

The head of the damaged reactor vessel in TMI-2 was placed on its storage stand in the reactor building in July 1984. The vessel head is wrapped with lead blankets and encompassed by sand-filled columns for shielding.

## Steady progress at TMI-2

*Past milestones pave the way for recovery teams to retrieve the fuel*

by Cynthia J. Hess and Stephen W. Metzger

The accident at Three Mile Island Unit-2 (TMI-2) on 28 March 1979 represents one of the most severe integral tests of commercial nuclear plant safety philosophy and safety systems performance ever encountered in a commercial light-water reactor.

The damage to the reactor core and the subsequent release of fission products to the primary coolant system, reactor building, and auxiliary building and systems are the most extensive experienced in any light-water reactor power system.

The accident has given the nuclear industry a unique opportunity to advance its understanding of plant behaviour during and after a severe core-damage accident, providing information unobtainable through other severe accident research, development, and test programmes. (Despite the heavy damage to the core and plant, radiation releases to the environment were found to have been very low.)

The opportunity to learn from the accident led to the joint establishment of a special programme by the

plant's owner, GPU Nuclear, the Electric Power Research Institute (EPRI), the US Nuclear Regulatory Commission (NRC), and the US Department of Energy (DOE). The programme was set up to obtain and analyse data on the accident and its aftermath; establish the accident's cause and consequences; develop new recovery techniques for responding to the unique challenges at TMI; and share the findings and technologies with the commercial nuclear power industry.

### **Decontamination: New techniques, methods**

Since the accident, the recovery programme has reached a number of milestones. In 1979, a water-processing system called EPICOR-II, which predominantly uses organic resins to absorb fission products, began to decontaminate the 21 388 cubic metres of accident-generated water from the auxiliary and fuel-handling buildings. Also that year, personnel conducted the first inspection of the reactor building using cameras and radiation instruments.

In 1980, a total of 43 000 curies of radioactive krypton gas was safely vented from the reactor building, permitting workers wearing protective clothing and

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respirators to enter the building on a routine basis.\* The plant owner and federal agencies thoroughly monitored the venting, and off-site exposures were well below government standards.

The following year, a new method of water decontamination was introduced into TMI-2. Called the Submerged Demineralizer System (SDS), the apparatus was used to process approximately 22 713 cubic metres of highly contaminated water that poured into the reactor building basement during the accident. Similar to the EPICOR-II ion exchange system, the SDS operates on the same principle as a home water softener. Whereas the softener removes unwanted minerals that make drinking water "hard", the SDS removes radioactivity.

The SDS differs from the EPICOR-II system in two major ways. First, it operates underwater in the Unit-2 spent-fuel pool adjacent to the reactor building, thereby protecting workers from high radiation. Second, the SDS uses an inorganic material called zeolite to absorb fission products from the water. The ion exchange process of the SDS effectively removed more than 99% of fission products, primarily caesium and strontium, from the contaminated water. After it passed through zeolite canisters, the water was further processed by the EPICOR-II system and stored in tanks.

#### **Radiation levels reduced**

In March 1982, GPU Nuclear conducted the first large-scale decontamination experiment in Unit 2. DOE was instrumental in defining and funding the three-week experiment that tested the effectiveness of various techniques and equipment for decontaminating large and complex surfaces. Since then, GPU Nuclear has been applying some techniques introduced in the gross decontamination experiment, along with other methods, to effectively reduce radiation levels in the building. The plant owner reported in mid-1985 that average dose rates were down to 67 millirem per hour on the entry level, 34 millirem per hour on the operating floor, and less than 15 millirem per hour in the area of defuelling. These figures dropped from the respective 430 and 240 millirem per hour recorded in 1980.\*\*

The predominant technique used in the 1982 experiment was hydrolasing: low- and high-pressure water spraying of the floors and walls and the surfaces of various equipment. Other techniques called for the use of strippable silicon coatings, mechanical floor scrubbers and detergents, and wheel-mounted spinjets. More recently, GPU Nuclear personnel have been scabbling the floors, whereby the paint and about 0.16 centimeters of concrete are loosened, then collected and packaged using a vacuum system. The scabbled floor is then repainted.

