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LIQUID METAL REACTOR
COVER GAS PURIFICATION
AND ANALYSIS IN THE USA

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Sodium Cooled Reactors in the USA

Two sodium cooled reactors are currently being operated in the United States of America for the U.S. Department of Energy. These are Experimental Breeder Reactor II, EBR-II, and the Fast Flux Test Facility, FFTF. EBR-II is located near Idaho Falls, Idaho and the FFTF is near Richland, Washington. These reactors are currently engaged in a wide range of testing including fuels and materials tests, and plant system performance and safety development.

The U.S. DOE program also includes designs of a next generation sodium cooled power reactor. The FFTF and EBR-II communities are providing input to these designs.

This paper discusses the efforts to develop and operate cover gas systems for the sodium cooled nuclear reactor program in the USA.

EBR-II Cover Gas Purification

Introduction

The Experimental Breeder Reactor II (EBR-II) is a 62.5 MWt sodium cooled pool reactor operated since 1964 by the Argonne National Laboratory for the United States Department of Energy. EBR-II operates with a 66 percent enriched uranium metallic driver fuel and conducts experiments with uranium oxide, carbide, and nitride fuels in the core. The EBR-II primary tank contains an 8.5 M^3 (300 SCF) argon cover gas plenum over the pool of 371°C (700°F) liquid sodium. Fission gases, air, moisture, and hydrocarbons enter the cover gas through subassembly fuel cladding breaches, fuel handling transfers, minor component and system leaks, and through maintenance of primary system equipment. The Cover Gas Cleanup System (CGCS) and the Argon Purge System are the two systems used to remove most of the impurities from the cover gas and are briefly discussed in this paper.

Cover Gas Impurities

Fission gases, including isotopes of Kr, Xe, and Cs are released into the cover gas space when fuel pin cladding is breached as a part of the Run Beyond Cladding Breach (RBCB) experimental program. Small amounts of these gases leak into the reactor building containment and restrict normal personnel activities. The high cover gas activity also hides other fuel cladding breaches so the gases are removed from the primary tank as soon as possible by the CGCS or the argon purge systems.

Air and moisture get into the cover gas via fuel handling, primary components maintenance, and occasional system or component leaks. These impurities chemically react with sodium to produce unwanted sodium oxides, hydrides, and hydroxides in the primary system piping and components.

Hydrocarbons, detected as methane, usually get into the cover gas from residual component cleaning solvents or as grease from failed turbine and pump bearings.

Impurity Detection Equipment

Several systems continuously or periodically sample the primary tank cover gas to detect and quantify impurities. Two systems continuously sample the cover gas for certain radioactive isotopes and two independent gas chromatograph systems sample the cover gas for oxygen, nitrogen, hydrogen, and helium. Two hydrocarbon analyzers sample the cover gas and give results as detectable methane.

Two oxygen analyzers are continuously used in the CGCS to detect air leaks in the system, to ensure oxygen levels are adequately low after system openings for repair, and to detect the amount of oxygen removed and accumulated in the cryogenic distillation column sump.

Cover Gas Cleanup System (CGCS)

The CGCS, Figure 1, was made operational in 1977 as a closed loop EBR-II system designed to remove and store gaseous fission products from the primary tank by recycling cover gas through a distillation column. The cryogenic distillation column is used for cleanup at flow rates of 28.3 to 283 liters/minute (1 to 10 SCFM) and removes oxygen and hydrocarbons in addition to the xenon and krypton. The column allows helium, hydrogen, and nitrogen to pass through as non-condensible gases and returns them to the primary tank cover gas. The system is used during reactor operation as desired to maintain a low cover gas activity.

The CGCS also has a xenon tag gas trapping system in which cover gas samples are processed and analyzed to identify the specific subassembly from which the tag gases evolved.

A third function, added recently on a test basis, is to supply a recycled cover gas purge to the large rotating plug annulus to suppress sodium aerosol migration and consequent plug sticking. In this function, the cryogenic distillation column is bypassed and fission gas cleanup is performed only as necessary to maintain acceptable cover gas activity levels.

The CGCS components are located both within the reactor building containment and outside the reactor building in a specially designed CGCS building. The sodium removal equipment, including a Controlled Temperature Profile (CTP) Condenser and two parallel sintered metal aerosol filters, is located in a shielded enclosure above the primary tank. The remainder of the equipment is in the shielded and air flow controlled CGCS building.

