PROTECTION OF OPERATORS AND ENVIRONMENT – THE SAFETY CONCEPT OF THE KARLSRUHE VITRIFICATION PLANT VEK

J. Fleisch, H. Kuttruf, W. Lumpp, W. Pfeifer, G. Roth, S. Weisenburger
Forschungszentrum Karlsruhe GmbH
Hermann-von-Helmholtz-Platz 1
76344 Eggenstein-Leopoldshafen, Germany

ABSTRACT

The Karlsruhe Vitrification Plant (VEK) plant is a milestone in decommissioning and complete dismantling of the former Karlsruhe Reprocessing Plant WAK, which is in an advanced stage of disassembly. The VEK is scheduled to vitrify approx. 70 m^3 of the highly radioactive liquid waste (HLW) resulting from reprocessing. Site preparation, civil work and component manufacturing began in 1999. The building will be finalized by mid of 2002, hot vitrification operation is currently scheduled for 2004/2005.

Provisions against damages arising from construction and operation of the VEK had to be made in accordance with the state of the art as laid down in the German Atomic Law and the Radiation Protection Regulations. For this purpose, the appropriate analysis of accidents and their external and internal impacts were investigated. During the detailed design phase, a failure effects analysis was carried out, in which single events were studied with respect to the objectives of protection and ensuring activity containment, limiting radioactive discharges to the environment and protecting of the staff.

Parallel to the planning phase of the VEK plant a cold prototype test facility (PVA) covering the main process steps was constructed and operated at the Institut für Nukleare Entsorgung (INE) of FZK. This pilot operation served to demonstrate the process technique and its operation with a simulated waste solution, and to test the main items of equipment, but was conducted also to use the experimental data and experience to back the safety concept of the radioactive VEK plant.

This paper describes the basis of the safety concept of the VEK plant and results of the failure effect analysis. The experimental simulation of the failure scenarios, their effect on the process behavior, and the controllability of these events as well as the effect of the results on the safety concept of VEK are discussed. Additionally, an overview of the actual status of civil work and manufacturing of the technical equipment is given.

INTRODUCTION

The VEK plant will be used to condition the HLW solution generated by the WAK plant which is in an advanced stage of disassembly (1). Application for construction and operation of VEK was filed in December 1996 by Forschungszentrum Karlsruhe GmbH (FZK) and the operational company Wiederaufarbeitungsanlage Karlsruhe Betriebsgesellschaft (WAK BGmbH). After two years of licensing and a public hearing, the first partial construction license was issued at the end of 1998. The licensing procedure comprises in total three partial permits for construction and two for the operation, one licensing step for the inactive start-up and a separate permit for the active operation. Since November 2001 the last partial construction license was issued, comprising of the total equipment installation including specific functional tests and the operation of the ventilation system as well as systems for power and media supply.

The VEK building shell will be completed probably in 2002 with the installation activities running in parallel since December 2001. The preparation of all manufacturing documents as well as the component manufacturing is already in an advanced stage. Key components such as the melter, vessels, evaporators and the total mechanical equipment will be ready for installation in VEK in the near future. Completion of the plant is covered in the third partial construction permit and will run until end of 2003. At the current stage of work, commissioning is scheduled to be covered in another, separate licensing step in 2003. Hot operation is scheduled to start in 2004 (2).

The extent of provisions against damages resulting from operation of the VEK plant is based on the existing protection goals as defined in the German Atomic Energy Act and the subsequent Radiation Protection Rules, which were recently adapted to the International and European standards. General goals of protection are as follows:

- Observance of subcriticality
- Safe containment of the radioactive material

- Safe removal of the decay heat
- Limitation of the radiation exposure so as to protect the public, the environment, and the personnel.

Accordingly, the plant had to be designed to withstand loads arising from both internal and external impacts.

Other general requirements result from the interim storage and final storage capability of the waste form produced (canisters), the short vitrification period to be achieved, exclusive of the HLW of WAK, and subsequent dismantling of the plant within the ongoing complete demolition of WAK.

