Working Report 2007-28

A Drying System for Spent Fuel Assemblies

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ABSTRACT

The report presents a proposed drying apparatus for spent fuel assemblies. The apparatus is used for removing the moisture left in fuel assemblies during intermediate storage and transport. The apparatus shall be installed in connection with the fuel handling cell of an encapsulation plant.

The report presents basic requirements for and implementation of the drying system, calculation of the drying process, operation, service and maintenance of the equipment, as well as a cost estimate. Some aspects of the apparatus design are quite specified, but the actual detailed planning and final selection of components have not been included. The report also describes actions for possible malfunction and fault conditions.

An objective of the drying system for fuel assemblies is to remove moisture from the assemblies prior to placing the same in a disposal canister for spent nuclear fuel. Drying is performed as a vacuum drying process for vaporizing and draining the moisture present on the surface of the assemblies.

The apparatus comprises two pieces of drying equipment. One of the chambers is equipped to take up Lo1-2 fuel assemblies and the other OL1-2 fuel assemblies. The chambers have an internal space sufficient to accommodate also OL3 fuel assemblies, but this requires replacing the internal chamber structure for laying down the assemblies to be dried. The drying chambers can be closed with hatches facing the fuel handling cell. Water vapour pumped out of the chamber is collected in a controlled manner, first by condensing with a heat exchanger and further by freezing in a cold trap. For reasons of safety, the exhaust air of vacuum pumps is further delivered into the ventilation outlet duct of a controlled area. The adequate drying result is ascertained by a low final pressure of about 100 Pa, as well as by a sufficient holding time.

The chamber is built for making its cleaning as easy as possible in the event of a fuel rod breaking during a drying, loading or unloading process.

The total cost estimate, without a value added tax, for manufacturing the apparatus amounted 410 000 euros, including 95 000 euros for designing costs and 46 000 euros for installation costs.

Keywords: Spent fuel drying, spent fuel encapsulation and final disposal of spent fuel.

POLTTOAINENIPPUJEN KUIVAUSJÄRJESTELMÄ

TIIVISTELMÄ

Raportti esittelee polttoainenippujen kuivauslaitteiston suunnitelman. Laitteiston avulla poistetaan polttoainenippuihin välivarastoinnin ja kuljetuksen aikana jäänyt kosteus. Laitteisto asennetaan kapselointilaitoksen polttoaineen käsittelykammion yhteyteen.

Raportissa esitellään kuivausjärjestelmän laitteiden perusvaatimukset ja toteutus, kuivausprosessin laskenta, laitteiden toiminta, huolto ja kunnossapito sekä kustannusarvio. Laitteisto on suunniteltu joiltain osin varsin yksityiskohtaisesti, mutta varsinaista detaljisuunnittelua ja lopullisia komponenttivalintoja ei ole tehty. Raportissa kuvataan myös toimenpiteet mahdollisissa vikaantumis- ja virhetilanteissa.

Polttoainenippujen kuivausjärjestelmän tehtävänä on poistaa nipuista kosteus ennen nippujen sijoittamista loppusijoituskapseliin. Kuivaus suoritetaan tyhjiökuivauksena, jossa alipaineen vaikutuksesta nippujen pinnalla oleva kosteus höyrystyy ja imeytyy pois.

Kuivauslaitteistoja on kaksi kappaletta. Toinen kammioista on varustettu vastaanottamaan Lo1-2 polttoainenippuja ja toinen OL1-2 polttoainenippuja. Kammioiden sisätila on riittävä vastaanottamaan myös OL3 polttoainenippuja, mutta tällöin kammion sisäosa johon kuivattavat niput ladotaan, pitää vaihtaa. Kuivauskammiot voidaan sulkea kansilla, jotka sijaitsevat käsittelykammion puolella. Kammiosta pois pumpattu vesihöyry kerätään hallitusti talteen ensin lämmönvaihtimella kondensoimalla ja lisäksi kylmäloukkuun jäädyttämällä. Alipainepumppujen poistoilma johdetaan vielä varmuudeksi valvotun alueen ilmastoinnin poistokanavaan. Riittävä kuivaustulos varmistetaan alhaisella, noin 100 Pa loppupaineella sekä riittävällä pitoajalla.

Kammio on rakennettu siten, että sen puhdistus olisi mahdollisimman helppoa, jos polttoainesauva rikkoutuu kuivausprosessin, täytön tai tyhjennyksen aikana.

Laitteiston valmistuksen arvonlisäverottomaksi kokonaiskustannusarvioksi muodostui 410 000 euroa, josta 95 000 euroa suunnittelukustannuksia ja 46 000 euroa asennuskustannuksia.

Avainsanat: Käytetyn polttoaineen kuivaus, käytetyn polttoaineen kapselointi ja käytetyn polttoaineen loppusijoitus.

PREFACE

The working report describing the drying system for fuel assemblies was prepared at Afore Oy, ordered by Posiva Oy.

The designing work was carried out mainly with Solidworks 3D-software and for some images was used Photoworks-software, to produce photorealistic images. Also some FEM-calculations were made with COSMOSXpress-software during the design process.

Mr Mikko Suikki acted as the project manager in Afore Oy. Mr Vesa Henttonen and Mr Mika Warinowski participated in the project.

Mr Juha Nieminen, Fortum Nuclear Services Oy (FNS), did the process calculations with APROS-software (chapter 5). APROS –model was made by Aino Ahonen/FNS. Harri Kontio and Tapani Kukkola/FNS participated as commentators.

Mr Nils-Christian Wikström of Posiva Oy acted as the orderer and the project supervisor. Special thanks also for the other members participating in the development work, Mr Petteri Vuorio, Posiva Oy, Mr Heikki Raiko (chapter 8.5), VTT Processes (VTT) and Mr Tapani Kukkola, FNS.

The report was translated into English by Paul Suominen.

1 INTRODUCTION

The report on a drying system for fuel assemblies presents a plan regarding research and development work carried out for a drying apparatus of fuel assemblies, whereby the moisture left in the assemblies during intermediate storage and transport is eliminated prior to placing the assemblies in a disposal canister for spent nuclear fuel. The apparatus is set up in the immediate vicinity of the fuel handling cell of an encapsulation plant. The fuel handling cell is a radiation-shielded chamber, in which the fuel assemblies can be handled safely by means of a remote controlled fuel handling machine (Nieminen 2006, Kukkola 2003 and 2006). In the earlier documents, the drying apparatus has been referred to as an autoclave but, since the process does not involve the use of a high temperature typical of autoclaving, the apparatus was renamed simply as a drying system for fuel assemblies.

Fuel assemblies come in three different lengths and have cross-sections characteristic of each type (Lo1-2, OL1-2 and OL3) (Raiko 2005). This is observed in drying chambers by providing the chamber interior with a rack suitable for the type of fuel. Initially, one of the chambers is equipped with a rack for Lo1-2 fuel assemblies and the other with a rack for OL1-2 fuel assemblies. Subsequently the other one or, if necessary, both chambers can be equipped with a rack which is compatible with OL3 fuel assemblies. The racks are of such a design that the positions of fuel assemblies are consistent with the same orientation as the interior of a disposal canister for spent nuclear fuel and the top ends of fuel assemblies stay in all cases at the same height. This simplifies the maneuvering actions of a fuel handling machine.

The purpose of drying is to remove the water left in fuel assemblies as thoroughly as possible in order to eliminate its compromising effect on the long-term safety of a spent fuel canister. Drying is performed as a vacuum drying process, which is a simple and effective way of removing water. The vacuum drying process requires neither heating of fuel rods nor the use of a powerful blast of air, resulting in lowest possible risks of damaging the rods or spreading the particles. To be functional, vacuum drying requires a vacuum instrumentation, including not only pumps but also a vacuum pipework, necessary gauges, a particle filter, a condensing heat exchanger with accessories, as well as a so-called cold trap.

The drying process was ascertained by calculating it with APROS software, which has been developed for the simulation of power plant processes. Included in the calculation were several various cases to enable assessing the process as regards its sensitivity to changes.

2 BASIC REQUIREMENTS

The basic requirement for designing the drying system comprises as follows:

- The drying chambers' fuel racks must have sufficiently loose tolerances for actually enabling the introduction of a long and heavy fuel assembly into a drying chamber. The sealings of a chamber hatch must not be damaged and the fuel assembly must not become stuck in the support structure.

- The system's devices must not release or spill anything onto the fuel assemblies.

- As much as possible, the actuators must be located outside the actual drying chamber room for enabling maintenance. The concrete wall in the chamber room has a thickness of about 1200 mm and its adjoining rooms have space for accommodating technical equipment.

- The wall penetrations of a drying chamber room must be impervious to radiation and as airtight as possible. (The penetrations are required to fulfill a so-called double-sealing principle, i.e. the breakup of an individual seal must not compromise the imperviousness of a penetration.) The air pressures of a fuel handling cell, a drying chamber room and adjoining rooms must be adjusted so as to direct possible air leaks always toward the fuel handling cell, in other words from cleaner to dirtier spaces.

- Electromechanical actuators are preferred to avoid oil leaks typical of hydraulic systems.

- Equipment inside the fuel handling cell and the drying chamber room must be designed and sized for a maintenance interval of about 5 years.

- Considerations in selecting materials for inside the fuel handling cell and the drying chamber room must include not only normal operating conditions and a 5-year maintenance interval but also both a radiation load and a resistance to chemicals and mechanical washing used for decontamination. Stainless steel or epoxy-painted surfaces are recommended. In the process of drying fuel assemblies, the apparatus will be subjected to a major radiation load, since the fuel assemblies are at this point devoid of any radiation shield.

- The equipment must be designed and built so as to enable its cleaning of contamination as easily as possible.

- The need for maintenance and replacement of parts must be minimized.

- All devices needed in normal operation must lend themselves to remote control from an operation control room.

- All actuators must be sensor-equipped in such a way that the status thereof is clear in real time at the control site.

- The electrical systems of both sensors and actuators must be backed up for the eventuality of a power failure.

- Despite a loss of power, the system shall stay in a safe state, i.e. the equipment must come to a standstill safely in such a situation.

- Fire risk must be low and the same applies to fire loads.

- The apparatus must have a maximum capacity of 100 canisters a year, in normal operation about 40 canisters a year.

- There must be reliable methods available for solving all the postulated problem cases, to solve and fix them.

- The apparatus' nuclear safety class is 2 for the fuel rack and 3 for other parts.

- The drying chamber is not a pressure vessel as defined in general standards for pressure vessels, so its design and manufacturing process need not comply with the valid pressure vessel standard SFS-EN 13445. However, the discussed standard does include a mention that pressure vessels for nuclear engineering shall be subject to specific regulation. According to the instruction YLV 3.1 Pressure vessels for nuclear facilities, issued by the Finnish Radiation and Nuclear Safety Authority (STUK), the safety-classified pressure containers, whose internal pressure above the liquid level is lower than or equal to 0.5 bar overpressure, shall be subject to the application of the instruction YLV 4.2 Steel structures for nuclear facilities, whereby, according to this source as well, the structure can be regarded as a normal steel structure. In consideration of its safety significance, it is nevertheless advisable to design, manufacture and document the apparatus in the way of a pressure vessel for ensuring a sufficiently high-quality final result.

3 DESIGN VALUES

The process of rating a drying capacity for the drying system has been based on a fuel assembly of the type OL1-2, having a total mass of 292-331 kg. The fuel assembly measures are 139x139x4398 mm. The fuel assembly does not have formations for water deposits. The assembly has a total area of about 18 m^2, of which 12 m^2 is in fuel rods, 5 m^2 in flow channels, and about 1 m^2 in other structures. Vertical surfaces make up about 95% of all surfaces.

Consequently, the total mass of 12 assemblies subjected to drying is in the order of 3600 kg and has a decay heat power of 1700 W. When delivered to drying, the assembly has a temperature of at least +20°C and probably less than +50°C. The reference values of all fuels (Lo1-2, OL1-2 and OL3) subjected to drying are listed in table 1 (page 14).

There are no special arrangements for fuel rods broken during transport or handling. The maximum amount of water that a single rod can accommodate is only 50 g, so even if all fuel assemblies fitted in a single canister should contain water (1 rod/assembly), the maximum water amount of 600 grams per canister would not be exceeded (Pastina & Hellä 2006). The previously identified leaking rods shall be handled separately.

Experimental measuring indicated that the water retaining capacity of a vertical steel surface is about 20-50 g/m^2, depending substantially both on a draining time and on a type of surface. Multiplication of this value by a total surface area produces the amount of water of 4-11 kg for a batch subjected to drying. The applied design value will be 7.5 kg of water. The assessment includes a major inaccuracy, since the draining of water off the surfaces of a fuel assembly is highly dependent on the surface type of fuel assemblies, the shape of spacer grid, as well as on the thickness of a crud layer. In addition, the amount of removable water is influenced not only by draining but also by the efficiency of ventilation in the fuel handling cell, as well as by the evaporating activity of decay heat power before the drying process has even started. However, the chosen system is quite insensitive to the amount of removable water, the drying time being the only aspect that changes according to the amount of water.

The drying chamber develops an internal volume of about 4 m^3. The lowest chamber pressure was determined to be 100 Pa (abs) and its highest pressure to be 5 kPa above atmospheric pressure.

4 DESCRIPTION OF THE DRYING SYSTEM

4.1 Layout environment

The apparatus will be located in the vicinity of the fuel handling cell of an encapsulation plant, for the most part underneath the handling cell floor. The handling cell further houses a docking station for a spent fuel transport cask, a docking station for a spent nuclear fuel disposal canister, as well as necessary manipulators both for fuel handling and maintenance operations.

Fig. 1 shows a part of the fuel handling cell, which houses fuel drying chambers and a spent fuel canister docking station with its accessories. Fig. 2 visualizes some of the spaces below the fuel handling cell, housing the actual drying chambers as well as vacuum equipment and accessories associated therewith. Both drying chambers are provided with apparatus units designated therefor, just one of said apparatus units being depicted in fig. 2. Both apparatus units are divided into three separate-level spaces according to radioactivity. The actual drying (vacuum) chambers are housed inside thick concrete walls for preventing the high radiation of fuel rods from denying access to other spaces. The bottom level room houses pressure sensors for the chamber, a condensing heat exchanger, as well as a cold trap. The radiation level of this space may increase slightly as a result of particles left in the pipework and vapours gathered in the heat exchanger, in the cold trap and inside the duct. The adjoining space houses vacuum pumps and a mechanical filter, which should remain relatively clean. The higher-level space, which has no contamination risk, houses refrigeration compressors required for the heat exchanger and the cold trap. A layout drawing for the apparatus units is presented in appendix 1.

Figure 1. *A view of the handling cell. Drying chambers are visible on the sides and the spent fuel canister docking station, the protective cone, and the atmosphere changing cap furthest in the back.*

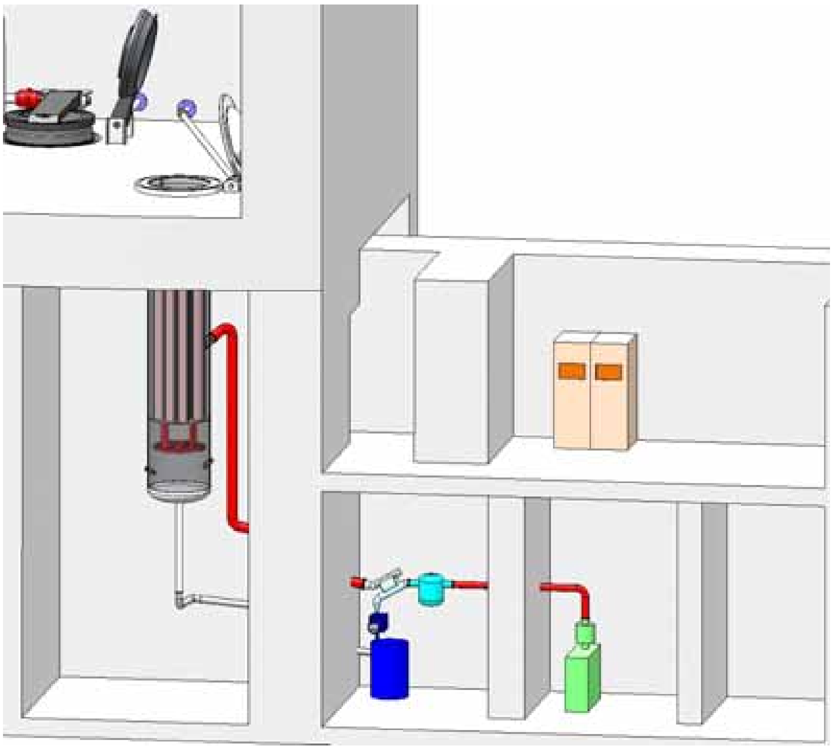

Figure 2. *Equipment for the drying system. OL1-2 drying chamber (as transparent) with its rack on the left, condensing and vacuum equipment at the bottom, as well as refrigeration equipment on the upper right. The figure is a section through the interior of an encapsulation plant.*

4.2 Drying chambers

The drying chambers are cylinder-shaped tanks (ø1000 x 5000 mm) manufactured in stainless steel, having a wall thickness (10 mm) designed to withstand the intra-tank vacuum. The bottom end comprises a normal pressure vessel base, but the top end is provided with an openable hatch that can be opened and closed, as necessary, by means of a gear motor mounted outside the fuel handling cell. The opening mechanism for hatches is similar to what is used at the spent fuel canister docking station (Suikki 2005). The chamber has a mass of about 2000 kg and that of the hatch is about 400 kg.