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\* In international usage, the curie has been replaced by the becquerel, which is equivalent to one disintegration per second, or to approximately  $2.7 \cdot 10^{-11}$  curies.

\*\* In international usage, the rem has been replaced by the sievert, which is equal to 100 rem.

Dose reduction also has been attributed to the removal of thousands of cubic meters of water from the reactor building basement and the shielding of other sources of radiation. Lead blankets and bricks have helped to block emissions from such sources as the air coolers on the entry floor and hatchways to the building's basement.

#### **Waste shipments**

In May 1982, the first SDS liner — containing radioactive zeolites — was shipped from TMI. Three of the liners were used in a DOE research project studying vitrification, in which the zeolites that removed the radioactive products were mixed with chemicals, heated to about 1323 kelvin, and cooled to form a glass log. Tests proved the glass effectively trapped the radioactive contaminants. The rest of the SDS liners were placed in special concrete overpacks and buried at a government laboratory.

The high-integrity container is so named because of its uncompromising makeup: steel-reinforced concrete with a steel inner-liner that is coated with epoxy to protect against corrosion. Developed in DOE research programmes, the container (2.1 metres high and 1.5 metres in diameter) meets US federal regulations and was endorsed by the nuclear industry. DOE continues to monitor the SDS liners in a burial demonstration programme, whose parameters of interest are pressure, temperature, moisture, and fission products.

#### **Void discovered in core**

In May 1982, workers lowered cameras into the reactor for a first look at the damage. Nicknamed "Quick Look", the project — though limited in scope — gave researchers concrete evidence of the actual condition of the core and upper internals. Engineers reviewing the data concluded that a number of fuel assemblies sustained considerable damage, leaving a void in the upper region of the core, with a rubble bed below.

The following year, technicians got a clearer picture of the void using detailed video examinations and a Core Topography System (CTS) specially designed and built for the project by DOE-contractor EG&G Idaho, Inc. Equipped with ultrasonic transducers, the CTS sensing head, lowered into the reactor, sent out an ultrasonic signal that reflected off the first barrier it encountered and returned to the transducer that sent it. The time the signal took to return told technicians the distance the surface was from the sensing head.

The resulting 500 000 data points revealed that the void was roughly symmetrical and in some places extended to the edge of the core. The size of the cavity was about 9.5 cubic metres, and at the deepest point it dropped about 2 metres from the underside of the plenum. Very few fuel assemblies remained intact, and those that were, were located at the periphery. Also, uppermost portions of fuel assemblies were hanging from the upper plenum assembly's underside — information essential to later plenum removal plans.

GPU Nuclear established the depth of the rubble bed through another series of tests, in which workers lowered a stainless steel rod (11.9 metres long and weighing 59 kilograms) into the rubble bed at 17 locations. They learned from the probe that the depth of the bed ranged from 36 to 117 centimeters. Personnel monitored the operation with the help of carefully positioned underwater cameras and lights, and the entire operation was recorded on videotape. The technicians meanwhile took advantage of the project to test a new visual enhancement technique that improves low-light or photon-starved images, such as those taken from a video monitor.

Samples taken from the core also have helped analysts to define the core's condition, as well as to develop tools and procedures for eventual defuelling. Key among their findings were the temperatures the core apparently experienced during the accident. Metallurgical examinations indicated some samples of the core debris reached the melting point of uranium-dioxide fuel. Among the evidence was a ceramic material of uranium and zirconium that forms when uranium-dioxide fuel pellets, in contact with Zircalloy cladding at such high temperatures, are dissolved by the zirconium, forming a liquid phase of zirconium-uranium-oxygen, termed "liquified fuel".