The effectiveness of the provisions underlying the VEK design was demonstrated in a detailed accident analysis. The results of this analysis showed that events like overfilling of components including the melter, malfunction of cooling systems, ventilation and media supply systems will not cause any incident with radiological significance. This also applies to assumed failures of power supply, instrumentation and control systems. Radiological relevant accidents during which the limits of normal operation could be exceeded, but would still remain far below the levels indicated in the German Radiation Protection Regulations are the leakage of the HLW receiving tanks or a sudden break of the melter off-gas pipe.

In support of planning, operation and licensing of VEK a nonradioactive prototype vitrification plant covering the core process technology was constructed and operated by INE of FZK. The testing took place under close-to-hot-operation conditions to maximize the benefits for VEK. The process demonstrations include ensuring active (VEK) operation so as to observe the goals of protection (activity containment, minimization of radioactive discharges, and protection of personnel), determining the plant operational parameters and their limits in normal operation, the effective retention function of the melter and the wet off-gas trains, demonstration of remote handling in the melter cell as the main process cell, preparatory personnel training for subsequent operation, and the supply of data and measures for safety analysis of the hot plant (3).

SAFETY DESIGN PRINCIPLES

Building

The VEK building was to be constructed on the existing site without any interactions with the running radioactive facilities, and was to benefit from existing installations of WAK or FZK. This refers to all the media systems, the high-level radioactive laboratory, and specific installations for off-gas cleaning in the HLW storage building. VEK did not have to be designed for longer-term interim storage and, for that reason, was to contain only a buffer store with natural air cooling for plant operation to decouple the vitrification process from off-site shipment to a central external interim storage of the canisters produced. Moreover, the plant had to be designed so that secondary liquid waste was avoided as much as possible and the total activity was immobilized in the vitrified product as the main stream. The discharge limits so far licensed for the WAK reprocessing site were to remain unchanged for the operation of the VEK plant.

The installations for HLW vitrification will be arranged in a new building to be erected adjacent to the existing HLW storage (LAVA) and ELMA (Expansion of Storage Capacity for Medium-level Waste) buildings. The building foundations are at approx. - 6 m and the dimensions of the building are 36 m x 29 m x 22 m. The outside walls and ceiling are 1.80 m thick, while the inner walls of the process area have a thickness of at least 1.10 m. The bottom slab is 2.40 m in the vertical dimension, (see Fig. 1).

The inner layout of the VEK building is determined by the arrangement of the hot cell areas. Along the longitudinal axis from North to South, there are the melter cell 2, the melter depot 3, the canister treatment cell 4, the canister buffer storage and subsequent loading station 5,6. On the Northern side, normal to the hot cell wing, there is the HLW receipt cell 1 with the HLW transfer channel, and on the southwestern side, there is the transport and storage cask lock area 10. All cells except the HLW receipt cell are equipped with remote handling devices, e.g. hand–manipulators. For repair and maintenance purposes one single power-manipulator is available for the total canyon. Specific installations are already scheduled during construction to support easy dismantling after the vitrification operation. The wet off-gas components (jet scrubber and NOx absorber) as well as the two lines of dry off-gas filters including a special Iodine filter unit are arranged in the separate cells 7 and 8, with the last one being equipped with remote handling tools.

The VEK plant has been designed to withstand earthquakes of the maximum intensity applicable to the site plus an extra margin for safety. Correspondingly, a maximum horizontal acceleration of 2 m/s^2 was used as the basis

