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**Krypton-85 Hydrofracture
Engineering Feasibility
and Safety Evaluation**

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FOR THE UNITED STATES
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KRYPTON -85 HYDROFRACTURE
ENGINEERING FEASIBILITY AND SAFETY EVALUATION

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*Los Alamos Technical Associates, Inc.

Nuclear Waste Programs

Krypton Hydrofracture

(Activity No. AP 05 25 05 0; ONL-WA02)

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ABSTRACT

Engineering studies have been made to determine the hazards associated with the disposal of ^{85}Kr using the hydrofracture process. To assess the hazards, an effort has been made to identify the equipment required to entrain and dissolve the noble gas into the grout stream at hydrofracture pressure (up to 350 bar). Off-the-shelf or slightly modified equipment has been identified for safe and effective compression and gas-grout mixing. Each monthly injection disposes of 1.6×10^6 Ci of ^{85}Kr . By connecting only one gas cylinder to the injection system at a time, the maximum amount of krypton likely to be released as a result of equipment failure is limited to 128,000 Ci. An evaluation by Los Alamos Technical Associates shows that releasing this amount of gas in less than one hour under worst-case meteorological conditions through a 30-m stack would result in a whole-body dose of 170 millirem at a distance of 1 km from the facility. A krypton collection and recovery system can further reduce this dose to 17 millirem; increasing the distance to the site boundary to 3 km can also reduce the dose by a factor of ten. Lung and skin dose estimates are 1.6 and 120 times the whole-body dose, respectively. These are all worst-case values; releases under more typical conditions would result in a significantly lower dose. No insurmountable safety or engineering problems have been identified.

1. SUMMARY AND CONCLUSIONS

This project is part of an evaluation of possible disposal methods for waste ^{85}Kr released from spent fuel during reprocessing head end operations. A study of the necessary equipment and associated hazards was requested by the Airborne Waste Management Program Office for the disposal of ^{85}Kr by entraining the gas directly into a hydrofracture grout stream. This study precedes funding of laboratory studies on the diffusion rates of krypton out of a grout matrix and the physical behavior of gas-grout mixtures under hydrofracture conditions. An engineering feasibility study was performed by the UCC-ND Engineering Division that focused only on the equipment unique to the injection of noble gases and was based on assumed behavior of gas-grout mixtures. The safety evaluation was performed by Los Alamos Technical Associates under subcontract to UCC-ND Engineering Division.

The assumed ^{85}Kr output of the Barnwell reprocessing plant has been used as the design basis for the engineering studies. To focus only on the equipment unique to the injection of noble gases, the design of the ORNL New Hydrofracture Facility has been used as a basis for solids and liquid handling, grout mixing and pumping equipment, well design and slotting procedures, and for specifying the grout parameters used in a typical injection. The ^{85}Kr inventory that could possibly be released by a catastrophic equipment failure is reduced by using ten monthly injections rather than a single annual injection. Gas shipments follow procedures currently used to ship ^{85}Kr from the Idaho Chemical Processing Plant to ORNL in DOE- and DOT-approved cylinders.

The ^{85}Kr injection system uses a three-stage diaphragm compressor to raise the noble gas pressure to 350 bar (5000 psia), about 150 to 200 bar higher than typical hydrofracture pressures and higher than any pressure surge that might occur. These compressors are entirely sealed and hold only a small volume of ^{85}Kr in the diaphragm cavity. A static mixer is used to entrain and dissolve the gas into the hydrofracture grout stream by a technique similar to that used to mix nitrogen gas and cement for underground injections in oil fields. The design employs several measures to limit the potential consequences of ^{85}Kr release that could result from equipment failures. To minimize the inventory of ^{85}Kr handled in each injection, monthly injections disposing of 1.6×10^6 Ci are used rather than a single annual injection (the current practice with liquid wastes at ORNL). The gas is kept in the shipping cylinders within secondary containment vessels until the injection; the cylinders are connected to the injection system one at a time. As a result, the maximum release likely from above-ground equipment failures is limited to 128,000 Ci. A 30-m stack enhances dispersion of any release away from plant personnel and reduces the site-boundary dose. A system is proposed to further reduce the consequences of a release by recovering 90% of the ^{85}Kr released. An on-line charcoal bed provides release monitoring and a 15-min response time for startup of emergency compressors. The ventilation system is designed to isolate the release and compress the atmosphere of the contaminated area into a storage tank. From the tank, the contaminated air can be transferred to the reprocessing plant for reconcentration or injected in its current composition at the hydrofracture site. A blowout preventer can be used to

prevent release of the gas-grout mixture already injected in the highly unlikely event of a catastrophic wellhead failure.

An accident analysis was carried out for scenarios including operator error, radiological incidents (leaks and spills), high winds, tornadoes, floods, earthquakes, fire, and unintentional shutdown of operations. Of these, the radiological incident was found to present the greatest potential risk. The impact of radiological incidents was evaluated using the computer code XQDDQ, which has been adopted by the NRC for meteorological evaluation of airborne releases from nuclear facilities. Summary results for site-boundary whole-body doses, under worst-case meteorological conditions, are listed below for the 128,000 Ci release at a distance of 1 km.

Ground release	390 millirem
Stack release	170 millirem
Stack release with 90% recovery	17 millirem

Lung doses and skin doses are a factor of 1.6 and 120 higher than whole-body doses, respectively. Increasing the distance to the site boundary to 3 km would also reduce the dose by a factor of ten. Although the numerical value of the skin dose is relatively high, no significant permanent injury, short or long term, has been identified for this type of exposure. Again, these doses represent worst-case meteorological conditions. Releases under more typical conditions would result in significantly lower doses.

Laboratory studies are needed to characterize more fully the behavior of

gas-grout mixtures. Diffusion rates for krypton in a solidified grout matrix are needed to quantify the acceptability of the final waste form produced by the hydrofracture process. Studies of the behavior of krypton in the liquid grout are needed to determine the extent of gas dissolution or entrainment as small bubbles and to provide engineering data for the design of mixing equipment.

Although the current engineering study is based on site conditions at the ORNL New Hydrofracture Facility, in practice the krypton hydrofracture facility probably would be located near the reprocessing plant it serves. For this reason, suitable geologic conditions must be identified at the proposed site. A brief study made by G. D. Brunton of the Chemical Technology Division suggests that suitable rock formations probably can be found at all sites currently in use or considered for reprocessing activities. A fracturing experiment in a test well would be required to prove the acceptability of a proposed site.

2. INTRODUCTION

2.1 Background and History

2.1.1 Radioactive properties of ^{85}Kr

^{85}Kr is a noble gas isotope produced by the fission of uranium or plutonium. The yield of ^{85}Kr per fission ranges from 0.0014 for the fission of ^{239}Pu to 0.0058 for that of ^{235}U . ^{85}Kr is radioactive with a 10.76-year half-life. Its two modes of decay are: 99.57% to ^{85}Rb by the emission of a 0.687 MeV beta, and 0.43% to ^{85}Rb by emission of a 0.173 MeV beta accompanied by a 0.514 MeV gamma.¹ The stable decay product, rubidium, is a reactive metal that often settles out of ^{85}Kr -air mixtures as an oxide dust. ^{85}Kr is the only isotope of the krypton and xenon noble gas fission products with a half-life greater than a few days. Thus, by the time spent fuel is processed, essentially all the noble gas activity can be attributed to this isotope. Although the decay is predominantly through beta emission, the low-incidence gamma ray becomes significant with the concentration of thousands of curies of ^{85}Kr . Biologically, krypton is nonreactive and contributes predominantly to a skin dose by immersion. Solubility of krypton in blood and body tissue is insignificant and the biological half-life of ^{85}Kr is considered to be zero.²

2.1.2 Chemical and physical properties of krypton and xenon

Although ^{85}Kr is the only isotope of radioactive significance, the chemical and physical behavior of noble gases released from spent fuel are

determined by all the isotopes present. An excellent summary of the properties, production methods, and uses of krypton and xenon was compiled by Cook.³ Both are inert monatomic gases under normal conditions. Critical properties, boiling points, and other data, including the pseudocritical properties of a mixture of equal molar fractions of krypton and xenon are listed in Table 2.1. The fact that xenon has a critical point that is near room temperature results in an unusually high compressibility as the gas is compressed to about 1000 psi.

Chemically, krypton (and xenon) is extremely inert. Some compounds can be formed with highly reactive elements such as fluorine or oxygen, but these compounds are weakly bound and unstable. Krypton can be trapped in compounds known as clathrates, particularly quinol clathrate, rather than actually forming chemical bonds; however, clathrates trap the krypton atoms in interstitial lattice positions as the compounds are formed.⁴

2.1.3 ⁸⁵Kr inventories

⁸⁵Kr is an isotope produced by fission. Very small amounts are generated by spontaneous fissions and cosmic-ray interactions. Some ⁸⁵Kr has been generated in the atmosphere and underground by the detonation of nuclear explosives. Most ⁸⁵Kr today is produced in nuclear reactors, particularly by the commercial power industry. At the reactor, noble gas fission products are collected in gas plenums at the ends of the fuel rods. Typically, less than 1% of the fuel rods lose cladding integrity during operation; thus over 99% of the noble gases

Table 2.1. Properties of krypton and xenon

	Krypton	Xenon	Mixture, equal mole fractions
Molecular weight	83.80	131.30	107.55 (average)
Critical properties			
Temperature, K (°F)	209.4 (-82.8)	289.7 (61.8)	249.6 ^a (-10.4)
Pressure, bar (psia)	54.9 (796)	58.4 (847)	57.0 ^b (827)
Density, kg/m ³ (lb/ft ³)	912 (56.7)	1110 (69.0)	
Compressibility	0.291	0.288	
Normal boiling point, K (°F)	119.8 (-244.0)	165.0 (-162.7)	
Triple point			
Temperature, K (°F)	115.9 (-251.1)	161.3 (-169.3)	
Pressure, bar (psia)	0.731 (10.6)	0.814 (11.8)	
Heat of vaporization (nbp) kJ/kg (BTU/lb)	107.9 (46.4)	96.3 (41.4)	
Densities, kg/m ³ (lb/ft ³)			
Gas at 295 K & 1 atm	2.49 (0.2170)	5.49 (0.3416)	
Gas (nbp)	8.5 (0.53)	9.6 (0.60)	
Liquid (nbp)	2422 (150.6)	3068 (190.8)	

^a Pseudocritical temperature calculated by Kay's Rule (R. D. Reid and T. K. Sherwood, The Properties of Gases and Liquids, Second Edition, McGraw-Hill, New York 1966).

^b Pseudocritical pressure calculated using modified Prausnitz and Gunn method.

remain in the fuel assemblies as they are removed from the core. Some reactor off-gas systems now include 30- or 60-day charcoal delay beds to allow all isotopes other than ^{85}Kr to decay before the gas is released. All the ^{85}Kr normally released at the reactor is discharged to the atmosphere.

Some reprocessing of spent nuclear fuel is now being carried out for experimental and military purposes. One facility, the Idaho Chemical Processing Plant (ICPP), recovers a portion of the noble gases by the cryogenic distillation method in the Rare Gas Recovery Facility.⁴ The recovered krypton-xenon mixture is sent to ORNL's Isotopes Division, where the krypton is purified and sold as an inert radioactive tracer gas. The amount processed is small; only a few cylinders containing less than 74,000 Ci of ^{85}Kr are shipped from ICPP to ORNL annually. Currently, the market for ^{85}Kr as a tracer far exceeds the available supply, and the gas is a valuable commodity.

The large-scale processing of spent commercial reactor fuel, whether fuel reprocessing or the stabilization of spent fuel as a waste form by releasing trapped gases, would greatly alter the commercial picture. It has been calculated that a 1.5×10^6 kg/year reprocessing plant, such as the Allied General Nuclear Services plant at Barnwell, South Carolina, would produce 16 MCi of ^{85}Kr from spent fuel annually. If recovered, the output of a single facility would increase the available supply a hundredfold. This would certainly exceed the market demand for the gas, resulting in its becoming a radioactive waste requiring isolation from the biosphere for over 100 years.

2.1.4 Release limits for ^{85}Kr

The U.S. Environmental Protection Agency (EPA) has recently published standards in 40 CFR 190 that limit the whole-body radiation dose equivalent to any member of the public as a result of planned discharges of radioactive material associated with the uranium fuel cycle to 25 millirem. These standards also limit the amount of ^{85}Kr entering the general environment from the entire uranium fuel cycle to 50,000 Ci per GW-year of electric power produced. The ^{85}Kr discharge limit is to take effect on January 1, 1983. The "uranium fuel cycle" is defined as all operations associated with power production, from the milling of uranium ore through reprocessing of spent fuel. Mining, waste disposal, and transportation of radioactive material are excluded from the scope of 40 CFR 190.

The 50,000 Ci limit represents a required recovery efficiency of about 90% for the ^{85}Kr generated in nuclear power production. This limit particularly affects reprocessing facilities, where most of the ^{85}Kr produced is released from the spent fuel elements. Some form of krypton recovery will thus be required at fuel processing plants, along with methods for the storage and ultimate disposal of the noble gas.

2.1.5 Hydrofracture at ORNL

Low-level aqueous radioactive waste solutions (less than 20 Ci/gal) have been disposed of using the hydrofracture technique at Oak Ridge since the mid-1960s. The liquid wastes are mixed with the appropriate solids

to form a cement-grout slurry. Oil field technology is used to create horizontal fractures in shale bedrock about 1000 ft deep by hydraulic fracturing. The radioactive grout is then pumped in sheets, about a quarter inch thick, into the fractures. Once set, the radioactive material is bound permanently into the strata. Detailed descriptions of the process are given elsewhere.⁵⁻⁷ The latter is an unpublished draft of the Preliminary Safety Analysis Report for the new hydrofracture facility under construction at ORNL. Excerpts of this document are included in Appendix A of this report. The hydrofracture process has proven to be a safe and effective way of stabilizing and providing moderately deep underground disposal for radioactive liquid wastes. The process could be used at other sites if geologic conditions can be shown to be favorable.

2.1.6 Proposal for hydrofracture of ^{85}Kr

This document addresses the engineering and safety considerations involved with the disposal of ^{85}Kr using the hydrofracture technique. This proposal had originally been made as an extension of proposals now being carried out to inject the gas directly into geologic strata, (domes or other cavities) or into a porous medium. Injection in a grout matrix is expected to provide all the isolation of the other deep-injection proposals, plus that of trapping the material in the grout.

Several approaches could be taken to the concept of hydrofracture disposal of ^{85}Kr , as discussed in the next section. This report covers the direct entrainment and/or dissolution of the gas into the grout as it is

being pumped into the well. The focus is on above-ground equipment; gas diffusion through the grout and surrounding strata is to be determined by laboratory experiments in the future. To focus on the equipment unique to the hydrofracture of krypton and not already proven by liquid waste injections, the ORNL New Hydrofracture Facility is used as a baseline design and site. The krypton injection system will be designed to be added to the existing design for that facility. Not only does this approach reduce the amount of design work required, but it also allows the use of the well-researched meteorological and demographic data available for the Oak Ridge site in assessing the impact of accidental releases. This does not imply that krypton recovered at a spent-fuel processing facility would be transported to Oak Ridge for disposal. In practice, a dedicated hydrofracture facility located near the processing plant would probably be constructed.

Because a spent-fuel reprocessing plant would generate low-level aqueous liquid wastes analogous to the ORNL wastes, the hydrofracture facility could be used for disposal of these wastes as well as ^{85}Kr . Because the salt content of the liquid wastes reduces the solubility of krypton, this combined disposal is considered the more conservative case and is used as the design basis for this report. Pure water could also be used to form the hydrofracture grout. Actually, the salting effect is likely to be far overshadowed by the effects of solids addition, which have not yet been accurately estimated. Complete dissolution of the noble gases into the grout is not necessary — entrainment as small bubbles may be equally satisfactory.

2.2 Relation to National Program

The evaluation of ^{85}Kr recovery and disposal methods is being administered by the Airborne Waste Management Program Office (AWMPO) under the Idaho Operations Office of DOE. A detailed discussion of the consequences of ^{85}Kr releases and the strategies being considered for krypton recovery and disposal appears in AWMPO's "Program Strategy Reference Document for the Management of Radioactive Airborne Wastes."⁸

2.2.1 Current status of krypton recovery and disposal

The recovery of noble gases from plant off-gas streams is difficult to accomplish, but several methods do exist. The Rare Gas Recovery Facility at ICPP uses cryogenic distillation of liquified noble gases,⁹ which are then shipped to ORNL for purification and sale. A pilot plant based on fluorocarbon absorption has been operated and refined at the Oak Ridge Gaseous Diffusion Plant.¹⁰ This system, termed "FASTER," uses the difference in solubilities of noble and other gases at various temperatures. It has been developed as part of the Advanced Fuel Reprocessing Program; as applied to the Barnwell commercial light-water reactor fuel reprocessing plant, is the reference process that produces the gas mixture for which disposal is assessed in this study. A method based on krypton absorption in liquid carbon dioxide (KALC) has been proposed for HTGR fuel reprocessing.¹¹

Activated carbon and molecular sieves could also be used; although these are simple, inexpensive approaches they offer small krypton loading

capacities leading to inefficient and ineffective operation. To date, the only operating krypton recovery system is the cryogenic distillation facility at ICPP; this is run for krypton and xenon production rather than as an off-gas cleanup operation and only achieves about 60% removal.

Methods for krypton disposal are developed to even a lesser extent. The only approach completely available today is storage in pressurized gas cylinders.

2.2.2 Alternate krypton disposal methods

Methods currently being evaluated for krypton disposal include the following.

1. Injection into underground formations.¹ The direct injection of krypton gas into underground formations, either caverns or porous strata, follows technology currently used by the natural gas industry for storage of large quantities of gas. Capacities of this approach are large, but normally some gas is lost from the formation. The percentage of this gas that actually reaches the atmosphere is being investigated.
2. Clathrate inclusion.¹² Although krypton is not actually chemically bonded, atoms can be trapped within an interstitial lattice structure of beta-phase quinol clathrates. Loadings as high as 57 cc Kr per g of quinol clathrate have been achieved, but questions remain about clathrate stability in an environment of decay heat, rubidium accumulation, and radiation damage.

3. Zeolite encapsulation.⁴ At high pressures and elevated temperatures, atoms of krypton can be trapped in internal pores of zeolite material. Effects of decay heat, radiation damage, and rubidium accumulation are not yet known, but zeolites may be more stable than clathrates for similar loadings. Equipment operating at high pressures and temperatures may pose further safety problems. Further research is under way to evaluate this process.
4. Ionic bombardment and sputtering.⁴ Both of these methods intersperse krypton atoms within a metal or similar solid. The former drives gas ions into a target material. The second adds layers of the solid material to the surface under a krypton atmosphere, trapping gas atoms within the solid structure as it is formed. Investigations are continuing into the stability of the products and the application of these methods on a large scale.
5. Storage in steel cylinders.^{13,14} The approach of storing pressurized gas cylinders in an underground repository is a currently available benchmark method against which other methods can be compared. Gas cylinders have been used for many years; lifetimes of over 500 years seem reasonable. Although eventually thousands of cylinders per year could be filled, suitable storage capacities can readily be maintained. Several drawbacks exist. A national repository has yet to be opened. The potential for the sudden release of hundreds of thousands of curies remains. Compatibility of cylinders with the repository media must be maintained (salt, for example, can be very corrosive to steel). And, if a pure inert atmosphere is

retained within the cylinder to reduce corrosion, the effects of unreacted rubidium metal on the cylinder walls must be evaluated.

It is within this context of an alternative evaluation that the hydrofracture of ^{85}Kr is being proposed. Questions arise about the performance of hydrofracture as well, particularly the behavior of gas-grout mixtures as they are dispersed into the formations and after the grout sets. This report discusses the design and safety of above-ground equipment, so that further evaluations can be carried out.

2.2.3 Potential hydrofracture options

In evaluating the hydrofracture of ^{85}Kr , three basic approaches can be identified. These include:

1. Disposal as a solid. Krypton could be loaded onto a solid adsorbent, such as activated charcoal or a zeolite, in a granular form small enough to be added to the grout solids mix. A variation of this approach recently suggested by Forsberg¹⁵ includes coating the loaded granules using pharmaceutical technology to eliminate the release of krypton as the material contacts water and passes through the injection equipment.
2. Disposal as a liquid. If the krypton could be dissolved into a reasonable quantity of liquid at atmospheric pressure, the liquid could be used as grout feed similar to option 1. Unfortunately, krypton is most soluble in organics such as perfluorotributylamine,¹ which are not likely to be compatible with aqueous grout mixtures.

3. Disposal as a gas. The most direct approach to the hydrofracture of ^{85}Kr would be the direct injection of krypton gas into the grout stream as it is pumped down the well. This report is based on the direct injection approach. Krypton-xenon gas is added to the grout stream at hydrofracture pressures (up to 350 bar, or 5000 psi) using the enhanced solubility of krypton in an aqueous mixture to hold the gas within the grout stream. The krypton may either be totally dissolved or entrained in the grout as small bubbles. As the grout sets, the dissolved gas may remain in solution or, again, may form small bubbles within the grout matrix. Pending future laboratory studies, either form is assumed to be an acceptable end product.

