Chapter 2
The History of HAMMLAB

25 Years of Simulator Based Studies

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Abstract The history of HAMMLAB is tightly intertwined with the history of the
OECD Halden Reactor Project. This chapter Þrst gives a short account of the
events leading up to the construction of the Halden reactor and the establishment
of the Halden Project, and why a research program on process control emerged
from the activities at the Halden reactor. A short summary of major activities in
the pre-HAMMLAB period follows. The major drivers for the establishment of
HAMMLAB in 1983 were the accident that occurred at the Three Mile Island
nuclear power plant in 1979 and the recommendations that followed from the
analysis of the accident. The Halden Project proposed the construction of a ManÐ
Machine Systems Laboratory to the Halden Board of Management, with the initial
idea to systematically, in a controlled setting, validate different operator support
systems and study various human performance issues. The purpose of this chapter
is to provide the reader with an overview of activities performed in HAMMLAB
over the 25 years of operation. In particular, the chapter demonstrates how
HAMMLABÕs focus has shifted and broadened from its initial focus on operator
support systems and human performance to more generic human factors studies
addressing issues such as stafÞng level, automation level and teamwork. Today,
the research carried out in HAMMLAB ranges from studies providing data for
human reliability assessment to studies directed at the design, testing and evalu-
ation of human system interfaces, and the development and testing of operation
support systems. In addition to this, research at the laboratory explores the
potentials of virtual and augmented reality technologies for extending and
improving teamwork and planning in various nuclear power plant settings.

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2.1 Introduction

Norway was a pioneer in the area of nuclear reactors. The Norwegian Institute for Atomic energy (IFA) at Kjeller outside Oslo put a Norwegian designed and built experimental heavy water reactor called JEEP in operation in 1951. As the Þrst Director of IFA, Dr. Gunnar Randers, wrote in a commemoration of the 25 year anniversary of the Halden Project in 1983:

> A part of the success of the JEEP reactor was a co-operation between the Netherlands and Norway called JENER (Joint Establishment for Nuclear Energy Research). After three years of operating the JEEP reactor, JENER wanted to move forward to build a second reactor with a power level of at least 20 MW and an operating temperature of at least 200 C. The Dutch partners, however, decided to proceed their line of research by buying a ready made test reactor, while the Norwegians decided to go their own path because they had become very interested in a new development: the demonstration of the stability of boiling lightwater reactors The design and plans for construction of a heavy water moderated boiling water reactor were put before the Norwegian parliament by the gov- ernment on 14th June 1955 and preliminary approved, but with a condition that the detailed Þnancial and technical plans should be placed before the parliament by the end of the year for the Þnal go ahead signal. On November 4th 1955 IFA placed a complete package before the minister of industry, and the government decided the same day to place it before the parliament. After 2 months of public hearings the plan was approved by parliament.

2.1.1 The Halden Reactor

IFA began the construction of the Halden Boiling Water Reactor (HBWR) in late 1955 by blazing a cave for the reactor in a small mountain in Halden, Norway. HBWR went critical on 29 June 1959, just three years after the approval in principle by the parliament.

2.1.2 The OECD Halden Reactor Project

During 1958 a new development changed the plans for the anticipated research at HBWR. In 1957, the nuclear agency of Organisation for European Economic Co-operation (OEEC), later the Organisation for Economic Co-operation and Development (OECD), had worked out a proposal for common European nuclear projects. The French pioneer Leo Kowalski proposed to turn the developing Halden Reactor into a common venture for Europe. Concurrently, the IFA team building HBWR began to realize more clearly the magnitude of the project they had embarked on, in particular the running budget and specialist staff that would be needed to exploit the HBWR to its full capacity when it became ready for operation.

Based on a proposal from IFA, Norway decided to offer the nearly finished Halden reactor to the OEEC without compensation on the condition that the running budgets for the next three years be supplied jointly by a group of interested European nations. Norway invited all participants to a signature meeting in Oslo on 11th June 1958. The international research program called the OEEC Halden Reactor Project (HRP) was then established under the auspices of OEEC Nuclear Energy Agency (NEA) with the initial aim to provide urgently needed reliable data for the design and operation of power reactors. This international research program was successful from day one, and went on under renewed three years contracts throughout the 1960s, went onto carry out reactor physics and reactor dynamics experiments, studying water chemistry phenomena and, by means of in-core instrumentation, studying fuel rod behaviour and performance.

2.1.3 Computerized Control and Operator Communication

During the mid 1960s the HBWR pioneers realized that process computers were important devices for the optimum operation of complex processes such as nuclear power plants. From 1967, research on computerized control was established by the HRP as an extension to fuel research. By the end of the 1960s, a new research area, which was called computer control research emerged in order to develop computerized control room technology and study Human Factors engineering issues.

Building and operating a new experimental reactor made the HBWR pioneers eager to take advantage of the emerging digital technology to acquire data from experiments and store the data in a way that could facilitate its reuse by the member organisations. This led to the procurement and installation of a large by the standards of the day, IBM-1800 process computer system. The use of the IBM-1800 enhanced computer knowledge dramatically among Project staff members and attracted young researchers who saw the potential in utilising computers also in other areas.

Two lines of ideas emerged from this young generation of engineers: the first was the use of control theory implemented in software to automatically control a nuclear power plant; and the second was the utilisation of minicomputers for data acquisition, data processing and data presentation on colour TVs. Research questions, such as these were formulated: Can control theory algorithms safely be implemented in software and used for plant control, and which algorithms would be the most useful? Can control room operators interact safely with a nuclear plant through computer screens? What would be the best way to present data acquired from the plant and what kind of devices would be the best to use to interact with screens to monitor and operate the plant?