The CTP condenser is a vertical annular cylinder filled with Raschig rings and heated with seven zones of external electrical resistance heaters. The gas flowing through the CTP condenser is progressively cooled to condense the sodium and return it to the primary tank. The unit is identical to the unit used in the Fast Flux Test Facility (FFTF).

The two sintered metal aerosol filters are mounted horizontally above the CTP to remove additional sodium and particulates. The filter end-of-life is determined by the continuously measured differential pressure which is being watched and evaluated to determine better end-of-life criteria. These filters are also identical to those used in the FFTF.

Positive displacement gas compressors provide the motive force for flow through the various CGCS components. All eight pumps are contained within a closed vessel to prevent fission gas release to the atmosphere if a pump should leak.

The cryogenic distillation column is housed within a shielded pressure vessel designed to contain all of the radioactive gases if the column should rupture and its contents completely vaporize. The temperature and pressure of the distillation column sump is controlled with a liquid nitrogen cooled condenser. The cover gas bubbles through the sump where condensible gases, including xenon, krypton, oxygen, and hydrocarbons, condense in the -182°C (-295°F) liquid argon and remain in solution. Some of the gases pass through the sump to the metal mesh filled column where a refluxing action of downward flowing recondensed liquid argon scrubs most remaining condensible gases out of the gas flow. Helium, hydrogen, and nitrogen pass through the distillation column because they do not condense at the liquid argon temperature. The distillation column removes 99.9% of the xenon and 99.0% of the krypton isotopes from the cover gas stream and retains all of the impurities in the sump for later disposal.

A charcoal absorber bed is connected to the distillation column sump for periodic collection, retention, and radioactive decay of the sump contents.

Cleaned cover gas is returned to the primary tank through either the originally designed reheater and tank penetration nozzle or through the large rotating plug annulus purge. The gas is reheated to minimize sodium fog formation in the cover gas space.

The CGCS is versatile enough to operate on demand or continuously at flow rates of 28.3 to 283 liters/minute (1 to 10 SCFM). At present, the system is operated continuously at 113 to 141 liters/minute (4 to 5 SCFM) for the rotating plug annulus purge and increased to 283 liters/minute (10 SCFM) for occasional cleanup periods.

Argon Purge System

The Argon Purge System, Figure 2, was effectively used for cover gas cleanup before the RBCB program generated large amounts of fission gas products. The argon purge system is still used occasionally to clean the cover gas by adding fresh argon and purging the impurity laden cover gas out of the primary tank. The removed cover gas is monitored for radioactivity, filtered, and released to the atmosphere. The system does effectively remove impurities and does reduce cover gas activity, but there is a maximum 91 liters/minute (3.2 SCFM) flow rate and the cover gas is not recycled. All of the components are located inside the reactor building containment.

Radiological Considerations

Approximately 29.6 TBq (800 Ci) of fission gases, primarily ^{133}Xe, are produced in each fuel pin of which approximately 50% is released to the cover gas for every breach in the reactor core. An average of 10 to 15 fuel pin cladding failures per year have occurred since the start of the RBCB experimental program in 1977 resulting in a potential release of 148 to 222 TBq (4,000 to 6,000 Ci) of fission gases per year. The CGCS cleanup has effectively reduced this activity to an average annual radioactive gas release of 7.4 TBq (200 Ci).

Cleanup of the cover gas via the CGCS results in higher radiation levels in the CTP condenser, the aerosol filters, the gas compressors, the distillation column sump, piping upstream of the distillation column, and in the tag trap system components. Components are shielded and access is restricted in the high radiation areas to minimize personnel exposure but the necessary radiation controls cause difficulty with some otherwise simple maintenance tasks. The highest radiation fields occur in the sodium removal equipment and in components of the tag trapping system.

Purification Problems

Most of the cover gas purification problems can be grouped into the categories of system impurities, system control, component failures, and radiation hazards. Some of the problems are periodic, others are ongoing, and most have been minor. No major problem has shut down the cleanup systems for extended periods or caused significant design changes.