2.2.4 Relation to overall plant waste program

Waste management at a reprocessing plant is complex and varied. Waste forms include high-level liquids, gases (krypton, iodine, tritium), miscellaneous contaminated solids, and low-level liquid wastes (rinses, etc.). Processes that dispose of several forms of waste may be preferable to a separate process for each waste.

Hydrofracture was originally developed at ORNL for the disposal of aqueous low-level solutions generated primarily as a result of fuel-cycle activities. A hydrofracture facility constructed at a reprocessing plant for noble gas disposal could probably also be used for the disposal of low-level aqueous wastes. This option is represented in this study by using aqueous low-level waste as the liquid media for mixing with the grouting solids rather than pure water.

2.3 Justification

The AWMPO has requested that studies of the krypton hydrofracture process be made to provide input data for the evaluation of alternative ^{85}Kr disposal methods. This study is limited to the definition of design and safety aspects of equipment required to make krypton injections. Later work would include experiments to establish migration of krypton through a grout matrix; the nature of the ultimate characteristics of the gas in the grout (solution, small bubbles, etc.); and the resolution of various uncertainties in equipment behavior and design identified by this study. Eventually, a test injection with tracer quantities of radioactive noble gases may be made. These later phases can be better planned with a reference design in hand.

To focus attention on only those systems unique to a krypton injection, this study is approached as a modification to the ORNL New Hydrofracture Facility currently under construction. This eliminates the need to redesign those portions of a hydrofracture facility for which a reference design is already available.

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3. SCOPE AND CRITERIA

3.1 Scope

This project deals with the preliminary design and safety evaluation of above-ground equipment required for the injection of 300 m³ (0°C, 1 atm) of krypton and xenon gas into a hydrofracture well. The design is based on entraining the gas directly into the hydrofracture grout stream in relative proportions that allow total dissolution of the krypton-xenon mixture into the grout. The gas may go entirely into solution or may become entrained in the grout stream as small bubbles.

As the grout sets, the gas may remain in solution or small bubbles trapped in the grout matrix may be formed. Either is assumed by this study to be an acceptable form of disposition.

This study assumes that the ⁸⁵Kr produced at a reprocessing plant is permanently disposed of in a hydrofracture facility dedicated to the disposal of reprocessing plant wastes. Such a hydrofracture facility would be located as near the reprocessing plant as geologic conditions allow. The facility could inject the noble gas waste using grout mixed with pure water or low-level liquid wastes. Because the latter method represents a more flexible operation, this study uses the ORNL operational injections of low-level liquid waste as a design basis. In this operation, the noble gas is dissolved directly into grout mixed with liquid waste. This study will concentrate on those systems specifically required for the gas injection, not proven by previous application, by basing the design on modifications to the ORNL New Hydrofracture

Facility under construction. Well designs, slotting, solids mixing, and grout preparation operations are assumed to remain unchanged. The cost of constructing a hydrofracture facility for reprocessing plant wastes will be roughly estimated by adding the costs of noble gas injection, containment, and off-gas systems to the cost of the ORNL hydrofracture facility now being constructed.

The scope of the ^{85}Kr injection system covered by this study begins with the receipt of noble gas shipping cylinders at the hydrofracture site and ends with the ^{85}Kr pumped down the well, entrained, and dissolved into the grout. This study does include the assessment of consequences resulting from the gas-bearing grout being thrown back from the well immediately after injection, but does not include behavior of ^{85}Kr once the grout begins to set. A preliminary evaluation of suitability of underground disposal of ^{85}Kr by hydrofracture is presented elsewhere.¹⁶

3.2 Design Parameters

3.2.1 Noble gas quantity and composition

The ^{85}Kr hydrofracture system shall be designed to accept 300 m^3 (0°C , 1 atm) of noble gas annually. The chemical composition is split equally between krypton and xenon. Because of the decay times between the use of fuel in reactor operation and the reprocessing of the fuel, ^{85}Kr is the only gaseous isotope generating a significant amount of radioactivity. A total of 16 MCi of ^{85}Kr is present in the incoming gas, representing an isotopic content of 7.14% ^{85}Kr in the total krypton

component. The above numbers represent the assumed output of the Barnwell Fuel Reprocessing Plant.¹⁶

3.2.2 Noble gas receiving conditions

For the purposes of this study, noble gas shipments will be in accordance with procedures of and using cylinders and shipping containers described in ICP-1077.¹⁷ This safety analysis for ⁸⁵Kr shipping containers imposes limits of 1000 BTU/h and 500 psig (293 watts and 35.5 bar) for each cylinder.* The heat limit implies a limit of ⁸⁵Kr content of 74,000 Ci per cylinder. The temperature at which the 500 psig limit applies is not specified. Calculations show that, for the composition given in Sect. 3.2.1, the heat and pressure limits are reached essentially simultaneously. At 74,000 Ci per cylinder, 217 cylinders would be required for the annual accumulation. To remain under the prescribed limits, the total number of cylinders is limited to 250 per year, and the annual noble gas accumulation defined in Sect. 3.2.1 is divided equally among the cylinders. The resulting noble gas receiving conditions are summarized in Table 3.1. The cylinders will be emptied to atmospheric pressure to reduce the transport index number from III to VI, as defined in 10 CFR 71. This reduces the shipment of empty cylinders, which contain residual ⁸⁵Kr, from a "large quantity" to a "Type B quantity" of radioactive material.

*Calculations in ICP-1077 apparently were based on peak rather than average beta energy

Table 3.1. Noble gas cylinder conditions

Total number of cylinders per year: 250
 ^{85}Kr inventory shipped per cylinder: 64,000 Ci
 Gas volume per cylinder: 0.045 m^3 (1.5 ft^3)

Assumed shipping procedure

Cylinder filled at ambient temperature
 Cylinder heats up to 350 K in transit
 Cylinder cools back to ambient as it is emptied
 Cylinder is emptied to atmospheric pressure and is not purged ("empty"
 cylinder contains residual ^{85}Kr)

Full cylinder conditions (at receipt)

^{85}Kr inventory: 66,080 Ci (64,000 Ci shipping quantity + 2080 Ci
 residual quantity)
 Gas volume (0°C , 1 atm): 1.24 m^3 (43.8 ft^3)
 Pressure: 35.9 bar (506 psig)
 Temperature: 350 K (170°F)
 Heat generation rate: 90.0 W (310 Btu/h)

Empty cylinder conditions

^{85}Kr inventory: 2080 Ci
 Gas volume (0°C , 1 atm): 0.039 m^3 (1.38 ft^3)
 Pressure: 1.013 bar (1 atm)
 Temperature: 295 K (70°F)
 Heat generation rate: 2.86 W (9.76 Btu/h)

3.2.3 ^{85}Kr injection conditions

The addition of ^{85}Kr to the hydrofracture grout stream will be compatible with current grout mixing and injection parameters, as described in Sect. 3.2.4. Injection of either the entire noble gas inventory received, or any portion of it that contains the total ^{85}Kr inventory (such as the total krypton gas component), is acceptable. These criteria assume separate compression of the gas and addition to grout at the hydrofracture pressure. The ^{85}Kr gas mixture shall be compressed in excess of 350 bar (5000 psi), the highest pressure expected to be seen in the grout stream, to ensure that grout does not back into the gas compression and metering system. Pending future laboratory studies on noble gas solubility in grout mixtures, solubilities of krypton and xenon in a 1 M NaNO_3 solution shall be used for this analysis. This study assumes that gas-grout mixing shall be proportioned so that the gas content does not exceed one-half the amount soluble in grout at any system pressure where dissolution is relied upon to prevent escape of ^{85}Kr . To minimize the consequence of a ^{85}Kr release, the gas inventories being held compressed in equipment and piping at high pressures are minimized as much as practical. The amount of piping in which ^{85}Kr is carried under pressure is minimized by adding the ^{85}Kr as near the wellhead as practical. Likewise, the gas-compression system is located adjacent to the well cell.

3.2.4 Hydrofracture operating conditions

The proven hydrofracture operating conditions on which the design of the

ORNL New Hydrofracture Facility is based will be used for all slotting, solids mixing, and grout-preparation steps, except that small variations and modifications in water addition may be encountered, provided the overall grout mix does not change. These operating conditions are described in the draft Preliminary Safety Analysis Report prepared for the New Hydrofracture Facility.¹⁸ The design of the ^{85}Kr injection system will be based on an annual liquid waste accumulation of 300 m^3 (80,000 gal). This is 80% of the design basis for the New Hydrofracture Facility but represents a typical annual volume and is a more conservative criterion from a noble gas solubility standpoint. Making ten monthly injections (with two months available for maintenance) rather than a single annual injection lowers the gas accumulation to 25 cylinders. Each injection then uses 30 m^3 (8,000 gal) of liquids. Major hydrofracture operating conditions to be used for this study are summarized in Table 3.2.

3.2.5 Radiation protection

The design of the ^{85}Kr injection system will meet all requirements of the Nuclear Regulatory Commission consistent with applications as a waste disposal facility for a commercial reprocessing industry. All applicable requirements of Title 10 of the Code of Federal Regulations will be met. Radiation exposures will be within the limits of 10 CFR 20 for both restricted and unrestricted areas. As an "As Low As Reasonably Achievable" (ALARA) goal, a maximum exposure of 1 rem/year to workers will be used as a design basis.

Table 3.2. Hydrofracture operating conditions^a

*Intermediate-level liquid waste (ILW) feed^b*Annual accumulation: 300 m³ (80,000 gal)Primary chemical composition: 1M NaNO₃

Maximum typical radioactive content: 2 Ci/gal

Solids feed, wt %

Cement (Type 1): 38.5

Fly ash: 38.5

Attapulgate: 15.4

Potters clay: 7.7

Retarder (sugar): 0.05

*Grout mix*Approximate annual total volume: 450 m³ (120,000 gal)

Ambient temperature: 295 K

Pressure range: 140-350 bar (2000-5000 psi)

Solids/ILW: 900 kg solids/m³ ILW (7.5 lb/gal)

^a For 10 injections/year, the following apply: liquid feed per injection, 30 m³, grout volume per injection, 45 m³; and noble gas per injection, 30 m³ (0°C, 1 atm) 25 cylinders.

^b An alternate liquid feed of 300 m³ pure water could be used.

As noted in Sect. 2.1.4, Environmental Protection Agency (EPA) standards limiting both the maximum dose received by any member of the public and the total amount of ^{85}Kr discharged to the general environment appear in 40 CFR 190. The scope of this regulation, however, specifically excludes waste disposal operations. No specific guidance for waste disposal activities is available at this time. To meet the intent of EPA regulations, this study will extend the coverage of 40 CFR 190 to include the hydrofracture facility. Releases of ^{85}Kr to the "general environment" will be taken to mean krypton escaping to the atmosphere from the aboveground facilities or diffusing out of the immediate vicinity of the underground grout sheets.

The limits given in 40 CFR 190 apply to the entire fuel cycle rather than to individual facilities. Thus, the annual dose limit of 25 millirem to any individual of the public shall apply to the net dosage resulting from the combined operation of the hydrofracture facility, the (presumably) nearby reprocessing plant, and any other fuel cycle facilities in the same area. Likewise, the ^{85}Kr release limit of 50,000 Ci per GW-year applies to the collective operation of all fuel-cycle facilities. For ^{85}Kr , the fuel-cycle facilities having the potential of significant releases include the power reactors, reprocessing plants, and waste handling and disposal facilities. Because no specific guidance is provided for translating the overall fuel-cycle limits to individual facilities, the following approach will be used to establish a baseline value for the hydrofracture facility. The facility described in this study serves one 1.5×10^6 kg/year reprocessing plant, which in

turn serves power reactors producing 50 GW of electricity annually. The total release limit for this segment of the fuel-cycle, therefore, would be 2.5 MCi. Krypton passing through the reprocessing plant's recovery system will probably be the most significant source of routine releases. Eighty percent of the fuel-cycle ^{85}Kr release will be expected at the reprocessing plant and 10% each at the reactor and at the disposal site. Thus, the benchmark value for annual releases at the hydrofracture facility that would be consistent with meeting the overall fuel-cycle limits would be 250,000 Ci/year.

ALARA philosophies dictate that ^{85}Kr releases be held as far below these limits as is practical with available technology. The facility described in this study compresses and injects krypton using completely enclosed equipment; no shaft seals or stuffing boxes are used through which routine releases would be expected. Under normal operation, the greatest potential for routine releases would involve residual krypton escaping when disconnecting lines, such as removing emptied krypton cylinders or changing the wellhead over to the slotting configuration. These releases can be held to acceptably small levels by proper operation and supervision. Thus, insofar as the design allows, releases of ^{85}Kr under normal operation will be held below 16,000 Ci/year (0.1% of the annual krypton throughput), and the normal whole-body dose at the site boundary will be held below 3 millirem/year.

3.2.6 General design criteria

This section describes the basic criteria for structural and mechanical design of the noble gas storage, compression, and injection systems and

modifications to the existing New Hydrofracture Facility required to accommodate the injection of noble gases. Structural criteria are those used in the design of the New Hydrofracture Facility. "Nuclear safety related" structures and equipment have been defined as the cells and all enclosed piping and equipment. Vessels and piping in the krypton compression and injection systems that contain noble gases at pressures above 36 bar (500 psi) and could result in the ^{85}Kr release limits specified in Sect. 3.2.5 being exceeded should they fail under normal operating conditions will be defined as "critical pressure retaining" vessels and piping. Shipping containers are not covered by this design.

3.2.6.1 Wind loadings. All nonnuclear safety related structures will meet the wind load requirements of ANSI A58.1 for exposure "C" at a basic wind velocity of 90 mph. The applicable governing codes will be used for loading conditions and acceptance criteria.

3.2.6.2 Tornado loadings. All nuclear safety related structures will be designed to accommodate the wind forces and missiles of the design tornado. The design tornado will be as specified by Nuclear Regulatory Guide 1.76 for Region 1. The loading conditions and acceptance criteria will parallel those for the design earthquake requirements of Sect. 3.2.6.4.

3.2.6.3 Water level (floods). For this study it is assumed that the hydrofracture site will be selected such that all structures are well above the maximum probable flood level.

3.2.6.4 Seismic loadings. The cells and all enclosed piping and equipment are classified as nuclear safety related. All structures and systems so classified will be designed to accommodate the design earthquake. The design earthquake will be characterized by design response spectra that may be developed from procedures specified in Nuclear Regulatory Guide 1.60. The maximum ground motion accelerations will be 0.15 g horizontal and 0.10 g vertical. Dynamic analysis will be performed in support of the design. The specified loading conditions will be as defined in ACI 349-76 for the safe shutdown earthquake.

3.2.6.5 Noble gas storage and injection equipment. All critical pressure-retaining vessels and piping containing compressed gas bearing the ^{85}Kr isotope will be designed, fabricated, and inspected in accordance with the ASME Boiler and Pressure Vessel Code, Sect. III, Class 3. Pressure vessels not defined as "critical pressure retaining" will be designed, fabricated, and inspected in accordance with Sect. VIII, Division 1 of the ASME Code. All critical pressure-retaining equipment will be enclosed within gastight cells, with ventilation routed through an appropriate off-gas system to ensure that the criteria outlined in Sect. 3.2.5 are met.

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4. ENGINEERING FEASIBILITY

4.1 Concept and Alternatives

4.1.1 Reference engineering flowsheet.

The design of the ^{85}Kr hydrofracture injection system is based on (1) using off-the-shelf equipment that has been proven safe and reliable in other applications, (2) minimizing the amount of ^{85}Kr held above-ground at high pressure (over 35 bar, or 500 psi); (3) segregating the krypton held in storage to limit the hazard potential of a storage vessel failure; (4) using a blowout preventer to protect against a massive ^{85}Kr release should a total wellhead failure occur; (5) mixing the krypton with the hydrofracture grout as near the wellhead as possible to avoid complicating the components of existing hydrofracture systems; and (6) providing a ^{85}Kr monitoring and collection system to allow safe recovery from accident situations.

Figure 4.1 is a block diagram of the ^{85}Kr hydrofracture injection flowsheet. Grout will be prepared in the same manner as at existing ORNL hydrofracture facilities. Monthly rather than annual injections reduce the volumes of grout used by a factor of ten [to 45 m^3 (12,000 gal)].

Krypton-xenon gas mixtures are received at the hydrofracture facility in shielded shipping cylinders of the same design as those now used to ship ^{85}Kr from ICPP to ORNL. Each cylinder contains 64,000 Ci* at 35.5 bar

* Plus empty cylinder heel; see Table 3.1.

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Fig. 4.1. Krypton hydrofracture injection flowsheet.

(500 psig). Cylinders are stored in secondary containment vessels, three to a vessel. Twenty-five cylinders are emptied during each injection. The compression system draws the gas directly from the cylinders; only one cylinder is valved into the compressor manifold at a time. The ^{85}Kr inventory connected to the compression system at any time is thus limited to 64,000 Ci, plus a small amount of gas still present in the piping from the previous cylinder. Diaphragm compressors with remote heads and triple diaphragms are used for krypton compression. Three compressor stages are required. The gas is contained within a small, sealed cavity, minimizing both leakage and the amount of ^{85}Kr held within the compressors. Pressure regulators maintain constant pressures at both the inlet and outlet of the compressor train. With constant compressor speed, the gas flow is thus held at a steady rate despite variations in both cylinder and wellhead pressures.

The krypton-xenon gas mixture is added at hydrofracture pressure to the grout in the well cell, as near the wellhead as possible. A ring of tangential injectors is used to distribute the gas into the grout in a spiral motion which is subsequently reversed with static mixer blades to complete the gas dispersion (Sect. 4.2.5.1). This procedure is based on procedures used in oil fields to foam cement with nitrogen.

Engineering studies will be required to establish an optimum design for ^{85}Kr hydrofracture purposes. The only other modification to the current standard hydrofracture wellhead design is the addition of a ram-type blowout preventer just underneath the surface. This device permanently pinches off and seals the well in the highly unlikely case of a

catastrophic wellhead failure, preventing the release of grout and the off-gassing of krypton that had already been injected into the formation but had not yet set.

Control of ^{85}Kr releases resulting from leaks or equipment failure is accomplished by a combination of containment and use of charcoal beds and an emergency storage tank. The containment and ventilation system is designed to limit the spread of ^{85}Kr and to limit the dilution of the krypton with room air prior to collection. The exhaust from areas containing significant quantities of ^{85}Kr is normally routed, via separate ducts, to one of two charcoal beds. These are designed to allow a 15-min delay before ^{85}Kr can enter the atmosphere following the design basis release (Sect. 4.2.7.1). During this time, the source of the release can be identified and either the release would be stopped or the area would be sealed off and the exhaust compressed directly into the emergency storage tank. If a significant amount of ^{85}Kr is adsorbed onto a bed, it too can be eluted into the storage tank. If the ^{85}Kr collected in the storage tank is sufficiently concentrated or the total gas volume is small enough, it can be routed to the compressor suction manifold and injected. Otherwise, it could be compressed into empty shipping cylinders and returned to the reprocessing plant for reconcentration.

Figure 4.2 shows the process flow diagram for the gas compression and gas-grout mixing subsystems. Flowrates, temperatures, and pressures are given for the gas mixture after each compression, cooling, and pressure control stage. The manifold with 25 cylinders attached is shown;

Fig. 4.2. Krypton-85 process flow diagram

[illegible][illegible]

Fig. 4.2. Krypton-85 process flow diagram.

each cylinder is supplied with a remote valve (either automatically operated or controlled manually from a shielded corridor) to permit valving the cylinders into the compression system individually. A nitrogen supply and associated piping is shown. This system is used to flush residual ^{85}Kr out of the compressor train when injection is completed and to provide dry gas to circulate through the compressors during warmup. A surge and reserve tank for contaminated recycle nitrogen is provided and is connected to the krypton off-gas system. Because nitrogen flowrates vary and are intermittent, they are not shown on the material balance.

The flowrates given are based on the criteria in Table 3.2 and on typical ORNL hydrofracture operating conditions. The gas is dissolved into the grout in proportions substantially lower than the amount that is theoretically soluble in 1 M NaNO_3 at hydrofracture pressures. At 140 bar (2000 psia), the gas injection rate is about one-fourth the amount theoretically soluble in the grout. The addition of solids, however, may substantially affect the solubility. Based on the theoretical solubility in 1 M NaNO_3 , off-gassing of this mixture would begin at a partial pressure of 17 bar (250 psia).

4.1.2 Alternatives

4.1.2.1 Gas compression and metering. The following approaches have been considered in compressing and metering krypton gas into the grout stream at hydrofracture pressures.

1. Direct gas compression. Routing the krypton-xenon mixture directly from storage into a compressor train has the advantages of a simple flowsheet and a minimal inventory of ^{85}Kr at high pressure within the compression system. The most common type of compressor, the reciprocating compressor with oil-lubricated rings or dry packing, is a large, bulky device with an unacceptable tendency to allow some of the gas to escape under normal conditions. Failures such as broken piston rods can occur, which would result in a substantial ^{85}Kr release. Small, high-pressure reciprocating compressors are not always available as off-the-shelf units. Flow control, especially for a compressor run outside its normal operating range, may become difficult. Many of the problems that arise with typical reciprocating compressors can be avoided by the use of diaphragm compressors. This type of compressor, which is generally smaller and holds the gas in an entirely sealed cavity, is described further at the end of this discussion.