The research program on computer control aimed to demonstrate on-line computer applications, in particular supervision, direct digital control and optimisations, and further to apply and demonstrate advanced supervision and control methods to obtain improved plant performance. HBWR was regarded as well

suited for such demonstrations, which could initiate further application of on-line computers in commercial power reactors. Netland et al. (1970) describes the application of so-called conventional control laws in their digitalized versions. This application was a natural starting point for the further work in the area of direct digital control, as it provided experience with algorithmic formulations, software organisation, operator-process communication, hardware, and safety aspects. The control functions implemented were the steady state control of nuclear power and of plant loops, as well as nuclear power ramp control. They were initially tested in reactor experiments, but later commissioned for use in routine reactor operation with satisfactory operational performance. Further work comprised the application of non-interacting control systems and optimal control systems based on what was known at the time as ÔÔmodern control theoryÕÕ (Roggenbauer et al. 1970, Bj¿rlo et al. 1971), as well as the development of software systems for plant supervision and core power distribution evaluation and control.

2.1.3.1 OPCOM 1968–1974

In order to study process control issues systematically, a computerized experimental control room called OPCOM (OPerator COMmunication) was designed and built at HBWR (see Fig. 2.1). OPCOM was located adjacent to the existing conventional control room (see Fig. 2.2). It was directly coupled to the plant, and operators could—during experiments when OPCOM was on line—monitor the plant status. In several periods during 1972 to 1974 operators could even operate HBWR directly through the computer screens (with the conventional control room in hot stand-by). For more information on OPCOM and results from this pioneering project, see Chap. 7 (Netland and Holt 1977).

Fig. 2.1 The OPCOM control room
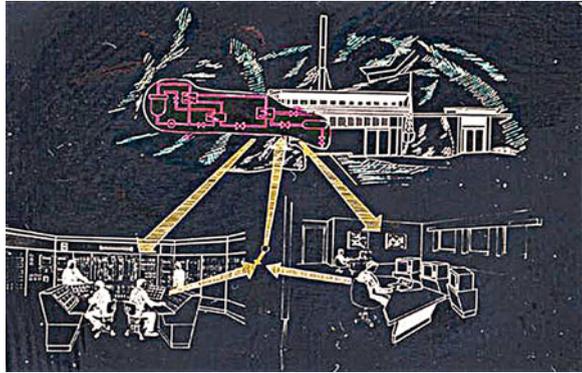
Fig. 2.2 The conventional
control room in hot standby

Fig. 2.3 DEMPÑdecentral-
ized, modular, multiprocessor
Ñhigh reliability computer
architecture

2.1.3.2 Highly Reliable Computer Architectures 1970–1980

The architecture of computer systems for process control developed rapidly during
the early 1970s, mostly due to the cost reduction of hardware modules, which
made more sophisticated hardware solutions economically attractive. High reli-
ability, parallel processing, increased throughput and more ßexibility were key
aims in this development. Multiprocessor systems, such as the DEMP computer
system, offered good solutions to most of the key problems. The DEMP
(DEcentralized Modular Processes) computer system was a highly reliable, mul-
tiprocessor system with generalized work division designed and developed by
HRP and tested at the HBWR (see Fig. 2.3). For reasons of functional, technical
and economical character, this approach appeared to possess promising features
for nuclear process control applications. The DEMP system was used at the
HBWR and various monitoring and digital control functions were implemented
(Berge et al. 1975).

2.2 What Were the Drivers to Build the HAMMLAB Facility?

The understandable conﬂict of interests between the fuels and materials research and the process control research, which both used HBWR as their research tool, led to a HRP decision in 1974 to move the process control and human factors research out of HBWR to simulator-based laboratories.

2.2.1 Drivers for the First Simulator-based Experimental Control Room

During the 1970s the vendor industry world wide picked up the potential of applying minicomputers for the purposes explored by the Halden pioneers 5–10 years earlier. The nuclear industry and regulators turned to Halden for advice on how to design Man–Machine Interface (MMI), in the best possible way.

2.2.2 STUDS Simulator 1974–1982

The OPCOM work was carried over to a new, completely simulator based facility. The ﬁrst simulator acquired was the STUDS simulator developed by Studsvik, Sweden (see Fig. 2.4). It was a so called compact simulator of the Ringhals 2 unit in Sweden, and was in use between 1974 and 1982. In conjunction with the use of the simulator for the ﬁrst time systematic research began to develop guidelines for good MMI design.

The initial focus was on developing guidelines for the use of colours, symbols, font sizes, alarm lists, trend curves and good human factors design principles. Hol and Øhra (1980) provide a summary of this work.

Fig. 2.4 STUDS simulator facility

2.2.3 The TMI Accident in 1979

The construction of the nuclear reactor in Halden, the formation of the OECD Halden Reactor Project, innovative research into computer control and the construction of the STUDS simulator paved the way for the creation of HAMMLAB in 1983. The Three Mile Island incident, however, provided further impetus and added urgency to HAMMLABÕs development. In 1979, the Three Mile Island Nuclear Generating Station, located on an island in Susquehanna River near Harrisburg, Pennsylvania, USA, underwent a partial meltdown, resulting in the worst civilian nuclear accident in US history. The incident was of great interest to human factors research around the world, as the accident appeared to be exacerbated by operator stress and the difÞculty of dealing with an overwhelming amount of frequently irrelevant information. The TMI accident was a wake-up call to the nuclear industry world wide. It pin-pointed the importance of the operator as a safety barrier and the need for high quality training and support tools to obtain high human performance in complex situations.