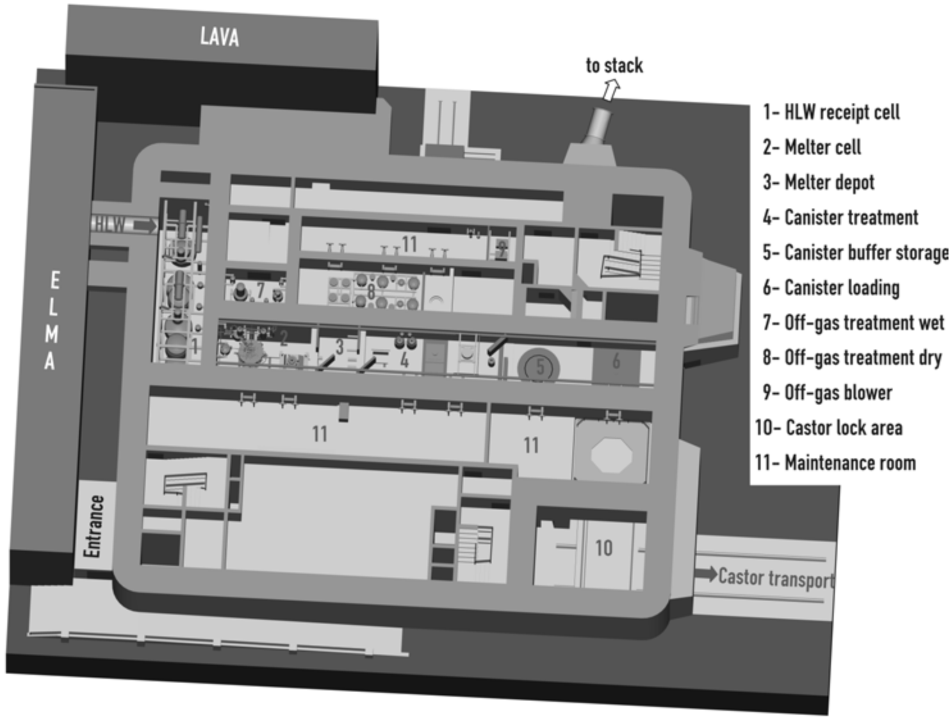

Fig. 1. Sectional View of the VEK Process Building at the 4.20m Level

for the earthquake load case. Although the airplane crash load case, with its probability of occurrence of approx. 10^{-7} per annum, is part of the residual risk, the complete VEK building was designed to withstand an airplane crash in order to minimize risk.

The steel reinforced concrete of the outer building shell is 1.80 m thick and is protected against penetration. The floor troughs of the cells, the tanks of the receipt cell and the stainless steel cell liners will remain intact even under these assumed loads. The existing openings are protected by additional structural measures. Important plant components are designed in such a way that they will continue to fulfill their technical safety functions even after an earthquake and, if applicable, operation can be continued after repair.

A recent photo of the VEK building is shown in Fig. 2. The first six sections where concrete was poured (foundation slab, walls and ceilings up to the ± 16.80 m level) were completed on the VEK construction site . In April 2000, the foundation slab of 2.40 m thickness with a total of approx. 250 t of reinforcement steel was

Fig. 2. Construction Site from South (Status November 2001)

poured. In addition to the anchoreplates required for the components, such internals as the wall frames of the radiation protection windows, the frames of the fire protection dampers, and physical protection systems were placed in the reinforcements. During the construction phase, the LLW tanks of 5 m^3 and 10 m^3, respectively, planned for the basement level, the shielding and stainless steel tubes of the buffer storage and the HLW transfer pipe were installed.

Process Equipment and Process Control

To supply power to VEK, a new facility was erected with redundant installations for emergency power supply, a fire alarm and a communication system, which are ready for operation. In addition, a redundant 20 kV supply was run to the WAK site. Should the normal power grid fail, two redundant emergency power generators would be available. In addition, another emergency power unit is planned for installation in VEK to supply selected components to prevent any higher radiation exposure to the environment and personnel in case of power supply interruptions. In this way, the power supply unit and VEK each have redundant uninterruptible power supply systems for safety-related facilities.

A computer-aided process instrumentation and control system has been planned for process control. In accordance with the guidelines of the German Advisory Committee on Reactor Safety, a major feature of the instrumentation and control concept of VEK is the breakdown of I&C functions into categories meeting staggered safety requirements. Category 1 refers to functions required to prevent intolerable consequences of accidents; this category does not occur in VEK. All instrumentation and control functions of categories 2 and 3 are integrated into a safety system. This is consistently separated from the operations I&C system, both electrically and in terms of instrumentation and control, in order to ensure that the process would be automatically changed into a safe state by the functions of the safety instrumentation and control system in case of defects or malfunction in the operating sectors.