Air leakage into the CGCS system is a periodic and recurring problem because part of the system operates at less than atmospheric pressure and very small piping joint or component leaks are readily detected. The system uses bellows sealed valves and welded joints where possible and mechanical joints are coated with a vacuum system thread sealant. Pinholes and minute fractures of valve stem and gas compressor bellows have been the most frequent sources of air leaks.

Air leakage into the CGCS system is detected on the sensitive oxygen monitors and creates a distillation column sump oxygen inventory problem. A potential explosion hazard exists in the sump if the oxygen in the sump converts to ozone and chemically combines with methane. To avoid this hazard, the oxygen and methane inventories are carefully controlled and the sump contents are dumped and replaced with fresh argon whenever either limit is reached.

Air leakage into the cover gas will also create sodium oxides that are carried by the cover gas into the CTP condenser and the aerosol filters. Thus far, these contaminants have not caused any detectable degradation of the CTP performance.

Air leakage also adds nitrogen to the cover gas. Although it is not detrimental to the EBR-II reactor systems, nitrogen is removed by the Argon Purge System to acceptable levels.

Methane gets into the cover gas as the detectable hydrocarbon resulting from greases, oils, or cleaning solvents entering the primary tank. Methane is effectively removed by the CGCS distillation column where the quantitative inventory is carefully controlled to avoid the explosion hazard discussed above.

System control problems are usually traceable to component failures and are corrected as they occur.

Component failures have included system monitors, piping trace heaters, gas compressors, valve actuators, and various meters.

The oxygen analyzers have evolved through several different brands to get the sensitivity and reliability required for the CGCS distillation column inventory requirements. An ozone analyzer was installed to measure the amount of ozone in the distillation column sump but was discontinued because of unreliability at the very low levels that were observed.

The pipe heating systems have been a continual problem with failed heaters, variable control thermocouple readings, and restricted access to parts of the system. The installed spare heaters and thermocouples usually allow continued operation of the system until the appropriate shutdown conditions can be obtained.

The CGCS gas compressors are small positive displacement pumps that have given very satisfactory service. The three failures have been caused by small fractures in the piston bellows which allowed air leakage into the system.

Periodic problems have occurred with electrically operated valve actuators and solenoid operated valves. Most air operated actuator failures have been traced to limit switch position malfunctions.

Conclusions

The EBR-II cover gas purification systems in use, including the Cover Gas Cleanup System (CGCS) and the Argon Purge system, effectively remove most impurities from the primary tank argon cover gas. The CGCS system is the preferred cleanup system because it can be automatically operated, has a relatively high flow rate to quickly remove high levels of fission gas activity, recycles the cover gas, and is directly connected to the fission gas tag sample system. The Argon Purge System is simpler in concept and operation but uses a much lower flow rate and does not recycle the cover gas. The impurities removed from the cover gas are fission gases from fuel pin cladding ruptures, chemical contaminants from fuel handling or primary system components maintenance, and chemical reaction products of air leaks into the system. The radiological hazards to personnel are minimized by shielding, restricted access areas, and careful monitoring of atmospheric discharges. The CGCS system with its cryogenic distillation column works well and should be considered for use in other reactor cover gas purification systems.

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FFTF Cover Gas Purification

Introduction

The Fast Flux Test Facility (FFTF) is a 400 Mwt, mixed oxide fuel, sodium cooled reactor with three primary cooling loops. Sustained power operation began in 1982, following two years of acceptance testing. The FFTF recently completed (July 86) its eighth cycle of power operation and has accumulated 887.8 EFPD (effective full power days). The FFTF is operated to test reactor fuels and materials and recently has been engaged in Inherent Safety Testing to demonstrate the ability of reactors of this type to safely handle unusual system failures without operator or control system intervention. At full power the mean temperature of the sodium in the upper plenum is 503°C (938°F).

The FFTF Reactor Cover Gas Systems

The Fast Flux Test Facility Reactor has an argon cover gas. Figures 3 and 4 are simplified diagrams of the systems that process the cover gas. At the FFTF, cover gas is not recycled. After processing to reduce radioactivity, waste gas is vented to the atmosphere via the containment heating and ventilating system.