Except for the hatch element, the drying chamber is located in a space below the fuel handling cell. The top part rim is a robust machined ring with a height of 100 mm from the floor and with a sealing face for a hatch seal. The sealing face is located on the outer edge of the collar for protecting it from possible collisions in the process of handling fuel assemblies and for making its cleaning as easy as possible, if any impurities fall off the fuel assemblies. The seal is attached to the outermost rim of the hatch for placing it as far away as possible from radiation emitted by fuel assemblies during the course of drying. The chamber base is provided with a drain fitting needed in chamber washing. The drain pipe is in size DN 100 for allowing also the passage of possible fragments released from fuel assemblies. The pipe is fitted with a leak-proof valve, and wash waters are conveyed to the facility's recovery system for active waters. Extending from a side of the chamber to vacuum pumps is a pipe of DN 160 mm in diameter. The fitting opening will be directed in such a way that falling particles or wash water cannot enter the vacuum duct.

The internal chamber surface must not include any protrusions as those could prevent the installation of a rack for fuel assemblies.

The chamber is provided with fittings for temperature sensors, the number of which can be several. It is advisable to set up sensors at various heights as well as on various sides of the chamber for reliable tracking of temperature changes taking place during the process. A suitable number would be for example four sensors mounted on various sides of the chamber at two different heights. The attachment fittings for sensors are also directed obliquely upwards in order not to collect particles or wash water. Being subjected to a high radiation load, the types and cabling systems of sensors must be selected very carefully. A working solution for the sensor could be a thermocouple which, being a full-metal component, is quite durable. In terms of process control, it would be beneficial if pressure could also be measured directly from the chamber, but in this respect it is probably necessary to settle for a compromise as pressure sensors are hardly able to tolerate the chamber's radiation.

Since the chamber cannot, in any condition, develop a notable overpressure, the tank does not constitute a structure that would be subject to the general pressure vessel standard. Both the chamber hatch design and a relief valve installed in the ductwork preclude the increase of the internal chamber pressure.

4.3 Fuel racks

Inside the chamber is fitted a rack of stainless steel, which accommodates a number of fuel assemblies consistent with the number fitting in a spent fuel canister. The rack is replaceable and available in designs specific for each type of fuel. The rack has its orientation consistent with that of the internal structure of a spent fuel canister for a loading operation as straightforward as possible from the dryer to the canister.

Fig. 3 displays racks called for by various types of fuel. The rack hangs in a chamber by its head flange supported by four brackets present at the top of the drying chamber. One of the brackets further includes a vertical guide for a correct orientation of the rack. This guide is visible in fig. 10. The rack has its bottom flange provided with four guide faces, the arrangement of which does not preclude installation of the rack. The lowermost component is a plate supporting the fuel assemblies during a drying process by the bottom end thereof. The racks are provided with eyebolts for lifting the same out of the chamber as necessary. The rack lengths without eyebolts are (Lo1-2, OL1-2 and OL3) 2900 mm, 3980 mm and 4450 mm, respectively. The rack masses are approximately 800 kg, 1200 kg and 1300 kg, respectively.

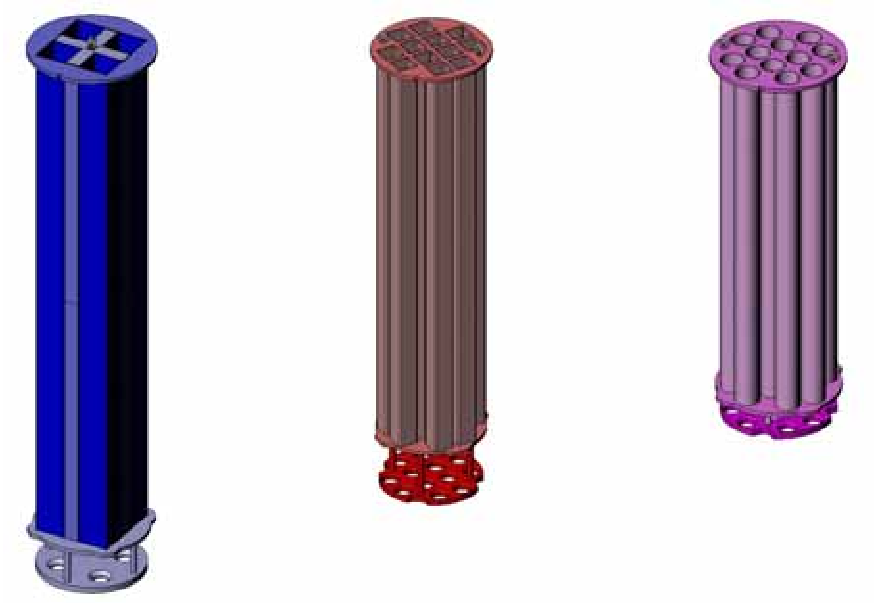

Figure 3. *Racks for various types of fuel assemblies. From left to right OL3, OL1-2 and Lo1-2.*

A fuel handling machine (Kukkola & Rönnqvist 2006) present in the fuel handling cell enables in principle the lifting of a rack out of the drying chamber, e.g. for repair or maintenance. However, the handling machine's reported maximum lifting capacity (1000 kg) falls a little short of what is needed for current racks (OL1-2 and OL3), so either the rack designs or the handling machine's lifting capacity must be modified.

4.4 Vacuum equipment

The vacuum system consists of a vacuum pipework with its valves, a condensing heat exchanger, a cold trap, and vacuum pumps. Also involved are measuring instruments and regulation and control systems necessary for the vacuum system. A flow diagram for the system is shown in appendix 2.

The vacuum pipework is a pipe system made of stainless steel and its diameter varies within the range of DN 40 to DN 160 mm. The pipework is provided with valves and dismountable flanges for enabling the removal of relevant components of the pipework for maintenance and cleaning. During maintenance operations, the valves located on both sides of the components reduces the spreading of possible contamination inside the pipework. The pipe includes also a vacuum discharge valve, enabling a controlled discharge of the drying chamber's vacuum after evacuation. The valve is located so that the supply air passes through a condensing heat exchanger, which also makes the supply air drier. It is advisable to construct the pipework from components which inherently discourage the accumulation of impurities inside the pipework.

The heat exchanger is a so-called plate heat exchanger, which is manufactured in acid-proof stainless steel. In such a device, the process medium and the cooling liquid are separated from each other by means of thin corrugated plates. The device is extremely compact and basically maintenance-free as the structure is generally sealed by welding and has no moving parts. Fig. 4 illustrates a heat exchanger from one manufacturer. In condensation service, the device should be set at a slight inclination in order to have an outlet fitting for condensed water in the lowermost position. Also advisable is to select a flow direction for steam in view of facilitating the migration of condensed water to the outlet point. A heat exchanger intended for use in food industry would make a good choice also in the present case for having the internal structure thereof optimized in terms of cleaning.

The heat exchanger has a water pump connected to its outlet fitting and the pump has a non-return valve connected to its delivery side. The volume flow rate of pumped water is not very high, yet the pump must be able to produce a sufficient pressure for propelling the condensed water out of the vacuum pipe through the non-return valve to normal atmospheric pressure. Since water flows gravitationally into the pump, the pump's suction power is of no consequence despite the fact that the operation proceeds in a vacuum environment. The pump of choice will be either a model which tolerates running dry, or else the suction line will be fitted with a simple surface level measurement to control operation of the pump. A peristaltic pump would provide a simple solution both in terms of achieving a running dry feature and precluding a leakage of pressure through the pump in a wrong direction, even without a non-return valve.

Figure 4. *Plate heat exchangers. Construction is compact and sealed by welding. Heat exchanger has a diameter of 240 mm and a thickness of about 270 mm.*

The heat exchanger includes also extra fittings, whereby the apparatus can be cleaned by rinsing as necessary. To be functional, the exchanger also requires a suitable cooling liquid, which in this case would be at about +5 degrees, making it as cold as possible for condensation, yet with a low risk of forming ice. In principle, the cooling could be performed even with cold tap water, but a better control and safety can be achieved by using a closed circulation with cold oil as a possible fluid. The system may also include a so-called cold accumulator that can be used for equalizing performance fluctuations during a process, such that the actual refrigeration compressor need not be oversized. Another benefit of cold oil is a lesser risk of corrosion because, even though the exchanger is constructed from basically corrosion-free material, pit corrosion may be caused by water in certain conditions. On the vacuum side of a heat exchanger the corrosion risks are minimal because of a low utilization rate of the apparatus as moisture is only present during early stages of drying and during a loading process.

The cold trap is a metal tank, having its surfaces chilled either by means of liquid nitrogen or a refrigeration compressor. The flowing air is guided to travel along the cold surfaces, whereby all moisture and possible hazardous fumes and gases condense and freeze on the cold trap surfaces. Since the storage and use of liquid nitrogen in a plant of this type is a rather inconvenient procedure, a compressor will be used in this instance. The use of a compressor is justified also for the reason that, as its main function is to collect water vapour, the trap temperature need not be extremely low, but e.g. -30°C could be enough. On the other hand, not even the performance of this trap need be very high either, most of the vapours becoming condensed by a heat exchanger upstream thereof. For this reason, the system keeping the trap cold need not to be of top performance and normal refrigeration compressor technology is likely to suffice. This represents a significant cost saving as opposed to so-called Cryo-pumps. The final construction will become clear as the designing progresses. The cold trap has also fittings, enabling its flush cleaning. Since traps available in the marketplace come in relatively small sizes, the device must be designed and manufactured for this very purpose.

The pumps used in the system comprise for example a combination RSV 601 B + 2063 from Alcatel, which is capable of providing a sufficient volume flow rate and terminal pressure for bringing the process to completion. The combination comprises a Root's pump along with a rotary vane pump. The pumps are pre-assembled in the rack for easy maintenance and, if necessary, even transport. The unit measures are 1250x365x980 mm (length x width x height). If necessary, the pumps can also be provided with an intake air filter. The filter has a function of minimizing the number of particles migrating into the pumps and to ensure thereby a long service life. Since the number and migration of particles in a vacuum pipe are difficult to assess beforehand, it is advisable to install such a filter in the system, at least for the start. The filters available from manufacturers are two-phase filters, built in an openable enclosure and including a washable or replaceable element of stainless steel wire mesh. According to manufacturers, the filters only cause a few percent increase in pumping time. The particle filter's clogging rate is monitored by means of a differential pressure sensor.

Near the pumps are also pressure sensors for measuring the level of vacuum. Since the terminal pressure is not extremely low, it is sufficient to use capacitive sensors in the system. The sensors are of a transmitter type, so display units can be placed in the operation control room. For a more reliable tracking of the process, the pressure sensors can also be mounted on the end of a pipe closer to the drying chamber for a more reliable verification of the vacuum existing in the very drying chamber. A problem is that these sensors may be contaminated by particles emerging from the chamber, resulting in more inconvenient maintenance thereof.

4.5 Control system

The process is controlled from an operation control room, in which all essential control and display devices are assembled. Actuator controls are electrically operated and, if necessary, some process operations can also be automated by means of a programmable logic. The motors for drying chamber hatches are controlled by means of frequency converters and the status thereof can be monitored by means of absolute angle sensors. Other aids for operating personnel include an adequate number of thermometers for supervising temperature of the pipework and cooling liquids, display units for pressure sensors, as well as necessary remote controlled regulation valves. Also measured is the volume of water condensed and pumped out of the heat exchanger.

5 CALCULATION OF THE DRYING PROCESS

5.1 Introduction

The work comprised modelling a vacuum drying process for fuel assemblies Lo1-2, OL1-2 and OL3, surveying a progress of the process, and making a sensitivity review for some of the process parameters.

The process was modelled and simulated by means of a process simulation program entitled APROS (Advanced Process Simulation Software), developed jointly by FNS and VTT (Technical Research Centre of Finland). The program is used for example in the automation renewal of Loviisa nuclear power plants as a basis of training and test simulators (Porkholm et al. 2005). In addition, it has been used for modelling the steam processes of nuclear facilities and conventional power plants (Porkholm et al. 1997), as well as severe accidents in nuclear facilities (Plit et al. 2000). The calculation was conducted with the APROS program version 5.07.06.

5.2 Calculation model

Fig. 5 illustrates a calculation model worked out with APROS and representing a drying process for fuel assemblies. The model consists of a drying tank, a condenser, a vacuum pump, as well as a pipework linking the same. The thermohydraulic solution applied in the model has been the 6-equation APROS model for a mixture of water vapour and air. In addition to process equipment, fig. 5 depicts measuring and regulation equipment that was used for controlling the pump and regulating the condenser surface.

The rods of fuel assemblies are each represented as an individual heat structure. The gap present between a fuel pellet and a protective shell had supposedly become closed by expansion. The estimated volume of water for an OL1-2 drying batch was 7.5 kg. Respectively, the volumes of water for other fuels were calculated in proportion to the surface areas of fuel rods for a more conservative result. Table 1 presents the values used in the calculation.

Table 1. *Numbers of assemblies and rods used in the process calculation, surface areas, calculated volume of water, and decay heat power for a batch of fuel to be dried.*

Fuel	Assemblies pcs	Fuel rods total/pcs	Fuel rods' total area/m²	Fuel assemblies' total area/m²	Amount of water liters	Decay heat power Watts
Lo1-2	12	1512	108	144	5.6	1370
OL1-2	12	1080	144	216	7.5	1700
OL3	4	1060	144	180	7.5	1830

Both drying tanks have the same size. Any of the three fuel assembly types can be fitted in the tank. The drying tank has been modelled as a cylinder-shaped thermal structure with a mass of about 2100 kg. The material used for the drying tank was stainless steel.

The racks were also modelled with a cylinder-shaped heat structure. The cylinder has a mass of about 1200 kg. The material used in the rack was stainless steel.

The flow channels or end pieces have not been modelled as the masses of these elements were not considered to have a significant impact on the calculation result.

The outer tank surface has a constant convective heat-transfer coefficient of 10 $W/m^2/K$. Other heat-transfer coefficients are calculated by the program.

The employed condenser was a tubular heat exchanger, the software offering no other heat exchanger options for condensing steam. The pipes' condensing side was determined to have initially a heat transfer area of 5 m^2 (50 pipes). The condenser has a jacket side volume of about 17 l. Cooling water arriving in the condenser has a temperature of 5°C and a mass flow rate of 1 kg/s in the pipes. The condenser has its condensate collector fitted with a valve, by the adjustment of which the condensate collector's surface level is maintained constant during boiling. This is to make sure that the condensed water has no way of covering the heat transfer surfaces. Prior to the commencement of final pumping, the condenser is totally drained of water for precluding the re-boiling of water left in the condenser as the pressure is falling.

The cold trap was not modelled, because the modelling of surfaces below 0°C could not be managed with the current program version. This was not considered a major flaw, because the condenser was found to condense the steam completely in the model.

In the basic case, the pipework has an inner diameter of 150 mm and the pipes have a length of 10 m both between the tank and the condenser and between the condenser and the pump.