2. Pressurization as a liquid. The technique of injecting nitrogen into cement being pumped down a well is used to float a cement barrier on water in oilfields. The process resembles adding krypton to a hydrofracture stream, although the quantities involved and gas-to-grout ratio are higher. Halliburton¹⁹ has found it more practical to condense the nitrogen, pressurize and meter it as a liquid, and vaporize it just prior to mixing with the grout than to compress and meter the nitrogen as a gas. This technique would be substantially more complicated with a krypton-xenon mixture. Because the boiling point of krypton is well below the freezing point of xenon, a distillation step

separating the two is required. The temperature difference between the boiling and freezing points of krypton is less than 4 K, necessitating very close temperature control to prevent either pump cavitation or freezing. Both decay heat and the heat of compression make this temperature control difficult. Pressurization as a liquid does not appear to be a practical alternative for the compression of krypton-xenon gas mixtures to hydrofracture pressure.

3. Compression by displacement. Equipment to pressurize and meter a liquid tends to be simpler than that required for a gas. The problem of compressing and metering krypton can be converted to one of pressurizing and metering a liquid by using the liquid to displace the krypton-xenon gas mixture. The gas is first charged into a pressure intensifier vessel at moderate pressures. A liquid in which the solubility of krypton is low is then pumped into the vessel. As the liquid displaces the gas, a pocket of compressed krypton collects at the top of the intensifier vessel. Once hydrofracture pressure is reached, a constant volumetric flowrate is maintained equal to that desired for the gas leaving the intensifier. In surveying liquids for one in which krypton is relatively insoluble, gas solubility was found to decrease with the polarity of the liquid.²⁰ For this reason, water represents a convenient choice of displacing fluid. A particular advantage of water is that the krypton that does dissolve into it can be disposed of by bleeding the water into the grout after the gas pocket has been disposed of. One of the primary disadvantages of this approach is the relatively large inventory of krypton that is held at high pressure, especially if

a single pressure intensifier is used to maintain operational simplicity. Protection against the release of an entire injection inventory of ^{85}Kr (1.6 MCi) requires a large off-gas system to prevent an unacceptable environmental hazard.

Recommendations. The use of diaphragm compressors actually combines the best features of options 1 and 3. A sketch and details of the compressors is presented in Sect. 4.2.3 (Fig. 4.14). The cyclic action of a piston is used to flex a diaphragm in a sealed cavity by the use of a hydraulic fluid. Radioactive gas is present only in the upper half of the cavity and only in very small amounts. Compression is actually by displacement by the piston pressurizing the hydraulic fluid. The displacement is cyclic instead of continuous, as with the pressure intensifier, and the diaphragm physically separates the fluid from the gas. Commercial models are available in designs intended for use with toxic or radioactive gases. Features available include remote diaphragm heads that allow the main compressor drive to be located outside the cell and triple diaphragm heads that provide warning of diaphragm fatigue failure without contaminating the hydraulic fluid or allowing the gas to escape. Under normal operation no detectable release of ^{85}Kr would occur even if a diaphragm should fail. A constant flow rate can be maintained by holding the compressor motors at the design speed and controlling the inlet and outlet pressures. A survey of vendors indicates that a three-stage compressor train is appropriate.

4.1.2.2 Control of ^{85}Kr release hazards. Control of the hazards presented by handling compressed ^{85}Kr gas can be achieved by a variety of

methods. Among the basic approaches are prevention of equipment failures that could release krypton, limiting the amount of krypton that could be released by a failure, providing secondary containment, providing appropriate ventilation for collection or safe dispersion of the gas, and the recovery and safe disposal of hazardous quantities of escaped ^{85}Kr . A discussion of other potential elements of a total system follows.

1. Inventory control. If the inventory of ^{85}Kr present at the hydrofracture facility could be minimized or physically segregated so that the single failure of any piece of equipment could not result in an unacceptable quantity of krypton being released, no further protective measures would be required. Because the facility handles millions of curies per year, this approach is not practical as the sole protective measure used. Inventory control is, however, effective in reducing the magnitude of release possible and thus in reducing the size and capacity of other systems provided to mitigate the consequences of the release.

2. Quality control. An extensive quality assurance program, particularly exhaustive nondestructive examination and testing of components critical to containment of ^{85}Kr , can be used to prevent krypton releases. Practically, no amount of quality control can ever result in the total elimination of equipment failures. Quality control thus becomes another approach to be balanced, in effectiveness and cost, with other measures, such as multiple barriers or extensive ^{85}Kr recovery systems, to determine the appropriate degree of examinations and tests.

3. Wellhead protection. One mode of ^{85}Kr release that merits special attention is the release of that gas pumped down the well and into the rock formation and mixed into grout which has not yet set. A total, catastrophic failure of the wellhead assembly, although not likely, could cause the release of a large inventory of ^{85}Kr , particularly near the end of an injection. The blowout preventer is used to positively prevent this type of release. In a sense, the use of a blowout preventer could be considered either a form of inventory control, controlling the underground inventory, or a type of quality assurance action, assuring the integrity of the entire wellhead assembly.

4. Fluorocarbon absorption. This option consists of a series of recovery systems that deal with releases having occurred in the primary containment system, rather than preventing or limiting the magnitude of release. Fluorocarbon absorption is the approach currently preferred for the removal of ^{85}Kr from reprocessing plant head end activities associated with LWR and LMFBR fuels. The high absorption rate of krypton and xenon in fluorocarbons, particularly R-12, at lower temperatures is used to separate the noble gases from dried carrier gas. Noble gases are then released from solution by heating the R-12. Although an effective system, the need for extensive off-gas pretreatment and extensive refrigeration necessitate expensive and complex equipment. A recent estimate made for TMI-2 applications gives a cost of \$15 to 20 million for a 275 SCFM capacity unit; this could easily be double the cost of the entire hydrofracture injection system.

5. Cryogenic distillation. As noted in the introduction, the only major krypton recovery facility now in operation, the Rare Gas Recovery Facility at ICPP, uses the cryogenic distillation method to separate krypton and xenon from carrier gases. The off-gas stream is dried, condensed, and distilled using technology similar to air liquefaction. All the complexities and costs of the fluorocarbon absorption approach apply with cryogenic distillation as well. This approach appears to offer no advantage over 4 and consequently is rejected.

6. Activated charcoal. Krypton and xenon are both more strongly adsorbed on activated charcoal than are the major components of air. They can be collected on a charcoal bed in equilibrium with their partial pressures in the carrier-gas stream. Charcoal beds are inexpensive to install and simple to operate. They are also very inefficient, especially at room temperature or above, and do not permanently trap noble gases but rather hold them in dynamic equilibrium with their concentrations in the carrier-gas phase. As a result, if a single charcoal bed is left on stream continuously, all the ^{85}Kr loaded onto it will eventually pass through the beds and out to the atmosphere (reactor off-gas charcoal adsorbers, which remain on stream continuously, do not actually trap noble gases but delay their release long enough for most of the short-lived isotopes to decay). Consequently, unless the beds are loaded and subsequently disposed of, they must be eluted into another collection or disposal system if amounts unacceptable for delayed release are adsorbed. Charcoal beds lend themselves to adsorbing sudden leaks; indeed, because the partial pressure of krypton

risks during a release, the capacity of a charcoal bed would be higher for short, large leaks (provided the total gas flow is not greatly increased) than for a slow leak. Activated carbon, therefore, provides a useful method to delay and monitor escaping ^{85}Kr , either prior to release if not significant, or to elution into some other recovery or disposal system once that system has been started up.

7. Passive tank storage. The ultimate in availability for an emergency krypton collection system would be one that requires no moving parts or utilities and operates in response to some physical characteristic of a release. For a large gas release in an airtight, slightly ventilated cell, the rise in cell pressure might be used to actuate the system. Evacuated emergency storage tanks, in which rupture disks or check valves open in response to a small rise in cell pressure, would be an example of such a system. The size of the tanks required to pull an adequate amount of cell air makes this approach impractical for major leaks; slow persistent leaks that would result in a large dilution with cell air would not be controlled at all. The airtightness requirements to establish an adequate pressure rise to trigger the system would also complicate the ventilation system design.

8. Compressor and storage tank. A basic and simple system for the collection and storage of krypton releases would be a compressed emergency storage tank. No separation of krypton from air is attempted; however, a scheme for disposing of the gas collected must be provided. Likewise, unless the compressor is run continuously, this approach does not lend itself to collection of sudden large leaks because some time

will probably be required for compressor startup. Within limits, however, the compressed storage tank does provide a basically reliable collection system. If time is available to seal off a cell in which a ^{85}Kr release has occurred and to start up the compressor, a tank sized to hold 2.3 cell volumes will remove 90% of the ^{85}Kr that was released (provided the release does not continue). Because no exiting air stream is present, recovery efficiency of the gas pumped out is not an issue. The storage tank can also act as a transfer system for other collection and recovery systems such as eluting a charcoal bed or holding contaminated cell exhaust for shipment to an offsite krypton recovery facility.

Recommendations. The selected approach to the control of ^{85}Kr releases combines the useful features of most of the above potential components. Because options 1 through 3 cannot be relied upon to prevent a potentially harmful release from occurring, some form of a krypton collection and recovery system is needed. Only options 4 and 5 offer truly effective krypton recovery from cell exhaust, yet both are prohibitively expensive for the hydrofracture facility. Therefore this study assumes that ^{85}Kr -contaminated cell air could be compressed into empty shipping cylinders and sent back to the reprocessing plant for reconcentration of the noble gases. This is easily accomplished if the reprocessing plant is adjacent to the hydrofracture facility. High-quality and reliable components will be used in the compression and injection system so that the use of this approach will rarely, if ever, be needed. Components will be designed and inspected in accordance with

ASME Sect. III, Class 3 requirements, in use for systems presenting similar radiation release hazards at commercial nuclear power plants.

The hydrofracture facility off-gas system selected for this study will be a combination of charcoal beds for immediate retention and monitoring and a compressed storage tank for longer-term handling and for exhausting air from a sealed area when necessary. The containment and ventilation system will be designed so that areas can be isolated and leaking ^{85}Kr is diluted as little as possible with building air during collection. Two charcoal beds will be provided to enable a loaded bed to be isolated and eluted to the storage tank if desired; the spare bed would remain available to go on line.

To limit the size of the charcoal beds, inventory control will be used to reduce the maximum leak expected. The contents of a shipping cylinder represents a convenient quantity as a limit for potential releases. Gas will be stored in cylinders, which will not be interconnected. At injection time, cylinders will be valved into the compressor system one at a time. The off-gas system will be sized to absorb the contents of two cylinders, or 128,000 Ci, of ^{85}Kr , representing an incident in which one cylinder strikes another during handling or a total failure of the compression system while a fresh cylinder is valved on (the contents of the previous cylinder approximating the inventory in the system piping). The release of the contents of two cylinders (128,000 Ci) is therefore defined as the design basis accident for this installation. Monthly, rather than annual, injections were selected to reduce the number of cylinders from 250 to 25 per

injection and to make direct manifolding practical. Because the "downhole" inventory eventually reaches the contents of all 25 cylinders, the use of a blowout preventer is essential to maintaining the 2-cylinder design basis failure as the maximum credible accident.

4.1.2.3 Standard or existing practices. The following is a discussion of systems for which standard industrial practices have proven safe and effective over the years. It also presents areas of technical uncertainties in which no current experience exists.

1. Gas shipping. This report does not address the design and analysis of shipping cylinders, but assumes that the containers and procedures now in use between ICPP and ORNL will be acceptable for use with the krypton hydrofracture system. These cylinders have been used to ship krypton for over ten years without any serious difficulties and have been given all the necessary DOE and DOT approvals. The specific design of the shipping cylinders has a negligible impact on the feasibility of the process as long as gas shipments in general can be shown to be feasible. An analysis of the risks of the shipping system has been carried out for the ICPP-ORNL shipments and is described elsewhere.¹⁷

2. Existing hydrofracture systems. Other than changing injection criteria from annual to monthly injections, the requirements for hydrofracture systems currently in use, including solids handling, grout mixing, slotting, etc. are assumed to be unaffected. Thus, this study is principally concerned with systems unique to the injection of ⁸⁵Kr.

3. Gas-grout mixing. This study assumes the acceptability of an injection ring-static mixer approach to gas-grout mixing similar to that used by Halliburton to foam cement with nitrogen prior to injection. The actual verification of this technique, including optimization of injector-mixer designs or the proposal of alternative methods, requires engineering studies of the behavior of gas-grout mixtures. This will be noted in the "system uncertainties" section (Sect. 4.3) of this report; an evaluation of alternative approaches is not presented in this study.

4.2 Subsystem Definition

4.2.1 Existing hydrofracture subsystems

As stated in the previous section, the Title I design of the ORNL New Hydrofracture Facility²¹ will be used as a reference design without addressing modifications that might be caused by using shorter, more frequent injections than the facility's design basis. The most descriptive and current discussion of the design and operation of the New Hydrofracture Facility appears in its Draft Preliminary Safety Analysis Report, generated in May, 1979.¹⁷ Because changes have been implemented in the construction of that facility, the document has not been revised and formally issued. A Final Safety Analysis Report is now being prepared (as of May 1981).

4.2.1.1 Scope of the New Hydrofracture Facility project

The Title I design for the ORNL New Hydrofracture Facility includes the following components:

1. a new hydrofracture operations building containing approximately 120 m² (1300 ft²) of floor area;
2. four observation wells drilled to a depth of approximately 335 m (1100 ft) and cased the full length;
3. eight rock-cover wells drilled to a depth of 180 to 210 m (500 to 700 ft) and cased to a depth of 150 to 180 m (500 to 600 ft), five observation wells, and the injection well itself;
4. a system of bench marks extending a distance of 610 m (2000 ft) from the injection well to the east and west directions;
5. utility systems at the new site, including air, water, and electric power;
6. an underground, doubly contained, stainless steel pipe line for transfer of waste from the intermediate-level waste storage tanks;
7. site clearing and grading and access road improvements;
8. equipment to blend and store cement mix solids, mix the solids with the waste stream, inject the waste grout into the well, monitor and control the operation, and collect cleanup solutions; and
9. an underground emergency waste tank with capacity of 150 m³ (40,000 gal).

Each of these components is discussed in more detail in the subsequent sections. The facilities and equipment described here provide a

complete system for the hydrofracture disposal of intermediate-level radioactive waste at the Oak Ridge National Laboratory.

4.2.1.2 Process description of ORNL New Hydrofracture Facility. Radioactive liquid wastes at the Oak Ridge National Laboratory are collected at a central facility, neutralized, and fed to an evaporator that concentrates them by a factor of 25 to 30. The concentrate is accumulated until a sufficient volume is on hand to warrant the disposal operation. This is usually in the range of 300 to 375 m³ (80,000 to 100,000 gal). At this time, a dry solids mix consisting of cement, fly ash, attapulgate, pottery clay, and sugar is blended in pneumatic blending tanks at the hydrofracture site. The blended solids are then stored in two 500,000-lb-rated (260 m³) bulk storage tanks. During an injection, the preblended solids are pneumatically conveyed to a feed hopper above the mixer cell.

Before the start of each waste injection series, the injection well casing is first slotted and a fracture is induced in the adjacent shale formation. Slotting is accomplished by pumping a sand-water mixture through a tubing string in the injection well and out a jet at the bottom of the string. The high-pressure jet erodes the well casing and the surrounding casing cement. The well is then pressurized with water until the fracture is initiated. Fracturing normally occurs at a pressure of about 170 to 240 bar (2500 to 3500 psi).

After the initial fracture has been induced, liquid waste is pumped from the ILW storage tanks into a jet mixer within the facility, where it is

continuously combined with solids being gravity fed from the feed hopper. Solids drop onto a weigh belt for metering and into a mixing hopper fitted onto the jet mixer. The mixed grout then flows into a mixing tub, which serves as both a deaerator and as a feed tank for the injection pump. The waste grout mix flows from the mix tub to the suction side of the 600 hp positive displacement injection pump and through a tubing string down into the injection well and out into the slot in the well casing.

As the waste flows out into the fracture, the fracture propagates ahead of it, and the grout spreads out in a thin sheet. A retardant added to the grout slows down the setting time so that it remains fluid for about twelve hours. The injection of the grout is normally carried out at a rate of about 45 to 70 m³/h (200 to 300 gal/min) and at a pressure of 140 to 200 bar (2000 to 3000 psi). Approximately 300,00 kg (650,000 lbs) of cement mix solids are needed for each 340 m³ (90,000 gal) of waste concentrate that is injected. Up to four injections may be made in each slot. Subsequent injections are made by reslotting the well at about 3 m (10 ft) intervals. A schematic flow diagram of the process is shown in Figure 4.3.

4.2.1.3 Injection and monitoring wells. Three types of wells are used at the shale fracturing facility: an injection well for the injection of waste grout, observation wells for the determination of the orientation of the grout sheet, and rock-cover monitoring wells for verification of the continued very low permeability of the shale above the grout sheets. A sketch of these well types is shown in Figure 4.4. The

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Fig. 4.3. Flow diagram of ORNL New Hydrofracture Facility.

Fig. 4.4. Sketch of hydrofracture wells.

injection well was drilled to a depth of 335 m (1000 ft) and a 14-cm (5-1/2-in.) casing was cemented down its entire depth. A 24.4-cm (9-5/8 in.) surface casing was also installed down to a depth of 75 m (250 ft). The injection well is capped with a wellhead assembly rated at 10,000 psi (670 bar). Waste is pumped down a 7.3-cm (2-7/8 in.) tubing string hung down the well and is injected into the formation through slots cut in the casing and surrounding cement. As the grout sheet propagates, it intersects the gamma monitoring wells. A gamma sensitive probe is lowered into these wells a few days after an injection to establish the depth and orientation of the grout sheet.

An array of nine gamma wells surrounds the injection well at distances of 60 to 150 m (200 to 500 ft) to permit the location of the grout sheet. These wells extend to the same depth as the injection well, and have a 6.4-cm (2-1/2 in.) cemented casing. A low-strength cement is used to allow yielding as the grout sheets uplift the overburden, preventing ruptures in the casing and leakage of grout into the wells. A network of eight rock-cover wells, of which the lower 30 m (100 ft) is uncased, extend to a depth of about 200 m (700 ft). These are used for periodic pressure testing of the strata to ascertain that accumulated stresses have not generated fractures in the shale that would result in an increase of the permeability of the rock cover. A network of bench marks, spaced at 60 m (200 ft) intervals, will be used to measure the surface uplift caused by the waste injections. A sketch of the monitoring well pattern is included in Appendix C.

4.2.1.4 Feed material and process flowsheets. Typical radionuclide composition for ORNL intermediate level waste concentrate is given in Table 4.1. This waste is a salt solution (1 M NaNO_3 and other minor constituents) containing up to 0.53 Ci/l (2 Ci/gal) of beta-gamma activity. Generally the major radionuclide is ^{137}Cs with ^{90}Sr averaging 0.026 Ci/l (0.1 Ci/gal) or less.

Table 4.2 gives a typical dry solids mix ratio. These solids have been blended with the liquid feed in ratios of solids to liquids ranging from 700 to 1100 kg/m^3 (6 to 9 lb/gal). The resulting grout has a density of about 1500 kg/m^3 (12.5 lb/gal) and an apparent viscosity of about 40 cp.

The process flow and instrumentation diagrams for current ORNL hydrofracture operations are given in Figs. 4.5 and 4.6. The equipment involved is described further in the next few paragraphs. Further sketches and flowsheets (utilities, fire protection, site geology, etc.) are given in Appendix C.

4.2.1.5 Facility equipment and subsystem descriptions

Structures. The new hydrofracture building houses a cell bank, three cells of which have reinforced concrete walls 0.76 m (2.5 ft) thick, and the necessary personnel and equipment support areas. In addition, solids storage, blending, and handling facilities are located outdoors. The building is constructed of reinforced concrete and masonry; its overall dimensions are 24.2 m (79 ft 6 in.) long by 16.5 m (54 ft). The main roof level is 4.4 m (14 ft 6 in.) above ground level. A high bay section 6.7 m^2 (22 ft^2) rises to 19.2 m (63 ft) above ground

Table 4.1. Radionuclide composition of
ORNL ILW waste concentrate

Nuclide	Specific activity Ci/m ³ (Ci/gal)	Estimated annual volume m ³ /year (gal/year)	Estimated annual curies (Ci/year)
¹³⁷ Cs	0.26 (1)	3 x 10 ⁵ (80,000)	8 x 10 ⁴
^{137m} Ba	0.24 (0.92)		7.4 x 10 ⁴
⁹⁰ Sr	0.026 (0.1)		8,000
⁹⁰ Y	0.026 (0.1)		8,000
¹⁰⁶ Ru	0.009 (0.035)		2,800
¹⁰⁶ Rh	0.009 (0.035)		2,800
²³⁹ Pu	2.6 x 10 ⁻⁷ to 2.6 x 10 ⁻⁶ (1 x 10 ⁻⁶ to 1 x 10 ⁻⁵)		0.08 to 0.8
²⁴⁴ Cm	2.6 x 10 ⁻⁴ (1 x 10 ⁻³)		80

Source: Radiation Protection, ICRP Publication 26, from
"Recommendations of the International Commission on
Radiological Protection," Pergamon Press, New York (1977).