The reactor vessel cover gas volume is approximately 5.5 M^3 (195 $ft.^3$) at full power. The vessel gas space continuously receives about 85 liters/minute (3 SCFM) of fresh argon from purges through annuli of the refueling machines mounted in the vessel head. This results in a complete vessel gas exchange every hour. An additional 75 liters/minute (2.7 SCFM) enters the system from the purges of the three primary heat transport system pumps. Of the flow leaving the reactor, approximately 20 liters/minute (0.7 SCFM) is sent via a sodium vapor trap to the Cover Gas Monitoring System. The remainder, 140 liters/minute (5 SCFM), is directed to the Primary Sodium Overflow Vessel and then through a sodium vapor trap to the Radioactive Argon Processing System.

The Cover Gas Monitoring System (FFTF)

Argon cover gas directed to the Cover Gas Monitoring System is first cleaned by a sodium vapor trap. In the Cover Gas Monitoring System are a Fission Gas Monitor, a Gas Chromatograph, and a portable sample collecting device, the Gas Tag Sample Trap.

The Fission Gas Monitor is a gamma radiation detector (liquid nitrogen cooled germanium diode) reading a similarly cooled charcoal filled sample column through a variable absorber/collimator mechanism. Single channel analyzers and associated electronics monitor gamma-ray activity for energy levels associated with ^{133}Xe, ^{85m}Kr, ^{125}Xe, and ^{135}Xe.

Six impurities are monitored by the Gas Chromatograph: helium, hydrogen, nitrogen, oxygen, methane and carbon monoxide. In the Gas Chromatograph, a sample passes through a separation column after which it is analyzed by thermal conductivity measurements and flame ionization detection.

The Gas Tag Sample Trap is a portable, shielded, cryogenically cooled charcoal column which concentrates isotopes of krypton and xenon for laboratory analysis. Ratios of these isotopes have been injected into the fuel pins of each fuel assembly to enable identification of failed fuel assemblies by isotopic analysis of the cover gas. In a similar manner, pressurized, tag gas filled creep rupture in the Material Open Test Assemblies (MOTA) are identified after they burst.

Sodium Vapor Traps (FFTF)

The FFTF Reactor Cover Gas System has two continuous sodium vapor traps, one upstream of the Cover Gas Monitoring System and one ahead of the Radioactive Argon Processing System (RAPS). Both systems have a condenser followed by porous metal filters. The former is sized for a flow of about 30 liters/minute (1 SCFM) while the latter can process upwards of 150 liters/minute (5 SCFM). Immediately upstream of the condensers are specially heated lengths of pipe, the preheaters, which are intended to vaporize sodium aerosol permitting efficient removal by condensation on the condenser media. Work related to recent flow restriction problems with the smaller vapor trap filters has led to a greatly improved understanding of aerosol production and vapor trap performance. Future designs will,as a result, be simpler.

Radioactive Argon Processing System, RAPS (FFTF)

The Radioactive Argon Processing System consists of a vacuum tank, two diaphragm compressors, a baffled Surge and Delay Tank, and four cryogenically cooled charcoal delay beds. Although the cryogenic unit only processes about 160 liters/minute (5.7 SCFM), blowers maintain a recirculating flow through the charcoal beds of about 700 liters/minute 25 SCFM). The effective transit time for argon through the system is about 16 hours or about nine half-lives of Ar-41. Krypton is delayed seven to eight days. The delay of xenon is much longer perhaps 10-15 weeks. No Xenon radionuclides have ever been detected in the outlet flow.

The Cell Atmosphere Processing System, CAPS, is similar to RAPS. It has compressors, vacuum and surge tanks, and two cold charcoal beds.

The CAPS cryogenic unit can act as a backup to RAPS and is usually bypassed while the remainder of the system handles essentially non radioactive gas from cells containing inert gas atmospheres.

Innovative Designs

Introduction

A recent emphasis of the U.S. nuclear power program has been toward demonstrating and developing those fundamental characteristics of sodium cooled reactor that will make such plants inherently safe. For example, EBR-II and FFTF have both been tested to demonstrate safe shutdown without immediate SCRAM and without operator action following loss of primary cooling pumps.

Two competing designs, PRISM, Power Reactor Inherently Safe Module, and SAFR, Sodium Advanced Fast Reactor will include many features that will make them inherently safe. These small modular designs are also competing on the basis of the unit cost of power. These designs will be evaluated by the U.S. Department of Energy (DOE) following their submittal in December, 1987.