Three Mile Island has been of interest to human factors engineer as an example of how groups of people react and make decisions under stress. There is consensus that the accident was exacerbated by wrong decisions made because the operators were overwhelmed with information, much of it irrelevant, misleading or incorrect.

As a result of the TMI-2 incident, nuclear reactor operator training has been improved. In addition, improvements in quality assurance, engineering, operational surveillance and emergency planning have been instituted. Improvements in control room habitability, and ÔÔsight linesÕÕ to instruments were made, ambiguous indications were eliminated and the placement of ÔÔtroubleÕÕ tags were changed; as some trouble tags were experienced to have covered important instrument indications during the accident. Improved surveillance of critical systems, structures and components required for cooling the plant and mitigating the escape of radionuclides during an emergency were also implemented. In addition, each nuclear site must now have an approved emergency plan to direct the evacuation of the public within a ten mile Emergency Planning Zone (EPZ) and to facilitate rapid notiÞcation and evacuation.ÕÕ

2.3 HRP Research as a Consequence of TMI

The TMI accident had a profound impact on the research strategy and related activities from 1979 and onwards. The annual technical report for 1981 (OECD 1981) states on page 11:

> The most important lessons learned from the Three Mile Island accident (ref. NUREG-0585) fall in the area of operational safety. InsufÞcient attention has been paid by all responsible levels to the operator and his fundamental role in both the prevention and the

response to accidents. This has emphasized that enhancement of operator performance deserves the utmost attention in the years to co*ff*e. Substantial improvements in operator performance can be obtained through a multitude of control room improvements, ranging from the introduction of computer assisted decision aids which rationalize and improve the quality of the information ßow, to changes in control room staff organization and operators task responsibilities.

On this background and accounting for the speciÞc needs of the Project participants, the research efforts at the Project are concentrated in two Þelds: (1) the development and validation of computer-based operator aids for diagnosis of core- and plant sta-tus, including alarm handling-, disturbance analysis- and core surveillance systems, and (2) general human factors experiments in the Projects ManÐMachine Systems laboratory followed up by Þeld studies at nuclear power plants, on the basis of which guidelines for control room layout and design of operator-process interfaces, enhancing the operators performance, are formulated.

2.3.1 Work Program for HAMMLAB

In March 1982 a workshop took place at Halden in order to discuss recommen-dations for a work programme at HAMMLAB. The workshop was attended by nearly 30 delegates from member countries. There was broad consensus among the delegates that experiments were needed to establish guidelines for the design of new control room solutions and that the recommendations had to be developed from the consideration of several speciÞc systems. The plans for the HAMMLAB facility were presented and approved at the workshop.

2.4 HAMMLAB: First Generation (1983–1990)

2.4.1 Infrastructure

The HAMMLAB facility was established in 1983. It included an experimental control room, experimentersÕ gallery, computer room, developersÕ room and conference room, see Figs. 2.5 and 2.6. The control room included two worksta-tions for the reactor and turbine operators and one workstation for a shift super-visor. In addition, alarm screens were provided for the operators.

2.4.1.1 NORS Simulator

The full-scale PWR simulator NORS was taken into use in HAMMLAB in 1983. The simulator was developed in a co-operation between Nokia Electronics and Imatran Voima Oy (IVO), both from Finland, and the Halden Reactor Project. Except for some minor differences, such as westernized vertical steam generators,

Fig. 2.5 HBWR operators participated in the first HAMMLAB experiment

Fig. 2.6 View from the Experimenters gallery into HAMMLAB

NORS simulated the behaviour of the Loviisa NPP in Finland quite well, both during normal operation and disturbances. It was installed on Norsk Data computers (ND) and was the main experimental vehicle of HAMMLAB for nearly 20 years (Stokke and Petterson 1983).

2.4.1.2 Data Management System, SCOPS

SCOPS was the acronym of the data distribution, storage and communication control system developed for HAMMLAB. It was used to transfer data and operator requests between the NORS simulator, the human system interface, operator support systems and systems in the experimental control room. SCOPS was executed on several ND minicomputers in a star configuration. The different system functions were separated into logically isolated tasks distributed in this structure. A message system was used to communicate between the software modules (van Nes and Skjerve 1983).

2.4.1.3 Human System Interface, NORS HSI

The human system interface (HSI) for NORS was developed to monitor and operate the simulated plant completely through the computer screens. In terms of hardwarewise the control room workstations were equipped with semi-graphic systems (Nord Color Terminals), and programmable touchpanel keyboards and trackerballs for operator interaction.

2.4.1.4 Experimenters' System, HOPES

An experimentersÕ system called HOPES (HAMMLAB Operation System) was installed in 1987. HOPES assisted experimenters and instructors in preparing, performing and evaluating experiments, helped system developers in making tests and system installations, supported staff during demonstrations and process experts in studying plant behaviour. Tasks were performed using menus, prede-Þned forms and function keys. Users no longer had to remember numerous commands to operate the simulator properly. But, as years passed by, the user interface of HOPES became quite old-fashioned with its character-based look. So when NORS was retired from HAMMLAB, so was HOPES (Kristiansen et al. 1987).

