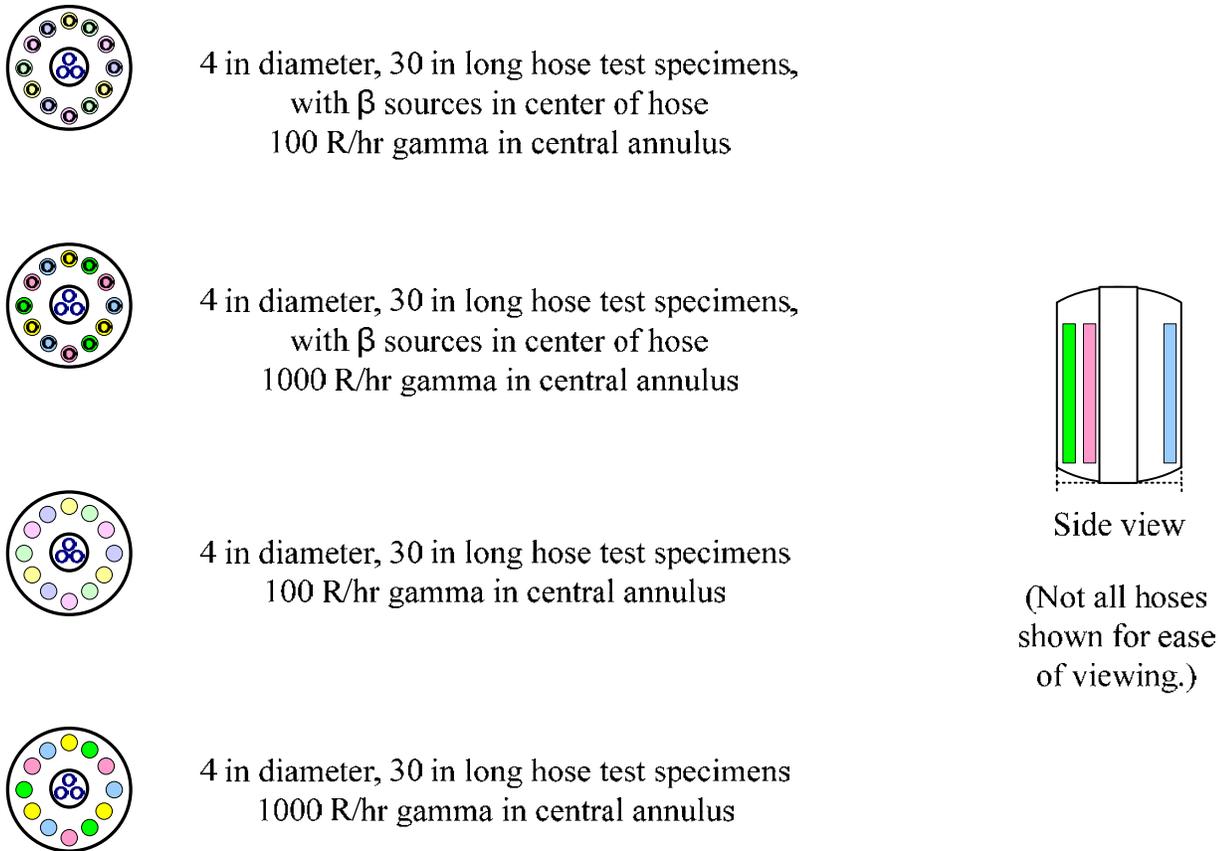
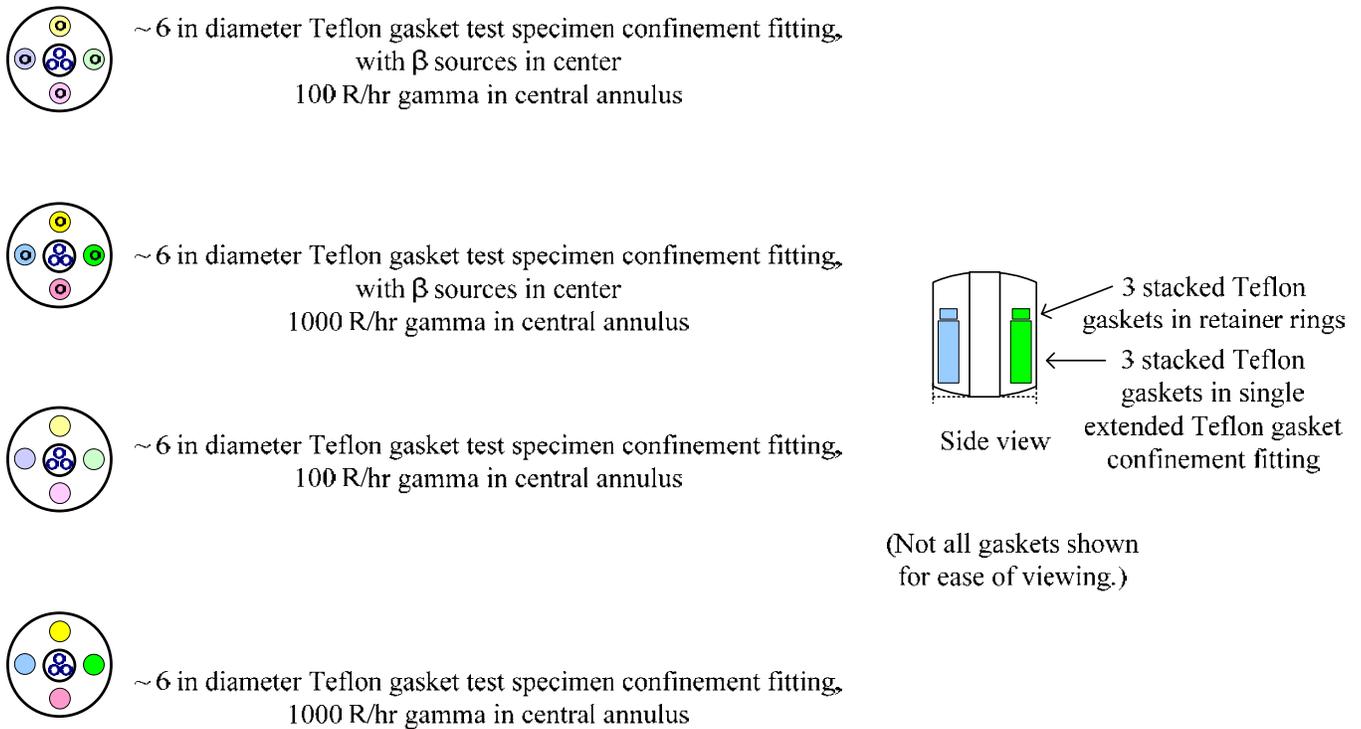


Figure 10. Schematic Diagrams of the Vessels to Be Used for the Hose Materials. Legend in Figure 12.

All 12 of these vessels to be used for Phase 1 will be allowed to equilibrate with the ambient temperatures and pressures in the GIF high bay or pool. The temperatures and pressures expected in the high bay are typical of those described as “ambient laboratory conditions,” except that ambient laboratory pressures at the elevation of the GIF (a little over 5,000 ft above mean seal level) is a little over 80% of the average pressure at sea level (1013 mbar). The temperatures and pressures expected in the pool, however, will be somewhat greater than ambient laboratory conditions, because (1) γ irradiation of the vessels might increase the temperature of the water in the pool somewhat, and (2) the vessels used for Paths 2.1, 2.2, 3.1, and 3.2 of Phase 1 (and for Phases 2, 3, and 4) will be placed at the bottom of the 18 ft-deep pool to achieve the maximum shielding available from the water in the pool.

For Paths 1, 2.1, and 3.1, in which the β and/or γ exposure rates will both be 100 R/hr, the samples will be irradiated for periods of 6, 12, 18, and 24 months. This will correspond to total exposures of 4.38×10^5 , 8.77×10^5 , 1.31×10^6 , and 1.75×10^6 R, respectively. Three of the 12 primary hoses and 3 of the 12 coupons of the composite hose materials; and 3 of the 12 confined Teflon gaskets, 3 of the 12 unconfined Teflon gaskets, and 3 of the 12 Teflon coupons will be removed after each of these irradiation periods or total exposures. This will provide triplicate samples of each of these materials for postexposure mechanical testing after each irradiation period or exposure.



**Figure 11. Schematic Diagrams of the Vessels to Be Used for the Teflon Gaskets.
Legend in Figure 12.**

For Paths 2.2 and 3.2, in which the β exposure rate will be 100 R/hr and the γ exposure rate will be 1000 R/hr, the samples will be irradiated to total γ exposures of approximately 10^5 , 10^6 , and 10^7 R. According to TFC-ENG-STD-34, Appendix B, Table B.1, these exposures correspond approximately to the “normal, reasonably bounding conditions for [the] selection of nonmetallic materials, [in particular, the] total absorbed radiation dose source term:

- For nonmetallic materials subject to continuous immersion in DST supernatant, 1.1×10^7 Rad
- For nonmetallic materials in equipment such as valves and piping, subject to infrequent exposure to DST supernatant waste, 1.3×10^6 Rad
- For nonmetallic materials in readily accessible, self-shielded equipment arrangements, such as above-ground pits, 1.3×10^5 Rad”

An additional total γ exposure of $> 10^7$ R will also be included as an overtest condition. The results from this total γ exposure of $> 10^7$ R will provide information as to whether these nonmetallic materials can successfully sustain total exposures higher than the maximum expected for nonmetallic materials subject to continuous immersion in the DST supernatant solutions.

As in the case of Paths 1, 2.1, and 3.1, 3 of the 12 samples of each type of nonmetallic material will be removed after total γ exposures of approximately 10^5 , 10^6 , 10^7 , and $> 10^7$ R, which will provide triplicate samples of each of these materials for postexposure testing.

100 R/hr		
	Teflon gasket and hose test specimens, remove at 4.38×10^5 R total exposure	(6 months)
	Teflon gasket and hose test specimens, remove at 8.77×10^5 R total exposure	(12 months)
	Teflon gasket and hose test specimens, remove at 1.31×10^6 R total exposure	(18 months)
	Teflon gasket and hose test specimens, remove at 1.75×10^6 R total exposure	(24 months)
1000 R/hr		
	Teflon gasket and hose test specimens, remove at 4.38×10^5 R total exposure	(6 months)
	Teflon gasket and hose test specimens, remove at 8.77×10^5 R total exposure	(12 months)
	Teflon gasket and hose test specimens, remove at 1.31×10^6 R total exposure	(18 months)
	Teflon gasket and hose test specimens, remove at 1.75×10^6 R total exposure	(24 months)

Figure 12. Legend for Figures 10 and 11.

3.3 Beta and Gamma Sources

Sealed β line sources containing ^{85}Kr will be used for Phase 1 (the β - γ comparison). Each source will consist of an approximately 10 in-long, 0.25 in-OD, 0.006 in-thick, aluminum-1100 or 3003 tube with 7.5 mCi/in of gaseous ^{85}Kr in stable gaseous Kr at a total pressure slightly below atmospheric. The half-life of ^{85}Kr is 10.73 yr. It emits a β particle with an end-point energy of 0.897 MeV and a 0.514 MeV γ ray, and decays to stable ^{85}Rb .

These sealed ^{85}Kr line sources will be placed inside the 30 in-long, 2 in-nominal-ID primary hoses and the confined and unconfined Teflon gaskets. Spacers (washers) will be used to align the line sources close to the centerlines of the hoses. These sources will produce exposure rates of about 100 R/hr at a distance of 1 in from these sources (i.e., on the insides of the hoses), based on information provided by the vendor. This is about 50% of the estimate of the reasonably conservative, bounding β exposure rate provided by WRPS (Subsection 2.3). The flat hose and Teflon coupons will be bent around other sealed ^{85}Kr line sources. The sealed ^{85}Kr line sources could be irradiated with 100 or 1000 R/hr of γ irradiation for Path 3 (Figure 9), because they do not contain Mylar⁹ windows.

Other possible β sources were considered before selecting the sealed ^{85}Kr line sources described above. Sealed ^{90}Sr β point sources are available, for example. These point sources consist of right-circular-cylindrical pellets with a diameter of about 0.25 in and a height of about 0.3 in, with a 0.210 in-diameter ceramic disc containing the ^{90}Sr . The sources are covered with 0.002 in-thick pieces of stainless steel. These sources could also be irradiated with 1000 R/hr of γ radiation, because they do not contain Mylar windows. Furthermore, these sources would produce a maximum β dose of about 1,900 R/hr at

⁹ Mylar is a registered trademark of DuPont Teijin Films, Wilmington, Delaware.

a distance of 1 in from the source, based on information from the vendor. This would be more than adequate to achieve the reasonably conservative, bounding exposure rate provided by WRPS (Subsection 2.3). However, such a point source or sources could not be used to uniformly irradiate the insides of the hoses. This is because the radiation emitted by the source would be confined to a narrow beam or conical region, and it would not be practical to irradiate hoses or Teflon gaskets in their in-service configurations.

Electron-beam (e-beam) irradiation of the materials specified for this study was also considered. Buckalew et al. (1984) and Buckalew (1989) used a Pelletron-Raster system, an electrostatic particle accelerator similar to a Van de Graaff generator with scanning capability, to compare the effects of β and γ irradiation of coupons of nonmetallic materials at SNL. Buckalew's Pelletron-Raster system could not be located, nor could anyone currently employed at SNL who is familiar with this equipment or its use. A vendor was identified, but it was decided not to propose reestablishing this capability at SNL because (1) it would not be practical to irradiate hoses or Teflon gaskets in their in-service configurations (Buckalew carried out his studies with coupons only), and (2) commercially available Pelletron-Raster systems cost in excess of \$500,000.