Table 4.2. Composition of dry solids mix

Ingredient	Wt%
Cement (Type I)	38.5
Fly Ash	38.5
Attapulgate	15.4
Potters Clay	7.7
Retarder (sugar)	0.05

Fig. 4.5. Hydrofracture process flow diagram.

5. Hydrofracture process flow diagram.

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level to allow the injection tubing string to be withdrawn during slotting operations under containment. The building floor plan is shown in Fig. 4.7; section views are shown in Fig. 4.8. Additional sketches are presented in Appendix C.

The three main cells include the injection pump cell, the mixing cell, and the well cell. An underground cell structure adjacent to the mixing cell provides space for the slotting waste tank and the liquid waste metering equipment. A control room is located east of the three cells. The diesel drives for the injection pumps are located in a louvered area south of the pump cell. Only the pump heads are located in the cell; a shielding wall stands between the head and the pump drive. A compressor room stands next to the well cell and ventilation equipment is upstairs; offices and a locker room are on the east end of the building.

Concrete cell structures are designed according to stress and deformation criteria, defined by ACI-349-76 for loadings involving the safe shutdown earthquake. Critical steel structures are designed to meet criteria defined by the AISC "Manual of Steel Construction" for loads involving earthquakes. All other structures that are not nuclear safety related are designed to the requirements of the Uniform Building Code for Seismic Zone 2.

Solids and liquid waste handling equipment. Four hoppers are used to store attapulgate, potter's clay, and fly ash prior to blending. A scale tank and two blend tanks are used for solids proportioning and blending operations. Air slide conveyors are used to transfer solids

Fig. 4.7. Floor plan, ORNL New Hydrofracture Facility.

Fig. 4.8. Section view, ORNL New Hydrofracture Facility.

during the blending operation. The blended solids are stored in two new 500,000-lb (227,000 kg) bulk storage hoppers. During an injection, the preblended solids will be conveyed to the feed hopper on the mixing cell roof by a variable output air fluidizer. From the feed hopper, solids will be metered into the mixer hopper with a weigh belt.

Liquid waste concentrate is collected in eight 190-m^3 (50,000-gal) stainless steel tanks located in an underground vault near the hydrofracture facility. A double wall transfer pipe connects the waste tanks to the metering pit adjacent to the mixing cell. From here, liquids are metered into the jet mixer inside the cell.

Grout mixing. The main component involved in grout mixing is the jet mixer. This is a solids-liquids proportioning jet designed specifically for hydrofracture grout mixing. The mixing hopper, which contains nonradioactive solids, is fitted directly onto the mixing jet. From the jet, the grout is discharged into the mixing tub. The tub serves both as a deaerator and as a feed tank for the injection pump. It is an atmospheric pressure vessel with a volume of about 2.3 m^3 (600 gal). The tub has a float-type liquid level measuring device and is arranged such that the liquid level can be viewed through a shielding window from the control room. All mixing equipment is constructed of stainless steel.

Injection pumps. The pump cell contains facilities for two Halliburton HT-400 triplex pump heads. One pump is used to make the actual grout injection; the second maintains water pressure on the annulus of the injection well to prevent grout from backing up the well. In

addition, the second pump serves as a standby pump to clear the well should the main injection pump fail. Only the pump heads are inside the shielded cell. The diesel-drive motor controls are located in a cubicle at the rear of the cell. Removable unit shielding will be used to permit operators to perform direct maintenance activities on the pump heads.

Wellhead and related equipment. The well cell is built around the injection well, which was drilled prior to the start of facility construction. The injection well was drilled to 335 m (1100 ft) and provided with a 14-cm (5-1/2-in.) casing. A surface casing of 24.4 cm (9-5/8 in.) diameter was also installed. The wellhead assembly, which is rated at 10,000 psi, supports a 7.3 cm (2-7/8 in.) tubing string that extends down the well. It also provides connections for the grout stream, annulus connections, pressure measurements, and for connection of the slotting head.

The slotting head consists of a 9.1-m (30-ft) length of tubing (the "slick joint") that extends down from the wellhead assembly, a hydra-jet catcher, and an assembly of tubing unions and flexible joints that will connect the jet catcher to an injection pump discharge connection on the high-pressure valve rack. The slotting operation involves pumping a sand-water slurry down the tubing string to a jet at the bottom of the string. The slurry erodes a slot in the casing and cement at that point. The slotting waste tank is used both for a contaminated water supply in mixing the slurry and as a discharge point for spent slurry. The sand settles out of the spent slurry, and the water is saved for the

injection. Slotting is carried out long after the previous injections have been sealed in with clean grout. Sketches of both injection and slotting configurations are presented in Appendix C.

In the unlikely event of a wellhead rupture, a large volume of grout could flow back out of the disposal formation and up the injection well. The consequences of such an accident have been minimized by addition of an enclosed emergency waste tank north of the main cell structure. The emergency waste tank is constructed of reinforced concrete to provide a holding capacity of 150 m³ (40,000 gal). The tank is located underground to permit gravity flow from the well cell. A sump pump is provided to return water from the tank to the slotting waste collection tank.

Confinement, ventilation, and health physics. The primary confinement barrier for all hazardous material is assumed to be the process equipment. Positive secondary containment is provided for that part of the high-pressure system that handles radioactive grout. Those parts of the facility that handle radioactive materials are designed to withstand the effects of all natural phenomena.

The control and change rooms are heated and air conditioned with a standard package unit. Cells are maintained at a negative pressure of 1 in. (25.4 mm) water gage, a system provides six air changes per hour. This is accomplished by three separate off-gas systems. One system draws air from the mixing tub and from the mixer cell and exhausts this air through one of two parallel filter systems. Each of these filter systems consist of two HEPA filters in series and an off-gas blower.

Either system will handle the $600 \text{ m}^3/\text{h}$ (350 cfm) design load. The second off-gas system draws $510 \text{ m}^3/\text{h}$ (300 cfm) of air from both the well cell and the pump cell (there is also a connection to the slotting waste pit, but no air flow is anticipated). A roughing filter and a HEPA filter in series are provided at the air exhaust from each cell. The filtered air stream is drawn through one of two parallel filter systems; each of these systems consists of a roughing filter, a HEPA filter, and an off-gas blower. Either system will handle the design load. The third off-gas system draws $3400 \text{ m}^3/\text{h}$ (2000 cfm) of air from the well pipe storage tower through a roughing and a HEPA filter in series and discharges it to the building stack.

The operation of the first two of these off-gas systems is essential to the safety of an injection; the injection will be terminated if either of these systems should fail. The third off-gas system is installed for use during the slotting operation; this operation will not be undertaken if this system is inoperative. None of the off-gas blowers is on the emergency power circuit. The injection would be halted should the power fail.

Shielding is designed for anticipated pilot plant wastes of considerably greater activity than ILW concentrate. The maximum allowable dose outside the shielding is 2 millirem/h. Radiation levels will be considerably lower with ILW concentrate injections.

A constant air monitor is installed in the operating room to measure the concentration of radionuclides in the air. This monitor records the

concentration of beta and gamma emitters and is set to alarm if the concentration of either approaches one-half the operational limit (1×10^{-9} $\mu\text{Ci/ml}$ for ^{90}Sr and 6×10^{-8} $\mu\text{Ci/ml}$ for ^{137}Cs).

Utilities and fire protection. The New Hydrofracture Facility will have provisions for general plant utilities including water supply, electrical system, compressed air, building ventilation, and sewage disposal. Injection operations are carried out intermittently, generally about twice a year. An adequate supply of water will be provided to satisfy requirements for potable water, process water, and fire protection. Air compressors will be provided for solids handling and instrumentation.

Electrical. Power is supplied to the New Hydrofracture Facility from a substation originally installed to support the ILW storage tanks. A permanent emergency generator, though not included in the ORNL facility, would be required to ensure continued ventilation in a facility designed for noble gas disposal.

Compressed air. Air compressors will be installed in the compressor room to provide the following: (1) 5 psig pressure for the solids handling equipment; (2) 30 psig pressure to the scale and blending tank equipment; (3) 20 psig to the Fuller-Kinyon pumps; and (4) 100 psig air, dried to a dewpoint of -20°F , for instrument air.

Water supply. Both potable and process water are supplied from the existing 6-in. (152-mm) underground potable water line serving the ILW storage tanks. The building process water system, covering all

application other than sanitary, drinking, and safety showers, will be supplied from the potable water source through a reduced pressure backflow preventer. Potable water will also be supplied directly to the fire protection sprinklers and hose bibbs. A potable hot water heater will be used for the rest room and shower facilities.

Plant wastes. Small quantities of radioactive materials will be released from the facility process off-gas system. In addition, the facility will generate a recycle stream of bleed back and washup water from the slotting and injection operations. This water will be returned to the ORNL ILW system or injected in the well. Small amounts of solid waste will be generated, including clothing, shoe covers, and gloves and contaminated tools and other items of equipment.

Fire protection. The facility will be protected by means of a wet-pipe sprinkler system in all areas except the cells and pipe storage tower where no protection is required. The diesel pump drives will be separated by means of a four-hour-rated firewall; a separate underground fuel tank will be provided for each drive.

Utility flowsheets. Flowsheets further describing many of the above systems are included in Appendix C.

4.2.2 New structures

This section describes the additional structures that will be needed to house the new equipment used in making krypton injections. Certain liberties have been taken with the facility layout. For example, it was

assumed that the well pipe tower could as easily have been assembled to load pipe from the west as the current design loading from the north, which directly conflicts with the location of the new compressor cell.

The layout was selected on the basis of minimizing the amount of high-pressure krypton piping and minimizing interferences with the existing layout and operations. This may not represent the optimal layout for a facility designed originally for krypton injections but is satisfactory for this study. Figures 4.9 and 4.10 give plan and section views of the new additions for the ^{85}Kr injection system.

4.2.2.1 Compressor cell. All process equipment handling significant quantities of ^{85}Kr will be located in a single shielded cell. This includes the compressor train and the off-gas systems but does not include the gas cylinders, which remain inside lead-shielded casks, or the emergency storage tank, which is too large for the cell and will be located in a vault outdoors (the equipment mentioned is described in the following sections). The same 30-in. (0.76-m) concrete wall thickness used in the design of the existing cells is also assumed to be adequate for krypton shielding without further evaluation. Actually, this thickness is probably overly conservative for the krypton system because ^{85}Kr is primarily a beta emitter. Roof plugs are provided for equipment installation and maintenance and for personnel entry. Because the only radioactive material that should be present is a gas, no floor liner is used; a protective coating such as Amercoat is used on all concrete surfaces to facilitate decontamination should it be required. Because a low-airflow rate is desirable for effective operation of the off-gas

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Krypton-85 building floor plan.

Fig. 4.10. Krypton-85 building

system, roof plugs will be sealed to reduce inleakage.

4.2.2.2 Krypton storage area. Krypton will be stored in shielded cylinders placed inside secondary containment vessels, three cylinders to a vessel. Storage capacity for thirty cylinders requires ten vessels. By keeping the cylinders inside lead casks, further shielding them by storing the cylinders below grade, and keeping the interconnecting krypton manifold either below grade or in a shielded pipe chase, the need for a shielded structure in the storage area is eliminated. A standard form of low-inleakage building construction will be used. The containment vessels will be arranged in two parallel rows of five; a bridge crane will be located above for cylinder handling. To limit the inleakage that might be associated with a large roll-up door that would allow trucks to enter the structure, a monorail extension of the crane bridge to the outdoors is used; the size of the door is limited to that required for cask entry and the actual unloading operation will take place outdoors. The grade and road layout of the site have resulted in the storage area being laid out at a lower elevation than the rest of the building.

4.2.2.3 Equipment room. Space is provided for the krypton compressor driver units, refrigeration equipment, etc. by extending the existing ground-floor compressor room to the north, making this area even with the new compressor cell. This area will handle no contaminated materials. The same masonry construction, with a louvered wall relocated, is used as was used in the original design.

4.2.2.4 Site. The major structure required aside from the main building addition is the underground vault for the emergency off-gas storage tank described in Sect. 4.2.7. Other site work will be minimal. The road bed will be extended into the cylinder unloading area. Utilities, fence plans, sewage, etc. will all remain the same as in the original New Hydrofracture Facility design.

4.2.3 Krypton receiving and storage

The krypton receiving and storage subsystem covers the handling and containment equipment necessary to unload incoming cylinder shipments and to safely store the gas until the next injection takes place. As discussed in Sect. 4.1.2.2, krypton will be stored in the shipping cylinders; injections will be made after 25 cylinders have accumulated.

4.2.3.1 Krypton shipping. This report does not address the design and safety of new shipping cylinders but rather proposes use of cylinders and procedures proven by over ten years' experience shipping krypton from ICPP to ORNL. These cylinders are described and analyzed in detail elsewhere.¹⁷ Shipments are currently made by truck, one cylinder per truck. Because ICPP fills only a few cylinders a year, trucking procedures are currently based on limited production; it may prove practical to increase the number of cylinders per truck. During shipment, the cylinders are encased in an insulated overpack (Fig. 4.11), which is an outgrowth of Oak Ridge Gaseous Diffusion Plant designs for UF₆ shipping cylinders. Cask integrity is thus based on crash tests performed in certifying the ORGDP containers. Thermal analysis for fires, etc. is described elsewhere.¹⁷

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Fig. 1.11. Krypton shipping container.

4.2.3.2 Krypton receiving. Upon arrival at the unloading station under the monorail extension of the cylinder handling bridge crane, the shipping package is lifted off the truck, the truck moved away, and the package set down in a vertical position. The cover of the overpack is removed, and the cylinder enclosed in the lead shielding cask (Fig. 4.12) is lifted out of the insulating overpack by means of an attached choker cable that remains on the cask. The cylinder-shielding cask assembly is then brought into the storage area and lowered into a containment vessel with the bridge crane. Cylinders are not connected to the manifold until the time of an injection. Once the cylinders are inside the storage area, the doors are closed and the ventilation returns to its normal low-airflow operation. The covers to the containment vessels are also replaced.

4.2.3.3 Krypton storage. Cylinders are stored in their lead casks for shielding in water-cooled secondary containment vessels, three cylinders per vessel. A sketch of the containment vessel is presented in Fig. 4.13. Although the criteria call for an injection after 25 cylinders have accumulated, ten containment vessels are used to provide some excess storage capacity and to allow damaged or otherwise suspect cylinders to be stored separately. The containment vessels are designed for 10 bar (150 psi) pressure to allow containment of the cylinder contents should the cylinders fail. Cooling to remove the 90 W (310 Btu/h) of decay heat per cylinder is provided by circulating 278-K (40°F) chilled water through a coil run along the interior of the containment vessel. A detailed heat-transfer analysis will await later

Fig. 4.12. DOT-approved krypton-85 shipping cylinder.

RETURN NOZZLE IS
DIRECTLY BELOW INCOMING NOZZLE.

Fig. 4.13. Secondary containment vessel.

design phases; some form of soft fin material contacting the cask surfaces could be used to improve heat transfer if necessary.

Cylinders will be connected to the krypton manifold at the time of an injection. Currently, the shield cask cap is being removed and the connection made manually, partially because most of the shipments now being made have a relatively low curie content. It may be necessary to return to the use of the remote valve access hole in making connections to reduce operator dosages, especially with three cylinders grouped together. The line from each cylinder runs to a separate nozzle on the side of the containment vessel; the remotely operated feed valves (controlled either automatically or manually from a shielded corridor) are located immediately adjacent to the vessel. Upon connecting the cylinders, the manifold is leak-tested with nitrogen prior to opening the cylinder valve. Once leak-tested, the feed valves are closed, the cylinder valves opened, and the containment vessel sealed again. Another remote valve is located in the off-gas outlet nozzle of each containment vessel. Hand valves are provided on the coolant loop. During an injection, the feed valves are opened one at a time as each cylinder is emptied, then closed again when the cylinder pressure drops to atmospheric. A beta detector is located in each containment vessel to detect leaks, and pressure indicators are provided for each cylinder.

4.2.4 Compressor system

The compressor system takes the krypton-xenon gas mixture from cylinder conditions to 350 bar (5000 psi) and ambient temperatures. This includes the compressors, the inter- and after-coolers, control systems,

and the nitrogen supply needed for purge and startup operations. Alternative approaches to the compression system have been discussed in Sect. 4.1.2.1.

4.2.4.1 Krypton compressor train. The selected compressor system uses three diaphragm compressor stages that have remote heads and triple diaphragms to ensure containment of radioactive gas. These compressors are readily available from at least two vendors. A sketch of a standard model having a single head and single diaphragm is shown in Fig. 4.14. The major features are the diaphragm in its concave cavity, the motor-driven hydraulic piston, and the oil make-up and relief piping. The piston applies a cyclic hydraulic force on the diaphragm, alternately forcing it up into the cavity and allowing it to relax. The space above the diaphragm is the gas cavity; gas is drawn in and expelled through valves at the top of the diaphragm head. An oil pump at the end of the crankshaft injects a metered amount of oil into the orifice cavity during each stroke. Some of this oil passes down the cylinder walls for lubrication, and the excess is discharged through a relief valve. The orifice plate distributes the hydraulic pressure evenly over the diaphragm surface.

Two options have been considered for use with a radioactive gas. A second hydraulic circuit can connect the diaphragm attached to the crankcase to one in a remote head. This allows the pump and motor body to be located in an uncontaminated area outside the cell; only the remote head would be in contact with the radioactive gas inside the cell. The other option uses a triple diaphragm, which has leak

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Fig. 4.14. High pressure diaphragm compressor.

detectors between diaphragms, for the head in contact with the radioactive gas. This allows a diaphragm failure to be detected and the compressor to be shut down before the other two diaphragms fail and the gas escapes into the hydraulic circuit. This study is based on implementing both options. The triple diaphragm-leak detection option certainly will be required. In many applications, however, the remote head option is not used and the entire compressor assembly is located in the contaminated area. Although more maintenance activities would take place in the cell as a consequence, the most frequent maintenance activity, that of replacing fatigued diaphragms, takes place in the cell in either case. Deleting the remote head option would lower compressor cost estimates from the range of \$150,000 to \$100,000.

The compressor train used in this reference design is manufactured by Autoclave Burton-Corblin. Similar units are available from other vendors. The first stage, a model A4 compressor, takes the krypton-xenon mixture from atmospheric pressure to 3.45 bar (50 psia). An A4C.250 stage then raises the pressure to 32.0 bar (465 psia), and an A4C.400 stage brings the final pressure up to 362 bar (5250 psia), which is above the 350 bar (5000 psia) pressure called for in Sect. 3.2.3 of the design criteria. An accumulator follows the last stage to take up any pressure surges. Heat exchangers are provided after each stage to remove the heat of compression. These are constructed from a coil of high-pressure tubing encased in a water jacket to maintain a 700-bar (10,000-psi) pressure rating and to minimize the potential for gas leakage. All connections will be welded, except the diaphragm heads and

valves, which must be bolted to facilitate maintenance. Design, fabrication, and testing will be to ASME Section III, Class 3 requirements. Typical diaphragm service life is about 300 h of operation; replacements will be made well before this accumulated service time has expired to guard against diaphragm failure resulting from fatigue. Valve lifetime is typically an order of magnitude greater.

4.2.4.2 Compressor control. The compressor models have been selected to compress the desired flowrate of 181 kg/h (22.1 SCFM) at the design operating speed of 400 RPM. The minimum feed pressure is the pressure of an "empty" cylinder, (i.e., atmospheric). With an atmospheric suction pressure, the train selected has an outlet pressure of 362 bar (5250 psia). If the motor speed and the suction and discharge pressures can be held constant, the flowrate will be held near the design rate. Precise flowrate control is not essential; variations of up to 20% are acceptable. Pressure regulators are being used at both ends of the compressor train to (1) maintain the compressor suction at atmospheric pressure despite cylinder manifold pressure variations between full and empty cylinder conditions; and (2) filter out variations in the discharge line pressure caused by variations in the hydrofracture well pressure. A back-flow preventer will also be installed to further ensure that grout will not back up into the compressor train.

4.2.4.3 Compressor utility requirements. If each compressor stage is driven separately, motors of 10, 10, and 15 HP are required for the first, second, and third stages, respectively. A power supply and motor controls for operation at the constant speed of 400 RPM are needed.

Emergency electrical power is not required for the compressor train.

Nitrogen is required for several purposes. Following a period of idleness, the compressors must be "warmed up" at low pressure to allow the hydraulic oil to circulate through all the lubricating, pressurizing, and makeup passages prior to operating at high pressures. This requires circulating an inert gas through the compressor train at essentially atmospheric pressure for about 15 min. The "warmup" operation is especially important with the remote head option. In addition, the compressor train must be purged with inert gas at the end of an injection to remove krypton activity from the system. Likewise, when maintenance activities are required, an additional purge will be used to ensure that all possible ^{85}Kr will be cleared out prior to personnel entry. The use of nitrogen rather than air as the inert circulating and purge gas guarantees that the gas will be moisture-free, preventing condensation on diaphragms and valves. Nitrogen also provides a carrier gas in purge operations that does not compete with krypton for adsorption on the charcoal beds as do some of the components of air. Nitrogen requirements will not be great in terms of volume; a few standard cylinders should suffice.