At the outset, the drying tank has a pressure of 0.1 MPa and the mass of air makes up a portion of 98% in the tank, the remaining 2% being water vapour. The initial temperature of fuel rods is 25°C, the initial temperature of fuel racks and the drying tank being 30°C. The tank has a constant ambient temperature of 30°C.

Pumping was performed according to the characteristic curve of Alcatel RSV 601 B + 2063. The pump is modelled with a pipe, to which was fed a flow rate of gas as a boundary condition.

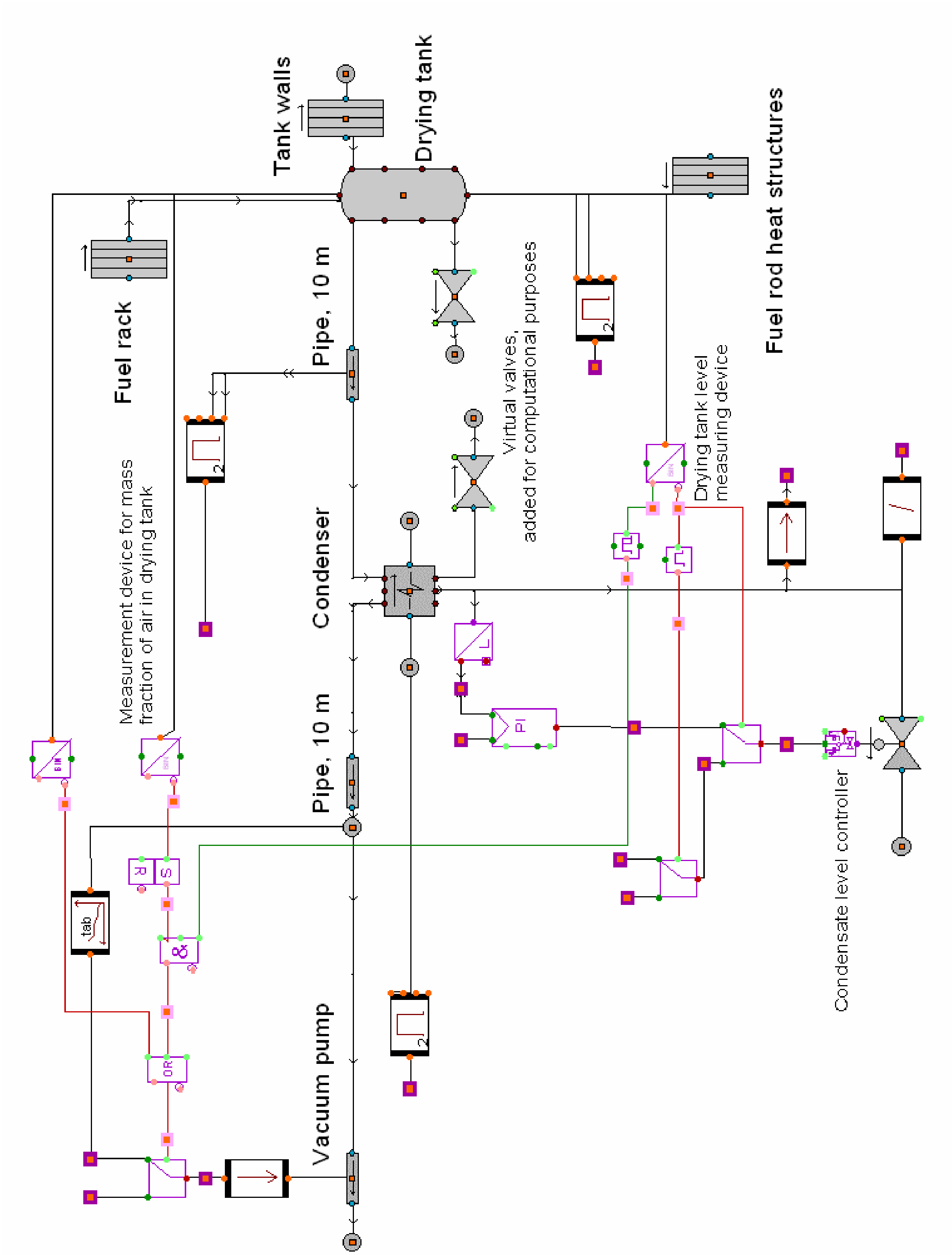

Figure 5. *APROS model of a drying process for fuel assemblies.*

5.3 Limitations of model

The current APROS program version takes no account of the impact of gases dissolved in water. A release model for dissolved gases is due for the next version of the program. Admittedly, the proportion of dissolved gases is slight and most of the gases escape from water probably as early as during the initial pumping.

The steam pressure tables of APROS run out at 625 Pa, so a decrease of the tank pressure e.g. to 100 Pa could not be modelled. Pumping was terminated as soon as the tank pressure had fallen to 700 Pa.

The type of heat exchanger and the way of pumping condensation water are slightly different from those described in the presented apparatus.

5.4 Progress of drying process

In the reference case, a vacuum pump starts sucking in a mixture of air and water vapour from a drying tank. The tank pressure falls in 15 minutes to about 3000 Pa, whereby the water starts to boil. The pump is stopped as the portion of mass provided by air in the tank falls to 1%. Water is boiling at an almost constant pressure and temperature. During boiling, the tank pressure is solely dependent on water temperature.

The condenser performs all of the pumping of steam during the boiling of water. The mass flow from tank to condenser equalizes to an almost constant rate as the time passes. The mass flow increases momentarily at about a 15-minute mark as the boiling begins. This spike is a result of the fact that, for a moment, steam is pumped simultaneously both by the pump and the condenser. The process can be seen in the curves of figs. 6-9.

When 0.01 dm^3 of water is left in the tank, the condenser is drained out completely, the pump is re-started, and the tank pressure is dropped to the program limit of 700 Pa.

5.5 Calculation results

In the case of each fuel assembly, the drying process model was run through 5 times at various parameters, so that the total number of runs amounted to fifteen. The reference model of choice was a model that was considered the best representative of the progress of a drying process as regards all three fuel assemblies.

5.5.1 Reference models

The reference model of choice for all fuel assemblies was a model with a 10 m pipe between the condenser and the tank. In this model, the condenser and drying tank can be located in different rooms. In the reference model, the tubular heat exchanger featured 50 pipes, representing a heat transfer area of 5 m^2.

In the case of all three types of fuel, the tank was pumped to the pressure of about 3000 Pa in 15 minutes. In the case of Lo1-2, the boiling time was about 3.6 h, in the case of OL1-2 it was 3.8 h, and in the case of OL3 it was 3.6 h. After the boiling was finished, the tank pressure fell in all cases to the pressure of 700 Pa in about five minutes. In the case of Lo1-2, the total time for drying was 3.9 h, in the case of OL1-2 it was 4.1 h, and in the case of OL3 it was 3.9 h.

5.5.2 Sensitivity analyses

Efficiency of the heat transfer process

Heat transfer efficiency values for the surfaces of fuel rods were changed and the effect on drying speed was tested. The reference case of choice was a case, in which heat transfer coefficients were found realistic and representative of a real condition with the transfer of heat to the outermost surfaces of a fuel assembly proceeding slowly. The program-calculated heat transfer coefficients varied in the reference case during the calculation process within the range of 0.1...1440 W/m²/K. The reference case was compared with a case, in which the heat transfer efficiency was 10-fold (in figs. 'HTE 10%'). The model was found quite stable since the program did not crash as a result of such a huge change in the heat transfer efficiency. The temperature of a gas present in the tank rose faster. The values of heat transfer coefficients rose to unrealistically high figures. Depending on a case, the 10-folding of heat transfer speeded up the drying process by 0.6-0.8 h. This led to a conclusion that even a major change of heat transfer efficiency does not have a decisive effect on the drying time.

Surface area of the condenser

The significance of a condenser's surface area was studied by modifying the tubular heat exchanger with respect to the reference model with a 20% increase and a 20% reduction in the number of pipes or tubes (60 tubes and 40 tubes). In the case of Lo1-2, the drying time of 40-, 50- or 60-tube models is almost equal. In the case of OL1-2, the drying time of 50- and 60-tube models is almost equal, but the 40-tube one shows a drying time which is about 5 minutes longer. In the case of OL3, the drying time of a 60-tube model with respect to a 50-tube one is shorter by 8 minutes and that of a 40-tube model is longer by 8 minutes.

Location of the condenser

The condenser was relocated by modelling a pipe of 0.5 m in length between the condenser and the tank (condenser near tank), replacing a 10 m pipe. The drying time was found to be about 5 minutes shorter for all three fuel types. The flow resistance in the pipe is at such a low level that there was no significant change of mass flow rate in the pipe.

Figures 6-9 illustrate fuel-specific reference models. Sensitivity analyses are presented in appendix 3. The figures show a pressure curve in the tank, a water volume in the tank, a temperature change of fuel rods, and a temperature change of a gas present in the tank.

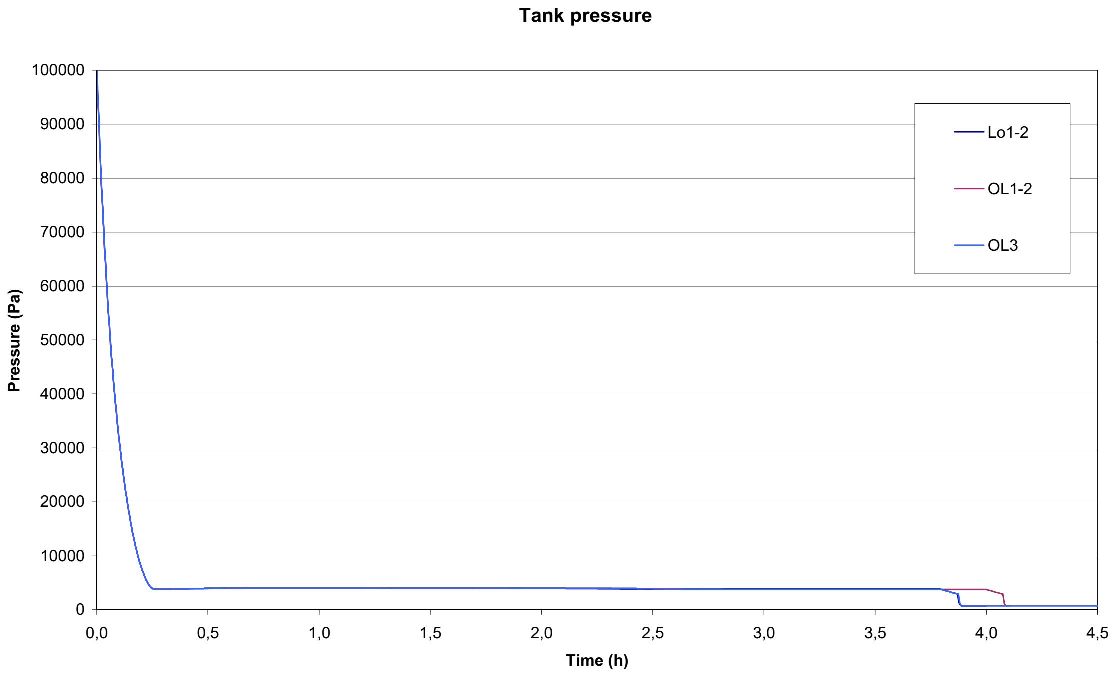

Figure 6. *Pressure in drying tank in Lo1-2, OL1-2 and OL3 reference models.*

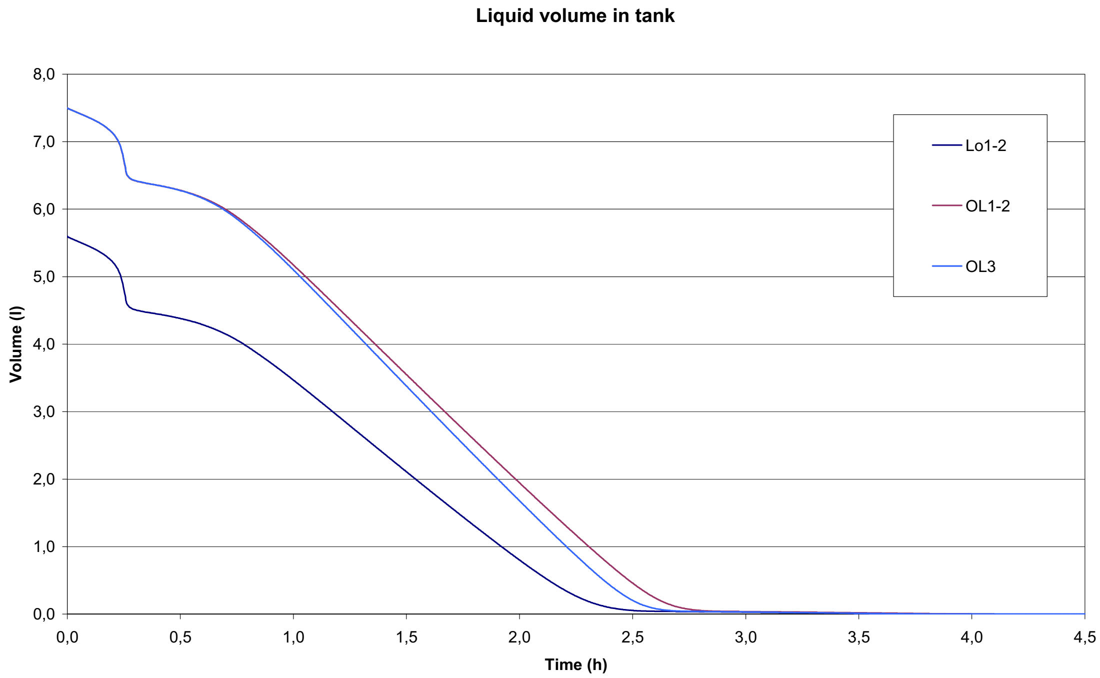

Figure 7. *Water volume in drying tank in Lo1-2, OL1-2 and OL3 reference models.*

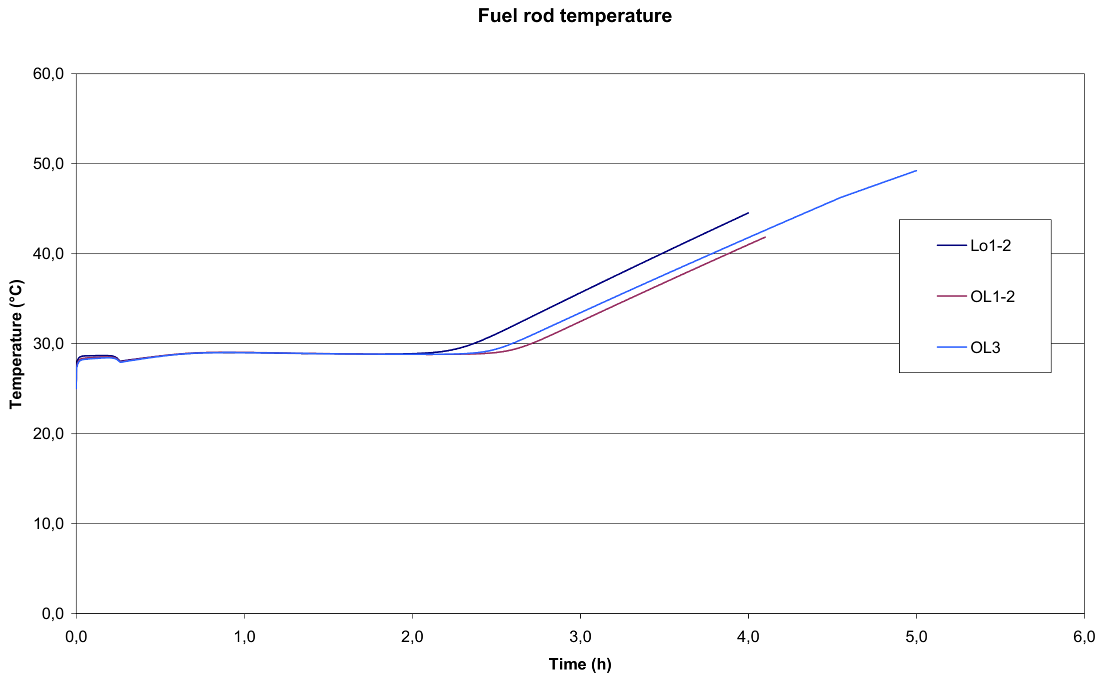

Figure 8. *Outer surface temperature of fuel rods in Lo1-2, OL1-2 and OL3 reference models.*