Sealed ^{60}Co source pins will be used for the γ irradiations in Phase 1 (and for those in Phases 2, 3, and 4). Each of these 18 in-long source pins will contain a total activity of 1000 Ci of ^{60}Co . This is the lowest activity of ^{60}Co that the vendor can provide. The preliminary test configuration calculations described in Subsection 4.4 suggest that a total activity of 100 Ci of ^{60}Co will be required in each source pin to produce an exposure rate of 1000 rad/hr on the inner sides of the nonmetallic materials in the enclosed regions surrounding the inner cavities of the test vessels. Therefore, shielding sleeves containing different thicknesses of various metals will be used to reduce the effective loading of the ^{60}Co source pins from 1000 to 100 Ci. These sleeves will be replaced periodically with less dense or thinner sleeves to maintain an essentially constant exposure rate of 1000 R/hr on the inner sides of the test materials as the ^{60}Co decays. These ^{60}Co source pins will be purchased from the same vendor from which SNL's Non-Reactor Nuclear Facilities Dept. 1387 personnel typically purchase γ sources for use in the GIF. All of the ^{60}Co source pins to be used in the irradiations of nonmetallic materials for this study will have to be purchased because (1) Dept. 1387 personnel are currently using all of their ^{60}Co source pins, and (2) they typically use ^{60}Co source pins with a total activity of 10,000 Ci.

3.4 Test Configuration

Subsection 4.4 describes the test configuration for Phase 1 (the β - γ comparison) along with those for Phases 2, 3, and 4 (effects of simultaneous exposure to multiple stressors). The configuration for Phase 1 is discussed along with those for Phases 2, 3, and 4, because eight of the vessels used for Phase 1 would be placed in the GIF pool essentially simultaneously with the six for Phase 2 in the baseline test program. The reduced cost alternative does not include Phase 1 testing. All phases will use similar temperature and air flow configurations.

3.5 Test Control and Monitoring

Subsection 4.5 describes the test control and monitoring system that will be designed and deployed for all 30 test configurations of 18 test vessels in the proposed baseline test program. This description includes the control and monitoring to be carried out for Phase 1 (the β - γ comparison).

4. PHASES 2, 3, AND 4: QUANTIFICATION OF SYNERGISTIC EFFECTS OF SIMULTANEOUS EXPOSURE OF NONMETALLIC MATERIALS TO MULTIPLE STRESSORS

4.1 Objectives and Strategy

The nonmetallic materials used in the Hanford tank farms (Subsection 2.2) are simultaneously exposed to four stressors: (1) radiation (β and γ), (2) elevated temperatures, (3) a nonradioactive, caustic (high pH), supernatant HLW simulant, and (4) elevated pressures.

It is not possible to use the sealed β line sources (see Subsection 3.3) in experiments at elevated pressures and temperatures, or in the presence of simulated supernatant solutions. Therefore, the effects of simultaneous exposure of nonmetallic materials to γ irradiation, elevated temperatures, simulated supernatant solutions, and elevated pressures will be quantified. Then, the β enhancement factor or β factor obtained from Phase 1 of this study (the β - γ comparison) will be used to include the additional effects (if any) of β irradiation. Subsection 3.1 describes the establishment of the β factor in detail.

The proposed baseline test program (Figure 2 and Table 1) is repeated here for ease of reference. The baseline program would include four phases. Phase 1 (see Section 3.0) would compare the effects of simultaneous β and γ irradiation of hoses and Teflon gaskets to those from γ only. Phase 2 would determine the effects of simultaneous exposure of hoses, Teflon gaskets, and EPDM O-rings to γ irradiation and elevated temperatures. Phase 3 would investigate the effects of simultaneous exposure of the same materials used in Phase 2 to γ irradiation, elevated temperatures, and a nonradioactive, simulated supernatant solution. Finally, Phase 4 would quantify the effects of simultaneous exposure of the same materials used in Phases 2 and 3 to γ irradiation, elevated temperatures, the chemical simulant, and elevated pressures.

A reduced cost alternative test program is also considered: it would eliminate Phase 1 tests, carry out the remaining three phases with the hoses only, and carry out only Phase 3 tests with the Teflon gaskets and EPDM O-rings. Section 7.1 of this test plan describes this reduced cost alternative in detail.

4.2 Facility, Test Vessels and Samples, and Test Conditions and Durations

Phases 2, 3, and 4 will be carried out in the GIF pool. The vessels for Phases 2, 3, and 4 will be certified for use at elevated temperatures and pressures, and for exposure to the simulated supernatant solutions. All of the vessels will be annular with an OD of approximately 2.5 ft, a length of about 4 or 5 ft, and a central cavity with a diameter of about 1 ft that is open to the GIF pool. Figures 13, 14, and 15 (see next three pages) show these vessels.

Six vessels will be used for each of Phases 2, 3, and 4. Three of these vessels will contain 12 primary hoses and 12 coupons of the composite hose materials. The other three will hold 12 confined Teflon gaskets, 12 unconfined Teflon gaskets, and 12 Teflon coupons; and 12 confined EPDM O-rings and 12 unconfined EPDM O-rings and 12 EPDM coupons.

For Phase 2, the three vessels with the hoses will be maintained at a temperature of 70, 130, or 180 °F and ambient (GIF-pool) pressures without the simulated supernatant solution. The three vessels with the Teflon gaskets and EPDM O-rings will be maintained at 70, 130, or 200 °F and ambient pressure without the chemical simulant. (As explained in Subsection 3.2, these pressures will be somewhat higher than atmospheric at the elevation of the GIF, because the vessels will be placed at the bottom of the 18 ft-deep pool.)

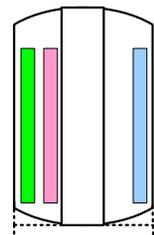
For Phase 3, the three vessels with the hoses will be maintained at a temperature of 70, 130, or 180 °F and ambient (GIF pool) pressures, and will be filled or nearly filled with the simulated supernatant solution. The three vessels with the Teflon gaskets and EPDM O-rings will be maintained at a 70, 130, or 200 °F and ambient pressure with the caustic chemical simulant.

In the case of Phase 4, the vessels with the hoses will be maintained at a temperature of 70, 130, or 180 °F and a pressure of 425 psig with the simulated supernatant solution. The vessels with the Teflon gaskets and EPDM O-rings will be maintained at a 70, 130, or 200 °F and a pressure of 400 psig with the chemical simulant.

For Phases 2 through 4, the γ exposure rate will be 1000 R/hr (Subsection 2.3). The samples will be irradiated to total γ exposures of approximately 10^5 , 10^6 , 10^7 , and $> 10^7$ R. Three of the 12 primary hoses and 3 of the 12 coupons of the composite hose materials will be removed after each of these total exposures. Similarly, 3 of the 12 confined Teflon gaskets, 3 of the 12 unconfined Teflon gaskets, and 3 of the 12 Teflon coupons; and 3 of the 12 confined EPDM O-rings and (if present) 3 of the 12 unconfined EPDM O-rings and 3 of the 12 EPDM coupons will be removed after each of these total exposures. This will provide triplicate samples of each of these materials for postexposure mechanical testing after each total exposure.



4 in diameter, 30 in long hose test specimens
1000 R/hr gamma in central annulus



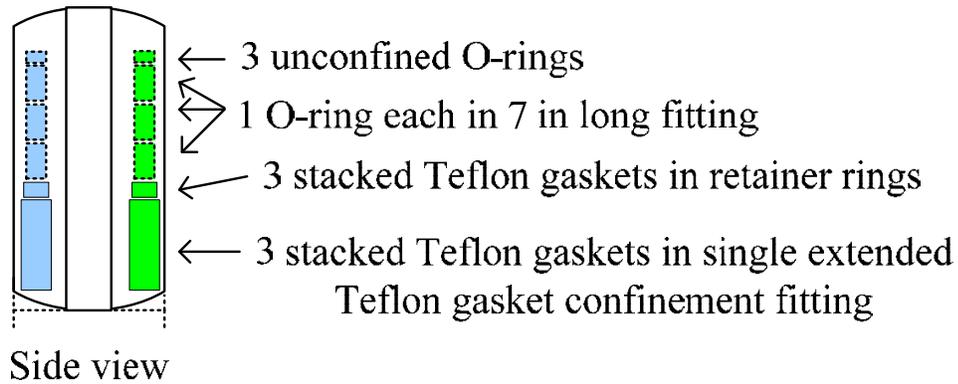
Side view

(Not all hoses
shown for ease
of viewing.)

**Figure 13. Schematic Diagrams of the Vessels to Be Used for the Hose Materials.
Legend in Figure 15.**



~ 6 in diameter gasket test specimen confinement fitting, and
 ~ 4 in diameter O-rings and fitting test specimens,
 1000 R/hr in central annulus



(Not all gaskets & O-ring stacks shown for ease of viewing.)

Figure 14. Schematic Diagrams of the Vessels Be Used for the Teflon Gaskets and EPDM O-Rings. Legend in Figure 15.

1000 R/hr

- Teflon gasket, O-ring, and hose test specimens, remove at 10^5 R total exposure
- Teflon gasket, O-ring, and hose test specimens, remove at 10^6 R total exposure
- Teflon gasket, O-ring, and hose test specimens, remove at 10^7 R total exposure
- Teflon gasket, O-ring, and hose test specimens, remove at $>10^7$ R total exposure

Figure 15. Legend for Figures 13, 14, 18, 19, 20, and 21.

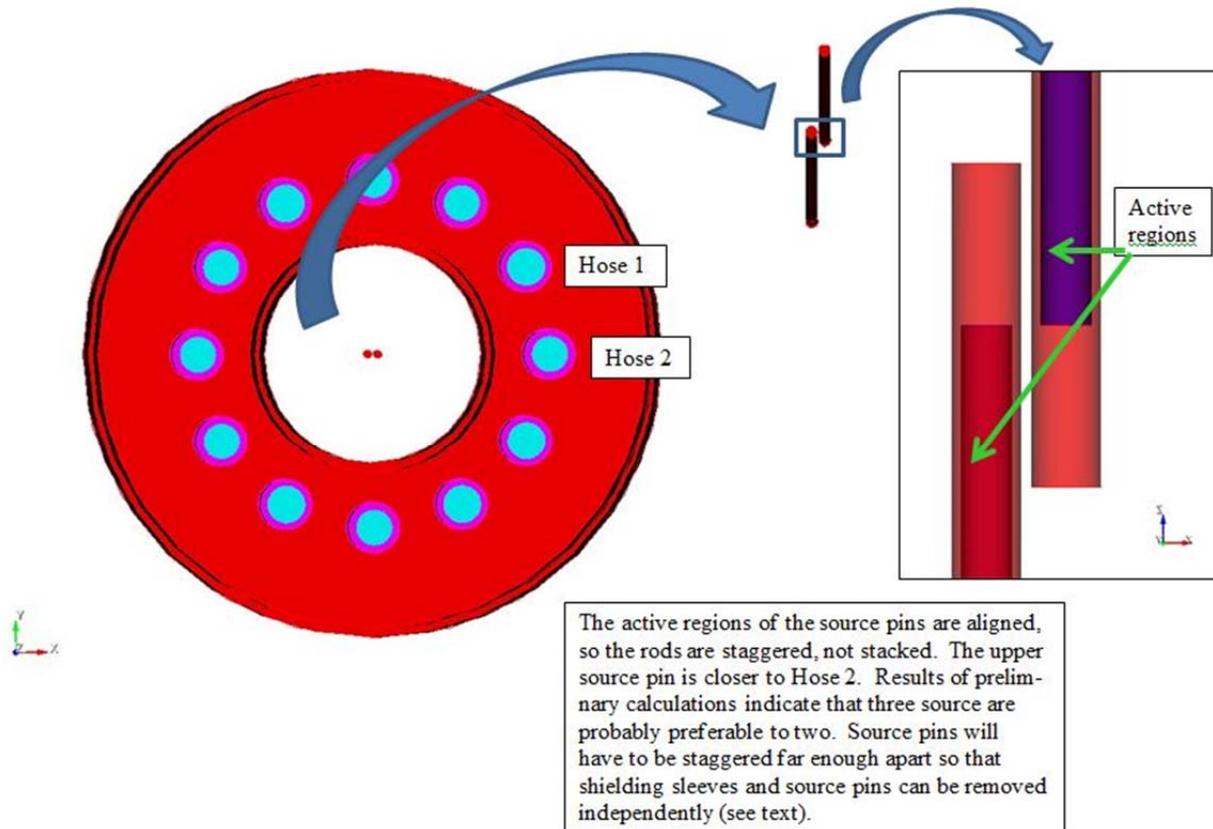


Figure 16. Schematic Diagram of Two Staggered ^{60}Co Source Pins.

4.3 Gamma Sources

Subsection 3.3 describes the sealed ^{60}Co source pins will be used for the γ irradiations in Phase 1 (and for those in Phases 2, 3, and 4). Each of these 18 in-long source pins will contain a total activity of 1000 Ci of ^{60}Co , which is the lowest activity of ^{60}Co that the vendor can provide. A total activity of 100 Ci of ^{60}Co will be required in each source pin to produce an exposure rate of 1000 rad/hr on the inner sides of the nonmetallic materials in the enclosed regions surrounding the inner cavities of the test vessels (Subsection 4.4). Therefore, shielding sleeves will be used to reduce the effective loading of the ^{60}Co source pins from 1000 to 100 Ci. These sleeves will be removed or replaced periodically (see below) to maintain an exposure rate of ~ 1000 R/hr on the test materials as the ^{60}Co decays.

4.4 Test Configuration

This subsection describes the test configuration for Phase 1 (the β - γ comparison) along with those for Phases 2, 3, and 4 (effects of simultaneous exposure to multiple stressors) of the baseline test program. The configurations for all four phases are discussed herein because eight of the vessels used for Phase 1 will be placed in the GIF pool essentially simultaneously with the six for Phase 2 in the baseline test program. The reduced cost alternative will allow placement of Phases 2, 3, and 4 simultaneously.