PRISM

Nine (9) PRISM modules producing 135 MWe each will be grouped with three (3) turbine generators in a full size power station. The reference core uses metallic fuel with a 468°C (875°F) outlet temperature.

This pool reactor concept being developed by General Electric Corporation for the U.S. DOE uses helium as a cover gas. In this concept the reactor pressure boundary including the cover gas space is sealed during power operation.

During refueling/shutdown phases, the cover gas space is evacuated and backfilled with fresh helium by a mobile reactor cover gas purge system. The radioactive waste gas is later reprocessed away from the reactor with a system of chemical reactions, filters, and cryogenic distillation.

A cover gas monitoring system for failed fuel detection, consistent with the sealed reactor philosophy is being developed.

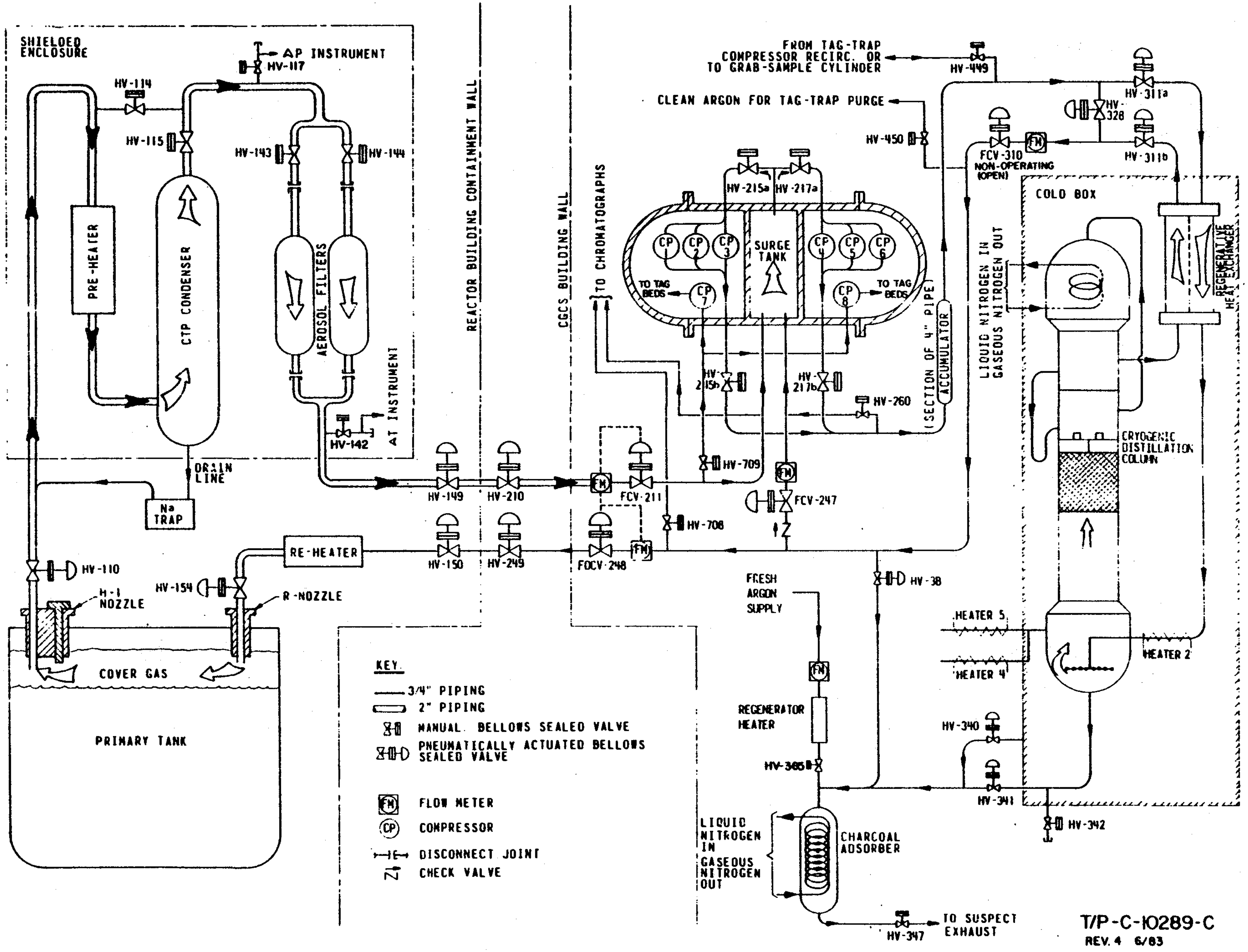
SAFR

Four (4) modules with four (4) turbine-generators each producing 335 MWe are grouped by Rocketdyne Division of Rockwell International Inc. into a single power station. The metallic fuel core will have a 510°C (950°F) outlet temperature.