2.4.2 HAMMLAB Research on Development and Validation of Operator Aids

The HAMMLAB research program started with focus on validation of operator aids. I will now give a short overview is given of operator aids that were developed, implemented and evaluated in HAMMLAB during the period 1983Ð1990. For more details on some of the operator aids, see Chaps. 10 and 13. A list of HAMMLAB studies during 1983Ð1990 can be found in Table, Sect. 2.10

2.4.2.1 Alarm System, HALO

HALO (Handling of Alarms using LOgic) was an advanced alarm system installed in HAMMLAB in 1983. HALO used logic expressions to reduce the number of active alarms during process transients. The remaining alarms were presented in a hierarchical display structure. The original HALO display design used only objects and colour coding to present the alarm situation. HALO was evaluated in two series of experiments, and it was coupled to the NORS simulator, which had a realistic alarm system including some 2,500 alarms (Visuri and Øwre 1981; Visuri et al. 1981; Visuri and Øwre 1982; Hollnagel and Øwre 1984).

2.4.2.2 Integrated Process Status Overview, IPSO

The drawbacks of sequentially addressing a number of small cathode ray tube (CRT) screens paved the way for investigating the potential benefits of implementing a dynamic large screen display providing operators with computer-generated plant and process overview information. The work was a co-operation between Combustion Engineering and the HRP (Gertman et al. 1986; Reiersen et al. 1987a).

2.4.2.3 Critical Function and Success Path Monitoring System, CFMS/SPMS

CFMS provided information to the operator on the status of a set of seven indicators called critical functions. When the operating criteria of each critical function were satisfied, the safety of the plant was ensured regardless of any other challenges or faults in the plant. The CFMS operating philosophy contained predetermined control actions and sequences to assure the integrity of the critical functions.

SPMS provided assessments of the status of success paths for the maintenance of critical functions. The design was based upon the instructions in the emergency procedures. While CFMS provided a description of the necessary conditions for plant safety, SPMS provided more detailed information for the recovery of challenged critical functions (Marshall et al. 1983; Hollnagel et al. 1984a, b; Gaudio et al. 1987; Øwre et al. 1987; Baker et al. 1998a, b).

2.4.2.4 Early Fault Detection System, EFD

EFD was based on running a number of small decoupled mathematical models, each describing the behaviour of a confined plant system, in parallel with the plant systems. These models were fed by plant measurements. By comparing groups of model variables with corresponding real plant measurements, rather than looking at one single variable at a time, errors could be detected earlier than by conventional alarm systems. EFD was not developed with the intention to replace conventional alarm systems (such as HALO), but to improve the alarm systems by providing early warnings before traditional alarm systems were triggered. In addition the EFD alarms had the potential of avoiding false alarms barring, and to distinguish between ordinary plant dynamics and real faults (Berg et al. 1985; Verle and Marshall 1987).

2.4.2.5 Diagnosis System DISKET

DISKET was originally developed at JAERI, Japan Atomic Research Institute, Japan, and the software was originally written in UTILISP, a dialect of LISP. This

system was translated into FORTRAN in 1986 and connected on-line to the NORS simulator. A knowledge base with a set of fault hypotheses suitable for the NORS simulator was made. NORS process data and information from EFD was compared with the knowledge base for possible match with fault hypotheses (Yokobayashi et al. 1987; Holmstr¿m et al. 1989; Endestad et al. 1992).

2.4.2.6 Computerised Procedure System COPMA

COPMA was developed to provide a computerised medium for executing procedures for nuclear power plants. It was designed for use in the control room in place of normal printed procedures. COPMA collects and monitors process data called for in the procedure. The COPMA system can also act as a partial control interface; certain actions speciÞed by the procedures can be carried out directly through the COPMA interface.

At its simplest, COPMA is merely a presentation medium for procedures. COPMA does not take over the responsibility for selecting the correct procedure, though it offers facilities for viewing procedures before beginning to use them. It also contains features whereby actions normally performed by an operator are automated (see Chap. 13) (Nilsen 1986; Larsen et al. 1987; Krogs¾ter et al. 1989; Lilja et al. 1988). A list of HAMMLAB studies during 1983Ð1990 can be found in Table 2.1, Sect. 2.10.

2.5 HAMMLAB: Second Generation-I (1991–1995)

2.5.1 Infrastructure

In 1991 HAMMLAB was relocated together with the Man-Machine System (MMS) researchers from the original building in Halden to another ofÞce building across the street. The NORS simulator continued to serve the experimental program. The control room was redesigned and new operator workstations were purchased. The computer infrastructure was renewed and the whole manÐmachine interface system was moved to UNIX platforms while the NORS simulator kept running on the older ND minicomputers (Fig. 2.7). The new laboratory was equipped with eye-movement recording equipment and more sophisticated systems for audio and video recording (Fig. 2.8).
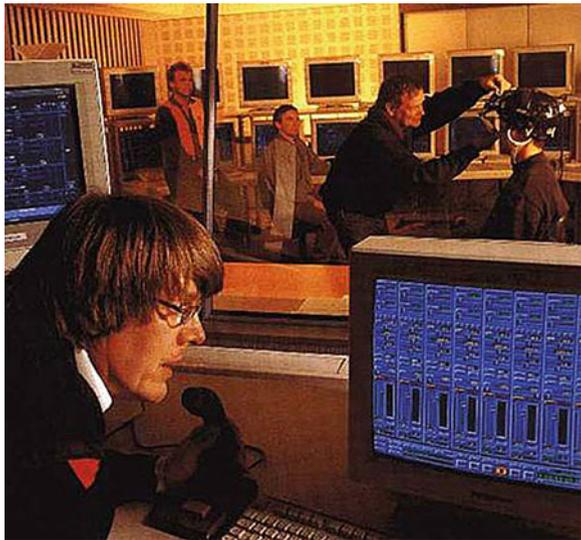
2.5.2 Experimental Program 1991–1995