A simplified scheme (without fire alarm and communications systems) of the suggested process control system for the VEK plant is given in Fig. 3. The architecture ensures a safe and reliable process control and operation system backed up by a high reliability protection system. The system will consist of the following four main parts:

- the protection system
- the non-nuclear part
- the operation and monitoring (including auxiliary panels)
- the emergency panels

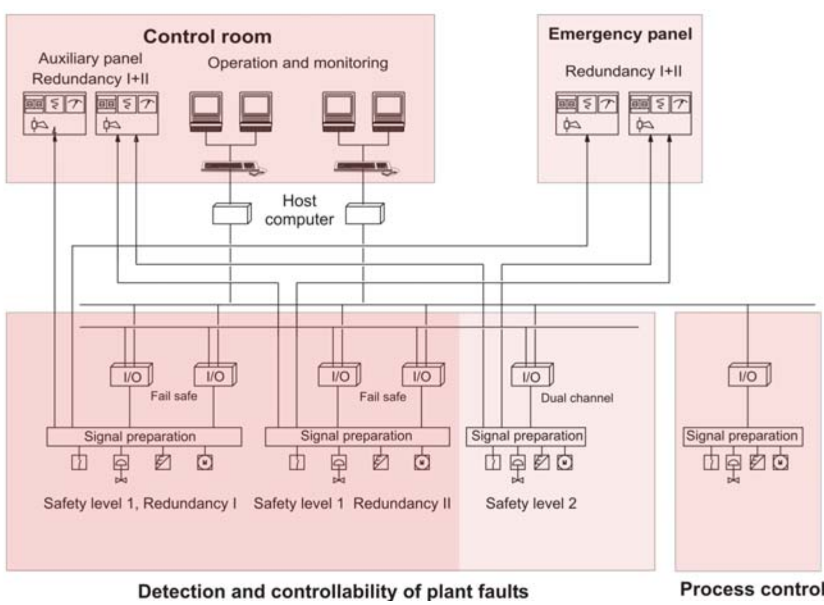

Fig. 3 Simplified Scheme of the Process Control System

The task of the protection system is the detection and control of plant faults and has to achieve high security-requests. It is divided into above mentioned safety levels 2 and 3. The safety level 2 equipped with fail safe technique and is redundant from actor up to sensor. The safety level 3 is equipped with a fault tolerable technique in a dual-channel version. The protection-system is not involved in the control of the process but monitors security-relevant signals and interlocks. In case of emergency, the protection-system switches the installation or parts of the installation into a safe condition automatically. Emergency cases could be, for example, malfunction of fail-safe modules itself, actuating of the seismic monitoring, exceeding of the threshold value of a radiation measuring point. The communication between safety level 2 and safety level 3 is carried out via high-speed link bus. The communication between the protection system and the non-nuclear parts including the terminals for operation and monitoring are carried out via optical fibre network.

The non nuclear part is built-up under the valid rules and regulations for engineering of electrical facilities but not necessarily to achieve high security-requests and can be complex and error tolerable. Installations belonging to the non-nuclear part are for instance: the process control system, the power generator for the glass pouring system of the melter, the glass frit feeding system, the melter power supply and others which are not involved in safety aspects or already covered by the protection system.

The operation and monitoring of the whole plant is performed in the control room. For the operators are two terminals, operated in parallel mode, with two monitors each available. The parallel mode assures a high system availability for this non-nuclear part. For monitoring purposes only a redundant designed auxiliary panel is installed in the control room. The task of the auxiliary panels is that the operators are additionally supported with selected actual and historic analogue and digital process data. The philosophy behind that is to get an overall plant overview in a nutshell. The auxiliary panels are directly connected to the signal preparation of the protection system and permanent in operation.

If the control room is not accessible for any reason, or an unexpected accident happened, a redundant designed emergency panel is available in a separate and shielded room. Via the emergency panels selected analogue and digital process data (actual and historic) are available. A process control function is not foreseen via the emergency panels. The emergency panels are directly connected to the signal preparation of the protection system and permanent in operation.