#### **Look inside the vessel**

In February 1985, the reactor's condition was defined still further with the first television pictures of the lower area of the vessel. There, analysts found what appeared to be as much as 20 metric tons of debris, some of which was once molten. The type of material was not clearly identifiable. Some pieces of debris were several centimeters across, larger than the predominantly gravel-sized pieces that form the rubble bed above. The preliminary findings suggested that the bottom of the vessel will have to be defuelled at least in part by loading the chunks of material into canisters rather than by vacuuming. (See box on page 20.)

Technicians will continue to collect samples from the core for analysis even after defuelling begins. The core boring equipment, with which workers will obtain samples, uses oil and gas drilling technology adapted for this new application. Scientists conducted proof-of-principle tests of various commercially available drill bits to evaluate their ability to penetrate a simulated TMI-2 fuel stub assembly. Workers who will be operating the equipment have since undergone training at the Idaho National Engineering Laboratory (INEL).

#### **Reactor disassembled, defuelling nears**

Steps toward core removal became more pronounced in July 1984 when the head of the reactor vessel was successfully moved to its storage stand in the reactor building. The head was removed "dry" — without flooding the refuelling canal. Planners agreed the extra shielding was unnecessary and to flood the canal would

have meant subsequent decontamination of the canal and processing of the canal water. The decision to remove the head "dry" was based on information from previous characterization and radiation measurements. Closed-circuit television examinations of the surfaces under the head and on top of the plenum showed no apparent damage or distortion and little debris. Tests on samples demonstrated that the debris also posed no pyrophoric hazards.

In December of the same year, the 49 895-kilogram plenum was jacked 18.4 centimeters, ensuring the assembly could be lifted out of the vessel without obstruction. Workers also knocked debris and broken end-fittings from the plenum's underside, reducing the amount of fuel and debris that could drop from the plenum during its transport later from the vessel to its storage stand. Four hydraulic jacks, each rated at 45 359 kilograms, were used in the plenum's initial jacking. The jacks were custom-designed to fit the space in which they were to be used, but the hydraulic cylinders were standard items. Four workers hand-pumped the jacks from a central pumping station, and the load on each jack was constantly monitored to prevent jamming.

After initial characterization, it was determined that the plenum could be lifted without having to flood the canal. Then in May 1985, the plenum was successfully lifted by its normal removal fixture and placed on a storage stand in the flooded deep end of the refuelling canal. Recovery teams now had access to the damaged reactor, whose defuelling is scheduled to begin in late 1985.