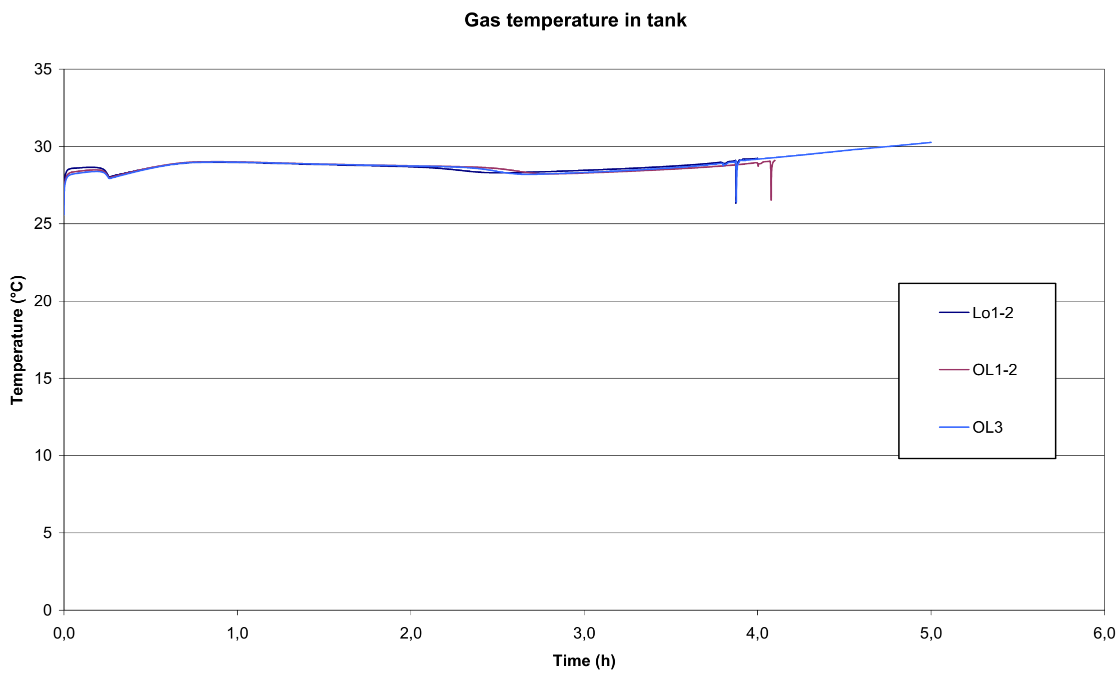

Figure 9. *Gas temperature in tank in Lo1-2, OL1-2 and OL3 reference models.*

5.6 Summary of APROS calculations

The selected reference was a model with a 10 m pipe between the drying tank and the condenser. The model was considered best in terms of representing a real situation with the tank and the condenser set up in different rooms. The time lapsed for a drying process was about 4 h in the cases of all three fuel types. In sensitivity analysis, the modified parameters had but a modest effect on the drying time.

The shortest drying time was obtained in the case in which a convective heat transfer between the fuel rod surface and the gas in the tank was more intense. However, this was not regarded as a realistic case and hence a poor heat transfer efficiency was used in the reference case. This case was considered most consistent with the condition in which the heat transfer from the rods to the outermost parts of a fuel assembly takes time.

If the condenser is placed alongside a drying tank in contact therewith, the drying time will be about 5 minutes shorter. Because of the radiation emitted by fuel assemblies, the location of a condenser intimately alongside a drying tank is not appropriate. However, even if the condenser is located in a different room, it is advisable to keep it as close as possible to the drying tank.

Temperature of the fuel rods remained in all cases almost constant for the duration of boiling. Towards the end of boiling, the temperature of the rods and at same time that of the steam present in the tank began to rise. When the drying was completed, the temperature of the rods had exceeded 35°C.

The size of a required heat exchanger was analyzed by increasing and decreasing the heat transfer area. The heat exchanger must have a heat transfer area of at least 5 m^2, when the cooling water has a temperature of 5°C and a mass flow rate of 1 kg/s.

The cold trap could possibly be omitted completely. According to the model, the condenser handles the entire pumping. Uncondensed gases have probably largely escaped from water even before the start of boiling with pressure falling in the tank. In the event of being released from a fuel assembly, radioactive particles will probably be trapped in the condenser.

6 DRYING OPERATIONS

The drying process is divided into operations as follows: Loading, vacuum drying, airing the drying chamber and unloading the assemblies. In addition, the vacuum drying itself is divided into initial pumping, which comprises pumping mostly air, a drying stage, which comprises pumping vaporized water, and a final stage for ensuring the final drying result. Diagram 1 shows the process in a simplified chart.

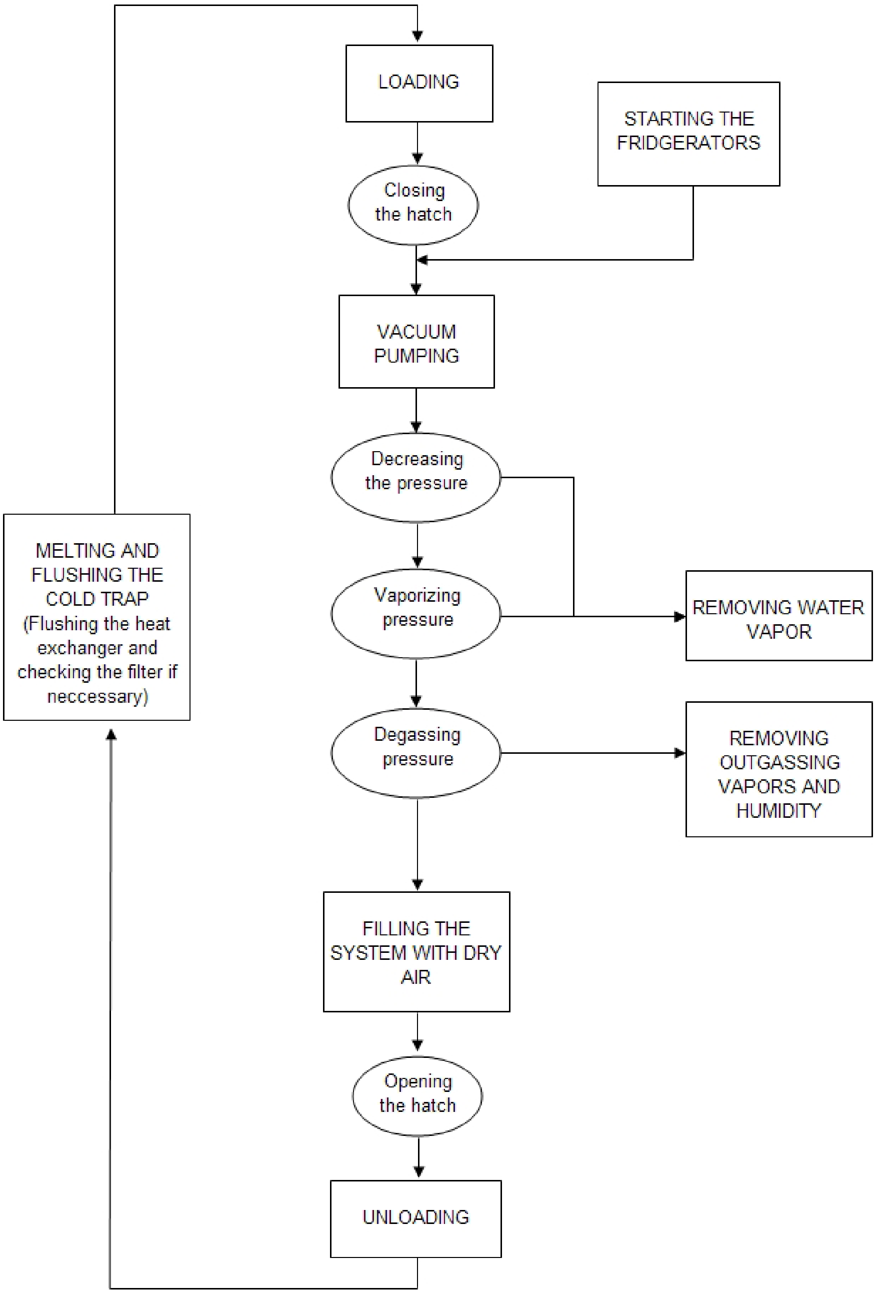

Diagram 1. *Flow diagram for the drying process.*

6.1 Loading a drying chamber with fuel assemblies and other preparatory measures

Fuel assemblies are transferred by means of a fuel handling machine from a fuel transport cask to drying chambers. The transport cask is docked to a docking ring present on the floor of a fuel handling cell. The assemblies housed in the transport cask have been loaded for providing each disposal canister for spent nuclear fuel with such a combination thereof that the total decay heat power thereof becomes as consistent as possible and close to a heat load allowed for the canister. The fuel assemblies are transferred one at a time, such that, upon being lifted up out of the cask, the assembly is left suspended on top of the cask for a period long enough to allow most of the water to drain back into the transport cask. The transfer operation is preceded by reading an assembly identification data from a legend present on the fuel assembly's handle, whereafter the data is charted and compared with records.

The draining operation is followed by transferring the assembly to an appropriate drying chamber. The drying chamber is able to accommodate at a time either 12 Lo1-2 or OL1-2 fuel assemblies or 4 OL3 fuel assemblies, i.e. the number equal to that accommodable in a corresponding disposal canister for spent nuclear fuel. The fuel assembly is delicately lowered inside a guide tube present in the drying chamber's fuel rack. The drying chambers' racks support the assemblies in such a way that the top ends of the assemblies settle more or less flush with the handling cell's floor level in order to retain as well as possible a visual contact with the location of the assemblies. Fig. 10 shows a few OL1-2 assemblies as loaded in a drying chamber.

When a drying chamber is fully loaded, the next procedure is to inspect the sealing surfaces cleanness. Possible impurities can be removed by means of a maintenance manipulator as necessary. The drying chamber hatch is closed hermetically for the duration of a drying process. A protective hatch is also lowered on top of the opening of a transport cask docking station.

Finally, the refrigerators for a heat exchanger and a cold trap are activated. The temperature of fuel assemblies rises slightly in response to both decay heat and ambience as the refrigerators chill to the operating temperature thereof.

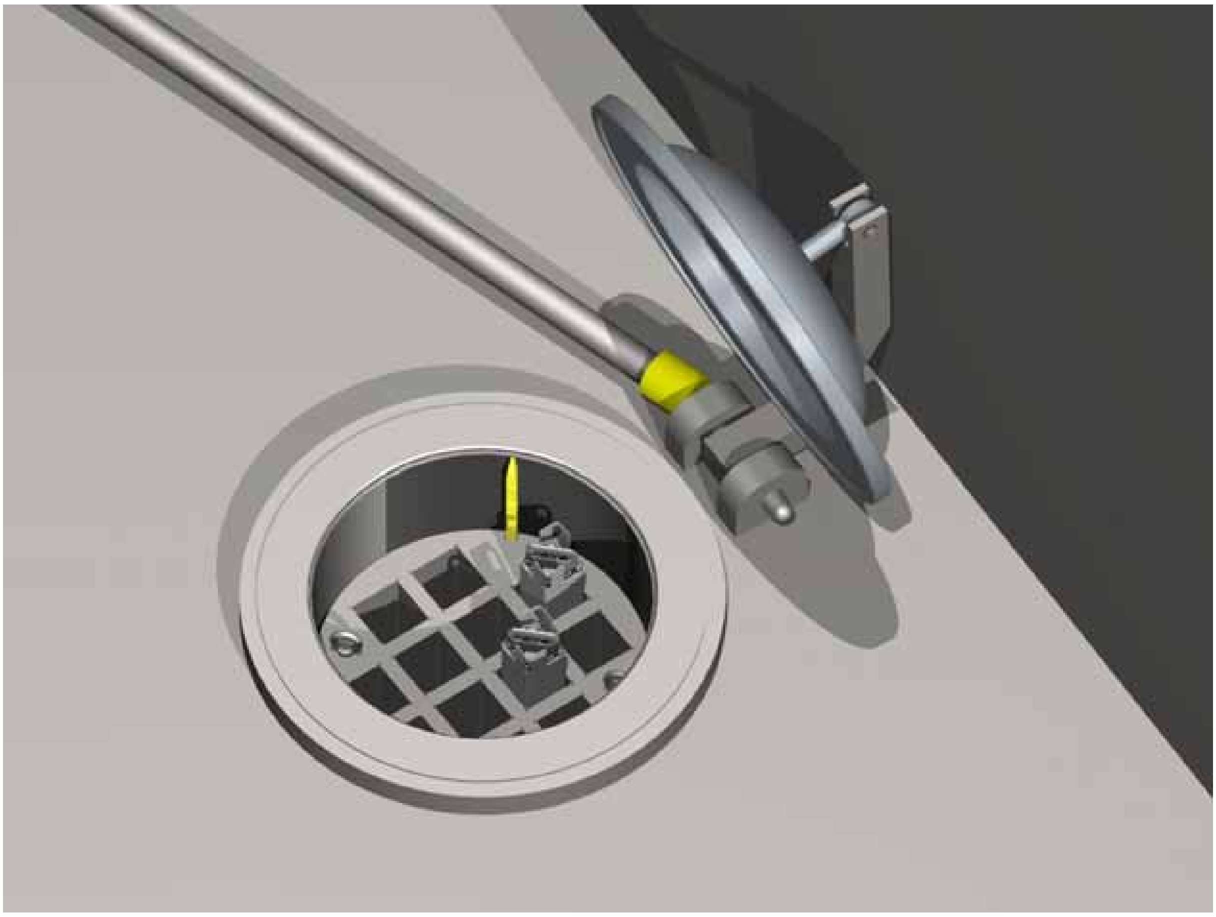

Figure 10. *Fuel assemblies as loaded in drying chamber. The figure shows also lifting points needed for the replacement of a drying rack, as well as a guide ensuring a correct rack orientation.*

6.2 Drying

6.2.1 General

The principle of vacuum drying is very simple, being based on the fall of water boiling temperature as pressure falls. Vacuum drying is quite an ordinary means of removing moisture from articles, being reasonably safe and economically attractive as a process, since elevated temperatures are not necessarily needed. Vacuum pumps are used to bring air pressure to such a low level that water begins to boil at normal room temperature (about 3000 Pa/+25°C, see fig. 11). A sufficiently long pumping time produces a good drying result.