Preliminary test configuration calculations were carried out with the TIGER codes (Franke et al., 2009) to establish the required activity of each sealed ^{60}Co source pin and the total number of source pins needed to maintain a γ exposure rate of 1000 R/hr for the nonmetallic materials proposed for this study. Figure 16 illustrates the test configuration used for the preliminary calculations. A staggered configuration will be used for ease of source handling. Furthermore, staggering the ^{60}Co source pins allows the active portions of each pin to be aligned with the inactive portion of the other pins, thereby avoiding γ -free regions in the cavities. Figure 16 shows two staggered ^{60}Co source pins in the cavity of an annular vessel. The results of these preliminary calculations are that: (1) a total activity of 100 Ci of ^{60}Co will be required in each source pin to produce an exposure rate of 1000 rad/hr on the inner sides of the hoses, and (2) three 18 in-long ^{60}Co source pins would be preferable to two in order to prevent decreases in the exposure rates at the ends of the hoses. The lowest-activity ^{60}Co source pins that the vendor can provide have a total activity of 1000 Ci. Therefore, shielding sleeves containing different thicknesses of various metals will be used to reduce the effective loading of the ^{60}Co source pins from 1000 to 100 Ci. These sleeves will be removed or replaced periodically with less dense or thinner sleeves to maintain an exposure rate as close as possible to 1000 R/hr on the nonmetallic materials as the ^{60}Co decays. Staggering the source pins will allow independent removal or replacement of the shielding sleeves (i.e., removal or replacement of the shielding sleeves from one of the source pins without having to remove one or both of the other source pins to gain access).

Additional test configuration calculations with the TIGER codes will be necessary prior to the start of any irradiation testing. These follow-on calculations will produce final test configurations with more definitive requirements for the numbers and placement of the sealed ^{60}Co source pins, definitions of the requirements for the densities and thicknesses of the shielding sleeves, how closely the vessels can be spaced in the GIF pool, etc. These follow-on calculations could in turn result in adjustments of the cost of these sources. These calculations could be performed during the preparations for the baseline program from October 2013 through September 2014.

Pending the results of the follow-on test configuration calculations described above, a conceptual test configuration for the baseline program is proposed based on the results of the preliminary calculations. Figure 17 illustrates the GIF pool, with all dimensions given.

The aqua-colored areas of the pool (Figure 17) are the portions that could potentially be used for the 26 of the 30 vessels that will be exposed to γ irradiation in the baseline test program. These vessels will include those in Paths 2.1, 2.2, 3.1, and 3.2 of Phase 1; and all of the vessels in Phases 2, 3, and 4 of the baseline program. The gray area of the pool (Figure 17) is the approximately 4 × 7-ft cask set-down area. This area cannot be used for testing.

Figure 18 provides our proposed, conceptual configuration for the deployment of Phases 1 and 2 in the GIF pool. The eight-vessel array proposed for Phase 1 appears to fit in the approximately 7 × 13-ft testing area to the right (south) of the cask set-down area, pending the results of the test configuration calculations described above. Figure 19 shows our conceptual configuration for the deployment of Phases 3 and 4 in the pool. The six vessels that will be used for Phases 2 and 4 are situated along the bottom and side of the sideways U-shaped area that begins at the upper-left part of the cask set-down area in Figures 18 and 19. Figures 20 and 21 show enlargements of the eight-vessel array proposed for Path 1, and the six-vessel array for Path 3.

4.5 Test Control and Monitoring

A test control and monitoring system will be developed and deployed for all 18 or 12 of the vessels, respectively, in the proposed baseline test program or the reduced cost option. Table 6 (which appears after Figures 17, 18, and 19) shows the test control and monitoring to be applied to each of the four phases of this study. The test control and monitoring system will be designed to be as similar as possible for all vessels to be deployed in Phases 1, 2, 3, and 4.

One or more of the following test variables will be controlled in all four phases of the baseline program or the reduced cost option: (1) the β and/or γ exposure rates, (2) temperature; (3) pressure, (4) the flow rate(s) of gas (compressed air) through the vessels and thus the concentrations of O_2 in the vessel atmospheres.

The values of the following test variables will be monitored and recorded for all of these vessels: (1) total β and/or γ exposure (by radiation dosimetry in the vessels), (2) temperatures (with thermocouples in the vessels), (3) pressures (with pressure transducers in the vessels), (4) the flow rate(s) of compressed air in the effluent from the vessels, and (5) the concentrations of O_2 in the effluent.

Thermocouples, pressure transducers, and β and γ radiation dosimeters suitable for the exposure rates defined for this test plan will be placed inside each of the vessels. Although the thermocouples and pressure transducers will be sheathed with stainless steel or other suitable alloys, they will probably have to be replaced, perhaps each time that samples of nonmetallic materials are removed for postexposure mechanical properties testing.

Continuous flow of compressed air through each of the vessels will be necessary to ensure that O_2 is present throughout these tests. Maintaining oxidic conditions in the vessels will replicate in-service conditions, but might not address diffusion-limited oxidation (Burnay and Hitchon, 1985; Gillen and Clough, 1989; Wise et al., 1997; Gillen et al., 2003), which could bias the results in favor of reduced damage. Oxidic conditions could also be representative of those in the primary hoses used in the Hanford tank farms. This is because air accumulates in these hoses after each use, and is probably present for at least some of time that supernatant solutions and suspended solids are pumped through the hoses. Therefore, oxidic conditions are certainly a relevant end-member condition when the insides of these hoses are exposed to β from ^{90}Sr and ^{90}Y associated with the suspended solids, and γ from ^{137}Cs and $^{137\text{m}}\text{Ba}$ associated with the supernatant solutions. Furthermore, oxidic conditions may persist during much of the time that solutions and solids are pumped through the hoses. Thus, if anoxic conditions develop and persist in the tests proposed in this test plan, the results could be criticized because the test conditions were nonconservative.

Compressed air is inexpensive relative to other inert carrier gases that could be used to maintain atmospheric O_2 concentration. However, compressed air might have to be pretreated to remove contaminants such as dust, moisture, oil droplets, and — especially during Phases 3 and 4 — atmospheric CO_2 . This is because the CO_2 in the compressed air would react with the caustic simulated supernatant solutions to be used in Phases 3 and 4. The composition of the simulant should provide sufficient buffering given the regular replenishment of the simulant.

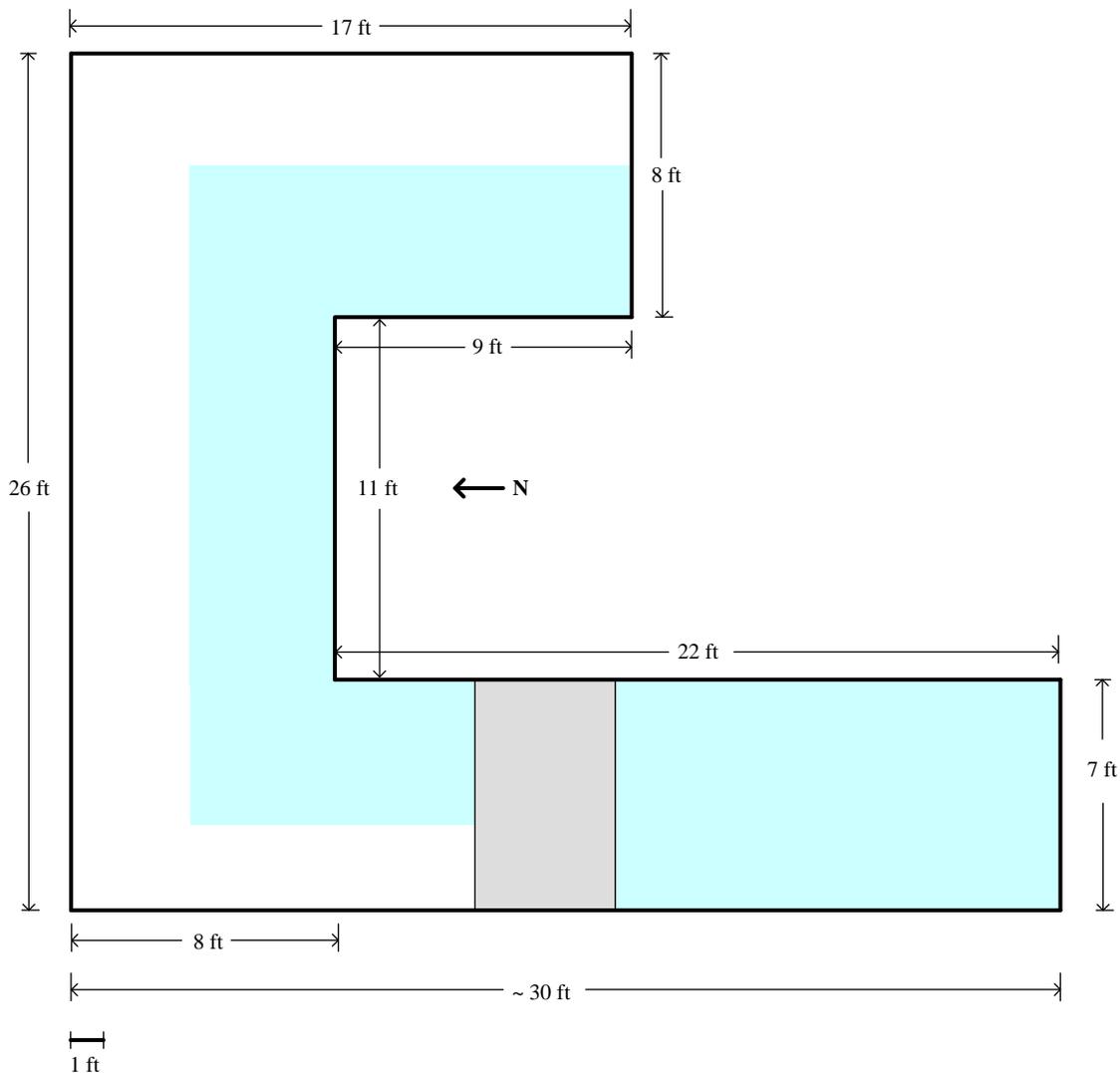


Figure 17. Schematic Diagram of the GIF Pool. See text for explanation of colors.

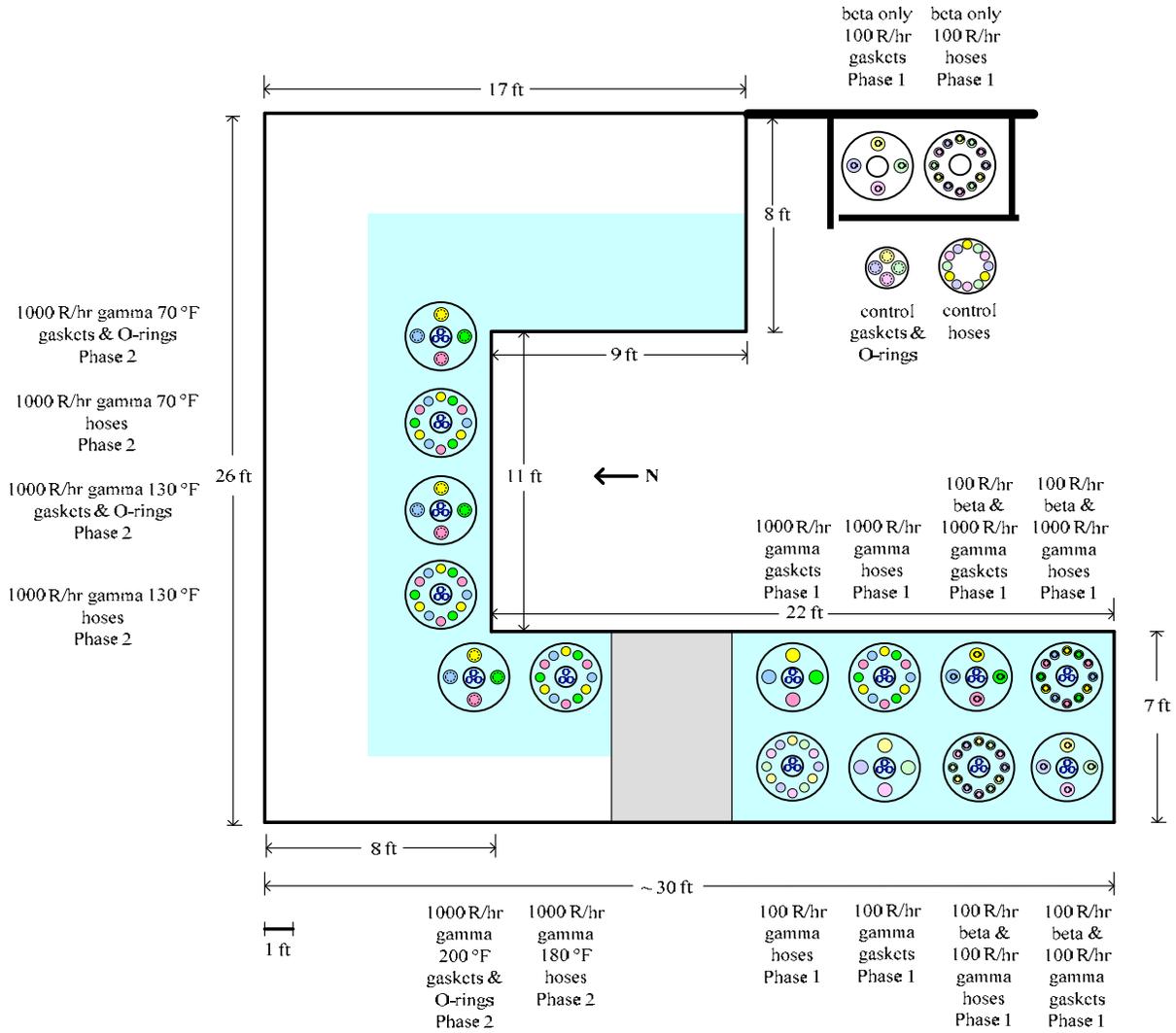


Figure 18. Schematic Conceptual Configuration for the Deployment of Phases 1 and 2 in the GIF Pool. Legend in Figure 15.