4.2.5 Gas-grout mixing

The gas-grout mixing subsystem blends the gas and grout streams at hydrofracture pressures, such that the krypton-xenon gas mixture becomes entrained in the flowing grout stream in proportions that meet the solubility criteria of Sect. 3.2.3. This subsystem does not provide for the

pressurization of either gas or grout nor cover modifications to the wellhead proper. The mixing point will be located within the well cell, as near the wellhead as practical, to maintain separation of the gas and grout streams to the greatest extent possible and minimize the possibility of compounding problems characteristic of having both streams at the same point.

Because the actual mixing characteristics of the gas and grout are highly dependent on the physical behavior of the individual and combined streams, the detailed design of the mixing equipment must await engineering studies of gas-grout behavior. This section describes a concept that has been applied in oil fields to mix nitrogen gas with cement prior to deep well injection to float the resulting foam on a water surface. In particular, experience has shown that the method results in a very controllable and consistent foam. Although the gas to grout ratio is much lower in the hydrofracture case, no obvious reason appears why the same approach would not be equally successful for krypton entrainment. The combination of a gas-injection ring and an in-line static mixer is used, as sketched in Fig. 4.15.

4.2.5.1 Annular injection ring. As shown in Fig. 4.15, the gas is injected into the grout stream by a ring of high-pressure gas nozzles protruding into the grout stream and oriented to generate a spiraling flow pattern as the mixture flows down the grout line. As noted previously, this approach is based on similar applications in oil field technology. The substantially smaller gas fraction of krypton-85 compared to the nitrogen in the foaming process may lead to abandoning the

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Fig. 4.15. Krypton injector ring.

spiral gas pattern entirely. Instead, the gas injection points could be distributed within the flow cross section and the static mixer could be used to provide mixing action. Other design concerns include ensuring the integrity of the equipment at the 700 bar (10,000 psia) pressure rating and length of service life under the operating conditions. Both the ASME Section III criteria for the gas subsystems and the API standards used for grout piping should be met to the greatest extent possible. Erosion of nozzles under a high-pressure, flowing grout environment must be considered. Plugging of nozzle orifices with grout as a result of incomplete clearing following an injection must be avoided. Operating procedures including rinsing the grout line with water and blowing out the nozzles with nitrogen must be strictly adhered to. Provisions should be provided for maintenance, especially nozzle cleaning or replacement.

4.2.5.2 Static mixer. The static mixer will be an in-line element of relatively standard design. In addition to mixing characteristics, integrity under high pressures and erosion by the grout stream are the major concerns. If a spiral motion is initiated by the gas injectors, the leading mixer vanes will be oriented to apply motion in the opposite direction. The mixer element must be replaceable as eventual vane erosion is likely because of the abrasive nature of the grout stream. The detection of erosion may prove difficult; occasional dismantling and inspection of the entire injector-static mixer assembly may be desirable. Crevices associated with both injector nozzles and mixer vanes may make difficult the decontamination of the assembly to

radiation levels suitable for contact maintenance. The final system design should avoid unnecessary crevices as much as possible because remote maintenance would not be practical. Standard mixer elements such as the Kenics KMOD-10 series or the Ross LPD Motionless Mixers, inserted directly into the grout line or into a section of different diameter, is assumed to be adequate.

4.2.6 Wellhead modifications

This subsystem covers modifications to the equipment connecting the gas-grout line in the well cell to the tubing string hung down the hydrofracture well and connecting the water line from the standby injection pump to the annulus of the well. The existing wellhead assembly is assumed to be adequate for service in making krypton injections. The focus of this section is on the addition of a blowout preventer beneath the existing wellhead to limit the amount of ^{85}Kr that could be released from the well in the unlikely event of a catastrophic wellhead failure. A schematic of the well cell and associated equipment is shown in Fig. 4.16. The injector-static mixer has been covered in the previous section and is not within the scope of "wellhead modifications."

4.2.6.1 Evaluation of available blowout preventers. The use of a blowout preventer as a safety device in hydrofracture operations has been considered since the first liquid waste injections at ORNL. Blowout preventers are designed for operation in oil wells, resulting in a substantially different operating environment than is seen in a hydrofracture well. In an oil well, the fluid flowing through the

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Fig. 4.16. Wellhead schematic.

device at best provides lubrication or at worst does not impede operation of the moving parts associated with the device. In a hydrofracture well, the intermittent operation with a cement grout, followed by long periods of idleness, results in grout accumulating in crevices in spite of rinsing operations. This eventually tends to cement parts together and reduce the probability of effective operation. In addition, the viscosity of the grout might impede closure even if proper operation is initiated. These problems can be accentuated in a safety device that may not be operated for many years.

Blowout preventers generally follow two major design principles:

(1) those that use some type of a check ball in the well flow stream; and (2) those that operate on the basis of a ram-induced seal. The check-ball types are more directly applicable to the tubing side of a well, although a plug can also be inserted to channel casing flow through a passage in which a check ball is present. The check-ball operation can be initiated by variations in the pressure or direction of the fluid in the well itself or can be controlled by a hydraulic fluid operated from the surface. Because the check ball would be located directly in the grout stream and requires a fair amount of freedom to move within the intended pattern, this type of preventer would tend to suffer most from the problems associated with intermittent grout injections. The Cameron Type "U" preventer is an example of a ram-seal device that replaces a short section of casing and rams a packing against the tubing and against the sides of the ram passageway, forming a seal of the casing side flow path. An extension of this concept to

close both casing and tubing sides of the flow uses a ram that, rather than fitting around the tubing, pinches the tubing closed. The Type "U" device itself only closes the casing side but can be tested and returned to its open position. Two units, with flow crossovers, would be needed to close both tubing and annular flow. The "pinch-off" device can close both flows with a single unit but cannot easily be tested because the tubing is destroyed. Considerable operator force is required to displace the grout stream and collapse the tubing. The Cameron Type "U" device is hydraulically operated but only rated up to 1500 psi (100 bar). Compressed gas can be used to provide greater motive force. Advantages, particularly to a high-motive force, "pinch-off" approach is that moving parts on the casing side are not normally in the grout stream, and operation is more forceful than the check-ball models. As a result, the likelihood of successful operation after years of idleness can be expected to be greater. The well would be permanently set in, but because a catastrophic failure of the wellhead would make clearing the well before the grout sets unlikely in any event, this does not appear to be a disadvantage unique to the use of a blowout preventer.

4.2.6.2 Recommendations for krypton injections. In the design of the ORNL New Hydrofracture Facility, the cost and uncertainty of operation associated with the use of a blowout preventer, coupled with the availability of other means of protection, led to the rejection of using such a device. A large pipe was connected to the well cell floor and led down to concrete collection tanks where grout that might be expelled as a result of wellhead failure can be safely collected and allowed to set.

This follows the approach used in the original ORNL hydrofracture facility.

After the ^{85}Kr has been added to the grout, however, the collection of the grout slurry alone is not adequate. When the grout pressure drops, the gas solubility decreases dramatically and the ^{85}Kr would outgas from the grout. The quantity of gas released can be much greater than the 128,000 Ci that is used as the design basis for the off-gas system. The exact amount of gas that could be released is speculative because such an incident has never occurred. The amount of grout that would be expelled and the amount of gas that might diffuse upward can only be assumed. Based on water experiments conducted early in the hydrofracture experimental program,⁵ 25% of the grout might be assumed to be ejected, and the ^{85}Kr released would be assumed to be equal to the amount of gas dissolved in this quantity of grout. An analysis of the consequences of such a release, excluding implementation of mitigating safety systems, is presented in the safety evaluation in Sect. 5 of this report.

During 15 years of hydrofracture operations at ORNL, no incident even remotely approaching a wellhead failure has ever occurred. Enclosing the wellhead in a reinforced concrete cell virtually eliminates some of the most common sources of wellhead failures in the oil industry: collisions with surface vehicles, shifting offshore oil platforms, etc. It may be that a quality assurance program that includes regular non-destructive testing of the integrity of the wellhead assembly can provide the necessary assurance that the well "blowout" will never occur.

Nonetheless, following "ALARA" and "defense in depth" principles, this study presumes the use of a ram-actuated, "pinch-off" type of blowout preventer. If the ultimate application of krypton hydrofracture becomes an element of reprocessing technology in widespread use, it may eventually be economically feasible to develop a blowout preventer designed specifically to address the unique problems and needs related to the hydrofracture process.

4.2.7 Krypton off-gas systems. This subsystem which serves as the primary containment system, deals with the detection, containment, evaluation, and recovery or safe release to the atmosphere of ^{85}Kr that escapes from the process equipment. This subsystem utilizes the structures described in Sect. 4.2.2 and the secondary storage containment vessels described in Sect. 4.2.3 as part of the collection system for escaped ^{85}Kr . It deals with the handling of escaping ^{85}Kr from the source of the leak through reinsertion to the injection system, shipment offsite for reconcentration, or safe venting to the atmosphere, whichever is appropriate for the magnitude and characteristics of the release. Other than minute quantities of ^{85}Kr that may remain trapped in the manifold connections and be released when the cylinders are changed, no krypton releases are expected. The off-gas treatment system is provided to handle gas released as a result of equipment failures and improper operating procedures.

The selection of components for the krypton off-gas system is discussed in Sect. 4.1.2.2. The major components include a containment and ventilation system, a ^{85}Kr monitoring system, an on-line charcoal bed and an

off-line spare, and a compressed storage tank for ^{85}Kr -contaminated exhaust gas that connects back to the injection system and to a manifold for charging cylinders for off-site shipment.

4.2.7.1 Design criteria. Because no significant ^{85}Kr releases are expected to result from normal operation, a set of accident scenarios must be defined on which the design of off-gas equipment can be based. The design basis releases must include the obvious maximum rapid release considered possible; but must also consider other scenarios that could tax the capabilities of the system, such as a slow leak of long duration in which case the ^{85}Kr would be mixed with a large volume of air.

The krypton off-gas system is designed to meet the dose and total release limits of 10 CFR 20 and 40 CFR 190, as discussed in Sect. 3.2.5. The upper limits for whole-body doses set by these standards are 5 rem/year to plant workers and 25 millirem/year to individuals of the public. ALARA goals for this design are to keep occupational whole-body doses to 1 rem/year and the site boundary dose to 3 millirem/year. An annual release limit of 250,000 Ci/year was determined to be a reasonable guideline consistent with the overall fuel-cycle limits of 40 CFR 190, and an ALARA goal of 16,000 Ci/year (0.1% of the annual ^{85}Kr throughout, representing a 99.9% disposal efficiency) was set for the plant design. The 10 CFR 20 limit for air concentration of ^{85}Kr in restricted areas is 1×10^{-7} $\mu\text{Ci/ml}$ (2×10^{-6} $\mu\text{Ci/ml}$ ALARA basis), and the site boundary limit is 3×10^{-7} $\mu\text{Ci/ml}$ (far above expected levels).

These values must be translated into specific operating criteria for the off-gas systems. By limiting the amount of ^{85}Kr stored in any single

vessel or connected to the compression and injection system at any time, the design basis accidental release has been held to 128,000 Ci. If the off-gas system is designed to recover at least 90% of any release, the amount of ^{85}Kr escaping to the atmosphere during the design basis accident would be 12,800 Ci. Because this incident would be a very infrequent occurrence, this value is consistent with the 16,000-Ci annual release goal. The ventilation system will be designed to maintain ^{85}Kr levels in occupied building areas below $2 \times 10^{-6} \mu\text{Ci/ml}$, alarms will sound if that level is exceeded. Some delay between krypton escaping the process equipment and being released to the atmosphere is also required (1) both to allow plant operators to monitor the release and determine whether or not recovery actions are appropriate and (2) to provide time for the startup of active recovery system components such as emergency compressors. Charcoal beds are provided to allow a 15 min. holdup for these purposes.

The design of the charcoal beds is based on holding the design basis release quantity of 128,000 Ci of ^{85}Kr for 15 min. prior to krypton breakthrough for the most severe set of trap operating conditions: a steady release and maximum air flow (greatest dilution) with a warm trap. The ventilation system is designed to isolate the area in which the leak is occurring (after allowing any personnel to escape the area) and to draw a minimum airflow from that area while the leak is in progress. The storage tank is designed so that once the leak has stopped, either because of corrective actions or by exhausting the krypton supply capable of leaking, it will hold enough contaminated air

during a purge operation so that the residual ^{85}Kr levels in that area's atmosphere can be safely vented through the stack without exceeding the aforementioned emission criteria. Provisions will allow discharging the contents of this tank either into the compressor manifold for hydrofracture injection or into empty shipping cylinders for transportation back to the reprocessing plant for reconcentration of ^{85}Kr in that plant's krypton recovery system. The charcoal bed can also be isolated and eventually eluted into the storage tank. A spare bed is provided for continued protection during these operations. No hydrofracture injections of fresh cylinders of ^{85}Kr will be made while significant quantities remain in the emergency recovery systems.

4.2.7.2 Krypton ventilation system. This system compliments the existing hydrofracture facility ventilation system and services only those areas in which significant ^{85}Kr releases are possible. It consists of a 30-m stack through which ventilation from both the standard and krypton systems is routed. Only the ventilation from krypton areas, however, is routed through the krypton off-gas system. As a result, different modes operate during and between injections. Areas in which atmospheres may become contaminated with ^{85}Kr during an injection include the well cell, the compressor cell, the storage area and secondary containment vessels, and the slotting waste tank (which could become contaminated with ^{85}Kr should a well clearing be required in the middle of a krypton injection). Between injections, only the storage area and secondary containment vessels contain significant quantities of ^{85}Kr ; between injections, airflow from the other areas bypasses the charcoal

beds. A larger airflow in the storage area results during cylinder loading operations, when doors are being opened.

During periods when no occupancy is allowed, only one air change per hour, or enough airflow to maintain a negative pressure of 3.4 KPa (1.0 in. water gauge) with respect to outside, is provided. When personnel are present, this is increased to six air changes per hour. The resultant airflows are tabulated in Table 4.3. The exhaust from each area is HEPA filtered, monitored for beta radiation, and valved to allow routing to the charcoal bed or to the storage tank. Areas not routed through the charcoal bed between injections also have connections to a bypass duct routed directly to the stack.

4.2.7.3 Off-gas equipment items.

Charcoal beds. The primary equipment items leading to the low-ventilation flowrates discussed previously are the two sets of charcoal beds. These operate by two modes. Between injections, when the facility is not in use other than to store the shipping cylinders, the beds operate at ambient temperature and are sized to allow a 15-min response time. During the actual injection, or while the cylinders are being attached to or disconnected from the compressor intake manifold, chilled water is circulated through internal tubes in the charcoal vessels, and through an off-gas cooler-condenser preceding the beds, to lower the bed operating temperature to 280 K (44°F). In addition, the ventilation switching station is continuously manned and the storage tank compressor idled to reduce the response time for switching away from charcoal bed recovery to 5 min. These two factors increase the allowable flowrate

Table 4.3. Krypton ventilation flowrates, m³/h (SCFM)

	Idle facility	Connecting cylinders	Injection
Storage area ^a	85 (50)	510 (300)	260 (150)
Compressor cell	<u>b</u>	<u>b</u>	100 (60)
Well cell	<u>b</u>	<u>b</u>	100 (60)
Slotting waste tank	<u>b</u>	<u>b</u>	50 (30)
Total	85 (50)	510 (300)	510 (300)

^a Includes secondary containment vessels.

b Bypassed.

through the beds by a factor of six and provide for the additional ventilation necessary for safe personnel entry to the cylinder storage area and for ventilation of additional areas during the injection.

The charcoal bed design is based on the $85 \text{ m}^3/\text{h}$ (50 CFM) operation between injections as follows: The lowest krypton loading rates are obtained with the least concentration of krypton in the gas stream. For a 15 min. breakthrough, the worst case would be the design basis quantity of 128,000 Ci (2 cylinders) mixed evenly in the $56.8 \text{ m}^3/\text{h}$ flow throughout the entire period. Calculations using equations of Long²² and McHenry,²³ using factors for competing adsorption of xenon and nitrogen taken from the latter, have been used to estimate the quantity of charcoal required. On the order of 1000 kg of 6 to 14 mesh coconut charcoal will be required. Each set of beds would require three vessels roughly of the dimensions indicated in Fig. 4.17.

Internal tubes that have longitudinal fins on the outside circulate coolant to remove the heat of adsorption and radioactive decay heat and to chill the beds during high flowrate periods. A detailed heat-transfer analysis, possibly including experimental data, will be required later. A cooler-condenser is needed for the incoming gas stream to prevent condensation on the beds resulting in loss of performance. After a set of charcoal beds is loaded with a significant amount of ^{85}Kr , it is isolated and the krypton is eluted to the emergency storage tank (described below). A countercurrent flow of an inert sweep gas (nitrogen or dry air) is used to carry the krypton from the beds to the tank. Hot water or steam also could be circulated

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Fig. 4.17. Sketch of charcoal bed.

through the tubes to raise the bed temperature to speed elution of the contents. Two sets of beds, located in the compressor cell, allow continued protection through loading and isolation of one set.

Emergency storage tank. Because any ^{85}Kr adsorbed onto the charcoal beds will eventually be eluted, some more permanent form of storage is required. This could be the bed itself, if it is permanently isolated after operation (at least, until the ^{85}Kr is to be disposed of), but if the bed is to be made available for service, another storage tank will be needed for elution. This tank also directly receives contaminated room air that has been isolated by the ventilation system. As such, the criterion for this tank is to remove 90% of the krypton present in any room in the krypton system (although if the krypton concentration is very low, less removal could be accepted). A purging operation that would avoid designing structures to withstand a vacuum would require a tank having a capacity of 2.3 room volumes. The krypton storage area is the largest room, having a 270 m^3 (9500 ft^3) volume; compressed to 36 bar (500 psig), this volume would require a tank 2 m in diameter by 6 m long (6.3 ft x 20 ft). This tank could be located in an underground vault east of the storage area.

Off-gas compressor. The off-gas compressor must be able to bring the pressure of contaminated room air from atmospheric to 36 bar (500 psia). Removing 2.3 room volumes of air from the krypton storage area in an hour would require a $620 \text{ m}^3/\text{h}$ (365 SCFM) compressor capacity. On the other side of the operating spectrum, at 36 bar (500 psia), the cylinders hold 1.2 standard meters (43.8 SCF) each. A

compressor sized for a maximum flowrate of about $260 \text{ m}^3/\text{h}$ (150 SCFM), the flowrate in the storage area during an injection, will be used to allow removal of the required air volume from the storage area in just under 2.5 h and still will be of a capacity reasonable for charging of the cylinders. Several empty cylinders could be charged with contaminated exhaust air at the same time. Piping and valves will be arranged such that the storage tank can be filled from the ventilation ducts, charcoal beds, or the nitrogen recycle tank in the compressor system. Likewise, cylinders can be charged from the storage tank, charcoal beds, or ventilation duct (particularly for the secondary containment vessels).

The most important characteristic required of the off-gas compressor is rapid startup. Precise flow control is not needed, although the ability to handle a large variation in flowrate is important, as indicated by the preceding paragraph. Because diaphragm compressors require a 15-min. startup procedure to circulate the hydraulic fluid through all the orifices and passages, they are better suited to controlled flowrates at a given set of conditions than as a part of an emergency system. A two stage teflon ring piston compressor may offer the best overall capability for this service.

Filters and stack. Each of the major ventilation streams in the ORNL New Hydrofracture Facility design, including the krypton ventilation system, has a separate set of filters and blowers. The well cell has dual HEPA filters at the cell exit point. Although the only radioactive material present in the new building areas is a noble gas,

HEPA filtration is still provided to protect the charcoal beds from dust accumulation. Roughing and HEPA filters are also provided at the bed exhaust to prevent charcoal fines loaded with adsorbed ^{85}Kr from being discharged to the atmosphere. Blowers will be located after the charcoal beds. All ventilation streams from the facility are mixed together at the stack.

For the purpose of the atmospheric dispersion calculations carried out as part of this study, a 30-m (100 ft) stack was arbitrarily selected. The stack would be designed to discharge about $5000 \text{ m}^3/\text{h}$ (3000 SCFM) at a velocity of 10 m/sec (33 ft/s). Because the actual stack design is highly dependent on the site-specific geographic and meteorological conditions, further details on the stack design are not addressed at this time.

4.3 System Uncertainties

This section briefly summarizes the uncertainties associated with the various subsystems described in the previous section. In addition, those aspects important to the feasibility and health or environmental safety of the process that are outside the scope of this study, but obviously need study, are listed. The type of action required to resolve specific uncertainties is noted for each case.

4.3.1 Gas-grout mixture behavior

Foremost among the uncertainties identified is the physical behavior of mixtures of noble gas and hydrofracture grout, before, during, and after the grout has set up. Determining the actual behavior of the mixtures

can only be done in the laboratory, an undertaking outside the scope of these engineering studies. This issue is broken down into several aspects below.