Helium reactor cover gas from all of four modules will continuously be purged to a single reprocessing/sampling system. In this system two cryogenically cooled charcoal columns will strip heavier atoms from the helium. The columns will alternately process helium and be regenerated (warmed).

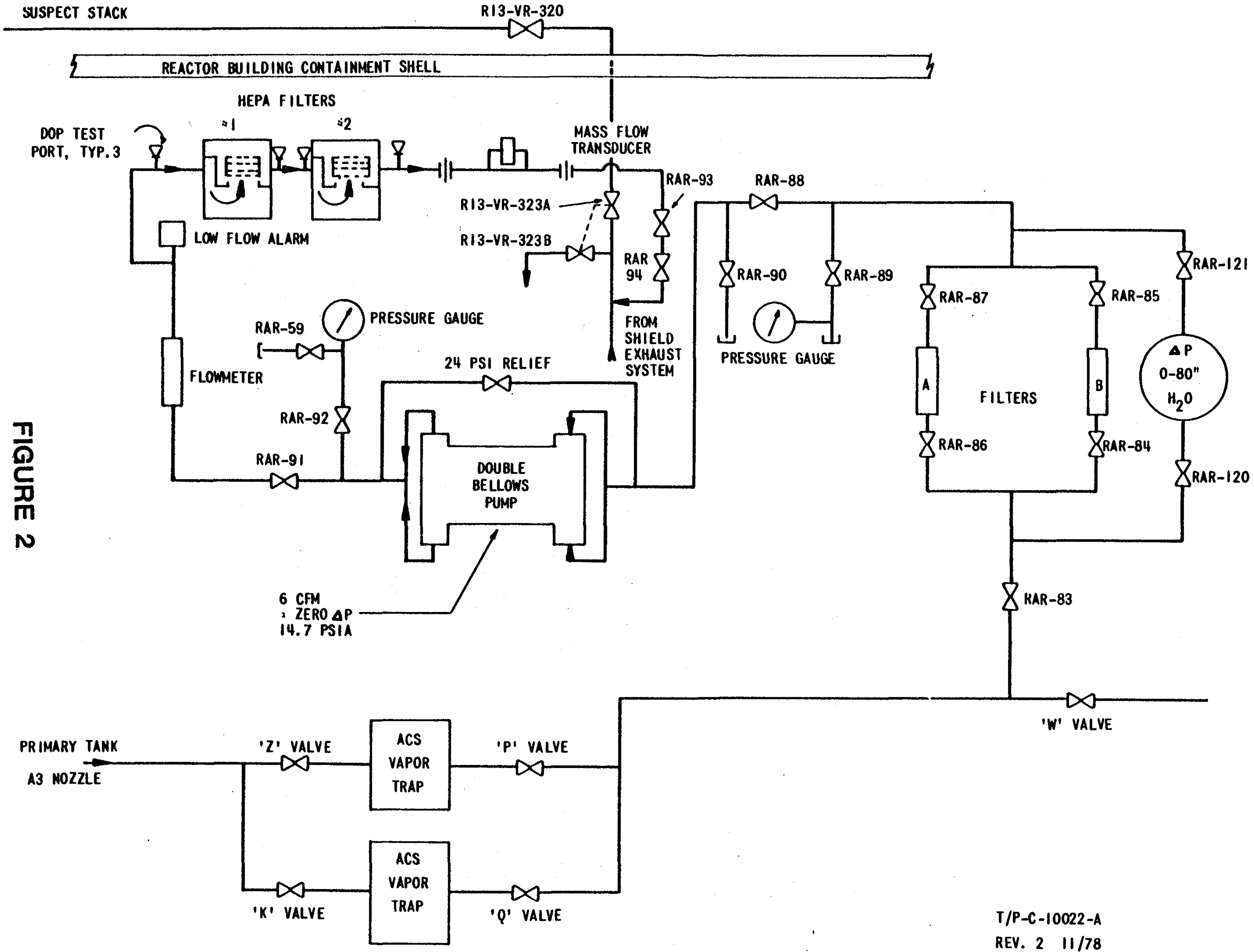
Radioactive waste gas will be further processed by large holdup tanks and charcoal beds at ambient temperature.