The HAMMLAB experimental program took a new direction during this period. The emphasis was moved from ÔÔvalidation of operator aidsÕÕ to studying new

Fig. 2.7 Eye tracking in
HAMMLAB II

Fig. 2.8 HAMMLAB II

concepts and new methods, and measures were developed to enable the researchers to study human performance. A list of HAMMLAB studies during 1991Ð1994 can be found in Table 2.2, Sect. 2.10

A concept called ÔÔIntegrated Surveillance and ControlÕÕ (ISACS), underwent much development and testing (see Chap. 9 and Folles¿ and Volden 1993a, b, c). Work was initiated to investigate the concept of ÔÔHuman ErrorÕÕ (Kaarstad et al. 1994). The Situation Awareness measure, originally developed to study air force pilotsÕ performance in the USA, was tried out for possible use in process control research (Hogg et al. 1994). A list of HAMMLAB studies during 1991Ð1995 can be found in Table 2.2, Sect. 2.10

2.6 HAMMLAB: Second Generation-II (1995–2000)

2.6.1 The HAMMLAB 2000 Project

An HRP workshop on ÔÔThe Long Term Development of HAMMLABÕÕ in 1995
(Felt et al. 1995) had the aim to discuss the need for a major upgrade of the
facility, and how to realize it. There was consensus among the workshop partic-
ipants that the activities in HAMMLAB were increasingly important (Fig. 2.9).
The workshop recommended that the Project start planning a new facility for the
experimental work in HAMMLAB including the purchase of new simulators and
establishing a new larger facility to house the activities.

   A HAMMLAB 2000 task force group with four prominent HPG members and
three Halden representatives was established with the mandate to contribute to the
formulation of the requirements of a new facility and provide the viewpoints of the
Halden Project members on the research agenda in a new HAMMLAB (Fig. 2.10).
This task force provided their recommendations in 1998 in a paper (session C5.9)
at the EHPG-meeting at Lillehammer in 1998 with the title ÔÔOutline of a research
agenda for HAMMLAB 2000ÕÕ. The HAMMLAB 2000 project was Þnalised with
the ÔÔFinal project SummaryÕÕ at EHPG 2001 and here one will Þnd an impressive
list of 24 reports from the planning work during the 5 years from 1996 to 2000.
The actual realisation took longer time than expected, but the new facility was
Þnally a fact in March 2004.

2.6.2 Infrastructure

The HAMMLAB control room operator workstations were maintained between
1995 and 2000 work initiated to move the whole manÐmachine interface system

Fig. 2.9 HAMMLAB II
with new large screen

Fig. 2.10 A lonely human in a highly automated HAMM-LAB II

from UNIX to PC-based platforms. A major new feature was the installation of a large overview display in HAMMLAB in 1996. Two new simulators were installed during this period—the FRESH and HAMBO simulators.

The Fessenheim REsearch Simulator for HAMMLAB, FRESH, was installed in HAMMLAB in 1998. The reference plant is Fessenheim-1 in France, which is a Westinghouse-like 900 MW 3-loop PWR built by Framatome.

The development of the HAMMLAB Boiling water reactor simulator, HAM-BO, was initiated in 1998. The reference plant is the Forsmark-3 BWR plant in Sweden. VTT Energy in Finland developed the simulator models with the aid of their APROS tool, while the man–machine interface was developed by the Project. The acceptance tests in June 2000 consisted of running 19 well-defined transients as well as running the simulator down from full power to cold shutdown and back up again to full power according to plant procedures.

2.6.3 Experimental Program 1996–2000

The Human Error activity continued in this period and much of the experimental program focused on providing measures that could be utilised in the Human Error program. An important new program called Human Centered Automation was launched, which was carried out in close co-operation with IRSN in France. Two significant experiments were conducted in co-operation with USNRC, the first one was the so-called staffing level experiment and the second an alarm display experiment. Results from the latter two experiments were also issued as NUREGs

by the USNRC. A list of HAMMLAB studies during 1996Ð2000 can be found in Table 2.3, Sect. 2.10

2.7 HAMMLAB: Second Generation-III (2001–2004)

2.7.1 Infrastructure

Work in the HAMMLAB second generation-III period continued with the same conÞguration as before. Light weight cameras substituted the more cumbersome eye-tracking devices that were used in previous periods. The NORS simulator retired after almost 20 years of service, mostly due to the fact that it was not possible to make the simulator run stably on PCs (Fig. 2.11). The detailed technical speciÞcation for HAMMLAB III in the upcoming MTO-labs started in early 2003 (Fig. 2.12).