4.3.1.1 Krypton diffusion in a grout matrix. The primary parameter in evaluating the adequacy of the ultimate waste form produced by the krypton hydrofracture process is the diffusion rate of the ^{85}Kr within and out of the grout matrix after the injection is completed and the grout sheet has set up. This not only evaluates the benefits of the hydrofracture process as opposed to other direct underground injection methods,¹ but provides input to the environmental assessment. Diffusion rates were specifically excluded from this study; a separate experimental program will be required to obtain this data.

4.3.1.2 Behavior of gas and grout slurry mixtures. The gas-grout proportioning for this study was based on adding the noble gas to the grout stream such that the mixture holds one-half the amount of gas that is theoretically soluble in the liquid waste solution. Two uncertainties may affect this proportioning: (1) The solubility of the noble gas was calculated for the liquid waste solution alone, as described in Appendix B, and does not account for the addition of grout solids. The solubility in the grout is likely to be less than in the liquid waste solution alone. Adding the gas at only one-half the rate soluble in the liquid roughly accounts for the effect of the solids. (2) The kinetics of adding gas to the flowing grout may result in the gas forming small bubbles entrained in the grout stream rather than entirely dissolving into the grout. As long as a predictable product in which the noble gas

is firmly bound in the grout sheet is the result, either entrainment or actual dissolution is acceptable. Resolving the above uncertainties and establishing an accurate limit on the ratio of gas to grout will require experimental data, possibly gathered through full-scale testing.

4.3.1.3 Mixing equipment design. Once the behavior of gas-grout slurry mixtures has been characterized, the details important to the design of gas-grout mixing equipment can be determined. It may be possible to use the same experimental apparatus to evaluate changes in injector nozzle size, orientation, or configuration. Alternatively, the experiments on mixture characteristics may define the parameters sufficiently that critical design factors can be identified outright. Experimental proof of the operation of the mixing equipment will undoubtedly eventually be required.

4.3.2 Siting

Whenever specific data was required, this study has used site conditions at the ORNL New Hydrofracture Facility. In practice, the krypton hydrofracture facility probably would be located near the reprocessing plant it serves. The most important site criterion, the suitability of underground rock formations for the fracturing process, is discussed further in Sect. 6.1. Specific site conditions will influence not only injection and monitoring well depths and layouts, but building layout, stack height, etc. Likewise, various parameters of the safety evaluation, including the distance to the site boundary, meteorological conditions, and area demography, will depend on the actual site chosen.

4.3.3 Blowout preventer

The uncertainties of the operation of commercially available blowout preventers, typically designed for service in oil wells, in the intermittent grout-injection process has been discussed in detail in Sect. 4.2.6. Some modifications to standard designs, particularly those that would guard against mechanisms being cemented together by residual grout from previous injections, may be desirable and a study by an engineering firm specialized in oil and injection well technology is recommended. Note that the safety evaluation indicates a site boundary dose of 150 millirem at 3 km (1.86 miles) for the case of a blowout in a totally unprotected facility. When (1) the mitigating effects of the well cell and ventilation system and (2) the extremely low probability of failure of a thoroughly inspected wellhead assembly protected by several feet of reinforced concrete are factored into the analysis, the use of an expensive and potentially troublesome preventer may not be justified.

4.3.4 Vertical fractures

This issue has been given general concern since the earliest liquid waste injections at ORNL, but a significant tendency towards vertical movement of grout sheets has not occurred in 15 years of injection experience. As a result, little can be said to further characterize the probability of vertical fractures occurring except that no mechanisms have been observed at the ORNL sites. As a result, the parameters used to analyze the effects of such an occurrence are highly speculative. This study assumes that 75% of the grout will remain to fill the well

and cavities in the fracture area and only 25% of the grout will be capable of reaching the surface before setting. Gas diffusion, in the few hours before the grout sets, is not assumed to be great; one-fourth of the total injection inventory, or 400,000 Ci of ^{85}Kr is the most that could be released. These assumptions are roughly based on an experiment carried out early in the study of the hydrofracture process in which water was used to initiate a fracture and the well was later reopened to determine how much water would flow back up.⁵ A site boundary whole-body dose of 1.2 rem at 1 km would result from this incident. In view of an apparently very low probability of occurrence, further study of this issue does not appear to be warranted other than to ensure that special site conditions at a proposed location do not enhance the probability of vertical fractures.

4.3.5 Well life

Monthly rather than annual injections would reduce the service life of a hydrofracture injection well. This study does not attempt to quantify the impact of this service-life reduction. Because the smaller, more frequent injections would tend to result in a waste deposition pattern much closer to the well itself, it may be possible to offset the service-life reduction by designing the facility such that several injection wells are used during the overall facility lifetime.

4.4 Summary of Design Standards

This section discusses design standards for the new structures and equipment required for krypton injections that have not previously been

incorporated into the design of the ORNL New Hydrofracture Facility. Generally, these standards are an extension of those used in the design of that facility and the standards for the ^{85}Kr operation called for in Sect. 3.2.6 of the criteria for this project.

4.4.1 Process vessels and piping

Vessels and piping in the ORNL New Hydrofracture Facility have been designed and fabricated in accordance with two major sets of standards: the high pressure injection system was designed to American Petroleum Institute (API) standards for high-pressure oil well equipment and the remainder of the process vessels and piping were designed to Sect. VIII of the ASME Boiler and Pressure Vessel Code. In addition, as stated in Sect. 3.2.6.5, those high-pressure noble gas systems having the potential of initiating a significant release of ^{85}Kr upon failure, and which are the primary containment barrier for ^{85}Kr , will be designed to meet Sect. III, Class 3 specifications of the ASME Code. These categories are summarized in Tables 4.4 through 4.6. Other miscellaneous standard systems, such as potable water supply or fire sprinkler systems, are designed according to the standards in common industrial usage.

The gas-compression system will be designed to the ASME Section III requirements of Table 4.4. The high maximum temperature is seen at the outlets of the second and third compressor stages before the heat of compression is removed. Lower design temperatures can be used at other points. Likewise, the compressor intake manifold is never at a pressure above the 36-bar (500 psig) full cylinder pressure and does not require the 700-bar (10,000 psig) rating.

Table 4.4. High pressure krypton standards

Codes and standards

ASME Pressure Vessel Code, Sect. III, Subsection NE

ASME Pressure Vessel Code, Sect. II and IX

ASTM Specifications

Design conditions

Maximum design temperature: 1000 K (1340°F)

Minimum design temperature: 274 K (33°)

Maximum design pressure: 700 bar (10,000 psig)

Materials of construction

Pipe: Schedule 80, seamless grade TP 304 stainless steel, to ASTM A-312

Connections: Butt welded except where disconnects required

Disconnects use 10,000-lb (4500-kg) welding neck flanges,
304 stainless steel, to ASTM 182 (lower pressures when
called for in design documents)

Plate: Type 304 stainless steel to ASTM A-240

Castings: Type 304 stainless steel to ASTM A-351

Fabrication

Welder qualification and procedures to ASME Section IX. All welds to be
fully radiographed according to NE-5320 of ASME Sect. III,
Subsection NE.

Table 4.5. High pressure injection standards

Codes and standards

API Specification for Wellhead Equipment 6A
API Specification for Pipeline Valves 6D
API Specification for Threading, Gaging, and Thread Inspection
5B
API Specification for Casing, Tubing, and Drill Pipe 5A
American Iron and Steel Institute
API Specification 1104
ASME Boiler Code, Sects. VIII and IX

Design conditions

Maximum design temperature: 325 K (125°F)
Minimum design temperature: 274 K (33°F)
Design pressure: 700 bar (10,000 psig)

Materials of construction

Piping and fittings: AISI 4140 steel having open-flange flow fittings with a 2-1/16 in. bore

Flanges: API type 6 BX integral flanges with API type BX 152 pressure energized ring-joint gaskets

Wellhead fittings: AISI 4140 steel to API Specification 6A

Fabrication

Welder qualification and procedures to ASME Section IX or API Specification 1104. All 4140 steel to have preheat and postheat treatments. All welds to be fully radiographed according to UW-51 of ASME Sect. VIII, Division 1. Hydrostatic pressure test to 700 bar (10,000 psig) after fabrication

Table 4.6. Process equipment standards

Codes and standards

ASME Pressure Vessel Code, Sects. II, VIII, and IX

ASTM Specifications

ANSI B 31.1, Power Piping Code

Design conditions

Maximum design temperature: 325 K (125°F)

Minimum design temperature: 274 K (33°F)

Maximum design pressure: 10 bar (150 psig)

Materials of construction

Pipe: Schedule 40, seamless grade TP 304 stainless steel to ASTM A-312

Connections: Butt welded except where disconnects required

Disconnects use 150-lb (68-kg) slip-on flanges, 304 stainless steel, to ASTM A-182.

Plate: Type 304 stainless steel to ASTM A-240

Castings: Type 304 stainless steel to ASTM A-351

Fabrication

Welder qualification and procedures to ASME Sect. IX. All welds to be fully radiographed according to UW-51 of ASME Sect. VIII, Division 1.

The gas-grout mixing system deals with both the high-pressure noble gas stream (Table 4.4) and the high-pressure grout stream (API standards in Table 4.5). The most applicable parts of both these standards should apply; good judgment should be used when conflicts between the two standards arise.

The secondary containment vessels, charcoal vessels, and other off-gas equipment are not primary containment barriers because they would not contain significant amounts of ^{85}Kr unless another system failed. For this reason, they will be designed according to the ASME Sect. VIII requirements of Table 4.6.

4.4.2 Structures

Concrete cell structures are designed according to stress and deformation criteria, defined by ACI-349-76 for loadings involving the safe shutdown earthquake. Critical steel structures are designed to criteria defined by the AISC "Manual of Steel Construction" for loads involving earthquakes. All other structures that are not nuclear safety related are designed to the requirements of the Uniform Building Code for Seismic Zone 2. Loadings are given in Sect. 3.2.6, General Design Criteria.

4.4.3 Electrical system

The electrical systems for the krypton injection structures and equipment will follow the same criteria as given in the Conceptual Design Report on the ORNL New Hydrofracture Facility.⁶ Among the standards to be followed are:

National Electric Code;
National Electrical Manufacturers' Association;
American National Standards Institute;
Institute of Electrical and Electronics Engineers;
Underwriters' Laboratories, Inc.;
ERDA General Design Criteria, Manual Appendix 6301;
National Fire Protection Association; and
IPCEA Standards.

4.4.4 Other systems

The HVAC, instrumentation, radiation protection, and general utilities systems essentially will be extensions of systems included in the reference ORNL New Hydrofracture Facility design. As such, design criteria for these systems will be as given in the Conceptual Design Report for that facility.⁶

4.5 Quality Assurance and Environmental Impact

4.5.1 Quality assurance

Each of the major subsystems of the krypton injection portion of the hydrofracture is briefly discussed below. In general, this design favors proven, "off-the-shelf" equipment over new concepts to provide a basis of experience of system performance. A formal Project Quality Assurance Assessment would begin in the conceptual design stage of the krypton hydrofracture project, as called for in UCC-ND Engineering Quality Assurance Procedure EQA-7.

Existing hydrofracture systems. Those systems that are already part of the reference ORNL New Hydrofracture Facility design are covered by the assessment and plan prepared for that facility and will not be repeated here.

New structures. Structures housing critical items will be designed to withstand all postulated accidents and natural phenomena. Proven construction techniques will be used, and no unusual problems are anticipated.

Krypton receiving and storage. The shipping and storage cylinders used in this design have been proven in service between ICPP and ORNL, and any further assessment is not within the scope of this project. The cylinder-handling equipment and secondary containment vessels are not of any unusual construction and should pose no particular quality problems. A design review will verify the adequacy of the equipment design and operating procedures during later project phases.

Compressor system. The diaphragm compressors selected in this study have been proven in industrial applications, including service with radioactive gases such as tritium and various nuclear facility off-gas streams. Extra provisions for isolation of nuclear materials and detection of diaphragm failures prior to breach of the primary containment barrier (the compression chamber itself) are incorporated into the selection. A high degree of nondestructive examination is called for by specifying ASME Sect. III Code requirements.

Gas-grout mixing. The approach to gas-grout mixing proposed in this study uses a version of equipment that has been used successfully in oil field technology for similar, but not identical, applications. It has been assumed that no quality problems would result in using the injector-static mixer device to mix noble gases into the hydrofracture grout. Design reviews and laboratory data are required to verify this assumption. A rigorous inspection program will be implemented to guard against mechanical failure.

Wellhead modifications. The operating environment encountered by the blowout preventer in hydrofracture service is drastically different from the environment encountered in oil wells, for which the standard devices are designed. Thus, it is recommended that an engineering firm with experience in the design and application of such devices undertake a study to identify desirable modifications and generally assess the performance capability of a blowout preventer operating on a grout stream. Testing of a proposed model under hydrofracture conditions would be useful if not practical. Inspection and field testing procedures will be developed at a later date.

Krypton off-gas system. Although the individual components of the off-gas system are simple, standard industrial items, their collective operation becomes complex. A careful design review, including a review of the potential release scenarios the system must respond to, will be necessary to assure the adequacy of the off-gas system. Operator training will eventually be important in later phases of the project.

4.5.2 Environmental impact

This subsection discusses only the systems added to existing hydrofracture designs necessary to inject ^{85}Kr and does not address the potential environmental impact of grout mixing, injection, and clean-up operations. These have been addressed in the ORNL New Hydrofracture Facility EIS.²⁴ As for the krypton injection system itself, the only environmental hazard results from ^{85}Kr . Chemically, the noble gases are inert and, if released, disperse readily into the atmosphere, quickly reaching insignificant concentrations. Decontamination involves purging with air or other inert gases; no potentially hazardous decontamination fluids or solid wastes result. ^{85}Kr is eluted from the charcoal beds after these have trapped a released quantity of gas; for this reason spent charcoal does not constitute a radioactive hazard.

In the event of a ^{85}Kr release as a result of equipment failures, the off-gas system collects the krypton gas and recovers significant quantities of the ^{85}Kr isotope. A stack is provided to enhance dispersion of insignificant quantities of ^{85}Kr . As an inert gas, ^{85}Kr has no mechanism for concentration into food cycles, etc., and only becomes part of the existing atmospheric inventory of the isotope. Once in the atmosphere, the only significant removal mode is by the 10.7 year half-life radioactive decay.

The environmental impact of the ^{85}Kr that has been properly injected into the grout sheet cannot fully be assessed until the diffusion rates of krypton out of a grout matrix have been determined in the laboratory. Unlike the surface release, dispersion is inhibited by the geologic

formation. If a significant diffusion rate is found, a possible small but continuous level of ^{85}Kr at the surface above the grout sheet could result. After about 100 years, radioactive decay would essentially eliminate any environmental hazard.

Injections of radioactive material do cause a temperature rise in the immediate vicinity of the grout sheets, as a result of radioactive decay heat. Calculations have been made²⁵ to estimate the maximum temperature rise resulting from ^{85}Kr injections based on a conservative set of assumptions, as described below. For the assumed conditions, the maximum temperature rise will be about 64 K (115°F) after about eleven years. This compares with a maximum rise of about 39 K (70°F) after forty years for a similar calculation for the ORNL New Hydrofracture Facility EIS.²⁴

For this calculation, a total of 100 injections is assumed, each of 60 M³ (15,000 gal). All injections are assumed to be made simultaneously and the grout sheets are assumed to be symmetrical and centered on the injection well. The grout specific activity is assumed to be 10 Ci/gal of ^{137}Cs and 107 Ci/gal of ^{85}Kr . These assumptions generally represent a "worst case" set of conditions.

The calculated temperature rise is the sum of the contributions from the two isotopes that were considered. The rise that is attributable to the ^{85}Kr peaks at about 45 K (80°F) after ten years and decreases thereafter. The temperature rise that is attributable to the ^{137}Cs peaks at about 25 K (45°F) after forty years and decreases slowly thereafter.

The sum of the two contributions is a rise of about 64 K (115°F) after about eleven years; this rise will decrease thereafter, first rapidly as the ^{85}Kr decays, then more slowly at the ^{137}Cs decays.

The calculated maximum rise is higher than that calculated for the ORNL New Hydrofracture Facility EIS (64 K vs 39 K or 115°F vs 70°F),²⁴ but almost certainly not enough higher to be a matter of great concern. The results obtained from the calculation are strongly dependent on the assumptions made; if and when disposal of waste by this means is seriously contemplated, the assumptions should be modified to fit the probable conditions and the values should be recalculated.

4.6 Cost

This study focuses on an analysis of the engineering feasibility and safety of the krypton hydrofracture process rather than actual design work; for this reason, no formal cost estimate was prepared. Several uncertainties and the general approach of systems added to the ORNL New Hydrofracture Facility design would limit the applicability of a detailed estimate even if it were attempted.

A price of \$150,000 has been obtained for the compressor train itself, including motors, coolers, and instrumentation. In surveying the total extent of cells and other structures, off-gas systems, cylinder storage and handling equipment, and monitoring systems required, the compressor train itself appears to be a relatively small fraction of the total cost of the krypton injection system. Ultimately, the addition of the krypton system could double the cost of a facility designed for liquid waste

injections alone. For the ORNL New Hydrofracture Facility, this cost was \$5.4 million (May 1978), including engineering and contingencies.²¹ An additional cost item is the land acquisition required to establish the exclusion zone around the facility that would allow dispersion of any ⁸⁵Kr cloud released before the public becomes exposed. If the 2.9-km (1.8-mile) radius on which the site boundary calculations of Sect. 5 and Appendix B were based is used, the land cost at \$500/acre would add \$3.5 million to the project. This would bring the total cost for a facility to dispose of both ⁸⁵Kr and low-level liquid wastes into the range of \$10 to 15 million.

The krypton hydrofracture process would dispose of noble fission gases at the same order of magnitude of cost as the disposal of low-level aqueous wastes by hydrofracture for equal volumes of waste (unpressurized). This cost would then be compared to those of the alternative approaches to krypton disposal outlined in Sect. 2 of this report.

5. SAFETY EVALUATION

5.1 Summary Assessment of the Krypton Hydrofracture Facility

The preliminary safety evaluation is restricted to the krypton hydrofracture process and associated equipment, to the extent that it has been defined. For the purpose of this evaluation, a reference hydrofracture facility has been assumed to assess interface and site-specific effects. The site-specific impacts are included as a point of reference only. Operating philosophy and decisions affect the safety of the krypton hydrofracture operation. This section identifies potential accidents that are assessed further in Appendix A.

5.1.1 The reference hydrofracture facility

The reference hydrofracture facility for the purpose of safety assessment for this report is the New ORNL Hydrofracture Facility. Only the interfaces between the reference hydrofracture facility and the krypton hydrofracture operation are taken into account. As a basis of comparison, the site characteristics of the New ORNL Hydrofracture Facility are used in this report.

The operation of the reference hydrofracture facility using low-level liquid waste will result in the release of small quantities of radionuclides in the facility off-gas and the disposal to the local burial ground of small amounts of radioactivity as a contaminant of miscellaneous solid waste. Essentially no release of radioactivity to the local streams is expected to result from facility operation. The operation of the shale-fracturing facility is expected to result in the

discharge of 2×10^{-4} Ci/year of beta-gamma emitting radionuclides to the atmosphere and the disposal of less than 1 Ci/year of radionuclides with the solid waste. The collective radiation exposures to the operators of the shale fracturing process is estimated to be 3 man-rem.⁷

These hazards are associated with the reference hydrofracture facility and could be eliminated for the krypton hydrofracture operation by using grout mixed with fresh water instead of the low-level waste slurry for hydrofracturing. The remainder of this section refers only to the effects of krypton on the hydrofracture operation.

5.1.2 Incremental impact of krypton hydrofracture

The design of the ^{85}Kr injection system will meet all requirements of the Nuclear Regulatory Commission (NRC) consistent with applications as a waste disposal facility for the commercial reprocessing industry. All applicable requirements of Title 10 of the Code of Federal Regulations will be met. Radiation exposure will be within the limits of 10 CFR 20 for both restricted and unrestricted areas. As an "as low as reasonably achievable" goal, a maximum exposure of 1 rem/year to workers will be used as a design basis. Releases to the general environment will also be within Environmental Protection Agency (EPA) limits as defined in 40 CFR 190. An annual release of 50,000 Ci will be taken as the maximum that meets paragraph 190.10(b) of 40 CFR 190. These values are the maximum allowed, and actual releases will be significantly smaller.

Because the krypton-xenon gases that could be released at the facility would be released to enclosed areas that are vented to the atmosphere

by a stack, the maximum exposure to the workers is expected to be less than the 1 rem/year limit.