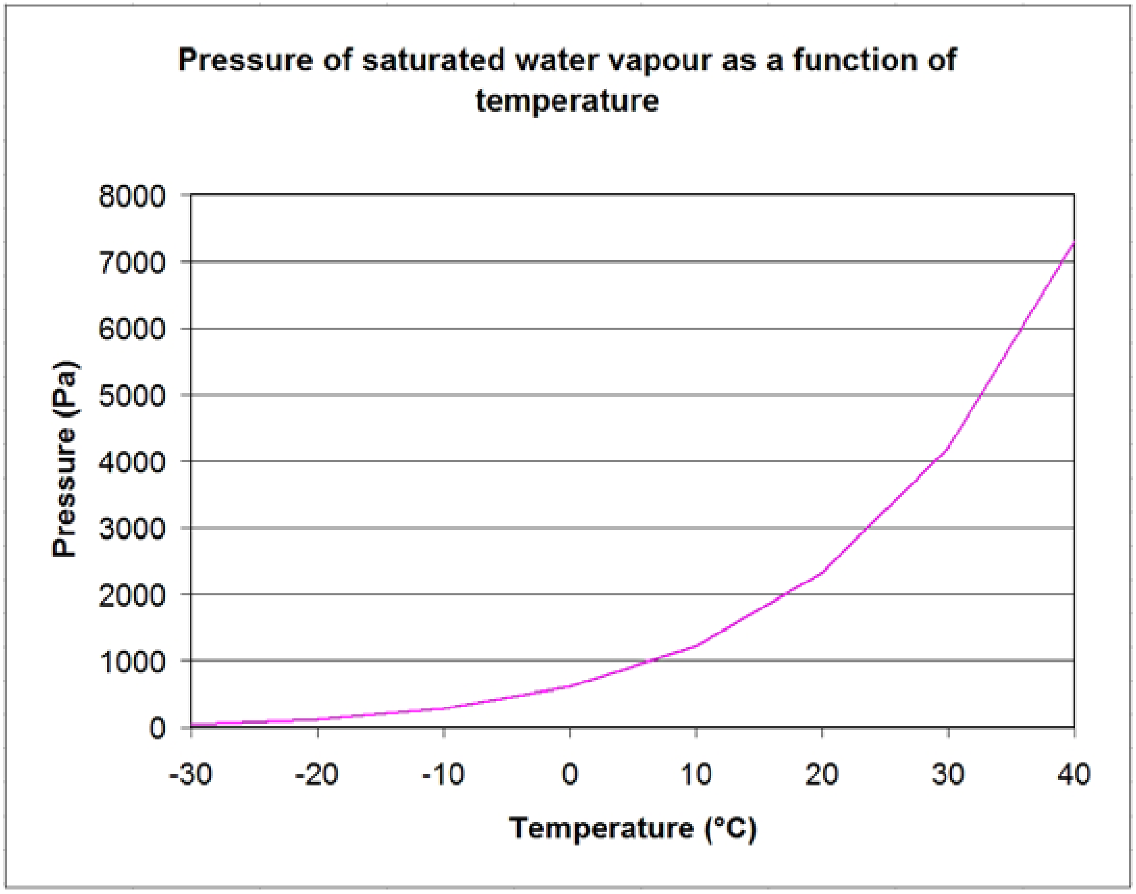

Figure 11. *Pressure of saturated water vapour as a function of temperature.*

Leaking fuel rods, which may contain water penetrated inside by way of cracks, have probably not enough time to dry on the inside. A small amount of water is nevertheless acceptable in a spent fuel canister. Water vapour entering a vacuum pipe will be condensed as effectively as possible by means of a heat exchanger present in the pipe and the condensed water is pumped out immediately and its amount is measured. The vapour that has managed to by-pass the heat exchanger will be collected, still upstream of vacuum pumps, in a cold trap, the water freezing on its ice-cold surfaces. Thus, the vacuum pumps remain cleaner, nor does the water vapour cause problems regarding operation of the pumps. The presently condensing water also favours the advancement of pumping as the condensation in itself increases vacuum. As a further safety feature, the exhaust air of vacuum pumps is even conveyed into a ventilation intake duct of the controlled area. Fig. 12 depicts by way of principle the migration of air, water vapour, and gas from a drying chamber to a heat exchanger, to a cold trap, and to pumps.

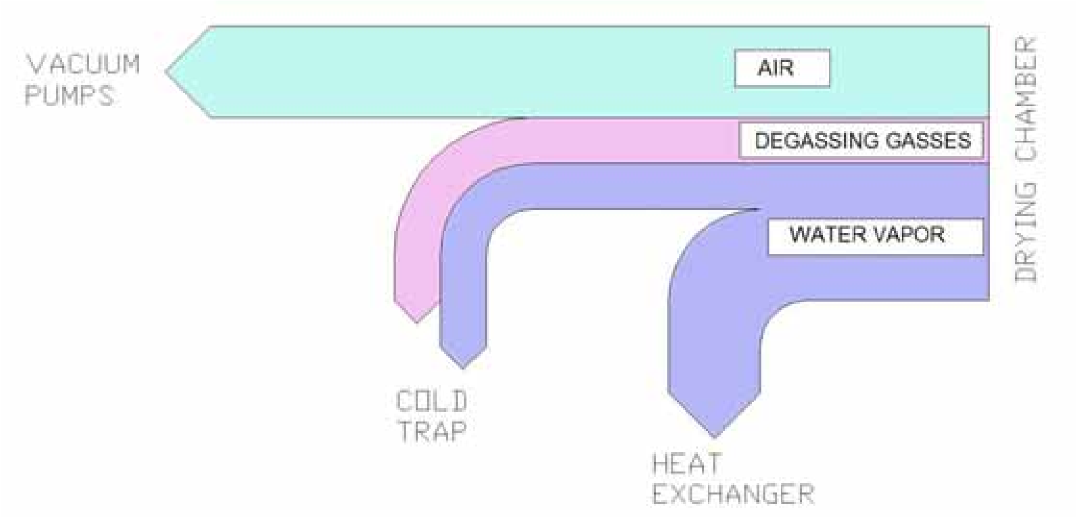

Figure 12. *Migration of gases in the drying system.*

6.2.2 Process temperatures

Since the vaporization process has a cooling effect on drying chamber surfaces, the temperature of a chamber room will be kept slightly higher (30°C) than normal room temperature. What is ensured thereby and by the inherent decay heat power of fuel assemblies is that the surface temperatures cannot fall to the extent that would allow condensation to occur during a drying chamber outgassing process. Moreover, the mass of evaporating water is extremely small as compared to the mass of fuel assemblies and a drying chamber. An optimal result will be achieved by controlling a pumping rate and by having a sufficient vacuum holding time. Excessively rapid pumping may cause temperature fluctuations, as well as vapour by-passing the heat exchanger. There is also a risk of water droplets freezing, the only consequence of which is, however, that the pumping time becomes longer.

6.2.3 Drying time

Initial pumping, wherein the pressure level falls to the neighborhood of 3000 Pa, takes about 15 minutes with a selected combination of pumps. In a drying stage, the theoretical pumping time based on decay heat power, for anticipated volumes of vapour, was about 4 hours for all fuels.

Since, after the vaporization of water, pressure begins a rapid descent, it is advised that pumping is not stopped until reaching a terminal pressure of about 100 Pa. At this point, the drying chamber air can theoretically contain as little as 3 g of water vapour. The vacuum can be sustained for the time being for making sure that water is eliminated from all surface pores and joints. At the same time, the rod temperatures are stabilized for a reduced risk of condensation in the loading process.

The computed total time (including loading and unloading) for the drying of 12 fuel assemblies is about 8 hours on the condition that the amount of water brought along by the assemblies is as anticipated. It should still be pointed out that the drying system is capable of handling even considerably larger volumes of water, just the drying time becoming longer.

6.2.4 Substances released from fuel assemblies

Although the flow rates in a drying chamber remain reasonably low, the fuel assemblies may release particles migrating into the vacuum pipe. A steel wire mesh filter associated with the pumps is capable of catching all particles larger than 1-2 µm. The heat exchanger is also functional as an effective particle filter as small particles adhere readily to the moist surfaces of a heat exchanger. As a result, small particles are also carried away by pumped water. If the presently dried fuel includes rods with a corroded gladding tube, it is possible that these rods shall release minor amounts of radioactive gases into the drying air. To be on the safe side, the pumps' exhaust air is conveyed into the ventilation system for the controlled area in an encapsulation plant.

6.2.5 Removal of condensate water

In principle, the condensate water pump of a heat exchanger could be replaced by an adequately large collecting tank which would receive the water draining from a condensate water fitting. However, this involves the risk that, during the process, water evaporates also from the collecting tank and finds its way back to the process. The boiling point pressure difference between the water of about +20°C in a drying chamber and the water of about +7-10°C in a condensate water tank is not more than 1000-1300 Pa, whereby it may be difficult to determine the exact time in the process when the duct extending to the tank should be closed by a valve. Since, from the standpoint of an overall process, it is recommended that the pumping be continued all the way to a terminal pressure of 100 Pa, the condensed water must be isolate completely from the vacuum pipe (the pressure of 100 Pa corresponds to the dewpoint of about -22°C). Since the pump can be almost any normal pump capable of producing over 1 bar pressure difference, there is no reason to exclude it from the system, the process becoming more straightforward and faster as the reflux of water is prevented. In the event that a tank is used, the tank should also be vacuum resistant and should be fitted with a venting tube for enabling the flow of water into the chamber.

6.3 Pressure equalization

When a desired drying result has been accomplished, the drying tank can be returned to normal atmospheric pressure. The pipe extending to vacuum pumps is closed and the pumps are stopped. Pressure is equalized by opening a valve, which is in such a position that the filling air travels through a condensing heat exchanger. Thus, the filling air is dried also by a heat exchanger, further reducing the risk of condensation.

6.4 Unloading of fuel assemblies from the drying chamber

After the drying is completed, the drying chamber hatch is opened and fuel assemblies can be unloaded. The docking station of a spent fuel canister has been loaded with an empty canister whose steel hatch is removed by means of the docking station's manipulator of an atmosphere changing cap. The spent fuel canister is set in such an orientation that the canister has its internal structure in a parallel relationship with the drying chamber's fuel rack for a passage as straightforward as possible from the drying chamber to the canister. The heat load acceptable for a spent fuel canister is not exceeded, because the fuel assemblies bound for drying were selected in such a way that the assemblies can be transferred straight into the canister.

7 MAINTENANCE OF THE SYSTEM

All pieces of equipment involved in the drying system are as maintenance-free as possible and located, whenever possible, clear of the areas exposed to radiation. A maintenance interval of 5 years has been planned for equipment to be placed inside a handling cell. The only maintenance-demanding components in the drying system to be placed in the handling cell are drying chamber hatches, which require maintenance for both bearings and seals. The position of seals in a hatch has been designed in view of placing the seals as far away as possible from radiation emitted by fuel assemblies.

The vacuum pipe does not normally need maintenance. A flushing operation for the heat exchanger and the cold trap can be executed from the operation control room by closing the duct valves and opening flush valves for the systems. The flush water is recovered in an active water treatment system. If necessary, such a flushing process can be automated for its execution by a single command after every drying cycle.

The suction filter of vacuum pumps is removed from its enclosure as necessary and washed with an appropriate solvent or replaced by a new one. The necessity of cleaning is readable from a differential pressure gauge measuring the filter's flow resistance. If necessary, the filter enclosure can be cleaned by vacuuming or wiping.

The vacuum pumps come with a maintenance schedule drawn up by the manufacturer, the observation of which does not call for any special actions as the pumps should remain clean of radioactivity in normal operation. If necessary, a maintenance process for the pumps involves also the maintenance and calibration of pressure gauges associated with the pumps. Pressure transmitters placed in the proximity of a drying chamber present more of a problem, because these are sensors which may become contaminated by particles emerging from the chamber. Indeed, the maintenance of these sensors could be limited to replacements effected only in major overhaul operations, because these instruments serve principally in a backup type of function and, thus, the calibration thereof is not of vital importance.

The maintenance of a drying chamber's thermal sensors must be timed to coincide with the maintenance of a fuel handling cell, which process comprises cleaning and overhauling the entire system. In principle, as long as fuel assemblies have not released active particles which have contaminated a drying chamber, entering the drying chamber room will be safe whenever there are no fuel assemblies in the drying chamber.

8 MALFUNCTION AND FAULT CONDITIONS

8.1 Problems during operation

In normal operation, the most likely problem aspect is a drying chamber hatch seal. In the event that the sealing face has retained impurities or the seal has damaged for some reason, a sufficient vacuum cannot be achieved. The service manipulator is provided with a camera that can be used for inspecting the condition of a seal and a sealing face and the manipulator can be used for cleaning the relevant surfaces as necessary. If the sealing face has suffered damage, the hatch can be disengaged and lifted by means of the service manipulator and a crane into a service room above the handling cell for repairs. This naturally requires that the hatch be provided with appropriate lifting points and with a latch readily openable by means of a manipulator.

8.2 Pump and filter problems

Possible maintenance and repair measures for pumps can be performed with relative ease, as the migration of contamination past a cold trap should be very insignificant indeed. The pumps are located in a space that should be readily accessible in normal operation.

In the event of becoming clogged, a mechanical filter used as a protection for the pumps may increase pumping time or even preclude the achievement of a desired terminal pressure. The filter is replaceable in a simple manner as the vacuum duct of a drying chamber can be closed during a drying process and a replacement can be performed without pressurizing the drying chamber.

8.3 Pipework leaks

As a rule, it is advisable to subject the system to a tightness inspection after every maintenance process in order to avoid taking up repair measures during operation. Because the in-system pressure level is not extremely low, the pipework tightness is not as critical as for example in a welding chamber system for the copper overpack of a fuel canister. However, if the leak level is of such a magnitude that a desired vacuum level cannot be reached, the leak site must be located and repaired. This nevertheless requires protection from possible contamination existing within the pipework.

8.4 Fuel rod damage

If there is an incident in the process of handling fuel assemblies that causes a fuel rod breakage for some reason and spreading of radioactive matter into a drying chamber, the drying system must be cleaned with utmost care. The drying chamber can be washed by spraying water through the handling cell opening e.g. by means of a service manipulator, and by allowing it to leave through a drain fitting at the base. If necessary, the rack inside a chamber can be lifted up for the duration of cleaning by means of a crane arranged in a service space above the handling cell. In the event of being contaminated as well, the vacuum duct can be disassembled and cleaned.

8.5 Nuclear criticality safety of the drying chamber

Fuel assemblies are disposed in the drying chamber the same way as in canisters. The number of assemblies is the same and a batch of assemblies to be dried in a single process is the same batch that is designed to be fitted in a single canister.

In terms of its geometry, the rack for the assemblies inside a drying chamber is similar to the interior of a canister. The canisters have been subjected to a nuclear criticality safety analysis (Anttila 2005), which concludes that all fuel types remain subcritical in the canister geometry, even in the case of fresh fuel, as long as the vacant interior spaces are not filled with water. Without any extensive investigations or demands on a fuel to be placed inside, it can be concluded that the drying chamber fulfils the nuclear criticality safety requirements as long as the employed structural solutions ensure that a large amount of water cannot enter to the drying chamber under any circumstances.

The flooding of water into a chamber is preventable because, first of all, if water should drain for some reason into the handling cell, the water level must rise by 100 mm before it starts running over the rim of a drying chamber. Secondly, the handling cell is provided with a floor drain for the outlet of wash waters, making this sort of flooding highly unlikely. The drain system must be designed in such a way that water cannot flood into the handling cell, even in a malfunction situation. Washing actions are not performed while there is fuel in the chamber. Neither does the handling cell involve any other, possibly leak-developing water systems in operation during a drying process. In other respects, the cell is impervious to such a degree that flooding water has no way of penetrating into a handling cell from outside the cell.

In addition, the bottom end of the drying shell is provided with a drain fitting that can be opened as necessary for discharging flood water. Extending from the chamber's bottom is a DN 100 pipe, normally used for discharging chamber wash waters. This drain pipe, which extends to a recovery tank for radioactive waters present on the lowermost floor, must be provided with a vacuum breaker, such the vacuum existing in the drying chamber during a drying process could not draw back from the recovery tank to the drying chamber in the event of the drain system's check or return valve having a leak.

If the fuel properties are changing in the future in a way that the risk for criticality is increasing, it is easy to add some neutron absorbing materials (like boron) in the drying shell rack construction, which will easily guarantee the subcriticality of the fuel configuration in any condition.

9 INSTALLATION OF THE DRYING SYSTEM IN AN ENCAPSULATION PLANT

In an encapsulation plant the equipment is distributed to numerous rooms which are separated from each other by radiation-shielding walls. The components are distributed in view of making maintenance measures as safe as possible and convenient to perform, despite the apparatus being possibly contaminated. Such a configuration sets demands regarding wall structures, which must be fitted as early as in the construction stage with pipes and penetrations relevant to the processes. In particular, penetrations for the wall of a handling cell and a drying chamber are challenging because of a high radiation load.

The installation of a drying chamber through the handling cell floor can be performed the same way as that of a canister docking station (Suikki 2005), i.e. the final imperviousness is ascertained by grouting and a stainless steel liner applied to the room surfaces. The gear motors used for driving the drying chamber hatches are present in an equipment room located reasonably far behind the end wall of the handling cell. In addition, since the shafts needed for driving the hatches extend at a relatively large angle with respect to the wall, it is more practical to divide the shaft into sections and to provide pivots with cardan joints. Hence, the location of a wall penetration does not need to be absolutely exact, whereby a penetration sleeve for the shaft can be fitted, if necessary, in position as early as during a wall casting operation. Alternatively, the wall can be cast solid and perform shaft penetration borings with a diamond drill at the installation stage.

From the drying chamber room come out at least a vacuum pipe, a drain pipe, and electric wires for sensors. In order to achieve high-grade radiation tightness, the simplest solution would be to install appropriately angled pipes inside a concrete wall. Since the pipes connecting thereto can be fitted afterwards, the installation of penetration pipes does not require extremely high precision.