Fig. 2.11 Finnish operators with light weight cameras

Fig. 2.12 HAMMLAB II experiment crew

2.7.1.1 Integration Platform (IP)

The fact that more simulators were brought into use in HAMMLAB raised the need for a set of general modules that could be reused for each simulator system. The idea of an integrating software layer, providing functionality for distribution of process variables, reception and routing of operator actions, and easy integration of support systems and HSIs, emerged. The external units interfaced to the IP in order to retrieve data or issue commands. The first version of the IP was installed on PCs in HAMMLAB in 2000. The Software Bus (SWBus) application was used for communication between the IP modules. Frequently used SWBus operations are encapsulated into suitable C++ classes providing a simpler and cleaner interface for application developers using the SWBus. The IP configuration flexibility is very valuable in HAMMLAB. When there is a need for data configuration changes, whether it is new variables or modifications to how data for a specific type of component is organized, only the data configuration files need to be updated. There is no need to modify the application code to cope with such changes; the IP has just to be restarted to distribute the modified set of data. The IP was a very important improvement when it came to SW maintenance and system integration in HAMMLAB. The overall design is described by Jokstad et al. (1999).

2.7.1.2 Human System Interfaces

Since 2000 the HSIs have been running on PCs. The baseline HSIs for both simulators includes a large-screen display, around 50 display formats, trend displays, logic diagrams, and our advanced alarm system presents alarms through soft tiles, lists or graphics.

2.7.2 Experimental Program 2001–2003

In this period three major activities emerged. The first was called ''Design, development and tests of innovative Human System Interfaces (HSI)''. The first HSI activity was directed at Task Based Displays (TBD). The second activity studied ''out of the loop performance problems'' through experiments with various degrees of procedure automation levels. The third new activity started in 2003 and was partly a continuation of the work on Human Error, but much more focused on providing data for the assessment of human reliability. A breakthrough in the experimental program on providing such data relevant for human reliability assessment came through the ''Task Complexity Experiment'' carried out in 2003 (Laumann et al 2005). A list of HAMMLAB studies during 2001–2003 can be found in Table 2.4, Sect. 2.10

2.8 HAMMLAB: Third Generation (2004–2008)

2.8.1 Infrastructure

The new MTO-lab building, including HAMMLAB, was inaugurated in March 2004 by H.R.H. Haakon Magnus, the Crown Prince of Norway (see Fig. 2.13). Excellent working conditions were provided for staff (see Figs. 2.14, 2.15, 2.16).

In 2007Ð2008 HAMMLAB was expanded with a new nuclear simulator: a full-scope simulator of the Ringhals-3 PWR plant in Sweden. This means that HAMMLAB from 2009 has three nuclear simulators available, the FRESH simulator (3-loop, 900 MW PWR of Westinghouse type), the HAMBO simulator

Fig. 2.13 H.R.H. Crown Prince Haakon of NorwayÑ in the middleÑduring the inauguration of the MTO-labs

Fig. 2.14 The MTO-lab, including HAMMLAB, the Halden VR-center and the new CIO-lab to the left

Fig. 2.15 HAMMLAB as of
2007 seen from the experi-
mental gallery

Fig. 2.16 HAMMLAB
experimental gallery as of
2007

(BWR, 1,200 MW, an ABB design) and the new Ringhals simulator (3-loop
900 MW PWR, a Westinghouse design).

All simulators are connected to advanced, fully digital, control room environ-
ments. The hardware/software platform for the simulators, the control room sys-
tems and the experimentersÕ systems for executing and analysing data from
experiments in HAMMLAB have also been upgraded, making HAMMLAB a
ßexible and efÞcient facility for the further research at the Halden Project.

In 2004, the Halden Virtual reality (VR) Centre, which was established in 1996
to complement HAMMLAB, and HAMMLAB were relocated in adjacent rooms,
only separated by a fold-away wall, thereby enabling joint utilisation of
HAMMLAB and the VR Centre (Fig2.17).

In order to increase the number of studies and experiments each year, the new
laboratory building has been equipped with a separate test and integration labo-
ratory. This makes it possible to plan, develop and test HAMMLAB solutions
before actually implementing them in the main laboratory. It will even be possible
to perform smaller studies in the integration laboratory, in parallel with larger
activities taking place in HAMMLAB. The CIO-lab (Collaboration lab for
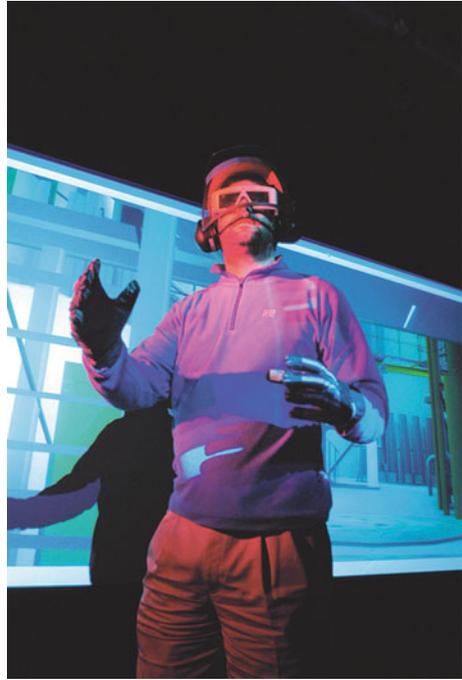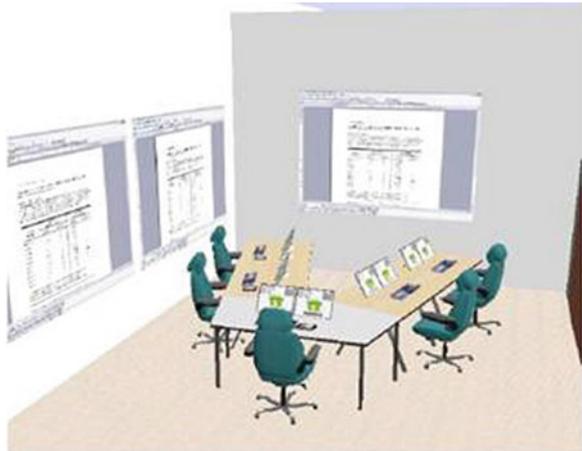
Fig. 2.17 The Halden VR
centre

Fig. 2.18 3D-representation
of the CIO-lab

Integrated Operations) is a new laboratory established in 2007 equipped for per-
forming experiments related to remote collaboration. This laboratory, placed to the
left of HAMMLAB in Fig. 2.14, has advanced technology supporting audio, video
and internet meeting collaboration, and will be a possible extension to the MTO
lab for performing studies related to future plants (see Fig. 2.18).