FIGURE 1



EBR-II CGCS MAIN LOOP (SIMPLIFIED)

FIGURE 2



EBR-II ARGON PURGE SYSTEM

FFTF COVER GAS FLOWPATHS

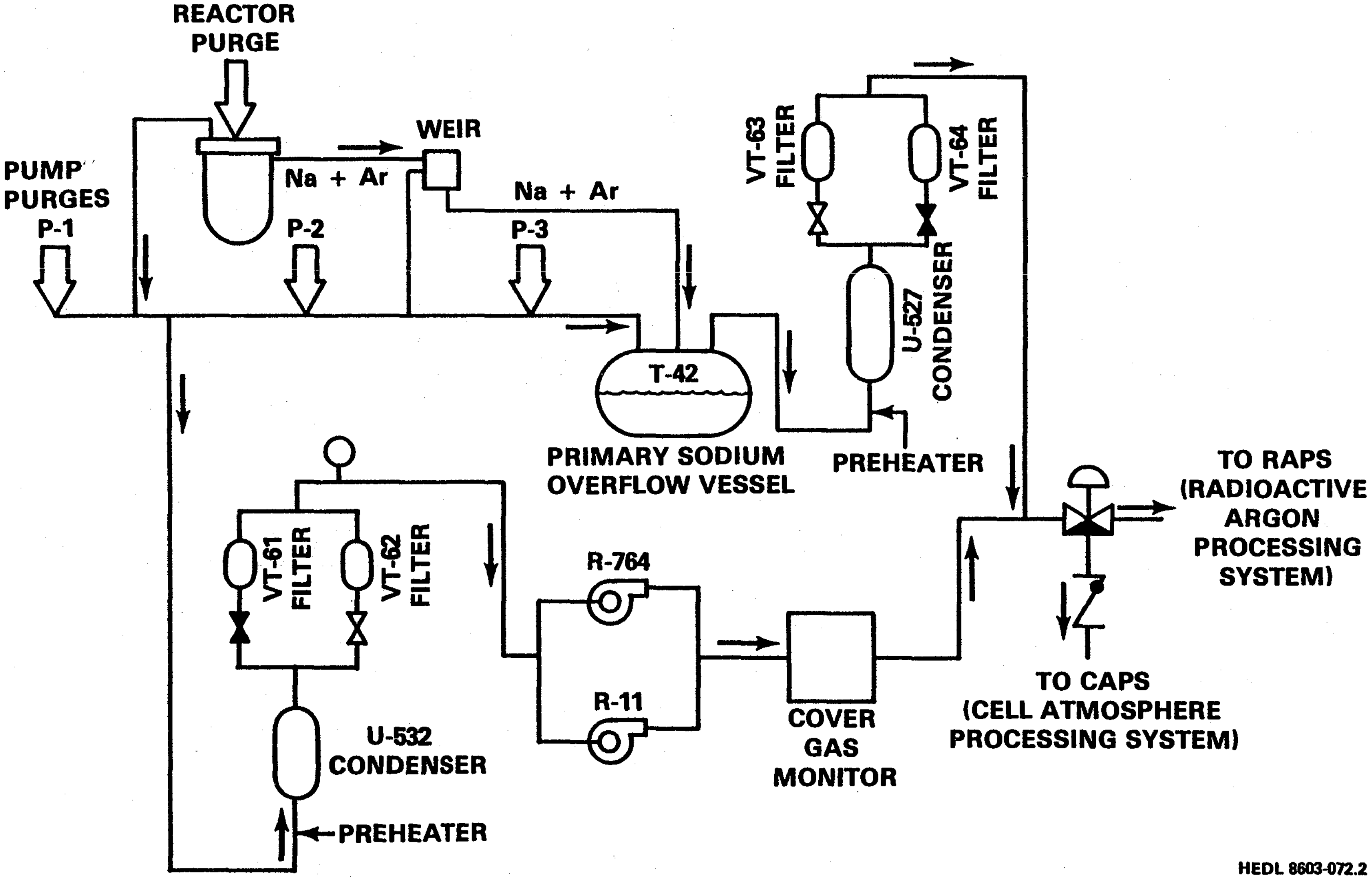