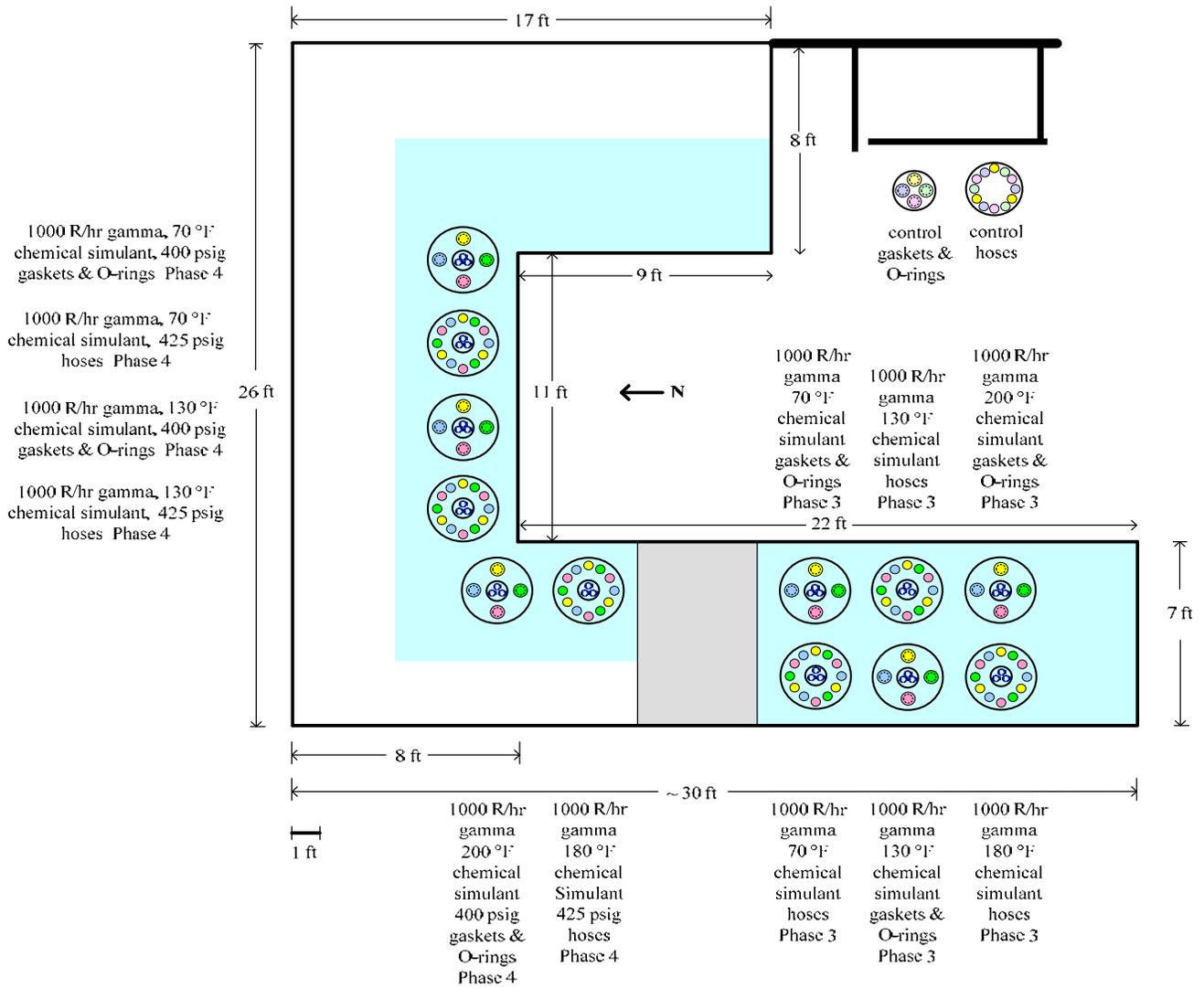


Figure 19. Schematic Conceptual Configuration for the Deployment of Phases 3 and 4 in the GIF Pool. Legend in Figure 15.

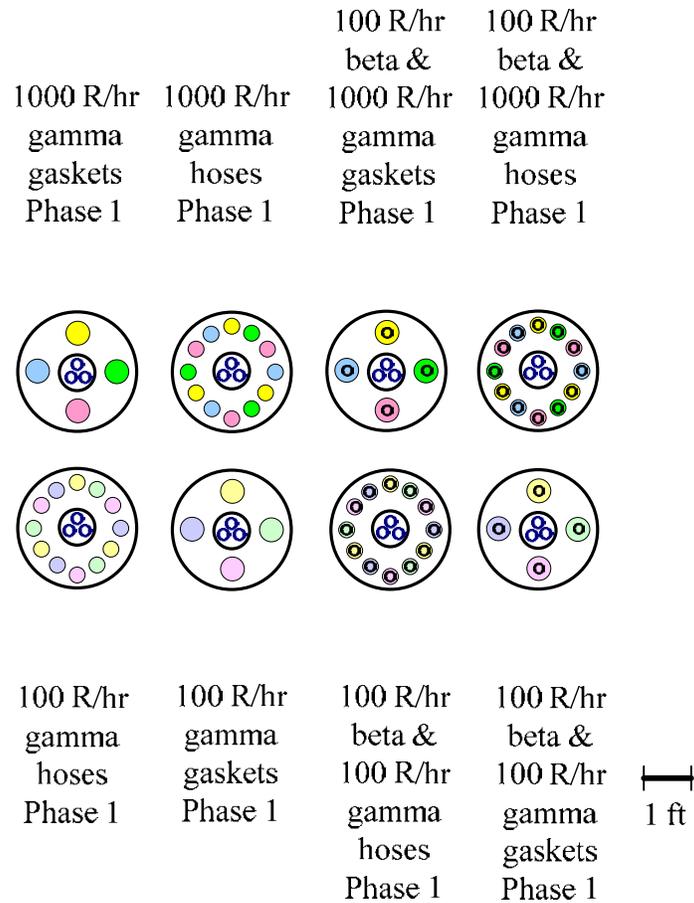
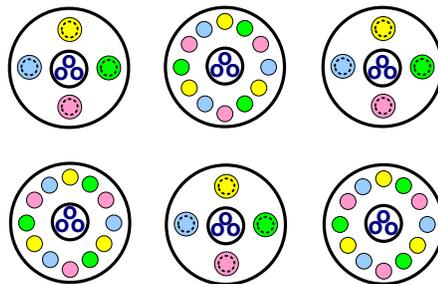


Figure 20. Schematic of the Eight-Vessel Area Proposed for Phase 1. Legend in Figure 15.

1000 R/hr gamma 70 °F chemical simulant gaskets & O-rings Phase 3	1000 R/hr gamma 130 °F chemical simulant hoses Phase 3	1000 R/hr gamma 200 °F chemical simulant gaskets & O-rings Phase 3
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1000 R/hr gamma 70 °F chemical simulant hoses Phase 3	1000 R/hr gamma 130 °F chemical simulant gaskets & O-rings Phase 3	1000 R/hr gamma 180 °F chemical simulant hoses Phase 3
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1 ft

Figure 21. Schematic of the Six-Vessel Area Proposed for Phases 2, 3, and 4. Legend in Figure 15.

Table 6. Test Control and Monitoring for the Irradiation of Nonmetallic Materials.

Test Phase	Radiation	Temperature	Pressure	Compressed Air Flow Rate & O ₂ Concentration	Remarks
1	Control: $\beta = 0$ or 100 R/hr; $\gamma = 0, 100, 1000$ R/hr Monitor w dosimetry	Equilibrate w ambient conditions in GIF high bay or pool Monitor w thermocouples in vessels	Equilibrate w ambient conditions in GIF high bay or pool Monitor w P transducers in vessels	Control flow rate so that O ₂ concentration in effluent is at or close to atmospheric Monitor effluent w flow meters & O ₂ sensors	Ambient T & P in the GIF pool will both be somewhat higher than ambient T & P in the GIF high bay.
2	Control: $\gamma = 1000$ R/hr Monitor w dosimetry	Control: T = 70, 130, & 180 °F (hoses & hose coupons) T = 70, 130, & 200 °F (Teflon gaskets & EPDM O-rings) Monitor w thermocouples in vessels	Equilibrate w ambient conditions in GIF pool Monitor w P transducers in vessels	Control flow rate so that O ₂ concentration in effluent is at or close to atmospheric Monitor effluent w flow meters & O ₂ sensors	Ambient P in the GIF pool will be somewhat higher than that typical of ambient laboratory conditions.
3	Control: $\gamma = 1000$ R/hr Monitor w dosimetry	Control: T = 70, 130, & 180 °F (hoses & hose coupons) T = 70, 130, & 200 °F (Teflon gaskets & EPDM O-rings) Monitor w thermocouples in vessels	Equilibrate w ambient conditions in GIF pool Monitor w P transducers in vessels	Control flow rate so that O ₂ concentration in effluent is at or close to atmospheric Monitor effluent w flow meters & O ₂ sensors	Ambient P in the GIF pool will be somewhat higher than that typical of ambient laboratory conditions. Chemical simulant will be replenished on a regular basis.

Test Phase	Radiation	Temperature	Pressure	Compressed Air Flow Rate & O ₂ Concentration	Remarks
4	Control: $\gamma = 1000\text{R/hr}$ Monitor w dosimetry	Control: T = 70, 130, & 180 °F (hoses & hose coupons) T = 70, 130, & 200 °F (Teflon gaskets & EPDM O-rings) Monitor w thermocouples in vessels	Control: P = 425 psig (hoses & hose coupons) P = 400 psig (Teflon gaskets & EPDM O-rings) Monitor w P transducers in vessels	Control flow rate so that O ₂ concentration in effluent is at or close to atmospheric Monitor effluent w flow meters & O ₂ sensors	Chemical simulant will be replenished on a regular basis.

Notes for Table 6:

β = beta radiation from sealed ⁸⁵Kr sources

EPDM = ethylene propylene diene monomer

F = Fahrenheit

γ = γ radiation from sealed ⁶⁰Co or ¹³⁷Cs sources

Phase 1: β - γ comparison at ambient high-bay or GIF-pool T & P, no chemical simulant. $\beta = 100$ R/hr; $\gamma = 100$ or $1000/\text{R}$,

Phase 2: Effects of γ & elevated T without chemical simulant at ambient GIF-pool P. $\gamma = 1000$ R/hr. Remove samples at 10^5 , 10^6 , 10^7 , & $> 10^7$ R (exact durations TBD)

Phase 3: Effects of γ , elevated T, & chemical simulant at ambient GIF-pool P. $\gamma = 1000$ R/hr. Remove samples at 10^5 , 10^6 , 10^7 , & $> 10^7$ R (exact durations TBD)

Phase 4: Effects of γ , elevated P & T, & chemical simulant. $\gamma = 1000$ R/hr. Remove samples at 10^5 , 10^6 , 10^7 , & $> 10^7$ R (exact durations TBD)

psig = pounds per square in (gauge)

R&A = review and approval

P = pressure

T = temperature

w = with

Compressors are less reliable than compressed-air tanks, so tanks of compressed air will be used instead of a compressor to maintain a slow flow rate and O₂ concentrations at or close to atmospheric in the vessels. The initial pressure of air tanks (~10,000–20,000 psig) is more than sufficient to maintain flow through the vessels, and will also be used to pressurize the insides of the hoses for Phase 4. Flow rates will be set as low as reasonably achievable, consistent with maintaining O₂ concentrations in the vessels outside the hoses at or close to atmospheric. This should minimize the number of the compressed-air tanks required for these tests.

Flow meters and O₂ sensors are planned for each of the vessels to be placed in the GIF high bay or in the GIF pool. A maximum of 18 flow meters and O₂ sensors (plus a few extra in case of malfunctions) in the baseline test program, or 12 flow meters and O₂ sensors (plus a few extra) for the reduced cost option would be required. (These are the maximum number of vessels to be placed into test at one time; see Subsection 7.1.) The other option would be to use a switching system that would allow one or a few pairs of flow meters and O₂ sensors to monitor the effluent from all of the vessels. However, the use of a dedicated flow meter and O₂ sensor for each vessel would enable continuous and more reliable monitoring of these parameters.

The flow meters and O₂ sensors will be placed on the exhaust outlet outside of the GIF pool, to prevent exposure to radiation. Oxygen sensors that use a laser diode oxygen analyzer or zirconium oxide sensors, such as those manufactured by Oxigraf or Advanced Micro Instruments, respectively, can provide continuous monitoring of effluent O₂ concentrations. These instruments are robust and do not use any consumable components that would require replacement or replenishment during the tests.

All of these control and monitoring instruments will be calibrated according to the QA requirements that are being developed for this study (Section 6.0).

The temperatures and pressures in the vessels, the flow rate(s) of effluent compressed air, and the concentration of O₂ in the effluent will be monitored essentially continuously (e.g., every 10 minutes or so) by a data acquisition system assembled from commercially available components. The data will be continuously recorded and saved, and archived on a backup system. The objective is to make these data retrievable online to authorized SNL personnel in Technical Areas 1 and 5, and to WRPS personnel at the Hanford Site in Washington, both via password-controlled access. Furthermore, password-restricted control of the test conditions to the SNL technologist(s) in overall charge of the tests will also be established. However, any and all remote access to the data acquisition system and remote control of the test system must be compatible with the ES&H and security requirements established by SNL for the GIF.