2.8.2 Experimental Program 2004–2008

In this period focus has still been on development and tests of innovative Human System Interfaces (see Chap. 1). The HSI work included co-operation with research teams in several member countries in addition to two universities in Canada. Three HSI concepts have been designed and tested in various ways. The systems are called Task-based, Function-oriented (FOD) and Ecological Interface Display (EID) systems. Three other HSI concepts have been designed and developed in co-operation with Nordic nuclear utilities and to some extent reported in the HWR-series, they are the Outage Large Screen display, the Information Rich Design (IRD) for Large Screens and Innovative BWR displays.

An important new activity started up in 2006 called the ÔÔInternational HRA empirical studyÕÕ. This is an evaluation study of HRA methods based on data from simulator runs in HAMMLAB, aiming to develop an empirically-based under-standing of their performance, strengths, and weaknesses. The main objective of the study is to compare the Þndings obtained in a speciÞc set of HAMMLAB experiments with the outcomes predicted in HRA analyses. A total of twelve teams from Halden Project member organisations completed the thirteen HRA method analyses on the scenarios during 2007 and work is expected to continue over the next few years. Results from the Þrst stage of the experiment were published at the EHPG-meeting in Loen in May, 2008 (Lois et al 2008).

A signiÞcant combined effort between the new HAMMLAB and the new VR-lab enabled HRP staff during this period to expand the activities to also include Þeld operators in the teamwork studies at Halden. The program on ÔÔExtended teamworkÕÕ involved technological breakthroughs both in terms of utilising virtual worlds and augmented reality technology in the experiments and in providing opportunities to bridge the classic HAMMLAB testing with activities performed in the VR-lab (see Figs 2.19 and 2.20, and Chap. 14). A list of HAMMLAB studies during 2004Ð2007 can be found in Table 2.5, Sect. 2.10

Fig. 2.19 The ÔÔcockpit con-trol roomÕÕ implemented in HAMMLAB for the Exten-ded Teamwork experiment

Fig. 2.20 VR used by Field Operators in Extended team-work experiment

2.9 Lessons Learned Reports

A number of lessons learned reports have been issued as summaries of development and experimental work in HAMMLAB a number of lessons learned reports have been issued. These reports contain summaries of results, recommendations for good design practice and various other recommendations.

Table 2.6, Sect. 2.10 contains the list of such lessons learned reports organised in chronological order.

It is the belief of the HRP that the experience, competence and infrastructure built up over 25 years of operating HAMMLAB is well suited to answer questions related to the quality and reliability of human performance in digital control rooms, as well as questions related to the development and introduction of various digital technologies and applications both in the short and longer time perspective. Consequently, it is our opinion that HAMMLAB as the unique facility it is, should be viewed as an important asset to the nuclear industry and nuclear regulators, particularly now as digital technology is increasingly introduced to both existing and new nuclear power plants.

The principal mission of HAMMLAB will therefore also in the future be to perform human performance studies in digital control room settings and Human Factors engineering research and development.

2.10 HAMMLAB Experiments and Lessons Learned Reports

Table 2.1 List of HAMMLAB experiments during 1983Ð1990

Title	Reference
The experimental validation of the critical function monitoring system (CFMS)	Hollnagel et al. (1983)
Pilot experiment on multilevel ßow modelling displays using the GNP simulator	Hollnagel et al. (1984a, b)
A comparison of operator performance using three display modes	Baker et al. (1985a)
Experimental comparison of three computer based alarm systems	Baker et al. (1985b)

Table 2.1 (continued)

Title	Reference
Proof of principle evaluation of the integrated process status overview (IPSO)	Gertman et al. (1986)
Further comparisons of operator performance when using differing display and control modes	Baker et al. (1986)
The evaluation of a prototype human–machine interface for the early fault detection system (EFD)	Verle and Marshall (1987)
A comparison of operator performance when using either an advanced computer-based alarm system or a conventional annunciator panel	Reiersen et al. (1987a, b)

Table 2.2 List of HAMMLAB experiments during 1991–1994

Voice output of alarms concerning critical safety functions in a NPP	Holmstr¿m and Volden (1991)
The second experimental evaluation of DISKET: the diagnosis system using knowledge engineering technique	Endestad et al. (1992)
A guideline evaluation of the human–machine interface of the ISACS-1 prototype	Folles¿ and Volden (1992)
The ISACS-1 evaluation: a simulator-based user test of the ISACS-1 prototype	Folles¿ and Volden (1993a, b, c)
The GOMS evaluation of the computerised procedure manual COPMA-II	Meyer (1993)
GOMS analysis as an evaluation tool in process control: an evaluation of the ISACS-1 prototype and the COPMA system	Endestad and Meyer (1993)
Validation of the post trip disturbance analysis system SAS II at Forsmark	Holmstr¿m et al. (1993)
Human error–the þrst pilot study	Kaarstad et al. (1994)
Measurement of the operatorÕs situation awareness of use within process control research: four methodological studies	Hogg et al. (1994)