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FIGURE 3

FFTF COVER GAS PROCESSING

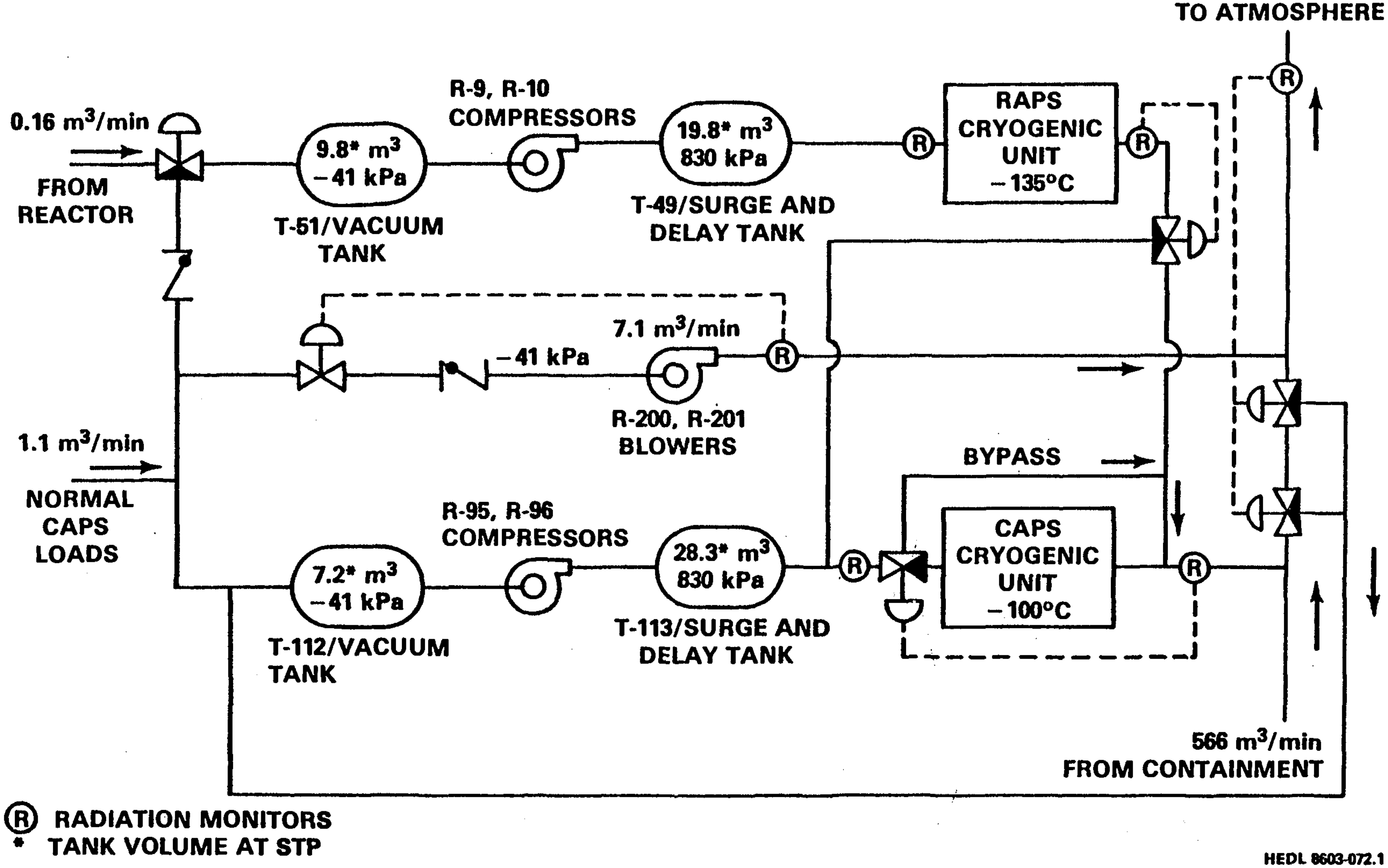

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FIGURE 4