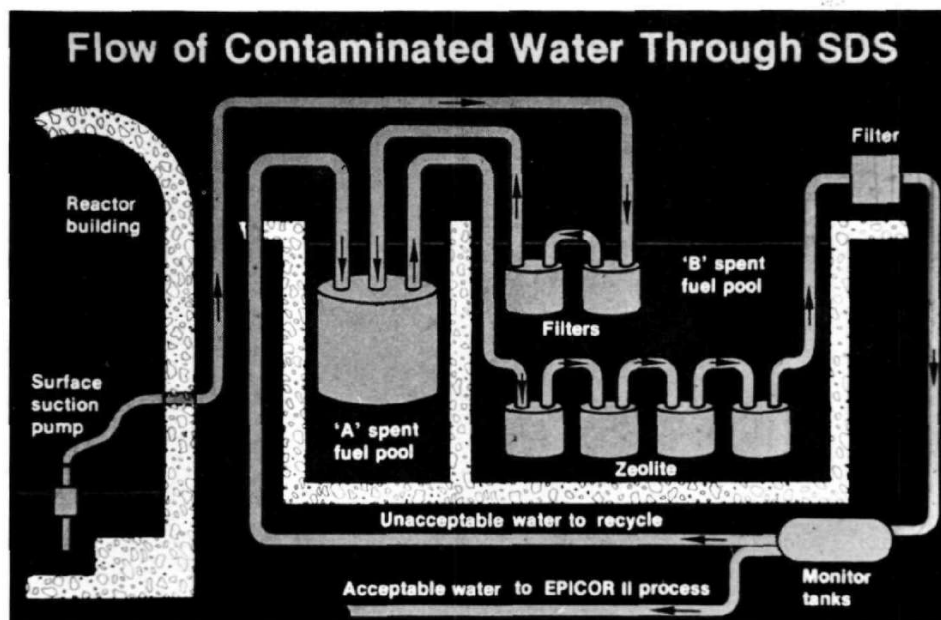
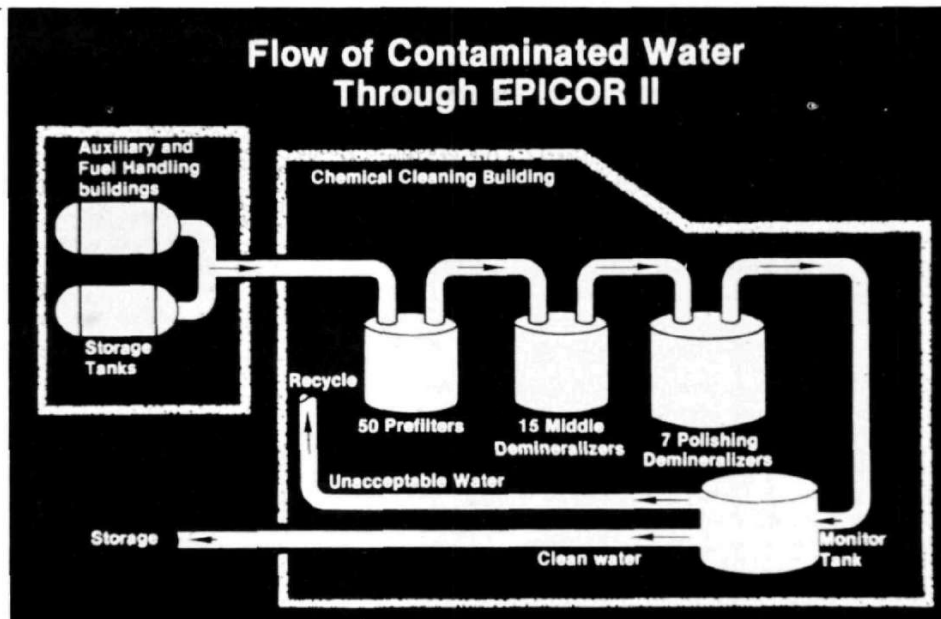
#### **Caesium eluted from demineralizers**

Just before plenum removal, another milestone was reached when, in March 1985, GPU Nuclear, with technical support from DOE-contractors EG&G Idaho and Westinghouse Hanford, completed caesium elution of the two makeup-and-purification demineralizer vessels in Unit-2. During normal plant operation, the demineralizer tanks remove impurities from water in the reactor coolant system. But during the 1979 accident, highly contaminated coolant water passed through the tanks, whose resins captured about 11 000 curies of radioactive caesium. The tanks also contained as much as 4.1 kilograms of reactor fuel particles.

After the tanks were remotely characterized, the high-activity radionuclides were eluted from the resins, and the resulting waste stream was processed. Upon project completion, caesium radioactivity in one demineralizer was reduced by approximately 70% and in the other vessel by about 90%.

The fission products were removed when a mixture of water and sodium hydroxide was pumped into each tank, where ions of caesium were exchanged for sodium ions from the sodium hydroxide. Consequently, the caesium was no longer bound to the resins, but dissolved in the water. Boric acid was added to this mixture to reduce its pH. Batches of the caesium mixture were then

Organic resins are used to absorb fission products in the EPICOR-II water processing system. In the Submerged Demineralizer System (SDS), inorganic material called zeolite is used to absorb fission products from water.



filtered and delivered to neutralizer tanks, after which they were processed by the SDS. The inorganic material in the SDS liner captured the radioactivity that was released from the demineralizer resins and packaged it in a state that was safe for shipment.