The penetration between condensation equipment and vacuum pumps is not as critical as the ones described above, but also here it is advisable to endeavor for a final result as safe as possible. In the figures included in the report, this pipe section is shown to be straight for the sake of simplicity, but in further designs the configuration of also this penetration is preferably optimized. The same applies also to the penetration of refrigeration pipes from condensation equipment to refrigeration compressors, the latter being located in a room one floor higher. Another feature that is worth observing involves power supplies required by the equipment, as well as control and sensor cables extending between these spaces and a fuel handling cell control room.

The drying apparatus requires a drain fitting for active waters for draining therein both condensed water and possible chamber, heat exchanger, and cold trap wash waters. The exhaust air of a vacuum pump must be conveyed into the outlet ventilation duct of a controlled area in an encapsulation plant and the drying chamber filling air is most preferably drawn off a controlled outlet air fitting for ensuring the quality of filling air.

10 COST ESTIMATE

The cost estimate for the system has been prepared according to the price level of the year 2006, and the manufacturing costs of equipment have been estimated based on experience. The cost bases have been itemised in more detail in Appendix 4. The current sales prices have been inquired for the most expensive components to be purchased. All the components listed in Appendix 4 refer to preliminary selections, and there are also alternative suppliers for them. Value added tax has not been included in the cost estimate.

The designing and installation costs of the system have also been included in the cost estimate for the share directly related with the actual system. It has been assumed that the building already contains the openings needed for the installation of the equipment as well as the necessary power supply and ventilation systems. It has also been assumed that the manufacturing of penetrations, pipe ducts and cable shelves for the pipe and wiring systems of the drying system should not be included in the costs for the drying system. The designing costs will be increased by two items differing from normal designing. Firstly, it will be problematic to select suitable components and materials, especially for the drying chambers and hatches, where both the radiation level and the vacuum are occasionally extremely high. Another factor increasing costs is the approval protocol and the amount of documentation needed for a nuclear engineering plant. The distribution of equipment into several different rooms within the encapsulation plant also adds the number of designing interfaces. This typically produces a greater number of designing stages, as the technologies representing different fields become at the same time more specific as the designing work advances.

The cost structure will also be affected a lot by finding the right sub-contractors. Even though the manufacturing of the equipment basically comprises normal engineering workshop technology, with regard to both the machining accuracies and materials, the expertise in the field of treatment of stainless steel as well as sufficiently big and precise machine tools will be required for manufacturing particular components.

Third rack, suitable for OL3 fuel assembly, is not included in this cost estimate, because it is needed much later. The price of the vacuum systems is relatively high, because it is assumed that there are two full sets of equipment. Because the drying system is in use only few hours per week, it is possible that there is only one set of vacuum pumps and coolers, if the more economical solution is required. Additionally, it could be possible to combine some functions with the spent fuel canister docking station, if necessary.

Drying chambers (2 pcs)	66 000 €
Hatches (2 pcs)	51 000 €
Racks (2 pcs)	36 000 €
Vacuum systems (2 pcs)	182 000 €
Control system	75 000 €
Total cost	**410 000 €**

11 OPTIONAL DRYING SYSTEMS

The selected vacuum drying represents the safest procedure, as the process should function well at almost room temperature, it is gentle for fuel rods, and the apparatus is basically simple.

Optional drying methods include heating, flushing with a dry gas (e.g. He) or various air circulation applications. Heating is a traditional way of drying, but in this case it would have been poor in efficiency because of relatively heavy-duty masses. It also would have caused unnecessary structural stress for fuel assemblies.

The most useful of the above methods is recirculated air drying, wherein the drying chamber air is circulated both through a condensing heat exchanger and a heat emitting cell, fig. 13. Between the cells is a heat pump, resulting in a minimal demand for extra energy. Drying temperature can also be very close to room temperature, the condensing cell temperature being maintained low by means of the heat pump. The principle is commonly applied e.g. in the laundry drying rooms.

However, the use of recirculated air drying for the drying of fuel assemblies is not practical for the following reasons. First of all, the number of active particles migrating into the system is likely to exceed that experienced in vacuum drying as the flow rate and volume of air are higher, resulting in the apparatus becoming more easily contaminated. Secondly, from the viewpoint of overall process it is preferred that the fuel assemblies be vacuumed as early as before changing of the atmosphere in a spent fuel canister as this enables avoiding eventual problems that may be caused by gases escaping from the surface or pores of fuel assemblies for the docking station processes of a spent fuel canister.

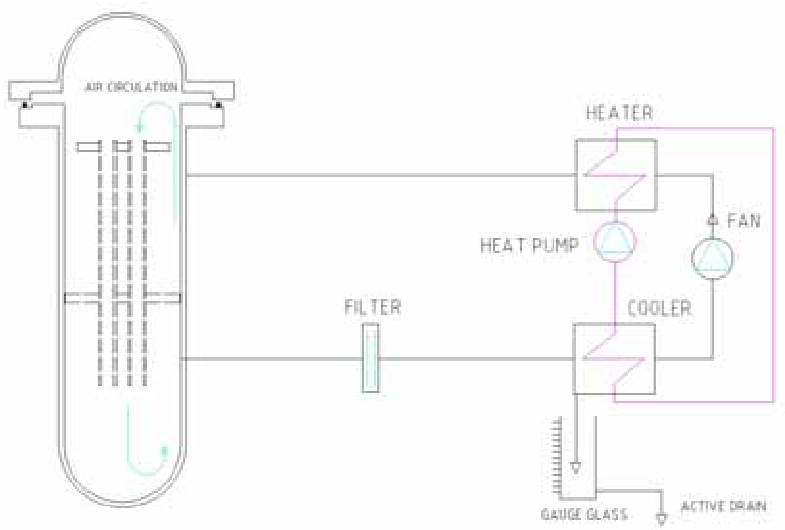

Figure 13. *Principle of recirculated air drying.*

12 SUMMARY

The report presents a plan regarding a drying system for fuel assemblies. The apparatus consists of drying chambers with hatches therefor, as well as of vacuum, condensation, measuring, and control systems.

The apparatus is capable of drying simultaneously 12 of the type Lo1-2 or 12 fuel assemblies of the type OL1-2. Both fuels are provided with specific drying chambers designated therefor, which can be modified also for the other fuel type by switching the relevant drying chamber's fuel rack as necessary. The chambers are so voluminous that fuel of the type OL3 can also be dried respectively by replacing the interior rack by one suitable for this particular fuel. The chamber is able to accommodate 4 pieces of these fuel assemblies, the same number being accommodable also in a spent fuel canister.

Several optional processes and relevant sets of equipment were contemplated as the designing work progressed. Vacuum drying was nevertheless chosen for the following reasons. First of all, the apparatus in all its aspects is reasonably simple and it seems to be the best in terms of protecting the apparatus from contamination. Secondly, from the standpoint of an overall process it is preferred that the fuel assemblies be vacuumed as early as in this particular stage as this provides a speedier and more secure atmosphere changing process in the spent fuel canister. The process was calculated with APROS software and was found functional and stable, since even the variation of miscellaneous variables did not cause major deviations in the process flow. The computed total process time for the drying of 12 fuel assemblies is about 8 hours

An objective in the design work has been to come up with simple and reliable equipment with little demand for maintenance. The normal annual throughput of an encapsulation plant comprises approximately 40 spent fuel canisters, the apparatus thus having a very low degree of utilization. The internal structures of a drying apparatus, which come to contact with fuel assemblies, have been designed for a maintenance interval of about 5 years. Other pieces of equipment in the drying apparatus are quite well accessible and, thus, can be serviced without special measures.

With a low degree of utilization as regards vacuum equipment and refrigeration compressors, it would be prudent to consider a certain combination of various pieces of equipment. Because the atmosphere changing process of a spent fuel canister applies quite similar engineering, the combination of these functions should be feasible at least in theory. Problems are created by a long distance between the systems and finding a suitable central location for the pieces of equipment for preventing the lengths of pumping and heat transfer lines from increasing too much.

The design work did not solve all of the most minute details, even though both 3D modelling and component selections have been advanced quite far. There is no need for this at this point anyway, since also other systems of an encapsulation plant are still in need of more detailed planning and this is naturally interactive with the drying system's equipment.

The estimated price for a set of docking station equipment was 410 000 euros (vat 0%), according to the current cost level. The cost estimate covers the price for the design, installation, manufacture and components of the drying system's sets of equipment, but not planning and installation classified as construction engineering processes.

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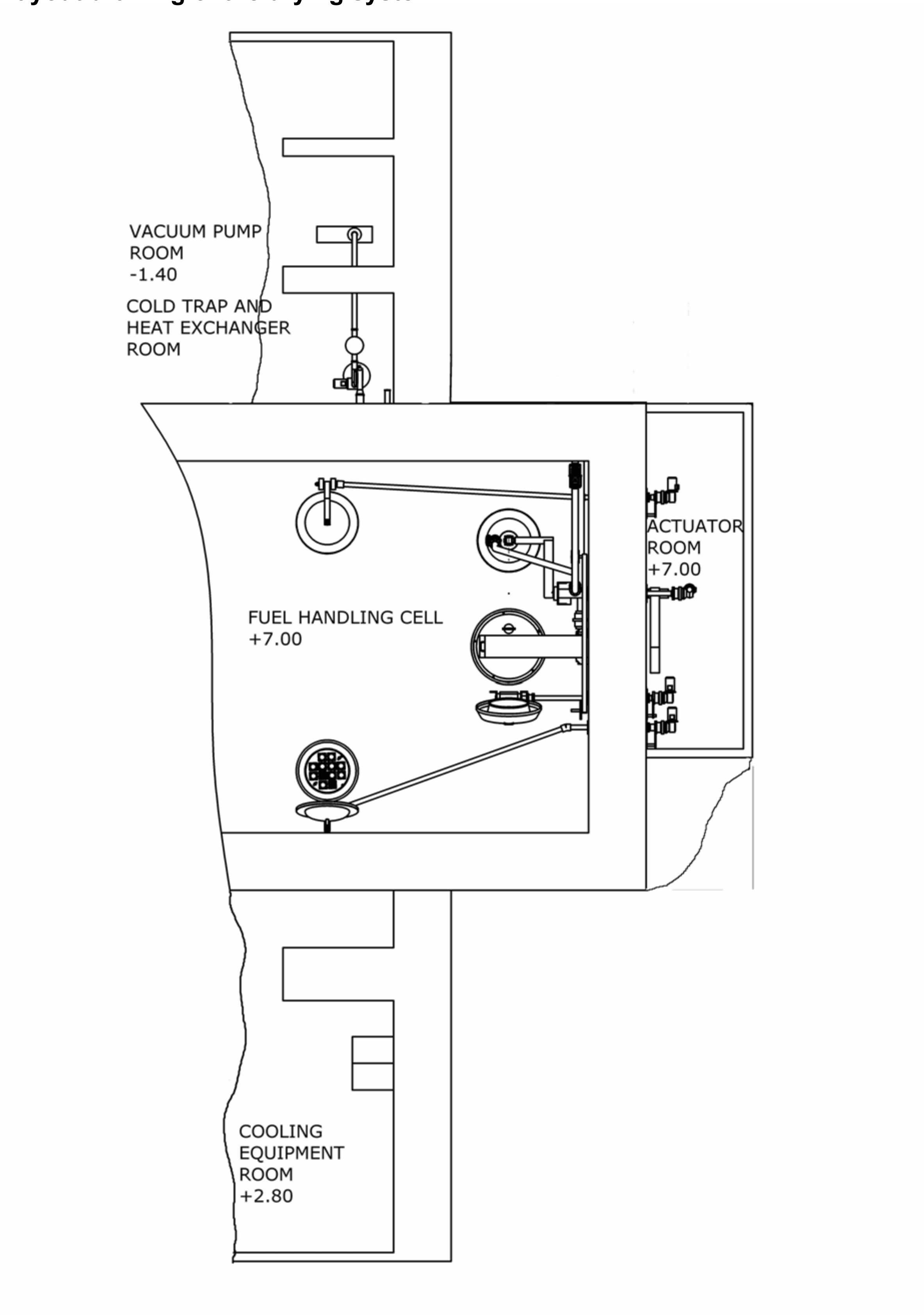
APPENDICES

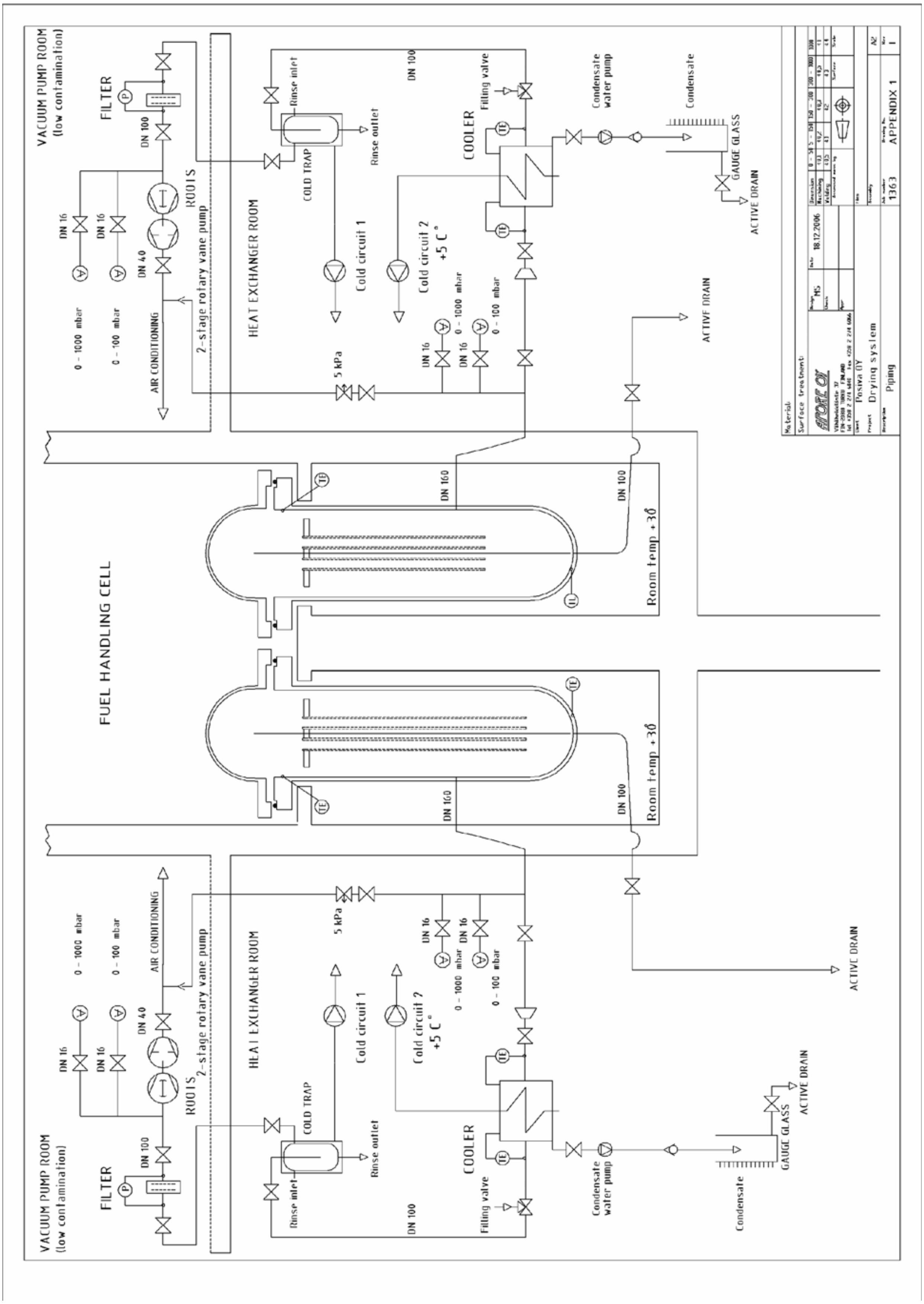
APPENDIX 1

Layout drawing of the drying system.



APPENDIX 2

Flow diagram for the vacuum system.