5. POSTEXPOSURE MECHANICAL TESTING

Postexposure testing will be based primarily on performance testing of the specific components (e.g., burst testing of hose specimens and leak testing of PUREX connector gaskets. This will provide a direct indication of component damage and impairment of function from the test stressors. In addition to the performance testing, material coupons will be subject to selected materials properties testing. Although more abstract, the changes in material properties will allow comparison to other historical materials testing and relative comparisons within this test plan of the effects of various stress factors.

Specific detailed postexposure performance testing procedures will be developed and will follow ASTM practice to the extent possible, given the specialized performance testing application. The coupon material testing will follow ASTM procedures where applicable. Testing will occur onsite at SNL facilities shortly after removal from the irradiation cell as reasonably possible to minimize changes in the postexposure time period.

5.1 Hose Burst Testing

A specific hose testing procedure will be developed and approved before testing. The hose burst-testing procedure will follow the Riverbend test procedure and guidelines in ASTM D380, as applicable.

The size of the 30-in samples used for the burst test will comply with ASTM D380, Section 5.1.3; using a specimen 3 ft in length (see Section 8 below for complete information on this and other ASTM procedures included in this section). The use of straight versus bent burst configurations is selected to be comparable to existing hose qualification. Burst tests will be performed with water at ambient temperature.

The burst test procedure will identify set-up; indicate how the system was displaced of air and identify how pressure was introduced; and reference applicable photos, drawings, and documents. The hose end-fittings will be blanked and equipped with test ports on each end to allow for pressure line measurement and purging of trapped air. A calibrated gauge will be plumbed in the pressure line to monitor pressure throughout the test. Water will be introduced to the system to displace all air. The pressure will be incrementally raised until failure. The ultimate pressure and type of failure will be recorded (e.g., hose split, termination failure, rupture, ply separation, etc.). Any visible deformation or leakage is typically classified as failure as good practice. Figure 22 shows similar burst tests on hose coupons.

A minimum specified burst pressure of 1700 psig, or four times design would be considered successful, but coupons will be taken to failure to understand allowable margin in the exposed coupons.



Hydrotesting of HIHTL coupons after crush test



Typical hose failure near swaged end fitting

Figure 22. Previous Burst Testing of HIHTLs.

5.2 PUREX Connector Gasket Testing

A specialized leak testing procedure will be developed that tests the ability of the connector gaskets to form an adequate seal. Each gasket will be exposed and tested while in the retainer, to ensure representative conditions and prevent damage solely from removal/reinsertion into the retaining ring. A fixture similar to the one shown in Figure 23 is anticipated, which was used for hydrotesting a specialized connector component. A fixture consisting of a connector nozzle and blanked connector head will be constructed. The fixture will be equipped with test ports for application of the leak test fluid, pressure measurement, and a flow meter or other means to measure leak rate. Field criterion for suitable PUREX connector connection is no visible leakage, which will likely be used as a test criterion.

After exposure, the gasket/retainer assembly will be inserted into the test blank connector. The connector will be placed onto the test nozzle and the connector torqued to the normal design torque of 70 ft-lbs (H-2-32420, Sheet 3). The test fixture will be pressurized to the design pressure (400 psig), and the connection inspected for leaks. If leaks are observed, the leak rate will be measured. The torque will then be gradually increased until the leak rate stops. If the leak cannot be stopped, the connector can be loosened and retightened to attempt to get a better seal. Leak rates at test pressures in excess of the design pressure (1.5 or 2 times) may be desired to better understand in-service design margins. Any gasket failures will be recorded and photographed.



Hydrotest setup for PUREX connector



Connector test assembly (nozzle bottom is fitted with test port)

Figure 23. Previous Test Setup for Hydrotest of PUREX Connectors

During development of the connector gasket test procedure, consideration will be given to ASTM F2378. It can be developed as a separate test or applied to connector leak test discussed above. This ASTM test method utilizes a test specimen compressed in increasing stages between the surfaces of two flat steel platens. After the specified press load is applied, fluid introduced into the center of the annular gasket compressed between platens, and a pressure of 4 MPa (580 psig) is applied. The fluid leak rate is measured. The test fluid pressure is relieved and the press load is increased to the next level. The fluid pressure is reapplied and the leak rate measured again. The cycle is repeated five times until a final press load of 32 MPa (4640 psig) is achieved. The press loads, internal test pressures, pressurizing fluids, and number of cycles can be varied as appropriate. Figure 24 shows a schematic of a test fixture used in this test.

Another similar standard gasket test procedure is ASTM F37. This test method provides a method of evaluating the sealing properties of sheet and solid form-in-place gasket materials at room temperature, and is suitable for evaluating the sealing characteristics of a gasket material under different compressive flange loads. A test specimen is compressed between the surfaces of two smooth steel flange faces. After the specified flange load is applied, the test fluid is introduced into the center of the annular gasket compressed between the flanges, the specified test pressure is applied, and the leakage rate is measured.

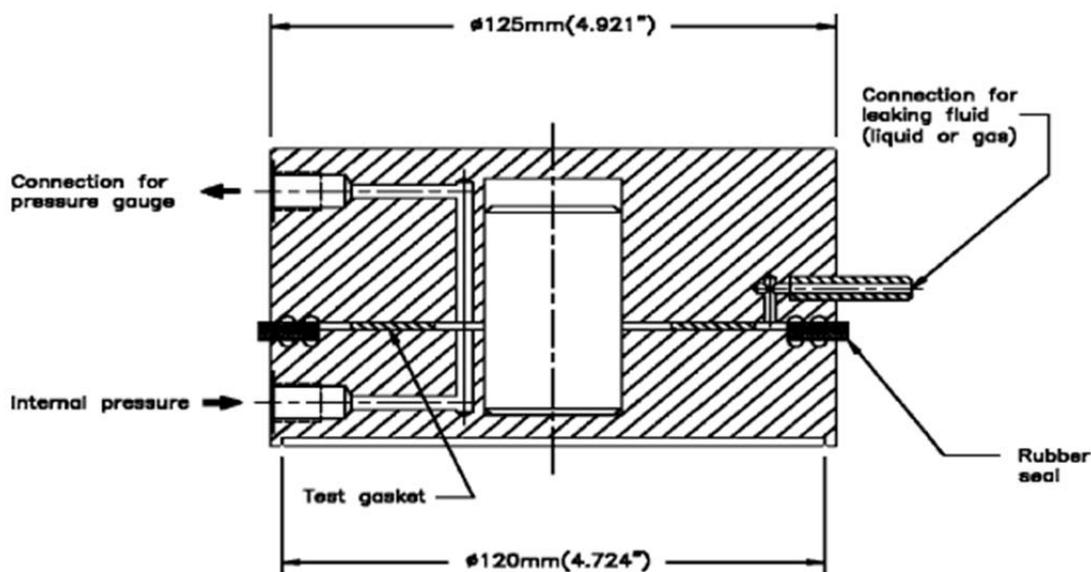


FIG. 1 Test Assembly for Determining Sealability of Gasket Materials

Figure 24. Test Assembly for Determining Sealability of Gasket Materials Taken from ASTM F2378.

Another gasket test considered was ASTM F36. This test determines the short-time compressibility and recovery at room temperature of gasket materials. It is not intended as a test for compressibility under prolonged stress application, or for recovery following such prolonged stress application, the inverse of which is generally referred to as “compression set.” Also, it is not intended for use above ambient temperature. A resiliency characteristic (the amount recovered expressed as a percentage of the compressed thickness), may also be calculated from the test data where desired.

5.3 Coupon Testing

Similar postexposure testing has been performed on coupons in the past (Nigrey, 2000) and provides guidelines for tests in this test plan. After irradiation and exposure to chemical waste stimulant, coupons were tested for a variety of materials property changes. The comprehensive testing consisted of measuring the specific gravity, dimensions, mass, hardness, compression set, Vapor Transport Rate (VTR) and tensile properties (tensile strength, ultimate elongation yield, and tensile stress). Most of these properties were evaluated using standardized test methods developed by ASTM International. For specific gravity measurements, ASTM D792 was used. In measuring dimensions and mass, ASTM D543 was used. For hardness measurements, ASTM D2240 was used. In evaluating compression set, ASTM D395 – Method B was used. For VTR measurements, ASTM D814 was used. Finally, for evaluating tensile properties, ASTM D412 – Method A was used.

Other SNL studies on nonmetallic materials, including EPDM, have used compression stress-relaxation (CSR) measurements to support aging prediction models (Celina et al., 1999a; 1999b)

A standard test method is mentioned and Shawbury-Wallace Compression Stress Relaxometer was used. The ASTM provides a relevant standard, ASTM D6147.

A smaller set of materials properties tests is anticipated for this test plan. For all coupons, changes in mass and hardness will be measured using ASTM D2240. For the hose-in-hose material coupons, tensile strength and ultimate elongation will also be tested (ASTM D412). For Teflon coupons, ASTM F36 and ASTM F38 will be used. For O-rings, compression set (ASTM D395) will be used. Sample preparation will utilize standardized test methods to cut, condition, and test the materials. The geometry of the material samples is specified by the test method.

Other studies on nonmetallic materials, including EPDM, have used CSR measurements to support aging prediction models considering only thermal degradation and oxidation at elevated temperature (Gillen et al., 1997; Gillen et al., 1999b; Wilson, 1996). A standard test method is mentioned and Shawbury-Wallace Compression Stress Relaxometer was used. The ASTM provides a relevant standard, ASTM D6147. CSR measurement will be considered on the materials coupons as well.

A summary of the materials tests that may be performed on the coupons is given in Table 7.

Table 7. Summary of Materials Property Test Proposed for Coupons.

Hose	Teflon	O-Rings
Dimension change	Dimension change	Dimension change
Mass change	Mass change	Mass change
Tensile strength	Compressibility and recovery	Compression set
Ultimate elongation	Creep relaxation	
Compression stress-relaxation	Compression stress-relaxation	Compression stress-relaxation
ASTM D412, D395, D2240, D6147	ASTM F36, F38, D395, D2240, D6147	ASTM D395, D2240, D6147

Consideration will be given to additional laboratory evaluation of the material coupons and failed specimens from performance testing. Analysis will be selected if it provides insight into the damage mechanism or the depth of polymer degradation. The number of samples for which these analyses will be performed will also be limited by the funds available, with the highest priority given to performance testing (i.e., burst testing of hose specimens and leak testing of PUREX connector gaskets) as discussed above. The methods may include Fourier transform infrared spectroscopy, thermogravimetric analysis, differential scanning calorimetry, photomicroscopy, scanning electron microscopy, and other examinations of the polymer microstructure.

6. QUALITY ASSURANCE

WRPS has specified that the quality assurance (QA) Program be based on the requirements of the American Society of Mechanical Engineers' (ASME's) NQA-1 standard (ASME, 2004).

A project-specific QA program plan will be developed during the preparation timeframe. Since this involves testing on safety significant components, all data will be collected under an approved NQA-1 program. Testing will be conducted to written, approved procedures and follow ASTM practices where applicable. SNL will be evaluated by Hanford site QA personnel. Pending results of the evaluation, SNL will be added to the Mission Support Alliance-Acquisition Verification Services Evaluated Supplier List.

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7. FACILITIES, EQUIPMENT, SCHEDULES, AND COSTS

This section describes the facilities, equipment, and schedules (Subsection 7.1) that were identified and estimated for the proposed baseline test program and reduced cost option. This section also presents a list of other alternatives, along with their advantages and disadvantages (Subsection 7.1).

7.1 Facilities, Equipment, and Schedules

Table 8 provides the facilities, equipment, and schedule for the proposed baseline test program. It is important to note that the schedule in Table 8 is based on three crucial assumptions: First, it is assumed that the funding for the first year of the baseline test program (preparations) will arrive at SNL at the beginning of October 2013. Earlier or later arrival of funding would result in commensurate changes in the schedule for Phases 1, 2, 3, and 4. Second, it is assumed that all 14 vessels required for Phases 1 and 2, and all 12 to be used for Phases 3 and 4 can be placed in the GIF pool simultaneously (Subsection 4.4). Third, it is assumed that all 14 annular stainless steel vessels required for Phases 1 and 2 can be placed in the pool from October 2014 through March 2015; and all 12 required for Phases 3 and 4 can be placed in the pool while those used for Phase 1 and 2 are being removed. As explained in Subsection 4.4, additional test configuration calculations with the TIGER codes (Franke et al., 2009) will be necessary prior to the start of the preparations for the baseline program in October 2013, or during this preparation period, depending on funding. The third assumption will be reevaluated during the preparations for the baseline program.

Table 8 includes all of the annular stainless steel vessels required for all four phases of the baseline program. It is assumed that the vessels to be used for Phase 1 will be identical to those used for Phases 2, 3, and 4 (Subsection 3.2).

Note that, for the baseline program, there will be 18 annular stainless steel vessels in test essentially simultaneously (Phase 1: 4 in the GIF high bay and 8 in the GIF pool, Phase 2: 6 in the pool). After the completion of Phases 1 and 2, 12 vessels would be in test simultaneously (Phase 3: 6 in the pool, Phase 4: 6 in the pool). These requirements will increase the number of vessels that must be purchased for the baseline program, and increase the initial space requirements for the GIF pool relative to those for the reduced cost option (Table 8).

To save space, Table 8 does not include the control and monitoring equipment or the postexposure mechanical testing equipment required for Phases 1, 2, 3, and 4 of the baseline program. However, the costs for the control and monitoring equipment, and the postexposure mechanical testing equipment are included in the cost estimate for the baseline program. Additional test configuration calculations with the TIGER codes (Franke et al., 2009) will be necessary prior to the start of the preparations for the baseline program in October 2013 or during this preparation period to confirm the number of the sealed β and γ sources required for the baseline program (Subsection 4.4).