Containing about 90% of the caesium originally in the demineralizers, the SDS liner generated from the elution process was shipped to Rockwell Hanford Operations (a DOE laboratory in Washington State) where it was buried in a special concrete overpack in May 1985. The liner was the last one that DOE accepted for research and development in its monitored burial demonstration programme.

Also, nearly all the containers (46 of 50) that were used to decontaminate the water from the TMI-2 auxiliary and fuel-handling buildings were disposed of permanently. Each one (called an EPICOR-II prefilter) was placed in a high-integrity container, permitting safe

disposal for more than 300 years without any threat to the environment. The remaining four prefilters are part of an NRC research programme.

#### Gas generation in waste containers

A significant safety concern relative to handling, shipping, and storing radioactive waste is the production of combustible gases in sealed waste containers. After evaluating the hydrogen gas generation problem, the NRC required that unless a container is shipped within 10 days of sealing or venting, the waste generator must conduct tests and take measurements to determine hydrogen and oxygen contents.

Because many waste generators would have difficulty conducting the tests and taking measurements, their only alternative used to be venting before shipment. Now they have another option. A new calculation to

### Defuelling: The next major step

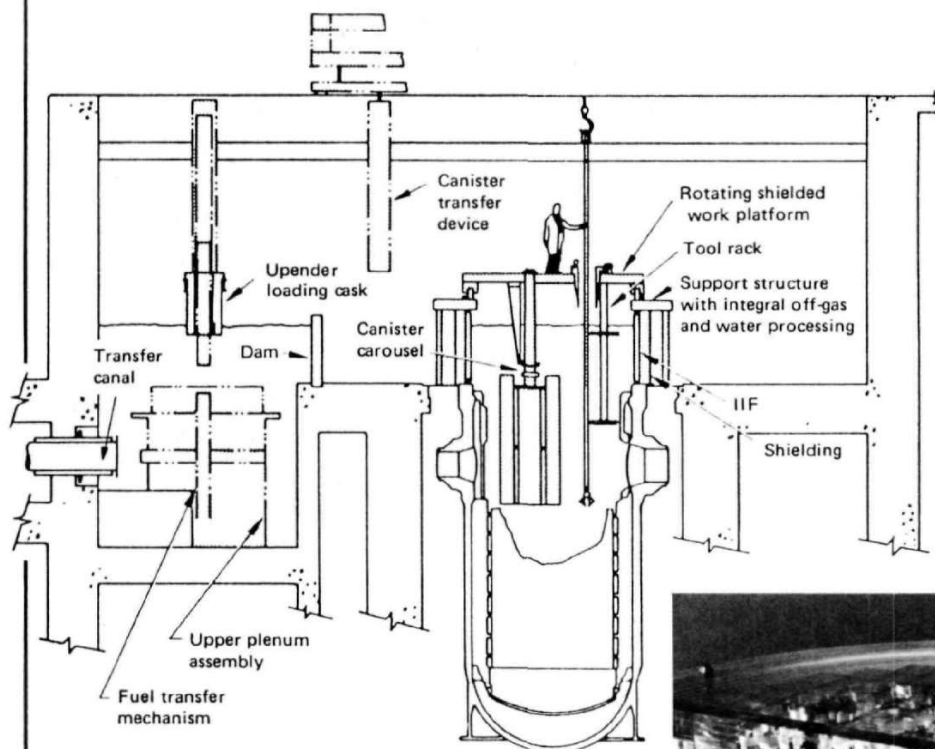
Set to begin this year, defuelling the damaged reactor promises to be the most difficult phase of the TMI cleanup, and the job is expected to last until well into 1987. Very few, if any, fuel assemblies remained intact. To retrieve and transfer fuel materials and debris, the recovery team has developed an innovative system, as illustrated here.