APPENDIX 3

Drying process sensitivity analysis results

Case Lo1-2

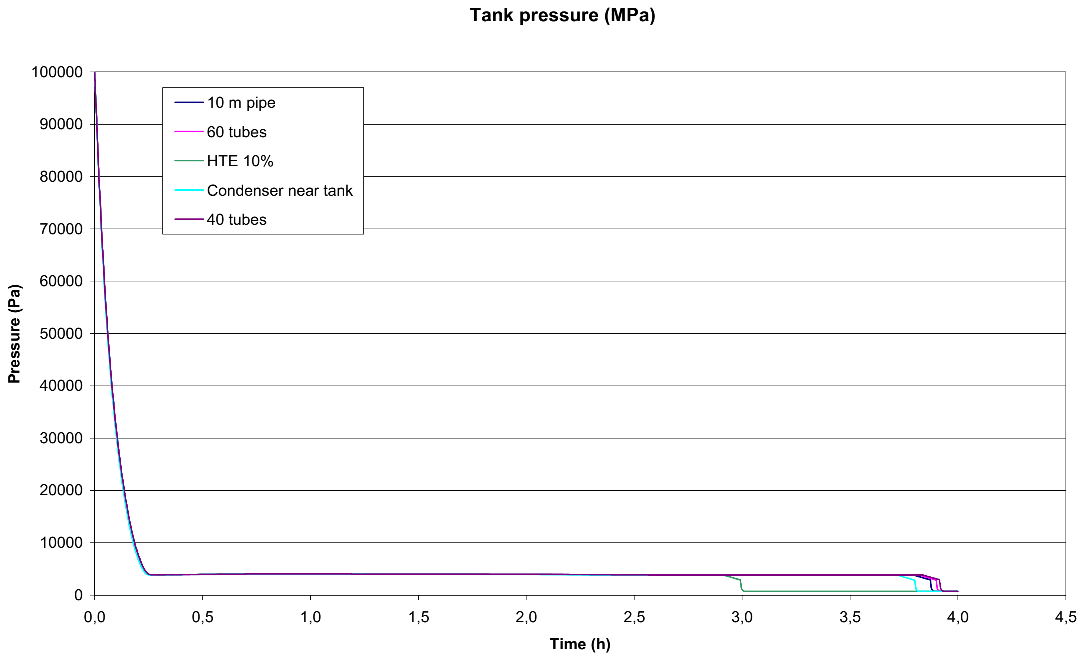


Figure 1. *Drying tank pressure in the case of Lo1-2. '10 m pipe' is the reference model graph.*

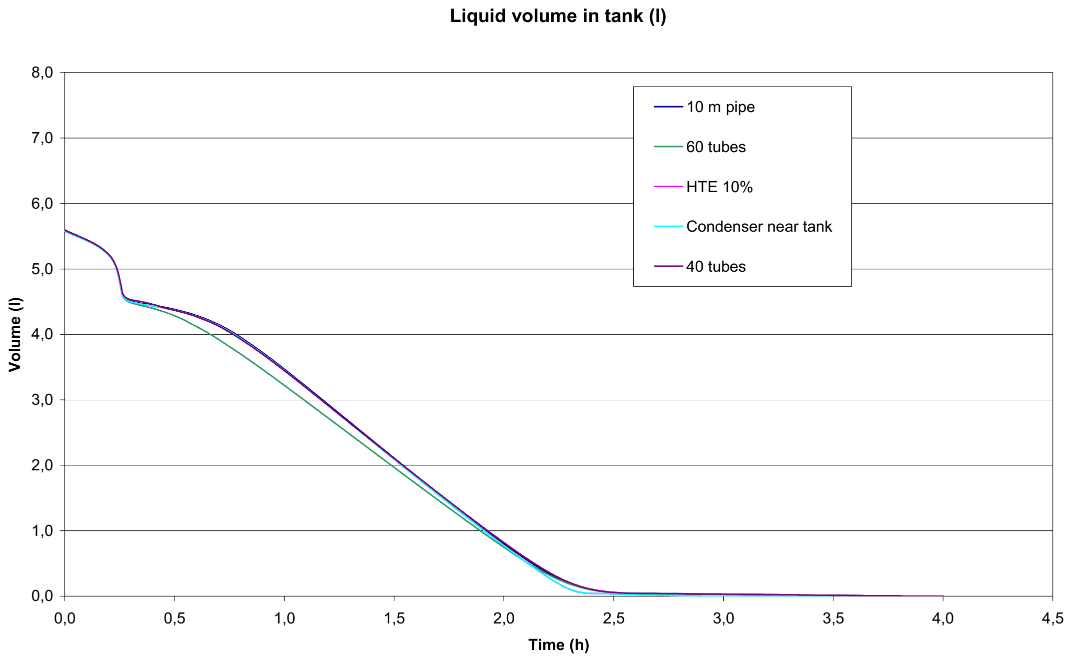


Figure 2. *Water volume in drying tank in the case of Lo1-2. '10 m pipe' is the reference model graph.*

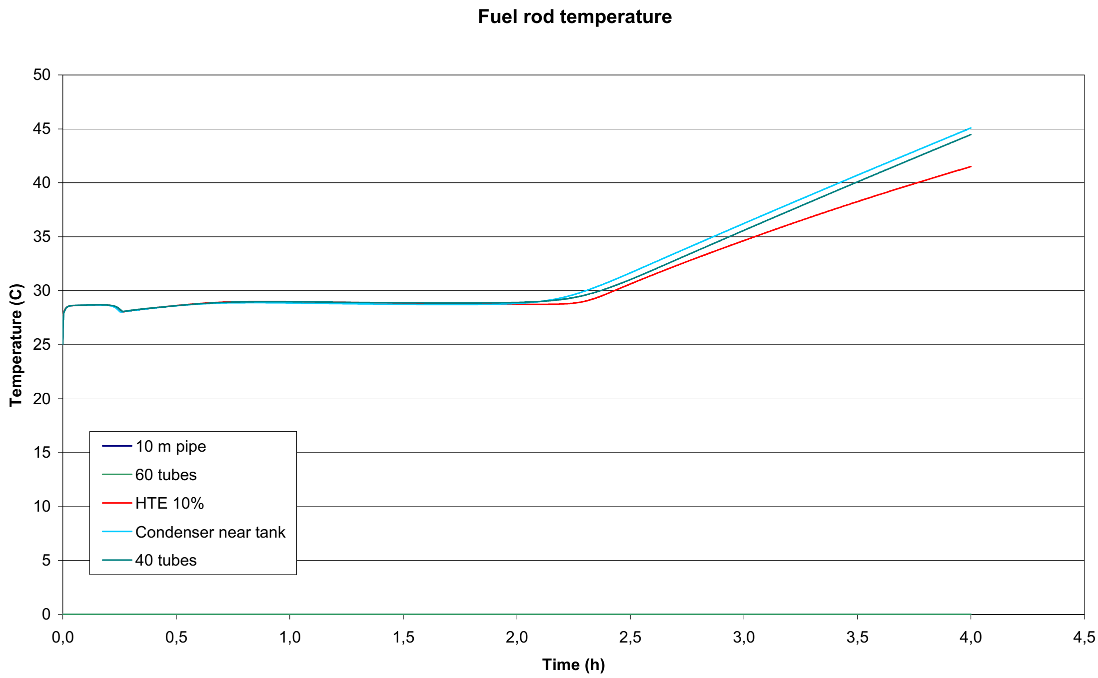


Figure 3. *Temperature of outer fuel rod surfaces in the case of Lo1-2. '10 m pipe' is the reference model graph.*

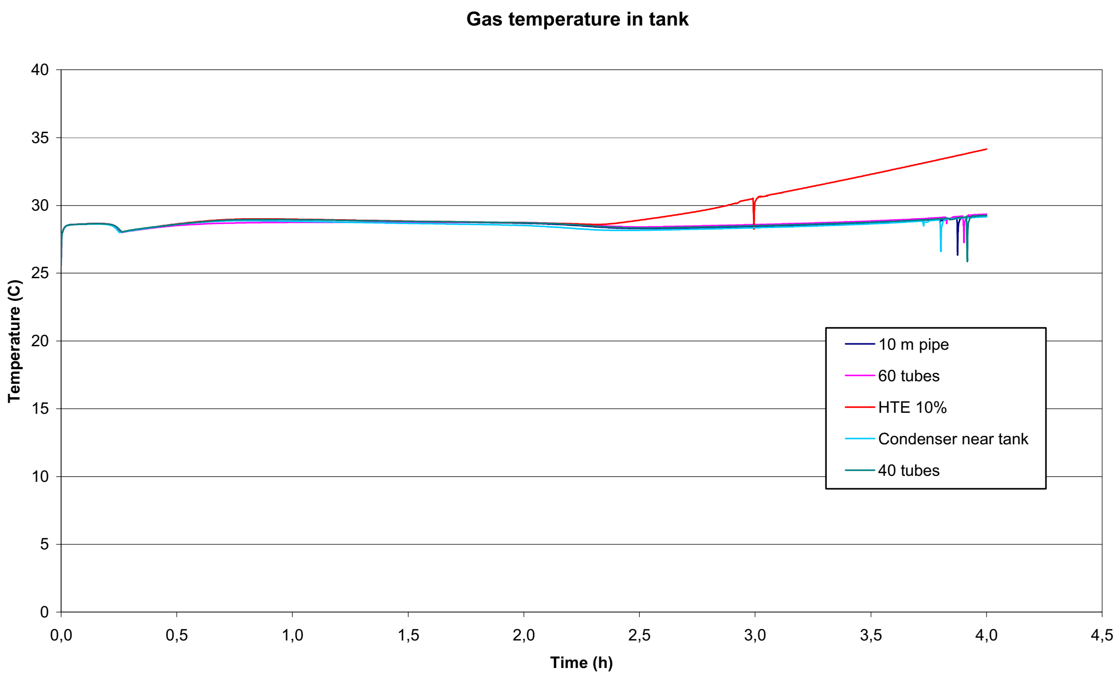


Figure 4. *Gas temperature in tank in the case of Lo1-2. '10 m pipe' is the reference model graph.*

Case OL1-2

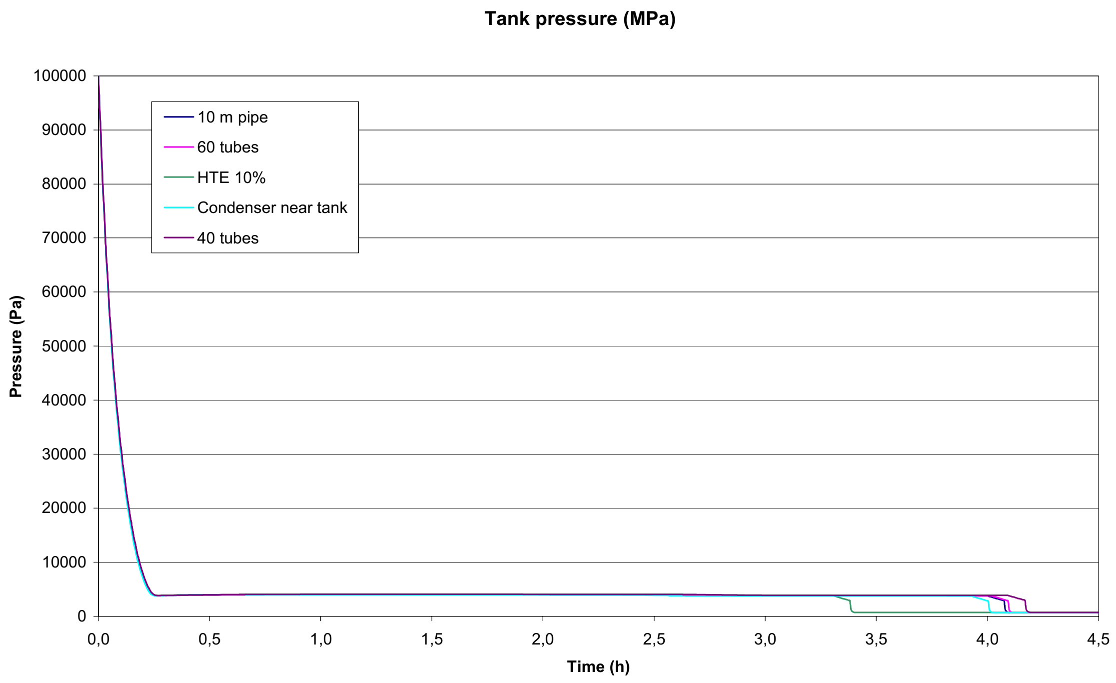


Figure 5. *Drying tank pressure in the case of OL1-2. '10 m pipe' is the reference model graph.*

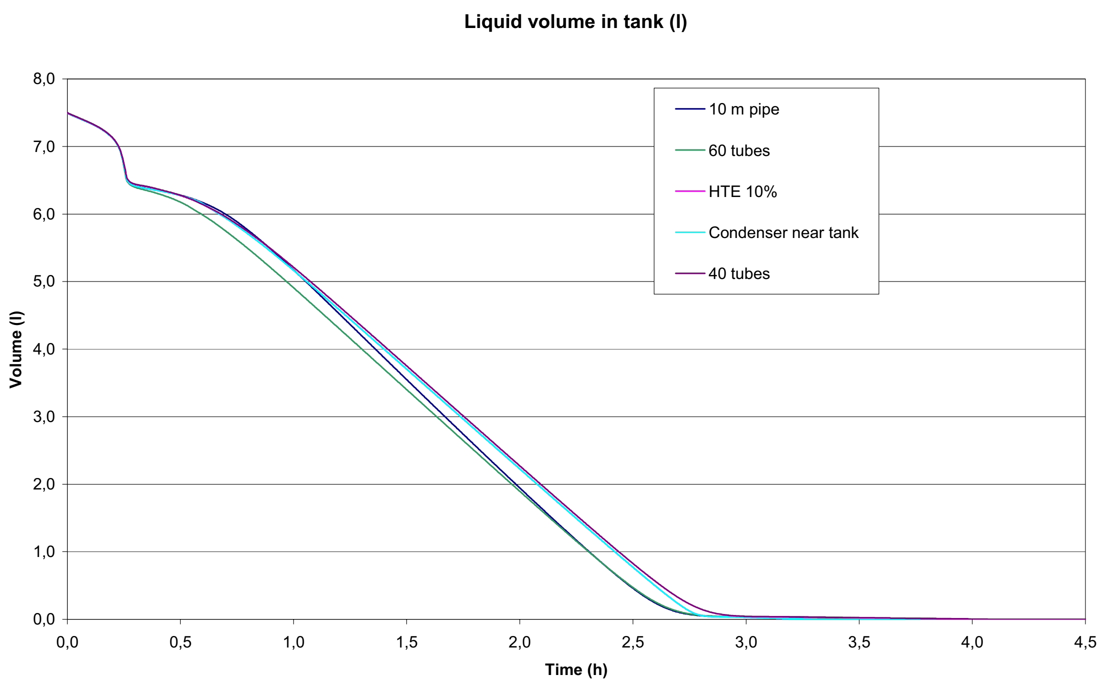


Figure 6. *Water volume in drying tank in the case of OL1-2. '10 m pipe' is the reference model graph.*

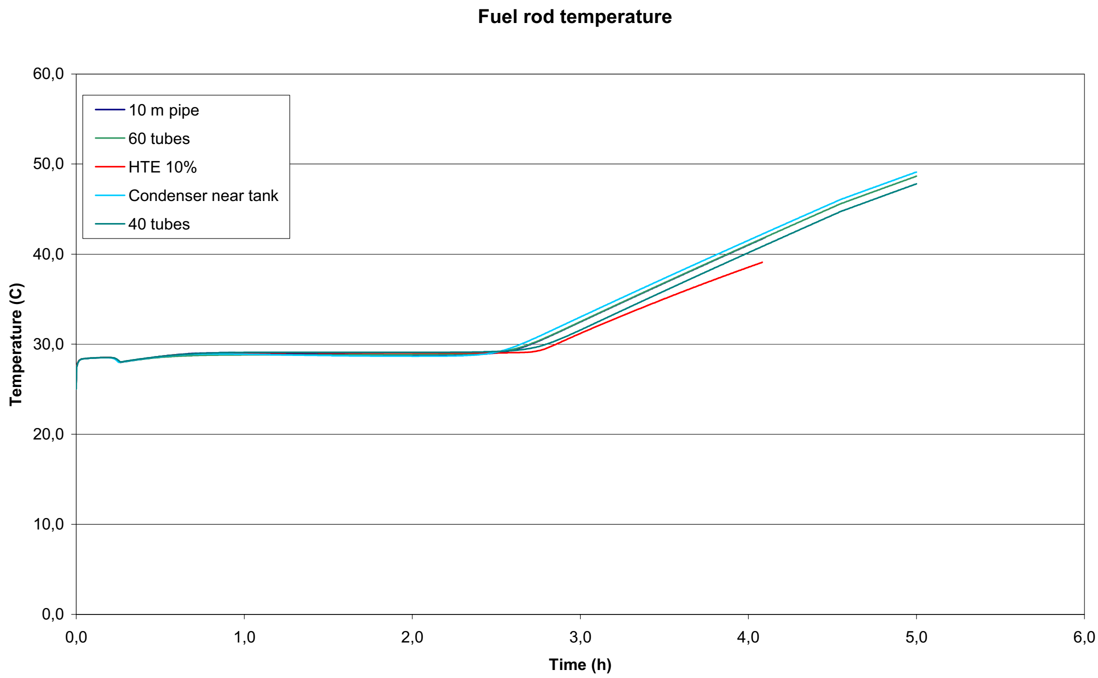


Figure 7. *Temperature of outer fuel rod surfaces in the case of OL1-2. '10 m pipe' is the reference model graph.*