Table 2.3 List of HAMMLAB experiments during 1996–2000

Human error–the third pilot study	Folles¿ et al. (1995)
Human error–the second pilot study	Kaarstad et al. (1995)
Results of the study of control room crew staffþng for advanced passive reactor plants	Hallbert et al. (1996)
Human error analysis project (HEAP)–the fourth pilot study: scoring and analysis of raw data types	Hollnagel et al. (1996)
Practical insights from studies related to human error analysis project (HEAP)	Folles¿ et al. (1996)
The effects of alarm display, processing on operator availability and crew performance	OÕHara et al. (1997)
A questionnaire comparison of two alarm systems	Collier (1997)
Human error analysis project–the fourth pilot study: verbal data for analysis of operator performance	Braarud et al. (1997)
The effects of advanced plant design features and control room staffþng on operator and plant performance	Hallbert et al. (1997)
Human centred automation/IPSN-experiment	Miberg and Hollnagel (1998)

Table 2.3 (continued)

Human-centred automation-2000	Skjerve et al. (2000)
Performance recovery and goal conßicts	Kaarstad and Andresen (2001)

Table 2.4 List of HAMMLAB experiments during 2001Ð2003

Human-centred automation	Skjerve et al. (2001)
	Massaiu et al. (1997Ð2001)
Teamwork and task management	Braarud and Ludvigsen (2001)
Integrated task-based display system	Andresen et al. (2001)
Procedure automation: the effect of automated procedure execution on situation awareness and human performance	Andresen and Heimdal (2002Ð2004)
Recovery	Ludvigsen et al. (2004), Laumann et al. (2004)
Task complexity	Laumann et al. (2005)

Table 2.5 List of HAMMLAB experiments during 2004Ð2007

Ecological Interface Displays	Welch et al. (2004)
Function-oriented displays	Andresen et al. (2004a, b)
Collaboration in VR	Nystad (2004Ð2005)
Task-based displaysÑI	Svengren and Strand (2004Ð2005)
Extended teamwork	Skjerve et al. (2004Ð2005a, b)
Lessons learned from the extended teamwork experiment	Skjerve (2008)
Ecological interface displays	Skaarning et al. (2005Ð2007)
Task based displaysÑII	Strand et al. (2005Ð2006)
PSFÑmasking experiment 2006	Braarud (2006Ð2008)
International HRA empirical study	Lois et al. (2008)
Training in VRÑa comparison of technology types	Sebok and Nystad (2005a, b)
Radiation visualization in VRÑa comparison of types and display technologies	Nystad and Sebok (2005)
A test of wearable computer equipment for plant personnel	Nystad et al. (2005)
Collaboration in a virtual process plant	Nystad and Strand (2004Ð2005)
A Comparative study of radiation visualization techniques for interactive 3D applications	Louka et al. (2007Ð2008)
Virtual collaborative training of maintenance operation and risk awareness	Nystad (2007Ð2008)

Table 2.6 List of Lessons learned reports

The experimental validation of the critical function monitoring system CFMS	Hollnagel et al. (1983)
A survey of manÐmachine system evaluation methods	Hollnagel (1985)

Table 2.6 (continued)

Lessons learned on test and evaluation methods from test and evaluation activities performed at the OECD Halden Reactor Project	Føllesø and Volden (1993a)
Source material for lessons learned from test and evaluation activities performed at the OECD Halden Reactor Project. A digest of studies from 1982 through 1992	Føllesø and Volden (1993b)
Summary of lessons learned at the OECD Halden Reactor Project: the design and evaluation of human–machine systems	Halbert and Meyer (1994)
On-line simulation and estimation: lessons learned from CAMS	Berg et al. (1995)
Summary of lessons learned at the OECD Halden reactor project on advanced control rooms, automation and allocation of function	Collier (1996)
Lessons learned using HAMMLAB experimenter systems	Sebok (1998)
Alarm system CASH: lessons learned based on operatorsÕ feedback and designersÕ experiences	Braarud et al. (1998)
Human performance assessment: methods and measures	Andresen and Drøivoldsmo (2000)
Recommendations to alarm systems and lessons learned on alarm system implementation	Sørenssen et al. (2001)
Useful and usable alarm systems: recommended properties	Veland et al. (2001)
Computerisation of procedures: lessons learned and future perspectives	Nilsen et al. (2003)
New tools and technology for the study of human performance in simulator experiments	Drøivoldsmo (2004)
Experimental control versus realism: methodological solutions for simulator studies in complex operating environments	Skraarning (2004)
Knowledge management in the NPP domain	Nilsen et al. (2004)
Studying human-automation interactions: methodological lessons learned from the human-centred automation experiments 1997Ð2001	Massaiu et al. (2005)
Function-oriented display system: lessons learned from the development process	Andresen et al. (2005)
HRAÑlessons learnt from previous experiments	Collier (2005)
Work practicesÑÞndings from previous HRP studies.	Kaarstad and Strand (2007)
Usability questionnaires and human system interface evaluations: review of standardised questionnaires and lessons learned from HAMMLAB	Andresen and Strand (2007)
Lessons learned from the extended teamwork experiment	Skjerve et al. (2008)

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