The defuelling system's central feature is a newly designed shielded work platform. The platform sits 2.7 metres above the reactor vessel flange, and rotates to give workers core access. The structure also serves as a support for in-vessel equipment, including a vacuum system and a carousel that will hold as many as five canisters for loading. The steel platform also effectively shields workers who stand on it to manipulate long-handled tools through a slot in the structure.

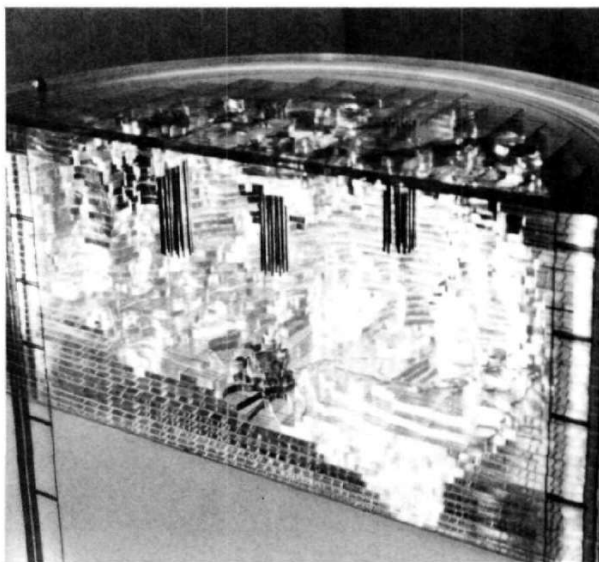
The manually operated tools for early defuelling will be mounted on the ends of handles from 9.1 metres to

11.3 metres long. These tools include locking pliers to grip large pieces of debris or adjust hoses and cables; three- and four-point grippers to pick up objects from the debris pile; a grapple to lift irregular pieces, such as end-fittings and spider assemblies; single-rod shears similar to scissors and capable of cutting one or two fuel rods at a time; a hydraulic parting wedge to separate and fracture material for easier handling and vacuuming; bolt cutters for light-duty vertical and horizontal cutting; and hooks and tongs to lift and move debris.

GPU Nuclear personnel will defuel the vessel by loading the debris into canisters. These will then go through several stages of transfer and storage before being shipped to the Idaho National Engineering Laboratory (INEL). The smaller debris will be vacuumed out of the vessel and filtered through specially designed canisters, while larger material will be "picked up" and placed directly in other



This schematic of the early defuelling system shows that a number of contamination controls have been incorporated to keep radiation levels as low as reasonably achievable. The photo shows a clear plastic model of the core void (light area). Developed from nearly 500 000 data points collected with a sonic sensing device, the model shows that the void extends to the edge of the core. Suspended materials in the model are stubs of fuel assemblies (few remained intact), and axial power shaping rods that were driven in after the accident.





special canisters or into baskets that will be lowered into the canisters.

All activities will be carried out with much of the refuelling canal dry; only the deep end of the canal is flooded (to provide shielding from the plenum stored there and the canisters that will be loaded with core debris). The open reactor vessel will continue to be shielded by the reactor-coolant-system water. Among the advantages of keeping the canal dry is that there will be less contaminated water to process.

Once loaded, the canisters (which have a design life of at least 30 years) will be lifted out of the vessel, into a shielding container, lowered into the deep end of the refuelling canal, and either placed in a storage rack or passed directly into a spent-fuel pool 12.2 metres deep. The pool can accommodate at least 280 canisters until GPU Nuclear is ready to transfer them to the truck bay

of the fuel-handling building, where they will be prepared for shipment to the INEL for research.

The loaded canisters (planners estimate there will be 250 to 280 of them) will be transported by rail to Idaho. Two specially designed rail casks, each capable of carrying seven debris-filled canisters at a time, will be required for the operation; after unloading their freight in Idaho, the casks will be returned to Three Mile Island for their next shipment.