5.1.3 Safety design criteria recommendations

Based on the safety evaluation of this study, the following safety criteria have been incorporated in the preliminary design concept and are highlighted here:

1. All pipes, fittings, and valves in direct contact with the feed-gas stream should be designed and fabricated in accordance with ASME standards to a design pressure of 700 bar (10,000 psi).
2. An emergency recovery system can be provided to recover any krypton gas accidentally released to the cells. The need for such a system is contingent on several factors, including site boundary distance and the demographic and meteorological conditions for a specific site.
3. Secondary containment vessels should be designed to withstand the pressure that would result from the loss of the entire krypton-xenon inventory within them and to contain such a release until the emergency recovery system could remove it.
4. An exhaust stack should be provided for this operation. The stack design will be site specific, but the following example indicates the improvement in dispersion provided by a stack at the reference hydrofracture facility. Use of a 30-m stack having a 10-m/s stack velocity to disperse any krypton accidentally released would provide

a factor of 2.3 lower public total dose commitment than a ground-level release and would protect operating personnel.

5. Based on site-specific parameters such as demography and wind conditions, the maximum quantity of krypton at risk should be limited. For the reference location, the maximum quantity of krypton placed at risk inside the cells at any time should be limited to 1.6×10^6 Ci.
6. An exclusion area should be established around the reference hydrofracture facility and evacuated during an injection.
7. The krypton off-gas system must be designed to meet the dose and total release limits of 10 CFR 20 and 40 CFR 190, as discussed in Sect. 3.2.5. The upper limits for whole-body doses set by these standards are 5 rem/year to plant workers and 25 millirem/year to any individual of the public. ALARA goals should be set to keep occupational whole-body doses to 1 rem/year and the site boundary dose to 3 millirem/year. An annual release limit of 250,000 Ci/year was determined to be a reasonable guideline consistent with the overall fuel cycle limits of 40 CFR 190, and an ALARA goal of 16,000 Ci/year (0.1% of the annual ^{85}Kr throughput, representing a 99.9% disposal efficiency) should be set for the plant design.

5.2 Accident Analysis

The accident analysis includes scenarios for operator error, radiological incidents (spills and leaks), high winds, tornadoes, floods,

earthquakes, fire, and unintentional shutdown of operations. These are the potential accidents that were identified by the preliminary hazards analysis and identified in Table A-4 as requiring an in-depth analysis. A criticality excursion is omitted because low-level waste does not present a criticality problem and the addition of krypton gas does not involve any additional criticality hazard. Of the accident scenarios, the radiological incident was found to present the greatest potential risk.

5.2.1 Consequence of operator errors

During the operation of the Reference Hydrofracture Facility, operator error could lead to situations that could potentially affect safety. Incorrect valving of the storage bottles could result in more than one bottle being opened to the gas manifold. In itself, this would not cause a problem, but it could allow more krypton to be released if a leak should develop. Improper connection of the cylinders to the compressor intake header could result in a leak of krypton gas within the secondary containment vessel. These connections will be pressure tested with nitrogen before the cylinder valve is opened. A slow leak not discovered in the pressure test would be contained by the secondary vessel until sufficient ^{85}Kr has accumulated for detection and initiation of the appropriate remedial actions. If a significant quantity of krypton were released, the emergency recovery system would be activated. Poor mix proportioning in the low-level waste-grout or in adding the krypton-xenon mixture could lead to either free water being present in the grout or large bubbles of gas in the grout mixture. This

condition could be a problem if it resulted in bleedback gas at the wellhead after an injection. As a preventive measure, procedures will specify that the grout be only 50% saturated with krypton. In actual fact, saturation is much lower than 50%. Operation of the equipment when maintenance work is in progress in the process cells represents the greatest risk attributable to operator error. Administrative controls will be used to prevent accidental occurrences. The most significant consequence of an operator error would be a radiological incident.

5.2.2 Radiological incident

The accidental release of radioactive krypton gas or the spillage of the liquid or solid waste after mixing with the injection grout present potential avenues of contamination. Because an accidental release of krypton gas will quickly disperse, such a release is not expected to have any long-term effects upon the environment. However, it is possible that the short-term effects of such a release could be exposure of workers and other onsite personnel to large radiation dose rates. Two basic modes of exposure are of importance when determining the radiological hazards associated with ^{85}Kr : exposure attributable to direct radiation and exposure from inhalation of the gas. The direct radiation exposure is from gamma rays that penetrate the body and are measured in terms of a total-body dose rate and from beta rays that are stopped by the skin and are measured in terms of a skin dose rate. A negligible portion of the skin dose rate is attributable to the gamma radiation. The exposure attributable to inhalation of the gas is essentially results from the effect of beta rays on the lungs, with some

gamma-ray effect. Because radioactive material in general may interact with the body and may not be exhaled immediately, inhalation exposures are traditionally given in terms of a 50-year lung dose. Although krypton is an inert gas which does not significantly interact with the body, the 50-year dose terminology persists in the literature. The National Council on Radiation Protection and Measurements (NCRP) has proposed some recommended dose limits for occupational exposure. These can be used as a basis for comparison with the exposures associated with postulated accidental krypton releases. The annual dose limit recommendations of the NCRP are: total body dose, 5 rem; skin dose, 15 rem; and lung dose, 15 rem.

The total inventory of ^{85}Kr present at the hydrofracture facility for one injection campaign will be 1.6×10^6 Ci. Thus, the worst case of an accidental release would be to release the entire inventory at ground level in a short time period. The worst consequences of this release would be incurred if it occurred in the summer during an inversion condition. Although this release is highly improbable, an assessment of the maximum individual risk is given as Case 1 in Table 5.1. The individual risks calculated are based on the atmospheric effluent concentrations of ^{85}Kr at various radial locations and segments for 16 downwind sectors. These concentrations have been calculated using a computer code, XOQDOQ, which has been adopted by the NRC for meteorological evaluation of releases from nuclear facilities. Background information for these calculations is noted elsewhere.²⁶⁻²⁹ Reference 30 discusses the significance of ^{85}Kr in the atmosphere. A great portion

Table 5.1. Exposures to individual at various site boundaries from accidental releases

Case 1: 1.6×10^6 Ci (25 cylinders) released at ground level in a SW direction under inversion conditions in summer

Distance to site boundary [km (miles)]	Lung dose (millirems)	Total-body dose (millirems)	Skin dose (rems)
0.8 (0.5)	11.7 rem	7.54 rem	896.0
1 (0.63)	7.7 rem	4.95 rem	588.0
2.4 (1.5)	1.02 rem	0.66 rem	77.7
3 (1.88)	0.613 rem	0.39 rem	46.8

Case 2: 128,000 Ci (2 cylinders) released at ground level in summer in a SW direction under inversion conditions

0.8 (0.5)	939	600	71.6
1 (0.63)	617	390	47.1
2.4 (1.5)	81	60	6.2
3 (1.88)	49	40	3.7

Case 3: 128,000 Ci (2 cylinders) released from a 30-m stack in a SW direction under inversion conditions in summer

0.8 (0.5)	408	260	31.1
1 (0.63)	268	170	20.5
2.4 (1.5)	35	25	2.7
3 (1.88)	21	17	1.6

Case 4: 12,800 Ci release from stack (2 cylinders with 90% recovery) in a SW direction in summer under inversion conditions

0.8 (0.5)	40.8	26	3.1
1 (0.63)	26.8	17	2.1
2.4 (1.5)	3.5	2.5	0.27
3 (1.88)	2.1	1.7	0.16

of the exposure to the public (about 95%), as a result of either ground- or elevated-level release, will occur in the first 64-km (40 miles) around the hydrofracture facility. Based on this, a maximum credible accident for the handling of krypton must be postulated and measures provided to ensure that it will not be exceeded. The minimum inventory of ^{85}Kr that will be placed at risk (i.e., quantity that would be released as a result of a failure) is that contained in two storage cylinders, or 128,000 Ci. The containment provided by the cylinder could be breached during onsite handling of the hydrofracture facility or the contents could be released during operations by a piping failure. If this accident occurred during the summer during an inversion condition, it would represent the maximum probable accident.

Cases 2, 3, and 4 in Table 5.1 give the maximum individual site boundary doses for the release of 128,000 Ci at ground level, through a 30-m stack, and through the stack after recovery of 90% of the ^{85}Kr released, respectively. These values show the site boundary lung, whole-body, and skin dose under summer inversion conditions. On the average, incidents probably would occur under less severe meteorological conditions and the consequences may be as much as one or two orders of magnitude lower. Lung dose estimates and skin dose estimates from the accidental releases are 1.6 times and 120 times the whole-body dose estimate, respectively. The effects of distance to the site boundary is shown in results at various distances.

At a 1 km (0.63 mi) site boundary distance, a 128,000-Ci release at ground level would result in a maximum whole-body dose of 390 millirem

under worst-case meteorological conditions. A 50-m stack reduces this dose to 170 millirem and ensures dispersion of the ^{85}Kr away from the plant operators. The proposed ^{85}Kr collection and recovery system would then reduce the maximum whole-body dose to any individual of the public to 17 millirem. Skin doses for these cases are somewhat higher (47.1 rem, 20.5 rem, and 2.1 rem for the three cases). However, for a single accidental release, no significant permanent physical consequence has been identified for skin doses of this magnitude.¹⁸

All ^{85}Kr at the hydrofracture facility will be secondarily contained by the cells or the secondary containment vessels. These enclosures will be designed to provide containment of the krypton if an accidental release occurs, even a release involving a very rapid rupture of the primary containment. An emergency recovery system will remove a minimum of 90% of the accidentally released krypton from the enclosures. Combining the public exposure reduction factor of 2.3 provided by the ventilation stack and the factor of 10 provided by the emergency recovery system allows 25 cylinders to be placed at risk (i.e., connected to one manifold) inside the facility without exceeding the risk associated with a single cylinder outside of the facility. To further reduce the potential consequences of a release, the storage bottles will be emptied one-at-a-time rather than by connecting and opening all 25 at once.

A scenario that involves the release of up to 128,000 Ci of ^{85}Kr gas would be an incident in which one cylinder strikes another during handling with the resultant failure of both cylinders. If this occurred in the krypton storage area, the operating personnel in the area could

be exposed to a total-body dose rate of up to 5.4 rem/h and a skin dose rate of up to 1.1×10^5 rem/h for the short period it would take to exit the area. An exposure of this type is unlikely because the cylinders are handled within shielded casks of an approved design that has passed all required drop, puncture, and fire tests. Cell and secondary containment vessel ventilation air from areas containing significant amounts of ^{85}Kr is exhausted to the atmosphere by the ventilation stack after passing through the on-line charcoal beds. If the krypton duct, bed, or area monitors detect a leak into a cell or a secondary containment vessel, alarms are activated and that enclosure is isolated from the other enclosures and the ventilation system. The affected enclosure exhaust ventilation air is routed to the emergency recovery system. If the charcoal bed that was on-line at the time of the incident has adsorbed a significant amount of ^{85}Kr , it too is isolated and the krypton eluted to the emergency recovery system. A second bed is provided to allow continued protection while recovery activities are carried out. These precautions ensure that 90% of any accidentally released krypton will be recovered and afford protection to both onsite and offsite personnel.

The possibility exists that the wellhead could rupture near the end of an injection and allow a large volume of the injected grout and gases to flow back out of the disposal formation, up the injection well, and into the injection cell from which it would overflow to the emergency waste tank. Some of the dissolved gases would come out of solution because of the reduced pressure. For the purposes of this analysis it is assumed that up to 25% of the injected gases could be evolved in this manner.

For this to occur, the wellhead would have to rupture and the blowout preventer, installed just below the surface at the wellhead, would have to fail. Up to 400,000 Ci of ^{85}Kr would be released to the wellhead cell. The gas volume released from the grout as the pressure drops would likely overload both the ventilation system and the charcoal beds. The wellhead cell would pressurize slightly (it could not be isolated immediately because this would result in a significant pressurization of the cell), possibly resulting in the spread of ^{85}Kr to adjacent areas. The design flow velocities and the 128,000 Ci loading capacity of the charcoal bed would also be exceeded, causing breakthrough of krypton at the bed exit in a short time frame.

All of the fractures that have been made over the last 17 years in the bedded shale at Oak Ridge have been essentially horizontal. The nature of the rock formations in Melton Valley is such that the formation of a predominantly vertical fracture is regarded as an extreme improbability.

Some consideration must be given to the consequences of the formation of a vertical fracture during a grout injection, however. If, despite expectations, a vertical fracture did occur and the fracture reached the surface, a grout spill of some magnitude would occur. If the vertical fracture occurred toward the end of an injection (after 1.6×10^6 Ci had been injected) some fraction would be squeezed out as the fracture closed. This would probably be no larger than the 400,000 Ci that was postulated for a wellhead rupture because the pressures involved and resistances to be overcome are similar.

Although this accident is not considered to be credible, the consequences will be analyzed. Any vertical fracture that reached the surface would emerge relatively close to the injection well (the injection volume, injection depth, and grout sheet thickness are such that a distant breakthrough point is virtually impossible). If it were near enough to the reference hydrofracture facility, some of the evolved krypton gas could be drawn into the building by the ventilation system. An air monitor will be installed in the operating room to record the concentration of krypton in the air and to alarm if the concentration approaches one-half of the operational limit. This would enable the operating personnel to evacuate the facility before significant exposures were incurred. The recommended exclusion area around the facility would be evacuated during an injection so that no personnel would be exposed in the immediate area of the vertical fracture. Based on an assumption of one-fourth of the ^{85}Kr reaching the surface of the vertical fracture, the site boundary doses would be one-fourth those given as Case 1 in Table 5.1.

5.2.3 Tornado Effects

All natural phenomena are site-specific. The ORNL waste disposal facilities are constructed to withstand the ORNL design-basis tornado. Because an injection is scheduled, at most, ten times per year, an injection would not be allowed to occur if tornado warnings for the area were posted. Upon receipt of a tornado alert during operation, appropriate action will be taken to ensure the safety of the operation and protect the personnel. The short duration of the injection would

make it extremely unlikely that a tornado alert would interfere with the operation.

5.2.4 High Winds

Wind environments are site-specific. All nonnuclear safety-related structures at ORNL meet the wind load requirements of ANSI A58.1 for exposure "C" at a basic wind velocity of 90 mph. The applicable governing codes are used for loading conditions and acceptance criteria.

All nuclear safety-related structures at ORNL are designed to accommodate the wind forces and missiles of the design-basis tornado, because the tornado event represents the more severe event.

5.2.5 Floods

Potential flood conditions are site-specific and must be evaluated on a case by case basis. At ORNL, the elevation of all of the proposed injection equipment is at or above the level of the maximum probable flood. A flood of this magnitude is not expected to have any effect on the injection or storage facilities.

5.2.6 Earthquakes

Seismic activity is site-specific. The ORNL site is located in an area of moderate earthquake damage (Zone 2). ORNL is approximately midway between two Zone 3 areas of major damage that are centered respectively around Charleston, South Carolina, and around Memphis, Tennessee.

The cells and all enclosed piping and equipment are classified as

nuclear-safety-rated. The hydrofracture and injection facility, including storage tanks, are designed to accommodate the design-basis earthquake. The design earthquake is characterized by design response spectra developed from procedures specified in Nuclear Regulatory Guide 1.60.

The possibility of a significant release of radionuclides from the facilities as a result of an earthquake is believed to be extremely small.

5.2.7 Fire

A wet pipe sprinkler system is provided to protect sensitive low-temperature areas of the facility. Because the injection pumps are the portion of the facility most vulnerable to fire, the pump compartments are separated by firewalls, are protected by extra hazard-designed wet pipe systems, and have separate underground fuel tanks. There does not appear to be any obvious mechanism by which a fire can result in a significant radioactivity release. The injection of krypton-xenon into the grout would not increase the fire hazard over that presented by the injection of low-level liquid waste.

The gas cylinders are of steel construction and are surrounded by high heat capacity lead shields. The amount of combustible material in the krypton storage room will be very limited and no fire can be postulated that would produce enough pressure to cause the cylinder to fail. A large fire during transportation, which involved diesel fuel and other combustibles in conjunction with the krypton shipping cask, was analyzed in ICP-1077. It was calculated that after exposure to 1075 K (1475°F)

heat for 30 min the cylinder would rise in temperature about 6 K (10°F) over a four-hour period. The pressure would not exceed 56 bar (800 psig), which is well below the 140 bar (2015 psig) design pressure of the cylinder.¹⁷ From the data it can be concluded that, even if a fire were possible in the krypton storage room, it would not significantly affect the krypton cylinders.

A fire could conceivably be started in a charcoal bed of the emergency recovery system if the temperature of the bed rose enough and if oxygen were present. Possible heat sources to raise the bed temperature would be the heat of adsorption of the gases loaded onto the bed and the radioactive decay heat of the adsorbed ⁸⁵Kr. Cooling water is circulated through the bed to remove this heat. Design reviews of the charcoal beds will be required to assure that sufficient bed cooling is provided. If a fire did start, it could be controlled by isolating the bed, depriving the fire of oxygen.

5.2.8 Failure of services

Although a utility failure during the injection processes could conceivably require some decontamination and cleanup, no emergency would exist. By the use of proper procedures, release of radionuclides to the environment would be prevented.

Electric power and water are the only utility services supplied to the reference hydrofracture facility. A failure of these utilities at any time other than during an injection will have no effect on any part of the facility except the krypton cylinder storage area. The failure of

the refrigeration system will cause the krypton cylinder area temperature to rise, although natural convection cooling is expected to maintain an acceptable temperature.

A failure of electrical power to the facility during an injection would cause krypton injection to cease because of lack of power for the gas compressor. Low-level waste (grout) flow would also be discontinued because the pump that feeds low-level waste to the grout-waste mixer is electrically driven. A portable emergency generator will be provided to supply power to ventilation, instrumentation, and certain other selected power requirements should a prolonged power outage occur.

An interruption in the supply of water to the facility for longer than 15 min during an injection would cause the grout injection to be terminated.⁷

5.3 Safety Systems

Safety systems assure that the operations of the facility will not cause unacceptable risk to the safety and health of the public and employees. Specifically, safety systems are those systems the primary function of which is to maintain containment of hazardous materials or to prevent the occurrence of unique process and/or facility hazards. The failure on demand of a safety system leads to unacceptable consequences with regard to the safety and health of the public or employees.

Safety systems can be either active or passive. Active safety systems are called "protection systems" and are subject to the single failure

criterion. Passive safety systems are not necessarily subject to the single failure criterion. An example of a passive system is the lead shielding around the krypton cylinders. A gap in the shielding would not necessarily lead to unacceptable consequences because an active system, radiation monitors, would also be present to detect the condition.

Safety systems must be assured to function during normal and process upset conditions as well as during the occurrence of fires, explosions, and natural phenomena.

5.3.1 Confinement systems

The primary confinement barrier for all krypton gas is assumed to be the process equipment. Those parts of the facility that contain krypton will be designed to withstand the effects of all natural phenomena. In the event of a single failure, the released gases will be confined or the loss limited such that the safety of the public will not be jeopardized. Positive secondary containment will be provided for the high-pressure systems that handle either waste grout or krypton gas.

A ram-type blowout preventer will be installed just below the surface at the wellhead to seal the well in the unlikely event of a catastrophic wellhead failure. This device would pinch off the injection piping and prevent the injected grout and krypton from flowing back out of the disposal formation and up into the wellhead cell.

5.3.2 Shielding

Shielding will provide protection to plant personnel from radiation from the krypton gas and assure that exposure is within limits stated in 10 CFR 20. Radioactive liquid or gaseous effluents released from the facility shall be as low as reasonably achievable.

5.3.3 Leak detection

Krypton monitors will be provided inside the cells, the secondary containment vessels, the operating room, the ventilation system ducts, and the stack to detect krypton releases from the primary containment.

The hydrofracture facility now being constructed for low-level waste will have a constant air monitor installed in the operating room to measure the concentration of radionuclides in the air. This monitor records the concentration of beta and gamma emitters and is set to alarm if the concentration of either approaches one-half the operational limit. These monitors will immediately detect any leakage of the krypton from the primary containment and alert the operating personnel. Enough redundancy will be provided among the monitors to assure that loss of a single monitor will not allow a krypton leak to go undetected.

5.3.4 Ventilation and offgas system

Outside air is drawn into the unloading bay and storage cell areas through a filter and is eventually exhausted to the building stack. Any air flow between areas is typically from the manned area towards potentially contaminated areas. Air circulation through the cells is a once-

through process. The hydrofracture facility stack will be sized for a discharge velocity of 10 m/s.

The krypton cylinders will be enclosed by pit-type secondary containment vessels in the storage area. The secondary containment vessels will be wrapped in cooling coils on the interior walls to remove the decay heat from the krypton. If the supply of cooling water were interrupted, the temperature of the cylinders would rise until it was limited by natural convection cooling. This increase in temperature would not reduce the integrity of the storage cylinders, and the decay heat would then be removed by the ventilation air.

Radiation monitors in the cell exhaust ducts, upon detection of critical amounts of ^{85}Kr , will initiate diversion of exhaust ventilation air to the emergency recovery system and isolation of the cell if necessary. The charcoal beds will provide a delay of 15 min between the time the krypton is released and when it enters the atmosphere. During this time the source of the release can be identified and mitigating actions taken.

6. SURVEY OF SUITABLE HYDROFRACTURE SITES IN THE UNITED STATES

The process of hydraulic fracturing (hydrofracture) has been widely used in the petroleum industry since its introduction in 1948. A similar process has been used to permanently dispose of low- and intermediate-level waste at the Oak Ridge National Laboratory. Between 1966 and 1976 4932.39 m³ (1,303,000 gal) of waste solution containing 1.924×10^{16} Bq (520,000 Ci) of ¹³⁷Cs and 1.3616×10^{15} Bq (36,800 Ci) of ⁹⁰Sr have been injected into the Pumpkin Valley member of the Conasauga formation.