FAILURE MODE EFFECT ANALYSIS

The effectiveness of the provisions underlying the VEK design was demonstrated in a detailed accident analysis. The criticality safety of VEK is ensured by limiting the concentration of fissile material in the HLW before its transfer into VEK installations (e.g. the receiving tanks). Fires inside the plant are controlled by the appropriate measures laid down in the fire protection plan. In a failure effect analysis conducted in the course of the licensing procedure, single events and their repercussions with respect to the observance of the goals of protection and ensuring activity containment, limiting radioactive discharges to the environment, and protecting the staff working in the plant, were studied. Overfilling of components, the melter included, malfunction of cooling systems, ventilation systems, and media supply systems as a rule will lead only to off-normal operating states. Accidents must be expected to occur only in individual cases, and will be without any radiological significance with respect to observance of the accident limit levels. This also applies to the assumed failure of power supply or of the instrumentation and control systems. As a consequence of the redundant design of the emergency power supply and safety instrumentation and control systems, respectively, no plant conditions are expected to occur in which potential releases would exceed the limits of normal operation.

Radiologically relevant accidents in which the limits of normal operation could be exceeded, but would remain far below the planning guidance levels of the German Radiation Protection Ordinance, are leakages of vessels and pipes or failures in the offgas cleaning system of the melter. The cells equipped with stainless steel floor troughs, and the permanently installed systems for leakage detection and leakage repair, ensure that countermeasures can be initiated and the plant in any case can be returned into a safe state. Possible overfilling of the melter with HLW will cause only off-normal operating conditions without any radiological significance. Accident analysis has shown that the representative events, "leakage of a HAWC receipt tank" and "break of the offgas pipe connecting the melter with the first off-gas scrubber," will give rise to an effective dose of < 0.2 mSv. This is far below the limit in the Radiation Protection Ordinance.

EPERIMENTAL INVESTIGATION OF FAILURE SZENARIOS

During the total net feeding time of about 3000 h, accumulated during five long-term test runs with the PVA prototype test facility, scenarios were investigated, which gave information about the impact of malfunctions/failures and the effectiveness of countermeasures. For experimental verification, a catalogue of scenarios was simulated, including events such as under-/overfeeding of the melter, overfilling of the melter and the glass canister, failure of off-gas pipe cleaning device, failure of scrubbing circuits in the off-gas components, loss of depression in the melter and in the off-gas line, failure of power supply to the melter and others. After the failures had been initiated, their development was first tracked without any interventions so that the effects and the diagnosing capability by means of process instrumentation could be evaluated. Then countermeasures were initiated to repair the defects in order to test their effectiveness. All the operating failures under study were clearly identified, and were controlled by the countermeasures provided for. As a major result for the safety concept of VEK, the findings were used to verify the instrumentation and control systems with respect to their safety classification.

Detailed results are given below for three selected scenarios: canister overfilling and melter underfeeding, reheating of the melter with solid glass.

Canister Overfilling

The failure event "*canister overfilling*" is based on the scenario that the regular termination of the glass pouring by the operator is not completed. In case of the bottom drain system that is used by the VEK melter glass flow is started and maintained mainly by inductive heating of the metallic (Inconel 690®) glass pouring channel placed in the melter bottom. Stopping is performed manually by gradual decrease of the induction power as the end of the pouring approaches. This procedure results in pouring accuracy of ± 1 kg. The target batch of the VEK melter is 100 kg (nominal canister capacity 400 kg). If there is no correct termination of the pouring, an automatic switch off of the induction heating occurs when the quantity of poured glass exceeds 100 kg. The question to be answered was if a canister could be subject to overfilling by the last batch, if there was no correct termination of pouring.

The test was performed during a regular pouring operation without intervention of an operator. After the automatic switch off of the induction power at the pouring batch limit, the glass flow stopped from a normal flow rate of 100 kg/h within 5 minutes with an additional glass discharge of 5.2 kg. Thus, overfilling of canister can be excluded as the remaining capacity in the canister plenum is about 25 kg.

Melter Underfeeding

Melter underfeeding happens if the actual feeding rate is below the throughput capacity of the melting system. In this case the low-temperature process zone on top of the hot glass pool ('cold cap') becomes less extensive than required (optimum conditions 80-95 % of pool surface). As a consequence, the barrier effect of the cold cap layer against the loss of semi-volatile elements or compounds from the glass melt is reduced. Elements the retention of which is sensitive to the cold cap coverage are for example cesium and ruthenium. Results of the tests are given in Table I. It contains melter decontamination factors (DF) for cesium, strontium and ruthenium obtained from a three days underfeeding period (about 60 % of nominal feed rate, 50-60 % cold cap coverage) compared with those from normal operation. As a reference, the design basis is also indicated. Obviously, underfeeding can distinctly raise melter emissions, which in the considered case could lead to a drop of the DF value of cesium far below the design limit.