Table 9 provides another breakout of the baseline test program which provides, by phase, the number of test vessels and their allocation to test articles, instrument, monitoring and control,

data needs, and posttest requirements. Table 10 provides this information for the reduced cost option to allow comparison of resource needs. The reduced cost option is described in greater detail below.

Table 8. Facilities, Equipment, and Schedule for the Irradiation of Nonmetallic Materials: Proposed Baseline Test Program.

Preparations	Set up and carry out code calculations (exposure rate-absorbed dose, shielding, test configurations, etc.); design, purchase, & annular stainless steel test vessels; design, purchase, assemble, & test control and monitoring equipment and postexposure mechanical testing equipment; SNL ES&H R&A; SNL leak test; and final WRPS R&A of preparations and procedures for the baseline program, materials, QA, schedule, etc.
Schedule	Start preparations: Oct. 2013; complete preparations: Sep. 2014
Phase 1	β - γ comparison at ambient lab P and T, no chemical simulant
Facility	Paths 1 (β only) & 4 (control): 4 annular stainless steel vessels (see below) in a dry, shielded area of the GIF outside the dry irradiation cells (probably the high bay) Paths 2.1, 2.2, 3.1, & 3.2: 8 vessels (see below) in the GIF pool
Equipment	12 P- & T-rated annular stainless steel vessels Each vessel would be 1.5 or 2 ft OD \times 3 or 4 ft high Each vessel would contain 12 30-in primary hoses & 12 hose coupons; or 12 confined Teflon gaskets, 12 unconfined Teflon gaskets, & 12 Teflon coupons Total quantities of ^{85}Kr β sources & ^{60}Co γ sources TBD
Schedule	Place vessels in the GIF pool or the high bay: Oct.–Dec. 2014 Remove vessels from the GIF pool or the high bay: Oct.–Dec. 2016 Complete posttest analyses & Phase 1 data report: Jan.–Mar. 2017
Phase 2	Effects of γ (1000 Rad/hr) & elevated T (70, 130, & 180 or 200 °F), ambient lab P, no chemical simulant. Remove samples at 10^5 , 10^6 , and 10^7 Rad (exact durations TBD)
Facility	All 6 annular stainless steel vessels (see below) in the GIF pool
Equipment	6 P- & T-rated annular stainless steel vessels ($P_{\text{max}} = 425$ psig; $T_{\text{max}} = 200$ °F) Each vessel would be 1.5 or 2 ft OD \times 3 ft or 4 ft high Each vessel would contain 12 30-in primary hoses & 12 hose coupons; or 12 confined Teflon gaskets, 12 unconfined Teflon gaskets, & 12 Teflon coupons; and 12 confined EPDM O-rings & (perhaps) 12 unconfined EPDM O-rings & 12 EPDM coupons Total quantity of ^{60}Co γ sources TBD
Schedule	Place vessels in the GIF pool: Jan.–Mar. 2015 Remove vessels from the GIF pool: Jan.–Mar. 2017 Complete posttest analyses & Phase 2 data report: Apr.–Jun. 2017
Phase 3	Effects of γ (1000 Rad/hr), elevated T (70, 130, & 180 or 200 °F), & chemical simulant (TFC-ENG-STD-34) at ambient lab P. Remove samples at 10^5 , 10^6 , and 10^7 Rad (exact durations TBD)
Facility	All 6 annular stainless steel vessels (see below) in the GIF pool

Equipment	6 P- & T-rated annular stainless steel vessels ($P_{\max} = 425$ psig; $T_{\max} = 200$ °F) Each vessel would be 1.5 or 2 ft OD \times 3 ft or 4 ft high Each vessel would contain 12 30-in primary hoses & 12 hose coupons; or 12 confined Teflon gaskets, 12 unconfined Teflon gaskets, & 12 Teflon coupons; and 12 confined EPDM O-rings & (perhaps) 12 unconfined EPDM O-rings & 12 EPDM coupons Total quantity of ^{60}Co γ sources TBD
Schedule	Place vessels in the GIF pool: Oct.–Dec. 2016 Remove vessels from the GIF pool: Oct.–Dec. 2018 Complete posttest analyses & Phase 3 data report: Jan.–Mar. 2019
Phase 4	Effects of γ (1000 Rad/hr), elevated T (70, 130, & 180 or 200 °F) & P (400 or 425 psig) & chemical simulant (TFC-ENG-STD-34). Remove samples at 10^5 , 10^6 , and 10^7 Rad (exact durations TBD)
Facility	All 6 annular stainless steel vessels (see below) in the GIF pool
Equipment	6 P- & T-rated annular stainless steel vessels ($P_{\max} = 425$ psig; $T_{\max} = 200$ °F) Each vessel would be 1.5 or 2 ft OD \times 3 ft or 4 ft high Each vessel would contain 12 30-in primary hoses & 12 hose coupons; or 12 confined Teflon gaskets, 12 unconfined Teflon gaskets, & 12 Teflon coupons; and 12 confined EPDM O-rings & (perhaps) 12 unconfined EPDM O-rings & 12 EPDM coupons Total quantity of ^{60}Co γ sources TBD
Schedule	Place vessels in GIF pool: Jan.–Mar. 2017 Remove vessels from GIF pool: Jan.–Mar. 2019 Complete posttest analyses & Phase 4 data report: Apr.–Jun. 2019 Complete final report: Jul.–Sep. 2019

Note: This table does not include the control and monitoring equipment or the postexposure mechanical testing equipment for Phases 1, 2, 3, and 4, to save space. Furthermore, this table does not include the sealed β and γ sources, because this information is not available yet (see text).

Table 9. Vessel, Instrument, Data and Posttest Summary for the Baseline Test Program.

Baseline Test Program				
	Phase 1	Phase 2	Phase 3	Phase 4
Total test vessels (in- pool and out-of-pool)	10	6	6	6
Vessel allocation and test article loading				
Out-of-pool vessel - gasket/O-rings	1	0	0	0
Out-of-pool vessel – hoses	1	0	0	0
In-pool vessels - hose	4	3	3	3
In-pool vessels – gaskets & O-rings	4	3	3	3
Hoses per vessel	12	12	12	12
Gaskets & O-rings per vessel	24	48	48	48
Instrumentation, Monitoring and Control				
Thermocouples - 2 per in-pool hose vessel , 8 per in-pool gasket vessel, 1 per out-of-pool vessel	130	96	96	96
Air flow rate 1 per vessel	10	6	6	6
Air O ₂ concentration 1 per vessel	10	6	6	6
Compressed air pressure supply/control	0	0	0	6
Leak detector, 2 per in-pool vessel	16	12	12	12
Pressure transducer, 2 per vessel with pressurized items	0	0	0	12
Heater controllers, 1 per vessel	0	6	6	6
Blank data channels	10	10	10	10
Data Needs				
Total computer data channels	176	136	136	154
Simultaneous readings	312		290	
Posttests				
Hoses to burst test	60	36	36	36
Gaskets & O-rings to leak test	120	144	144	144
Total burst and leak tests	180	180	180	180

Table 10. Vessel, Instrument, Data and Post Test Summary for the Reduced Cost Option

Reduced Cost Option			
Hoses: Phases 2, 3, and 4; Gaskets & O-rings: Phase 3 only			
	Phase 2	Phase 3	Phase 4
Total test vessels (in- pool and out- of-pool)	3	6	3
Vessel allocation and test article loading			
Out-of-pool vessel - gasket/O-rings	0	0	0
Out-of-pool vessel - hoses	0	0	0
In-pool vessels - hose	3	3	3
In-pool vessels – gaskets & O-rings	0	3	0
Hoses per vessel	12	12	12
Gaskets & O-rings per vessel	0	48	0
Instrumentation, monitoring and control			
Thermocouples - 2 per in-pool hose vessel , 8 per in-pool gasket vessel, 1 per out-of-pool vessel	72	96	72
Air flow rate 1 per vessel	3	6	3
Air O ₂ concentration 1 per vessel	3	6	3
Compressed air pressure supply/control	0	0	3
Leak detector, 2 per in-pool vessel	6	12	6
Pressure transducer, 2 per vessel with pressurized items	0	0	6
Heater controllers, 1 per vessel	3	6	3
Blank data channels	10	10	10
Data Needs			
Total computer data channels	97	136	106
Simultaneous readings	339		
Posttests			
Hoses to burst test	36	36	36
Gaskets & O-rings to leak test	0	144	0
Total burst and leak tests	36	180	36

The reduced cost option will eliminate the Phase 1 (β - γ comparison) tests. The issue of relative damage from β versus γ radiation will be settled through alternate means. Novel to this test plan, other irradiation studies do not include β irradiation. The issue may be addressed by a thorough literature study, expert analysis/opinion, or by limited materials coupon study. This can be determined at a later date, and if a β - γ adjustment is required, it can be applied to the results of the Phase 2, 3, and 4 studies, which can only be performed with γ sources. Hoses will still be tested at the varying levels of the 4 primary stressors as described in Phases 2, 3, and 4, allowing for meaningful data collection and a better service life prediction model to be developed.

In the reduced cost option, PUREX connector gaskets and O-rings will only be tested as described in Phase 3, with chemical stimulant, varying temperature and varying radiation exposure up to two years total. This will demonstrate gasket acceptability in a “proofing” sense and give insight into the effect of increasing radiation levels to the gasket material in the confined geometry of the PUREX connector.

The primary advantage to the reduced cost option is significant reduction of the cost and reduction of the schedule. The primary savings in the reduced scope program are

- Eliminates the high cost and handling of β sources
- Reduces the number of test vessels from 18 to 12
- Reduces the number of test hoses, gaskets, and coupons by almost one half
- Reduces the amount of postexposure testing and analysis required
- Reduces the number of test, instrument, and control loops required

Most significantly, the reduced cost option reduces the size requirements such that all test vessels can fit into the pool at the GIF at the same time, allowing for Phase 2, 3 and 4 to occur simultaneously. This will cut two years off the total schedule and allow for significant labor savings. Data collection will be completed on the hoses much sooner than the baseline.

7.2 Costs

The cost estimate for the work described in this study is included in RPP-PLAN-54568_rev1. This document contains Sandia Proprietary Information.

Table 11 identifies five other possible alternatives, along with some advantages and disadvantages of these options. The effects of these alternatives on the number and/or size of the vessels, the number of vessels that could be placed in the GIF pool simultaneously and to what extent this would shorten the overall schedule, etc., have not been evaluated. However, WRPS may specify within the statement of work to conduct this testing to include these alternatives, however the budget estimates provided do not apply to these alternatives and would need to be addressed for an accurate cost.

Table 11. Additional Alternatives That Might be Considered to Reduce the Required Time or the Cost of Irradiation of Nonmetallic Materials.

Potential Alternative	Advantage(s)	Disadvantage(s)
Use 10-in instead of 30-in samples of primary hoses, and similarly smaller samples of confined Teflon gaskets and confined EPDM O-rings	<p>Would decrease the number and/or size and hence the cost of vessels required</p> <p>Would increase the number of vessels that could be placed in the GIF pool simultaneously and shorten the schedule</p>	Would decrease defensibility of the results
Use coupons only instead of along with materials in their in-service configurations	<p>Would decrease the number and/or size and hence the cost of vessels required beyond that achievable with 10-in hoses, etc.</p> <p>Would increase the number of vessels that could be placed in the GIF pool simultaneously and shorten the schedule beyond that achievable with 10-in hoses, etc.</p>	Would decrease defensibility of the results beyond that sustained with 10-in hoses, etc.
Reduce the number of samples exposed to identical conditions for identical durations from three to two or even one.	<p>Would decrease the number and/or size and hence the cost of vessels required</p> <p>Would increase the number of vessels that could be placed in the GIF pool simultaneously and shorten the schedule</p>	Would decrease defensibility of the results
Carry out γ irradiations for Phases 2, 3, and 4 at just two temperatures instead of three	<p>Would decrease the number and/or size and hence the cost of vessels required</p> <p>Would increase the number of vessels that could be placed in the GIF pool simultaneously and shorten the schedule</p>	Would limit the reliability of interpolating or extrapolating performance data to other temperatures
Limit total exposures to $< 0.8 \times 10^7$ R	Would decrease the total time required for each phase of the test program and hence shorten the schedule	Would not obtain results for total dose of 1.1×10^7 R (the expected fatal dose for EPDM) and for overtest dose

Potential Alternative	Advantage(s)	Disadvantage(s)
Use single upper-level temperature and pressure instead of individual design temperatures and pressures	May be able to use single larger vessel to minimize procurement cost of vessels and sources.	Size limitations may not allow full realization of potential cost savings. GIF safety and handling concerns. Reduced defensibility by requiring extrapolation at bounding conditions.