The theory of rock hydrofracture can be paraphrased as follows: When a homogeneous body of rock is fractured by pressurized fluid pumped into a borehole in the rock and the fluid pressure is confined to a short segment of the borehole, a single fracture will form and propagate perpendicular to the least principal stress vector in the rock.

The orientation of the three orthogonal stress vectors in any given volume of rock depends upon the tectonic history of the rock and its compressive strength relative to adjacent rocks.

The presence of residual stress components in a rock formation is usually site specific and the orientation of these stress vectors may vary with depth. The least principal stress vector is usually perpendicular to the ground surface down to depths of 300 to 600 m. Its magnitude at these depths is usually proportional to the weight of the overlying rock.

At depths greater than approximately 600 m, the least principal stress vector may be at any angle to the ground surface from normal to

parallel. Hydrofracture is a technique commonly used by engineers to determine the direction of the residual stress components in a rock at depth.

The tensile strength of most rocks including basalt and granite is small; therefore, almost all rocks will hydrofracture with equal ease. Also, existing bedding planes, joints, or other "planes of weakness" have little effect on the direction of propagation of a hydrofracture crack.

The criteria for the hydrofracture disposal of the volatile fission product elements with half lives of the order of 10 years (^{85}Kr and ^3H) will be determined by the maximum retention time necessary for the approximately 10 half-lives decay period that will bring the atmospheric release level down to NRC ALARA standards. If there is little or no net flow of fluid through the rock; i.e., the rock is impermeable, the subsurface disposal depth will depend upon the diffusion constants of the ^{85}Kr and ^3H in the rock medium. The approximate distance of migration of the elements through an impermeable rock is of the order of magnitude of 100 cm in 100 years, if one assumes a value of 10^{-6} cm/s for the average hydraulic conductivity of rocks of this type. The hydrofracture disposal of these elements at depths of 100 m or greater will provide path lengths to the ground surface of at least 1000 times those needed for containment.

Impermeable rocks at depths of 100 to 600 m occur at nearly all DOE facilities and sites in the United States. Table 6.1 lists a few sites and the rock type that could be suitable for ^{85}Kr or tritium disposal at

Table 6.1

Site	Impermeable rock
Oak Ridge, Tenn.	Conasauga formation, argillaceous rock
Nevada Test Site	Welded tuff
Hanford, Wash.	Basalt
Arco, Ida.	Basalt
Savannah River, S. C.	Triassic red beds, argillaceous rock
Sheffield, Ill.	Argillaceous rock
West Valley, N. Y.	Devonian shales
Morehead, Ky.	Argillaceous rock
Barnwell, S. C.	Argillaceous rock

these sites. Pinpoint selection of an injection well site will necessarily depend upon the details of the geology at a specific location. These geological data can be acquired from literature surveys, surface mapping, and core drilling after the site has been selected.

In summary, an extensive geological survey for sites for hydrofracture disposal of volatile fission products is probably unnecessary and inappropriate. The sites selected on the basis of political, engineering, or safety criteria should be evaluated for geological suitability on an ad hoc basis. The probability that appropriate geological criteria can be met at a given site is very high (>90%).

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Appendix A

PRELIMINARY HAZARDS ANALYSIS

The preliminary hazards analysis systems approach is employed for this safety analysis. The logical development of the relative risk levels is shown in Fig. A-1. Risk has been defined as the product of probability of occurrence and the severity of consequences. Relative levels of probability and severity are postulated, providing the means for meaningful risk evaluation. Calculated risk values are used to rank potential accidents, determining the events that would be of significant impact to the facility and eliminating inconsequential considerations. Each of the safety-related categories shown in Fig. A-1 is evaluated both individually and with respect to the other appropriate categories. The evaluation is summarized in a continuous diagonal matrix chart composed of separate sections for each category, depending on size. The matrix form provides a visual tool for assessing safety, a format for relating all components of the safety evaluation, a record of the hazard evaluation process, and a basis for computerizing the hazards analysis, if desired. Each entry in the matrix represents a consensus of the individual members of the team performing the safety evaluation. The value of this approach and format is that (1) it gives safety analysts a checklist to ensure that no important items are missed, (2) it shows what components were included in the evaluation, (3) it indicates a unique location of documentation, and (4) it allows for later review of the safety analysts' assumptions. This approach ensures that the analyses relates directly to the goals and objectives of the project (validity), that data evaluation can be proved (integrity), that physical protection of the data is assured (preservation), and that the data can be readily located and made available for use and review (retrievability).

Figure A-2 displays the evaluation of the facility's hazard and energy sources in a level-4 breakdown structure. The energy sources are subdivided into three 2nd-level components: hazardous materials,

operational energy sources, and natural phenomena. The category "operational energy sources" is further divided into the following subtopics: electrical, thermal, and mechanical. Electrical considerations for the hydrofracture facility pertain to instrumentation and power supply that could conceivably give off sparks or overload. Thermal energy sources will include krypton decay and the heat of compression as well as inefficiencies inherent in the various compressors. Mechanical failure—failure of a compressor accumulator tank, cylinder, gas manifold, pressure piping on valves—could lead to a release of radioactive krypton gas. The relative importance of the 4th-level components is shown in the triangular group of squares directly to the right of the component listing. For example, for the hazardous nature of materials, the relative importances are described in the triangle defined by squares in row 4, column 5 (4,5), (4,9), and (9,9). The categories that indicate hazard are explosive, combustible, flammable, abrasive, and radioactive. Looking at entry 5, COMBUSTIBLE, the bar in square (4,5) (the intersection of explosion and combustible) points down vertically toward COMBUSTIBLE, indicating that the hazard from combustible materials in the facility overrides the potential for an explosion in the facility. This is because the likelihood of an explosion is small. If an explosion would have been considered to be more likely than combustion, the bar in square (4,5) would be horizontal, pointing toward EXPLOSIVE. The bar in square (5,6) points toward COMBUSTIBLE, indicating that combustible materials are more important considerations than flammable materials. A check of all the squares of column 5 and row 5 (sum the vertical lines in the column and combine with the sum of the horizontal lines in the row) indicates that combustible materials are more important, from a safety viewpoint, than 2 out of the 5 materials listed. Thus, the relative importance is indicated as "2." In like manner, entry 8, RADIOACTIVE, has a relative importance of "4" (4 vertical lines in column 8 and 0 horizontal lines in row 8). The RELATIVE IMPORTANCE of each material is recorded in column 9. Thus, in this example, "relative importance" is a ranking of the severity of the hazards associated with the listed materials, the larger number corresponding to a greater severity. These relative importances are

preliminary in nature; they are based on a knowledge of the facility and site and are derived from the safety analyst's intuitive feel for the probability and severity of the hazard. These hazards are ranked in Figs. A-2, A-3, and A-4 only to allow the analyst to put his thoughts to paper easily and do not enter into the relative probability and severity assessment shown in Figs. A-5 and A-6.

Another apparent feature of Fig. A-2 is the placement of a number of solid circles in the boxes to the right of the triangular regions. A solid circle in a box indicates that there is a correlation between two of the entries. For example, the solid circle in location (1,5) of Fig. A-2 indicates the presence of solid combustibles in the facility. Location (3,4) indicates the possible presence of an explosive gas in the facility such as diesel fuel fumes. This exercise helps to "gel" the safety analyst's thoughts and to focus his attention on the identification of the important safety considerations. Another form, Table A-1, supplies additional information for the two solid circles in this example. Each square in the series of diagonal matrix charts, Figs. A-2 through A-6, is given a unique identification number. The first digit of the three-digit number refers to the matrix number: (1) hazard and energy sources, (2) accident severity/accident impact, (3) accident probabilities and prevention measures, (4) potential accidents and mitigation measures, and (5) operator error/equipment malfunction. The last two numbers refer to the location on the particular matrix. In the example, the locations of interest are (1,1,5) and (1,3,4). Comments associated with these two locations are contained in Table A-1. These comments are used to further clarify the facts that solid combustibles may be generated in the operation of the facility and may be present in the form of paper or packaging materials and that it is conceivable that diesel fuel fumes can attain a potentially explosive mixture and could be both combustible and flammable.

Table A-2, accident severity categories, assigns a number and a descriptor to categories of accident severity. The number scale is arbitrary, but it is effective in ranking the relative consequences of

an accident. This number scale is used in the analysis of potential accidents in Figs. A-5 and A-6.

Table A-3, accident probability levels, assigns a number and an adjective to statistical probability levels. The number scale, though arbitrary, is an effective way to rank the probability for an event to occur. This system is used in Fig. A-6 in analyzing potential accidents.

The concept of risk level or relative risk is used in this report. Risk is generally considered to be the product of the probability of the occurrence of an adverse event and the consequence of the event if it does occur. Thus, a minor event that can occur frequently may have the same "risk level" as a major event that occurs infrequently. The number systems established in Table A-2 and Table A-3 are used to derive numerical values for risk level and relative risk.

Figure A-5 lists the relative severity of accidents. Relationships between potential accidents and effects on people, the program, or on the environment are noted.

Figure A-6 contains accident probability considerations including consideration of preventive measures and safety systems as well as the probability levels (from Table A-3) that result. The severity levels are carried over from Fig. A-3 and multiplied by the probability level in order to get risk level. These results are summarized in Table A-4.

Figure A-3 shows the relationship between potential accidents and mitigation measures and the relative importance of mitigation measures to the safety of the facility.

Figure A-4 shows the relative importance of operator errors and equipment malfunctions to facility safety; they can conceivably contribute to a facility accident.

The preliminary hazards analysis serves as a screening device to identify the potential accidents that require more detailed analyses. The results of this screening are shown in Table A-4, which lists the relative risks of potential accidents. The accidents that are identified by Table A-4 as requiring further analysis are analyzed in detail in Sect. 5. The accidents of highest potential risk are fire and radiological accidents. The so-called "industrial" accident includes minor conventional accidents such as cuts, abrasions, contusions, falls, etc., that can occur in production facilities. These do occur, but usually have minor consequences and are not considered to be of prime importance to this analysis. Even though the risks of tornado or a seismic event are small for this particular structure and location, a limited and perfunctory analysis is performed on each to justify ignoring them.

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Fig. A-1. Risk development methodology.

Fig. A-2. Hazard and energy sources (chart #1).

Fig. A-3. Potential accidents and mitigation measures (chart #4).

Fig. A-4. Operator error/equipment malfunction (chart #5).

Fig. A-5. Accident severity/accident impact (chart #2).

Fig. A-6. Accident probabilities and prevention methods (chart #3).

Table A-1.

Comments on hazards

No.	Comments
1,1,5	Some solid combustibles will be generated in the operation of the facility and may be present in the form of paper, packing materials, etc. The charcoal beds in the off-gas system are combustible
1,1,7-8	Abrasive and radioactive solids may be present in the waste sludge mixed with the grout (e.g., plutonium or rubidium)
1,1,11-12	Any combustible solids that are present can conceivably be ignited by an electric spark from these electrical sources
1,1,22-28	Solid wastes can be dispersed by any of these events
1,2,5-6	Diesel fuel used for the injection pump engines is a combustible liquid. Flammable liquids are defined as any liquid having a flashpoint below 100°F and having a vapor pressure not exceeding 40 psia (2,069.6 mm) at 100°F (37.8°C). Liquids with a flashpoint at or above 100°F (37.8°C) are referred to as combustible liquids. By this definition, diesel fuel is considered to be flammable
1,2,7-8	The radioactive liquids and gases are mixed with the abrasive grout
1,2,11-12	Liquid diesel fuel can conceivably be ignited by a spark from these electrical sources
1,2,14	It is conceivable that process liquids can be adversely affected by electrical equipment. The jet mixer pump is electrically driven
1,2,22-28	Any liquids can easily be affected by any of these events
1,3,4-6	Collected diesel fuel fumes can become explosive, combustible, or flammable
1,3,8	The krypton gas contains about 7% ⁸⁵ Kr, which is highly radioactive
1,3,11-12	Diesel fumes can conceivably be ignited by an electric spark

Table A-1 (continued)

No.	Comments
1,3,14-15	Bottled krypton gas can be accidentally released by or from these systems
1,3,16	The compressed gas system is used to handle radioactive krypton gas
1,3,19-20	Process gases receive heat from the compressor equipment and produce heat through radioactive decay
1,3,22-24, 26-28	Radioactive krypton gas can be released by any of these events
1,4,11-12, 14-15, 19, 22-24, 27-28	An explosive mixture of diesel fumes can conceivably be ignited by an electric spark, blower motor spark, engine exhaust manifold, or by events related to natural phenomena. The diesel fuel is located in an isolated cell to minimize the potential for occurrence and to mitigate the consequences
1,5,11-12	It is conceivable that any combustibles present can be ignited by an electric spark
1,5,14-15	It is conceivable that any combustibles present can be ignited by a spark from this equipment
1,5,19	It is conceivable that a charcoal fire could be initiated in the ventilation system equipment
1,5,22-24, 27-28	It is conceivable that any combustibles present can be ignited by any of these phenomena
1,6,11-12, 14-15, 19, 22-24, 27-28	As detailed in 1,4 above, flammable diesel fuel could be ignited by these sources
1,7,22-28	Abrasive material from the waste can be dispersed by any of these phenomena
1,8,14-15	Radioactive krypton gas can be dispersed by an accident caused by the remote handling equipment and by a failure of the air equipment to cease venting the various cells

Table A-1 (continued)

No.	Comments
1,8,16	Radioactive krypton gas can be dispersed by a leak in the compressed gas system
1,8,20	The krypton gas produces heat through radioactive decay
1,8,22-28	Radioactive material can be dispersed by any of these phenomena
2,1,6-7	An explosion could conceivably be precipitated by either a seismic event or a tornado
2,1,11-13	An explosion coupled with a radiological release could affect all of these
2,1,15-17	An explosion could have an effect on all of these
2,2,6-7	A fire could conceivably be caused by either a seismic event or a tornado
2,2,11-13	A fire coupled with a radiological release could affect all of these
2,2,15-17	A fire could have an effect on all of these
2,2,20	A fire could spread to become a forest fire and affect public land
2,3,6-7	A radiological incident could be caused by a seismic event or a tornado
2,3,9	A flood, however unlikely, could spread radioactive contamination
2,3,11-13	A radiological incident could affect workers, onsite personnel, and the public
2,3,15-19	A radiological incident could affect the equipment, facility, and site by release of the krypton. If a seismic event caused a fault that intersected a gas-bearing grout layer, potentially the flora, fauna, and water could be affected
2,4,6-9	An industrial accident could be caused by all of these

Table A-1 (continued)

No.	Comments
2,4,11-12	An industrial accident could affect both workers and onsite personnel
2,4,15-16	An industrial accident can be expected to adversely affect either equipment or the facility
2,6,11-12	A seismic event at the facility could precipitate events such as fire, explosion, or radiological release that could affect workers, onsite personnel, and the public
2,6,15-19	A seismic event could damage equipment and the facility. If a fault interrupted a grout layer then potentially the site, flora, fauna, and water could be affected
2,7,11-13	A tornado at the facility could precipitate events such as fire, explosion, or radiological release, which could affect workers, onsite personnel, and the public
2,7,15-17	A tornado can be expected to damage all of these
2,8,11-12	High winds could affect workers and onsite personnel by causing industrial accidents
2,8,15-17	High winds can conceivably damage any of these
2,9,11-12	High winds could affect workers and onsite personnel by contributing to industrial accidents
2,9,15-17	A flood can conceivably damage or result in the contamination of all of these. However, it should be noted that flood of this magnitude is extremely improbable
3,1,2-4	An explosion can result in a fire or a radiological incident
3,1,6-7	An explosion can conceivably result from either of these phenomena
3,1,16-20	All of these will act to prevent an explosion
3,2,3	A fire could precipitate a radiological incident

Table A-1 (concluded)

No.	Comments
3,2,6-7	A fire can conceivably be initiated by these events
3,2,13	Building walls will help to contain a fire
3,2,16-20	All of these will help to prevent a fire
3,3,6-7	These events can act to cause a radiological release
3,3,9	A flood, however unlikely, could spread radioactive contamination
3,3,13-15	Building walls, filter system, and safety tank will all act to prevent a radiological release
3,3,17-20	All of these will act to prevent or limit a radiological release
3,5,6-9	All of these could contribute to the occurrence of industrial accidents
3,5,17-20	All of these procedures will act to prevent or limit an industrial accident
4,1,6	Building walls can be expected to mitigate an explosion
4,1,9-12	All of these procedures will help to limit an explosion or the effects of an explosion
4,2,6	Building walls can be expected to contain a fire
4,2,9-12	A fire will be limited by all of these procedures
4,3,6-13	A radiological incident will tend to be limited by all of these. A radiological incident will be detected by the radiation monitors
4,5,9-11	An industrial accident will tend to be mitigated by all of these

Table A-2.
Accident severity categories

Category	Descriptor	Description
4	Catastrophic	May cause death or system loss
3	Critical	May cause severe injury, severe occupational illness, or major system damage
2	Marginal	May cause minor injury, minor occupational illness, or minor system damage
1	Negligible	Will not result in injury, occupational illness, or system damage

Table A-3.
Accident probability levels

Level	Descriptor	Description
5	Frequent	Likely to occur frequently
4	Probable	Will occur several times during the life cycle
3	Occasional	Likely to occur sometime during the life cycle
2	Remote	So unlikely that it will probably not occur during the life cycle
1	Extremely improbable	Probability of occurrence is vanishingly small
0	Impossible	Physically impossible to occur

Table A-4.

Relative risks

<u>Accident event</u>	<u>Relative probability</u>	<u>Relative severity</u>	<u>Relative risk</u>	<u>Further analysis</u>
Explosion	1	3	3	None
Industrial	4	2	8	None
Radiological	3	3	9	Analyze consequences in Sect. 5
Fire	2	2	4	Analyze consequence in Sect. 5
Tornado	1	2	2	None
High winds	2	2	4	None
Seismic	2	2	4	None
Flood	1	2	2	None

Appendix B

SOLUBILITY OF KRYPTON AND XENON IN 1 M NaNO₃

Appendix B

June 12, 1980

F. J. Peretz

Solubility of Krypton and Xenon in 1 M NaNO₃ as a function of Pressure T=298°K.

The solubility of krypton and xenon in 1 M NaNO₃ was estimated using a six step procedure:

1. Solubility data for krypton and xenon in water at 1 atm and 298°K was located from Clever (1).
2. Salting-out coefficients in 1 molal NaCl at 298°K were determined (1).
3. Utilizing a procedure described by Morrison and Johnstone (3), salting-out coefficients in 1 molal NaNO₃ were estimated at 298°K.
4. Solubilities of krypton and xenon were calculated using the salting-out coefficients in 1 molal NaNO₃ and the solubility data in pure water.
5. A correlation for extending the solubility to high pressures by Frolich, et al. (2) was used to calculate ideal solubilities at high pressure.
6. The ideal solubilities were corrected for nonideality at higher pressures using a generalized correlation.

The results of the study and a copy of the calculations are attached. These estimates should be adequate for initial design calculations.

Although no correlations were found, it appears from the small amount of experimental data that I was able to find that the solubility of a nonreacting mixture such as xenon and krypton may be calculated by summing the product of the mole fraction times the individual component solubilities.

References

1. Clever, H. L. , editor, Solubility Data Series, Vol. 2, Krypton, Xenon, and Radon - Gas Solubilities, Pergamon Press, Oxford, England.
2. Frolich, P. K. et al., "Solubilities of Gases in Liquids at High Pressure," Ind and Engr. Chem., 23 (6), 548.
3. Morrison, T. J. , and N. B. B. Johnstone, "The Salting Out of Non-electrolytes. Part III. The Inert Gases and Sulphur Hexafluoride," Chem Soc. Journal of London, p. 3655, 1955.

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Fig. B-1. Solubility of krypton and xenon in 1 M NaNO₃.

Appendix C

REFERENCE DRAWINGS ON ORNL NEW HYDROFRACTURE FACILITY

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C-1	ORNL new hydrofracture facility site plan	C-3
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Fig. C-1. ORNL new hydrofracture facility site plan.

Fig. C-2. Subsurface geology at ORNL hydrofracture site.

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* SAMPLE NUMBER ALSO CORRESPONDS TO DEPTH IN FEET.

Fig. C-3. General description of core from the "Joy" test well.

Fig. C-4. Pattern of observation wells at ORNL hydrofracture sites.

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Fig. C-5. Perspective ORNL new hydrofracture building.

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SOLIDS MATERIALS HANDLING AREA
PERSPECTIVE LOOKING NORTHWEST

Fig. C-6. Perspective solids handling area.

Fig. C-7. Section view.

Fig. C-8. Injection well.

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INJECTION BELL
SLOTING CONFIGURATION

Fig. C-9. Slotting configuration.

Fig. C-10. Environmental control flow diagram.

C-10. Environmental control flow diagram.

Fig. C-11. Fire protection system.