The casks have undergone a number of computer analyses, as well as actual drop tests using a one-quarter scale model. The result of the tests: The casks can safely contain the TMI-2 debris even under the extreme conditions of hypothetical accidents. (The casks were designed for EG&G Idaho by Nuclear Packaging, Inc., with two levels of containment and with seals that meet "leak tight" criteria; thus the casks meet US federal regulation 10 CFR 71.63 and ANSI N14.5.)

quantify hydrogen gas generation in sealed containers was developed by EG&G Idaho, a DOE contractor. Acknowledged by the NRC, this calculation considers the quantity of gas produced per unit of energy absorbed by the waste, the amount of energy resulting from the decay process which is returned in the waste container and absorbed by the waste, and free volume of the container, including interstitial voids inherent in the waste form. The calculations can be performed on a desktop computer using known, representative, radioactive waste information.

### Lessons learned for plant design

In an ongoing characterization programme, engineers are investigating the consequences of the loss-of-coolant accident on the instruments and components in Unit-2. The capability to receive readout signals from, and supply energy voltages to, Class 1E instruments is essential to reactor control during periods of environmental stress. After a series of tests, researchers concluded that many anomalies that components demonstrated were due to moisture intrusion. This work will have strong bearing on cable and connection design and will help to improve manufacturing and installation procedures.

In the course of this study, scientists and engineers recognized the need to develop a system that would permit component performance assessments by gathering electrical characteristics from remote locations. Consequently, a very special Electrical Circuit Characterization and Diagnostic System was designed. The system provides a means to acquire basic data on electrical channels and store and format the data for easy handling and analysis.

### Robots aid recovery

During the past few years, robots have played an important role in the TMI-2 recovery programme, helping to reduce worker radiation exposure. To date, five separate machines have been used to test or probe in areas that personnel could not enter until radiation levels were lowered and surveys completed.\*

SISI (for surveillance and in-service inspection) is a tiny tank-like machine that weighs 11.3 kilograms and was used for photographic and radiological inspections. Also employed was a 181-kilogram robot with a mechanical arm that could lift 68 kilograms. This robot was capable of conducting high-pressure water sprays and was equipped with television equipment.

"Rover-1" was a 454-kilogram machine equipped with three television cameras and two radiation detection devices for extensive monitoring.

Another similar machine, called "Rover-2", was additionally equipped with a boring device to obtain concrete samples from the basement walls. A smaller machine, nicknamed "Louie", obtained radiation readings and performed decontamination work in small areas.

Now in the conceptual stage is another robot, called Workhorse, that is scheduled for delivery by early 1986. The robot will be the largest, most powerful machine of its type used so far at TMI and will have computer intelligence enabling it to do repetitive actions.

\* For related article, see "Robots for nuclear power plants", *IAEA Bulletin*, Vol.27, No.3 (Autumn 1985).



Containing an EPICOR-II prefilter, this demonstration "high integrity container" is being buried at the US Ecology disposal site for low-level radioactive waste.

### Technological foundation

Currently, engineers are studying possible approaches to defuelling the reactor's lower vessel region, and locations outside of the vessel where fuel debris was transported as a result of the accident. In preparation, technicians are conducting radiological surveys to locate fuel and fission products. This work, in addition to the accomplishments of the previous six-and-a-half years, will provide a sound technological basis for formulating decisions that will lead to the ultimate disposition of the TMI-2 plant.

Since the 1979 accident, the GPU Nuclear recovery effort and the US Department of Energy's research and development programme at TMI have continued to move steadily forward. Each step of the way, important questions about the nature and impact of the accident have been answered. Some achievements over the years have been highly visible in the news. But the recovery team sees this progress more as simply meeting the day-to-day challenges of a unique situation while keeping the nuclear power industry well informed.