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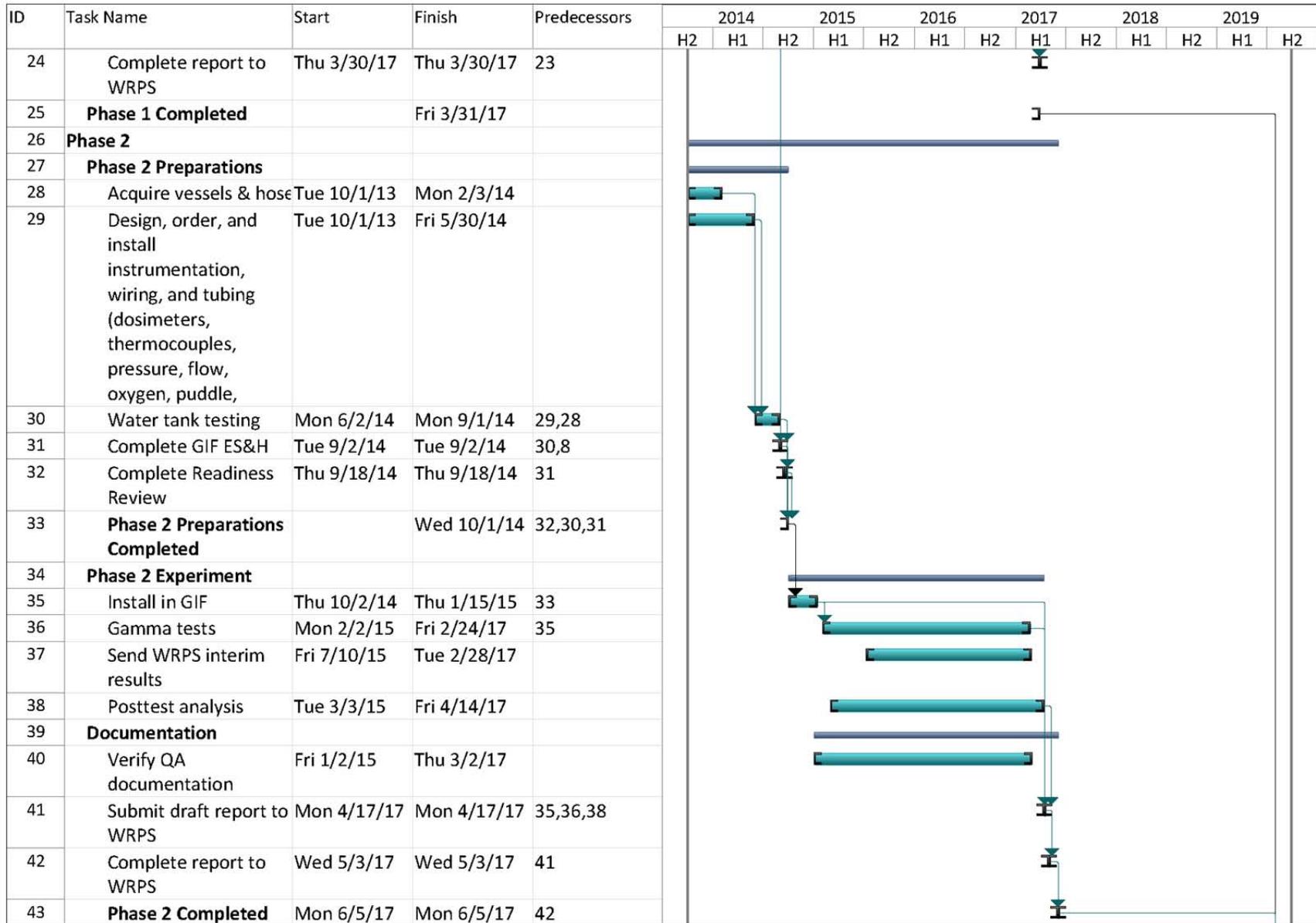
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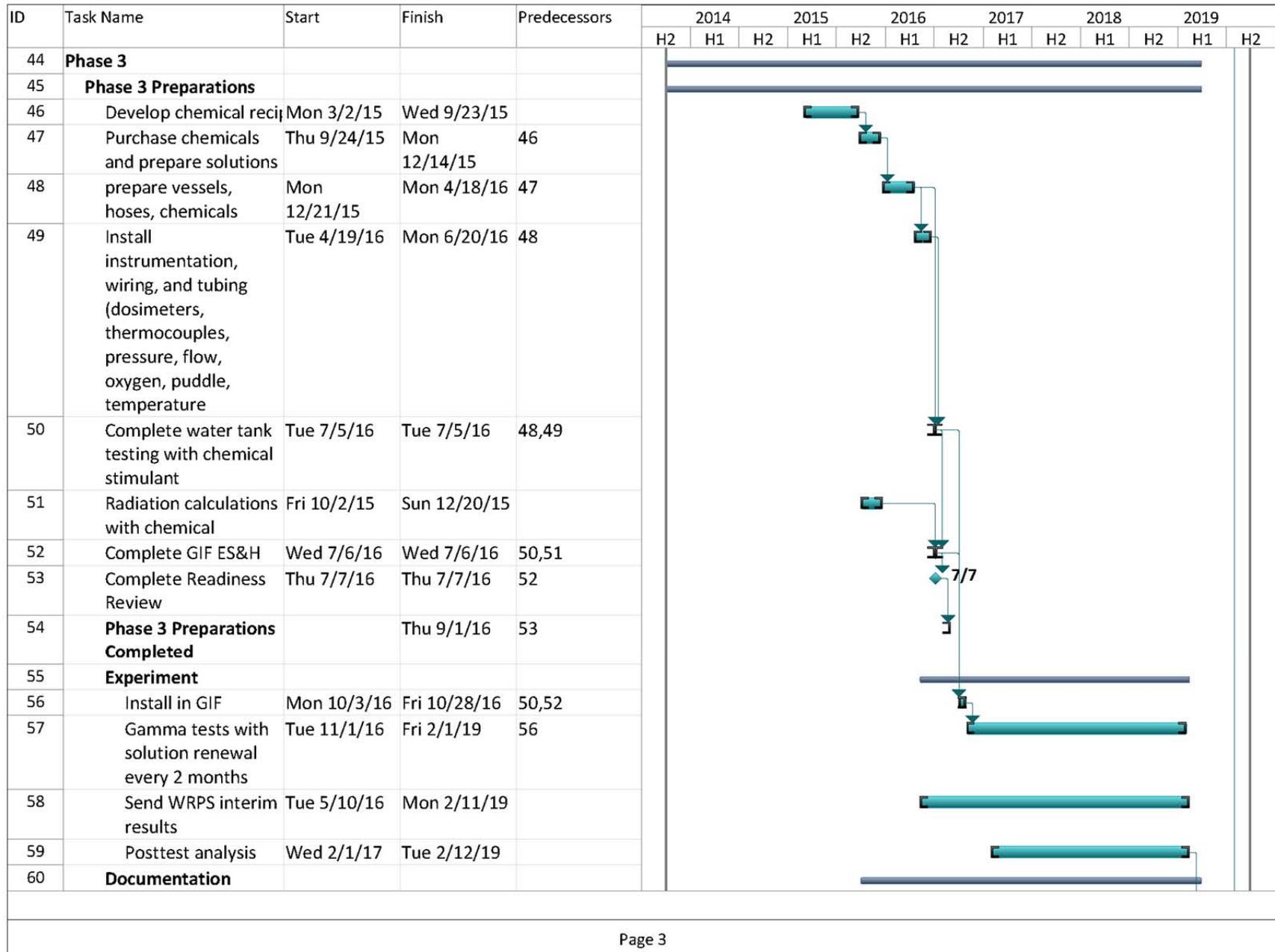
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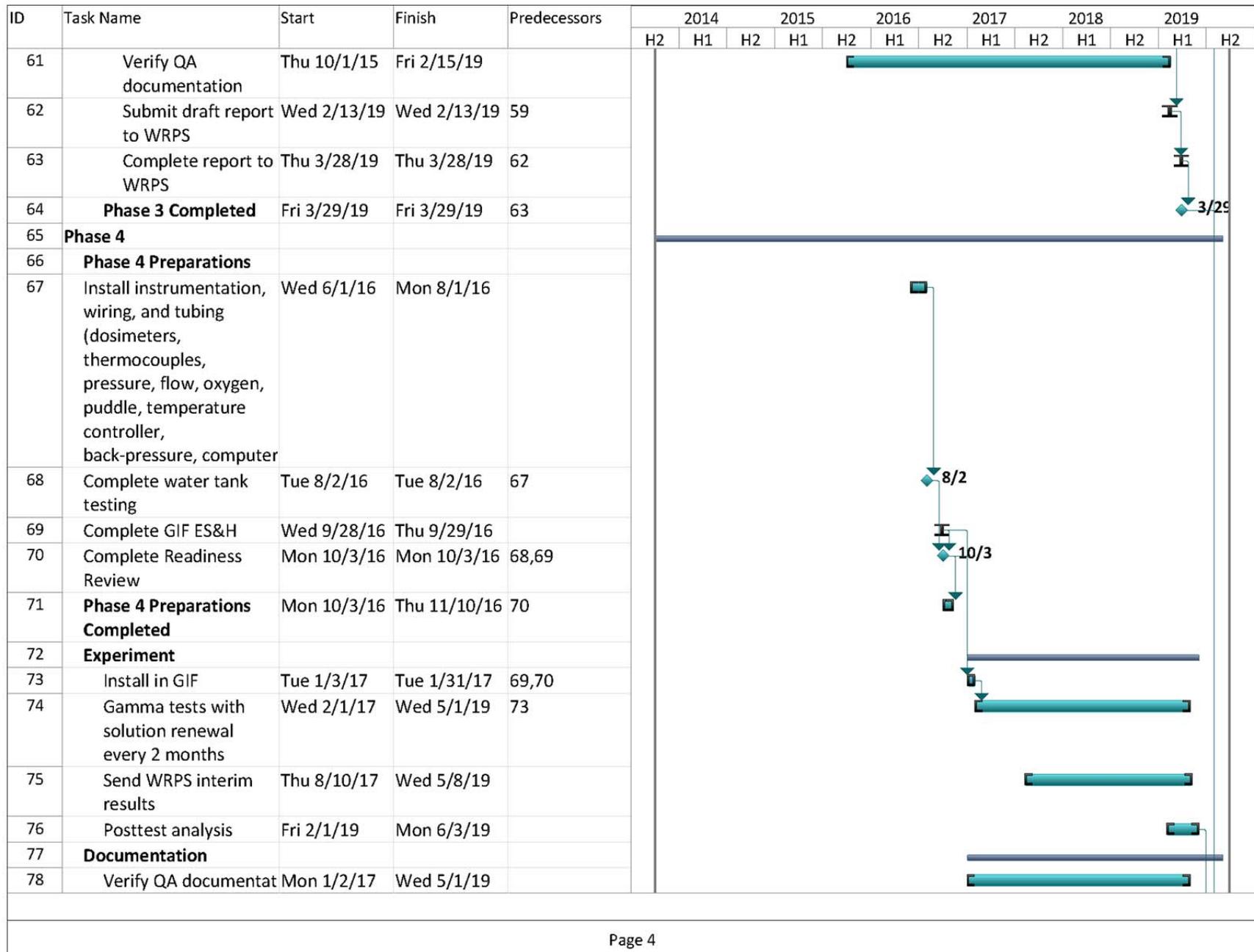
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APPENDIX A. GANTT CHART FOR THE BASELINE TEST PROGRAM

ID	Task Name	Start	Finish	Predecessors	2014		2015		2016		2017		2018		2019	
					H2	H1	H2									
1	Phase 1															
2	Phase 1 Preparations															
3	Design, order, acquire vessels and modify PUREX connector/test fixture	Tue 10/1/13	Fri 5/30/14													
4	Acquire hoses	Mon 11/4/13	Fri 4/4/14													
5	Design, order, install and test instrumentation (wiring, tubing)	Tue 10/1/13	Fri 5/30/14													
6	Send WRPS design	Mon 2/3/14	Mon 2/3/14													
7	Water tank testing	Thu 6/5/14	Fri 8/29/14	5,3,4												
8	Radiation calculations	Wed 10/2/13	Mon 12/16/13													
9	Acquire beta sources	Tue 12/17/13	Thu 6/19/14	8												
10	Acquire gamma source	Tue 12/17/13	Thu 6/19/14	8												
11	GIF ES&H	Tue 10/1/13	Mon 9/1/14													
12	Complete Readiness Review	Tue 9/2/14	Fri 9/5/14	7,8,9,10,11												
13	Phase 1 Preparations Completed	Thu 9/18/14	Thu 9/18/14	11,12												
14	Phase 1 Experiment															
15	Install in GIF	Tue 9/30/14	Fri 10/31/14	11,12,13												
16	Beta tests	Mon 11/3/14	Mon 11/28/16	15,8												
17	Beta & Gamma tests	Mon 11/3/14	Mon 11/28/16	15,8												
18	Gamma tests	Mon 11/3/14	Tue 11/29/16	15,8												
19	Send WRPS interim results	Thu 5/15/14	Wed 11/30/16													
20	Posttest analysis	Fri 2/27/15	Tue 2/28/17													
21	Phase 1 Documentation															
22	Verify QA documentat	Tue 10/1/13	Fri 3/3/17													
23	Submit draft report to WRPS	Fri 3/3/17	Fri 3/3/17	20												







ID	Task Name	Start	Finish	Predecessors	2014		2015		2016		2017		2018		2019	
					H2	H1	H2									
79	Submit draft report to WRPS	Wed 6/5/19	Wed 6/5/19	76												
80	Complete report to WRPS	Fri 6/28/19	Fri 6/28/19	79												
81	Phase 4 Completed	Fri 6/28/19	Fri 6/28/19													
82	Draft Cumulative Final Report to WRPS	Thu 8/1/19	Thu 8/1/19	81,64,43,25												
83	Revise Cumulative Final Report to WRPS	Mon 9/2/19	Mon 9/2/19	82												
84	Cumulative Final Report Issued	Thu 9/26/19	Thu 9/26/19	83												
85																
86																
87																



APPENDIX B. LIFETIME PREDICTION MODEL

B-1. LIFETIME PREDICTION MODEL

It will be necessary to develop a comprehensive lifetime prediction model based on accelerated aging methodology so test data results can be used to determine service life for the polymeric materials used in waste retrieval systems. The new model will evaluate the effect of all four stressors evaluated in the test plan (temperature, pressure, chemistry, and radiation). Only ethylene propylene diene monomer (EPDM) hose-in-hose transfer line (HIHTL) assemblies (and similarly constructed EPDM hose jumper assemblies) are required to be tracked and assessed for future use. As a result, for the purposes of this appendix, it is assumed that only the EPDM HIHTL assemblies will be subjected to a lifetime prediction model.