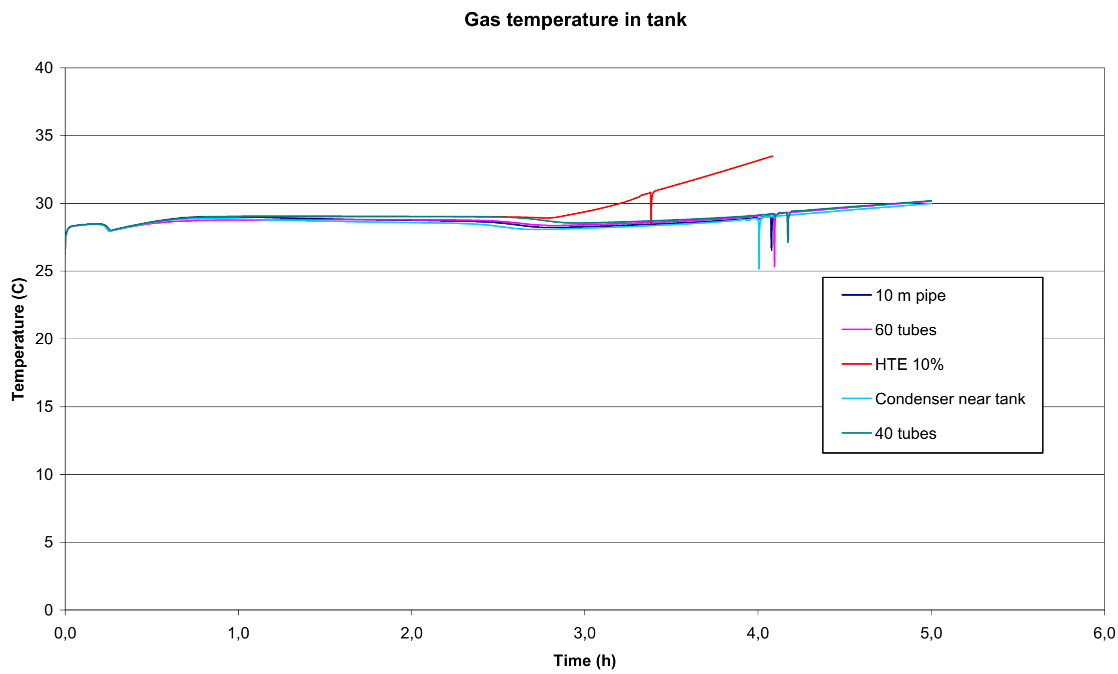


Figure 8. *Gas temperature in drying tank. '10 m pipe' is the reference model graph.*

Case OL3

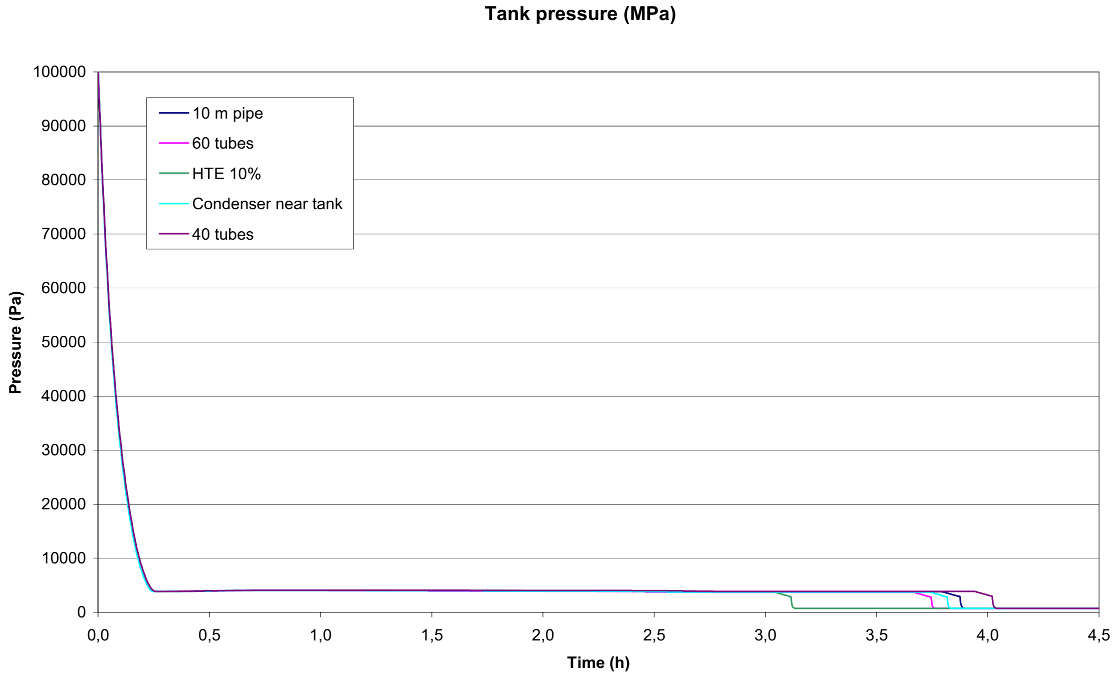


Figure 9. *Drying tank pressure in the case of OL3. '10 m pipe' is the reference model graph.*

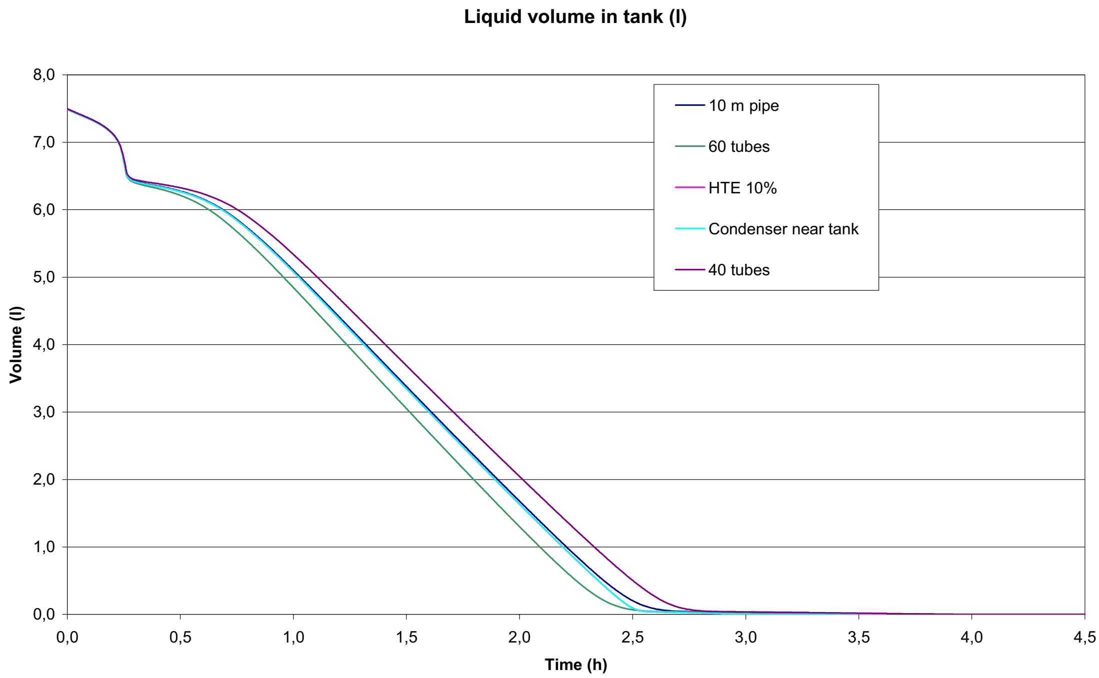


Figure 10. *Water volume in drying tank in the case of OL3. '10 m pipe' is the reference model graph.*

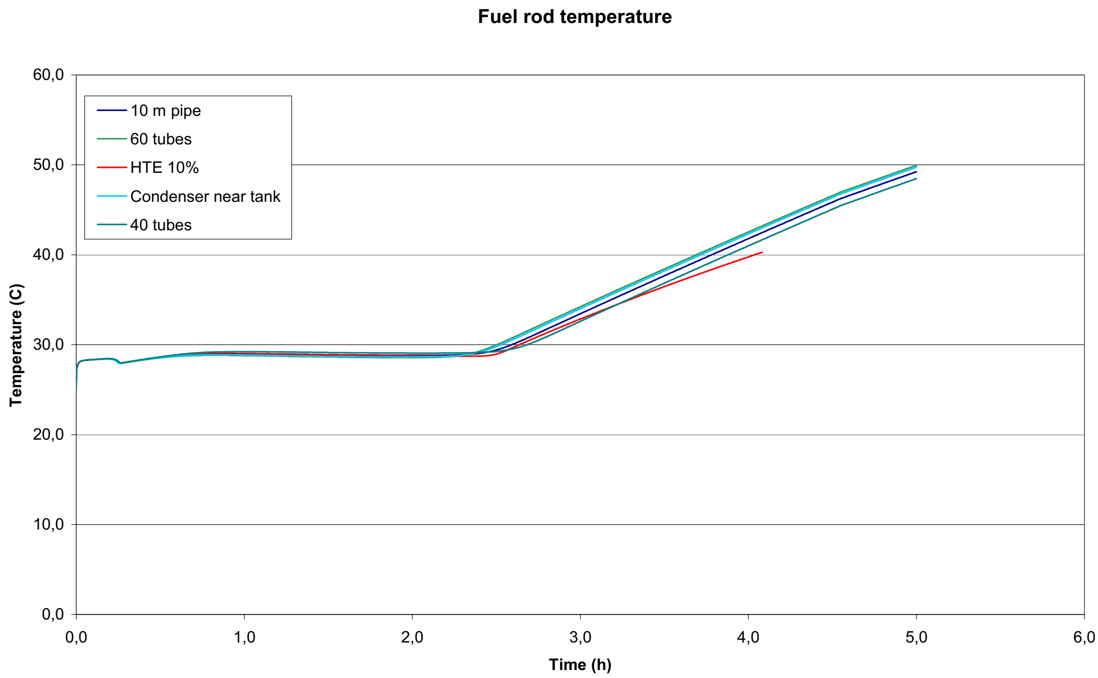


Figure 11. *Temperature of outer fuel rod surfaces in the case of LO3. '10 m pipe' is the reference model graph.*

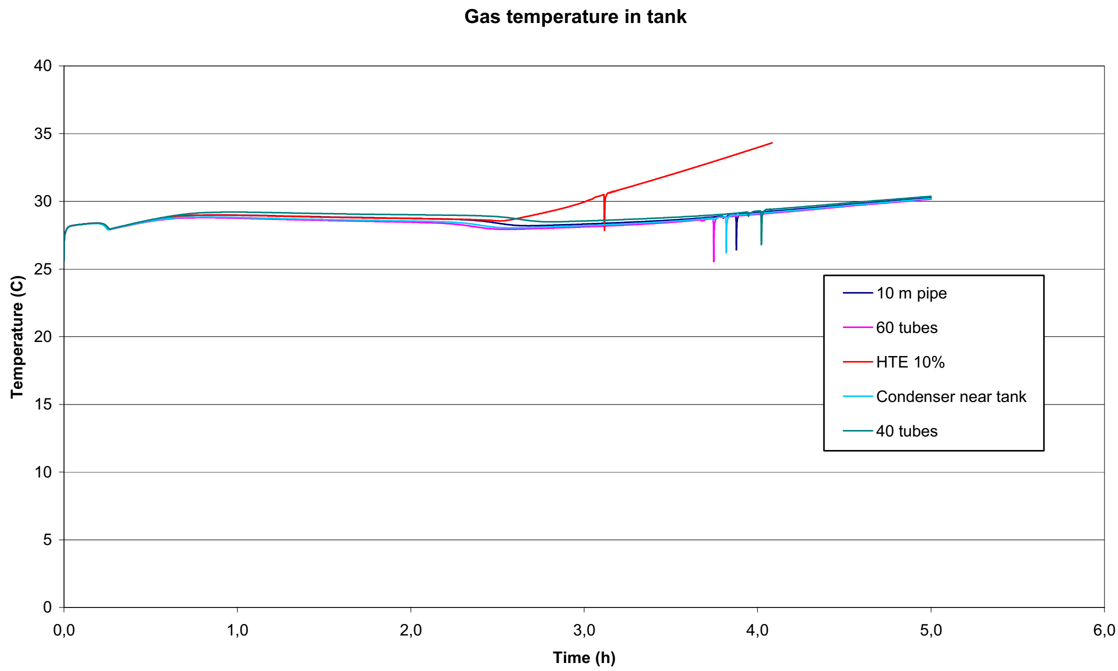


Figure 12. *Gas temperature in drying tank in the case of LO3. '10 m pipe' is the reference model graph.*

APPENDIX 4

Costs of a Drying system for fuel assemblies

Description	quantity/unit	unit price	total
Drying chambers (2 pcs)			
Steel construction	2 x 2000 kg	10 €/kg	40 000 €
Accessories	1 as a whole	1 000 €	1 000 €
Design	300 h	50 €/h	15 000 €
Assembly	250 h	40 €/h	10 000 €
			66 000 €
Hatches (2 pcs)			
Shaft	2 x 700 kg	10 €/kg	14 000 €
Steel construction	2 x 400 kg	20 €/kg	16 000 €
Coupling (Jaure Bauart MT 165)	2 pcs	500 €	1 000 €
Accessories	1 as a whole	2 000 €	2 000 €
Gear motor: Bonfiglioli Transmittal –planet gear unit, size 306L2/MVF86FC, Pmotor=1.0 kW	2 pcs	2 000 €	4 000 €
Design	200 h	50 €/h	10 000 €
Assembly	100 h	40 €/h	4 000 €
			51 000 €
Racks (2pcs)			
Steel construction	2 x 1200 kg	10 €/kg	24 000 €
Design	200 h	50 €/h	10 000 €
Assembly	50 h	40 €/h	2 000 €
			36 000 €
Vacuum systems (2 units)			
The vacuum systems pipelines and valves: About 15 m tubing DN100-DN150 and necessary vacuum fittings, about 20 pcs vacuum valves.	1 as a whole	25 000 €	25 000 €
Pump: ALCATEL RSV 601 B + 2063	2 pcs	13 000 €	26 000 €
Cold trap cooler	2 pcs	20 000 €	40 000 €
Cold trap unit	2 pcs	6 000 €	12 000 €
Cooler for heat exchanger	2 pcs	10 000 €	20 000 €
Heat exchanger: Raucell 240-120-105	2 pcs	4 000 €	8 000 €
Filter with pressure loss measuring	2 pcs	3 000 €	6 000 €
Design	500 h	60 €/h	30 000 €
Assembly	300 h	50 €/h	15 000 €
			182 000 €

Control system			
Including PLC, sensors, frequency converter drives, cabling and control devices	1 as a whole	30 000 €	30 000 €
Design	500 h	60 €/h	30 000 €
Assembly	300 h	50 €/h	15 000 €
			75 000 €

TOTAL	**Manufacturing**	**269 000 €**
	Design	**95 000 €**
	Assembly	**46 000 €**
		410 000 €