Table I: Melter decontamination factors for cesium, strontium and ruthenium obtained from melter underfeeding and normal operation. Comparison with design values.

Element	Melter decontamination factor		
	Underfeeding	Optimal feeding	Design
Cesium	19	42	30
Strontium	73	133	60
Ruthenium	7	13	5

Melter Restart

This scenario is based on the assumption that a sudden power failure lasts a sufficiently long period of time, that the melter cools down and the glass melt inside becomes solid. A melter with full inventory of solid glass - if not able to be restarted – would complicate the dismantling and would contribute to a higher amount of solid high level waste. In case of a Joule-heated ceramic melter as will be used by VEK restart needs external heat sources as solid glass does not provide the physical properties required for Joule-heating. The ability for restart was successfully demonstrated with the melter of the PVA prototype test facility. With the full glass melt inventory the power supply was switched off until the glass melt temperature had decreased to below 100°C. The recorded temperature curves revealed that a power failure up to about half a day can be tolerated by the system without losing the Joule-heating properties. For restart the melter was equipped with four external SiC heaters inserted through openings in the melter ceiling. These openings are used during routine operation for temperature measurement, melt level detection etc.. Heating up of the melter was controlled according to a tempering program. Moderate temperature rising rates of 3-4°C were applied to protect the refractory material. After about 24 days of external heating, the glass melt temperature was high enough to enable Joule-heating. Data of the reheating experiment is shown in Fig.4. It contains the curves of the temperature controlled by the heating-up program and the temperature of the two power electrodes which reflect the glass melt temperature. Joule-heating initiated at about 700°C.

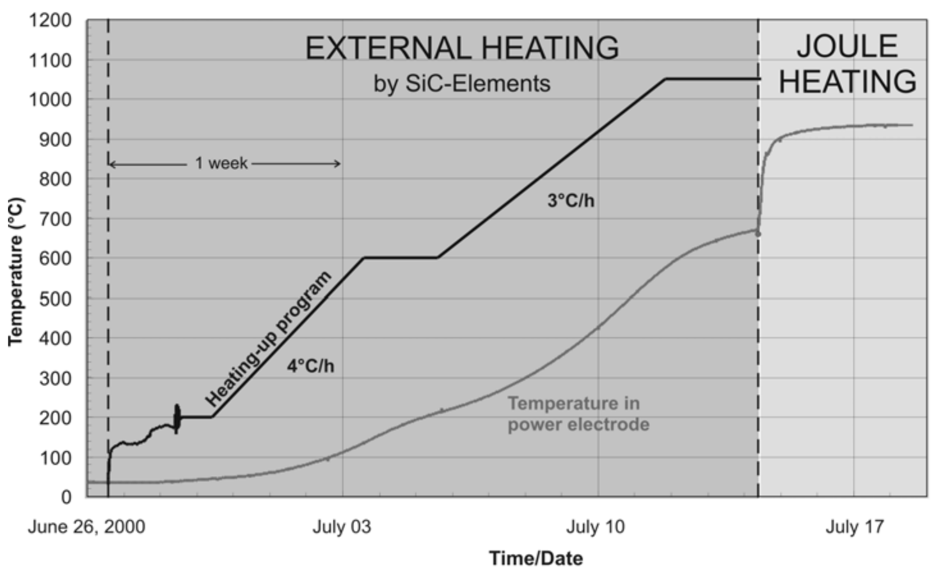

Fig. 4. Temperature curves recorded during restart of a melter cooled down with full glass inventory

CONCLUSIONS

The safety concept of the VEK plant ensures a maximum of protection of the public, the environment and the operators. Appropriate analysis of accidents and their external and internal impacts form the basis for a safe construction and operation. The consideration of earthquakes and plane accident scenarios in the design of the building and process installations results in a high standard of safety. The use of an optimized process control system will also contribute to the safety features of the VEK. The prototype testing of normal as well as process upset conditions and failure scenarios proved to be a great benefit for the VEK safety concept.

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