Currently, the HIHTL assemblies are limited to three years of service life unless a formal life extension analysis is performed per the recommendations in RPP-6711 (Appendix L). The accelerated aging and life prediction techniques that were developed in RPP-6711 are based on concepts employed by the Arrhenius, Eyring, William Landel Ferry, and Palmero and DeBlieu methodologies. Additionally, the well-established Palmgren-Miner concept (Miner's Rule) was applied to account for the cumulative damage of the hoses due to the cyclic nature of their use for retrieval efforts. The life prediction efforts resulted in a service life equation that uses temperature and pressure to determine the total remaining life in the selected hoses.

The service life equation was based on sound methodology, but a number of deficiencies in the approach were noted during testing, as described below:

1. Testing was performed using only water as the internal media,
2. Radiation dose was not applied during testing, and
3. The test temperatures did not reflect temperatures expected during field operations.

Namely, the synergistic effects of chemicals, temperature, radiation, and pressure on the hose's useful life were not studied. It is anticipated that the testing described in this test plan will account for the synergistic effects of the listed stressors.

Historically, the majority of accelerated aging studies have utilized the Arrhenius methodology to determine the expected life of a component (Gillen and Clough, 2001). The Arrhenius methodology is a chemical rate theory that assumes that linear behavior can use temperature to predict useful lifetime of a component. Additionally, as described in further work by Gillen (2001, 1985) and Burnay (1991), additional stressors may be taken into account by using the time-temperature superposition (described below), or similar equation modification methods. Burnay (1991) identified an advantage of the time-temperature superposition in that it does not require detailed knowledge of the degradation reaction mechanisms, but also identified limitations in that a single mechanism must be dominant. Burnay (1991) concluded that his superposition was of most use where extrapolations were made to lower temperatures and dose rates than those tested experimentally. Further analysis will be required to determine an appropriate comprehensive aging model that incorporates all four stressors.

B-2. TIME-TEMPERATURE SUPERPOSITION

Time-temperature superposition was developed by Gillen (2001) as a method for consolidating data on a measured variable that is a function of time and another parameter such as temperature. For example, the variable percent of elongation-at-break (PEAB), for a polymer is dependent on time and temperature. To obtain these data, polymer samples are aged at a fixed temperature in a vessel. At predetermined time intervals, some samples are withdrawn and the PEAB is measured for each sample. From these measurements, a PEAB curve is generated as a function of exposure time. The experiment is repeated again at a few more temperatures, from which additional PEAB curves are generated as a function of exposure time. To consolidate these curves, Gillen (2001) proposed that for each curve there is one “shift” parameter for each temperature that multiplies the exposure time. This shift parameter is obtained by first selecting a base curve, typically the curve with the longest exposure time required for a given PEAB. Then for each remaining curve, a shift parameter is determined that minimizes the difference between the base curve and other curves taken different temperatures than the base curve. A fit of all the shift parameters is determined as a function of temperature. For the PEAB, Gillen (2001) found that the logarithm of the shift parameter is linear with the inverse of absolute temperature. This is a classical Arrhenius fit, and the slope of the curve provides the activation energy. Departures from linearity of the shift parameter indicate that the activation energy is temperature-dependent. As an alternative to assuming that the shift parameter follows an Arrhenius fit, the shift parameter may be added to the exposure time instead of multiplying by the shift parameter (Gillen and Celina, 2001). In this case, a linear fit of the shift parameter with temperature may provide a better basis for extrapolation.

For example, consider hypothetical measurements of the burst pressure as a function of exposure time at 1000 R/hr for three temperatures, 50, 65, and 90 °C. The hypothetical data are given in Figure B-1.

To extrapolate to other temperatures, we find that if the exposure time for the data at 65 and 90 °C are multiplied by 2.5 and 10.0, respectively, the data collapses to one curve as given in Figure B-2. (These data were artificially created, and thus there is no scatter for the collapsed curve of burst pressure. For realistic applications some scatter in the collapsed curve should be expected.)

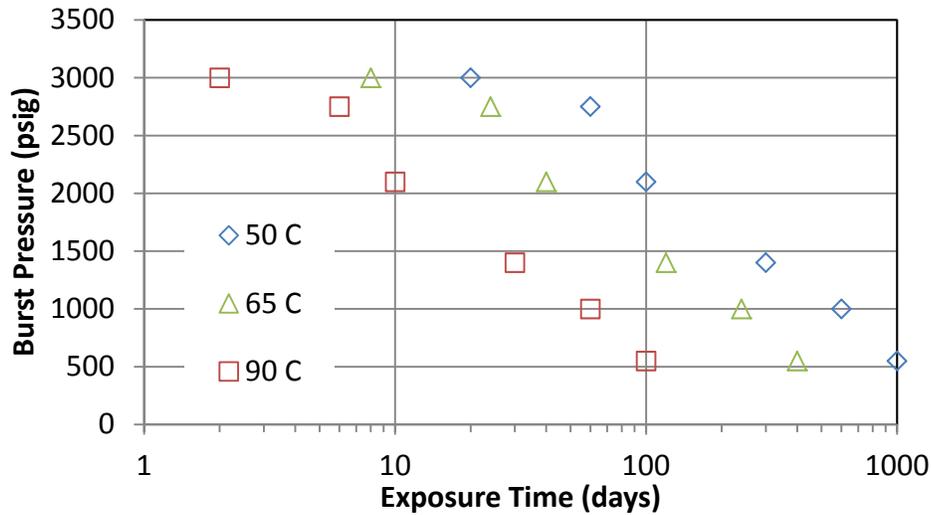


Figure B-1. Hypothetical Burst Pressure Measurements at Three Temperatures.

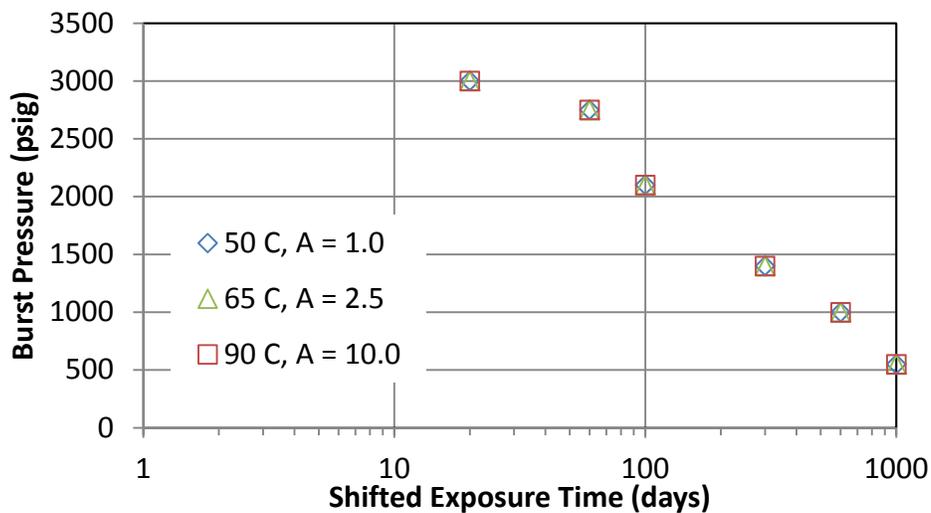


Figure B-2. Hypothetical Burst Pressure as a Function of Shifted Exposure Time, Where the Shift Factor A is Determined so that the Data Collapses to a Single Curve.

A plot of the time shift parameter is given in Figure B-3. The curve is extrapolated to an inverse temperature of 0.0034, corresponding to a temperature of 21 °C. The value of the shift parameter at this temperature is 0.167. Thus the extrapolated burst pressure curve can now be calculated with the shift parameter, and is given below in Figure B-4. Essentially, for each point on the base curve, the time value is multiplied by 1/0.167 for the same value as the burst pressure. In this example, from Figure B-4, after 6000 days (16.4 years), of exposure at 21 °C, the burst pressure would be 550 psig.

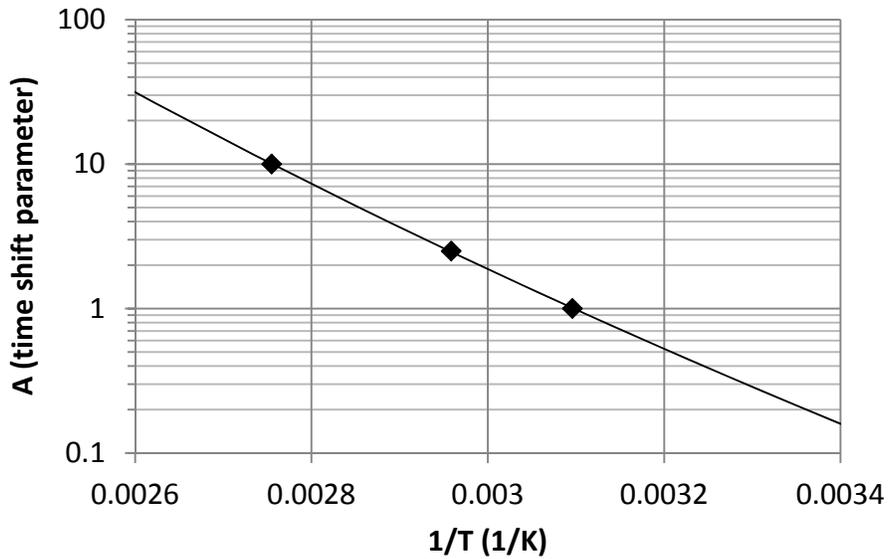


Figure B-3. Time Shift Parameter as a Function of Inverse Temperature Extrapolated Above and Below the Three Values of the Time Shift Parameter Obtained from the Burst Pressure given in Figure B-4.

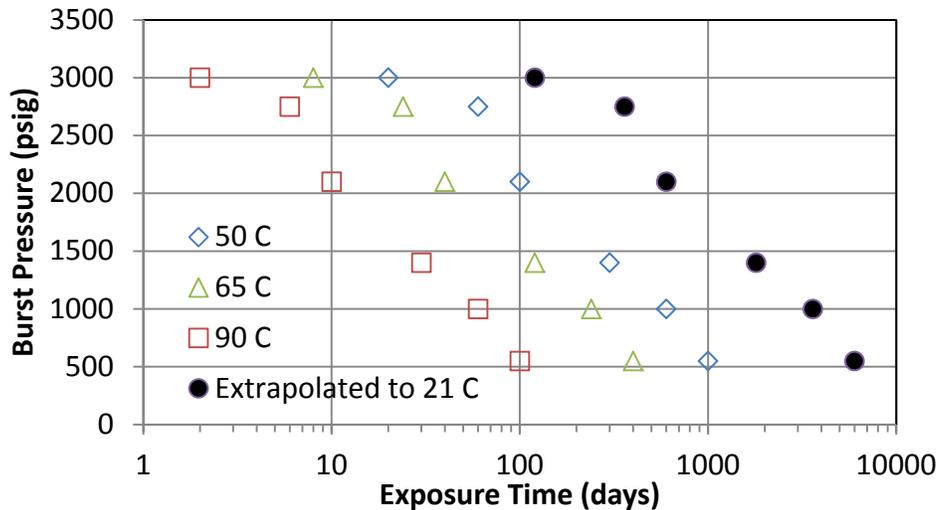


Figure B-4. Hypothetical Burst Pressure Data Shown with Open Symbols, and the Extrapolated Burst Pressure Shown with Filled Circles. The Extrapolated is Based on an Arrhenius Fit to the Time Shift Parameter Given in Figure B-2.

B-3. MINER'S RULE

To account for cumulative HIHTL damage, the Miner's Rule must also be applied, and the data fitted appropriately. Although used in a different context in RPP-6711, Miner's Rule describes the simple concept that degradation is cumulative, and that failure is a result of the accumulation of damage with time. Damage is simply a function of an applied stressor (or multiple stressors) and the number of cycles that the stressors are applied. The application of this method relies on the experimental completion of aging the HIHTL to a selected failure criterion such as PEAB. Discussion on the proper selection of failure criterion is further addressed in literature.

The final HIHTL life predictions will be based on the extrapolated results of the combined Arrhenius and Miner's Rule equations. However, to ensure accurate results, two main factors must be considered during testing to avoid non-Arrhenius behavior of the data: (1) Diffusion limited oxidation effects (discussed in Section 2.7.4.2), and (2) ensuring that the results are not extrapolated far from the test data. As further described by Gillen (2001), more confidence can be given to results if test data mimics the intended results as accurately as possible.

B-4. TESTING CONDITIONS

This test plan specifies four different stressors that will need to be incorporated into comprehensive models. Previous work has only looked at time, temperature, and radiation, where radiation testing was done at high dose rates requiring a large amount of extrapolation to predict performance. In this testing three out of four stressors (i.e., elevated temperature, elevated pressure, and the presence of a chemical simulant) are in the anticipated operation range. The fourth stressor, radiation, will be elevated over most field conditions to facilitate realistic testing times. The reasonably bounding dose rates selected for this test plan are an order of magnitude (or greater) more realistic than historical irradiation aging test conditions (e.g. Nigrey, 2000).

Due to the selection of three stressors, temperature, pressure, and chemistry, within operating conditions, the modeling will primarily account for the extrapolation of radiation. The model will also account for the remaining stressors, but should not require significant extrapolation. Therefore, the service life determined from the data gathered from this testing will be less dependent on modeling and more dependent on actual performance as test specimens are aged under realistic test conditions. The resulting resolution of may permit justification for extended service life while still maintaining an adequate margin of safety.

B-5. CONCLUSIONS

Although an appropriate aging model cannot be selected before the data are collected, based on past experience, the Arrhenius methodology will most likely be used to predict HIHTL life. Due to multiple additional stressors associated with this testing, an appropriately determined comprehensive model will be required. Additionally, Miner's Rule should be applied to account for cumulative damage of the HIHTLs. By selecting stressors closely mimicking field conditions, much errant and non-Arrhenius behaviors can be greatly reduced.

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