NDT AND INSPECTION OF TRITIUM REMOVAL FACILITY

Paper: B-9-0915

B. Schulze, J.P. Dufour, R. Zmasek
Canada

TRITIUM REMOVAL FACILITY

1. INTRODUCTION

CANDU REACTOR

CANDU heavy water reactors produce tritium in the moderator and coolant circuits through neutron absorption by the deuterium atoms in heavy water. The concentration of tritium, in the form of DTO molecules builds up slowly with time of reactor operation. A typical yearly production rate of tritium is 2400 curie for each megawatt of electricity produced and as a consequence, a 600 megawatt Candu reactor produces 1.4 million curie of tritium per year. Tritium decays to $_3He$, a non radioactive species, and has a half life of approximately 12 years.

Both Ontario Hydro and AECL are constructing plants to remove tritium from heavy water to maintain the tritium concentration below the equilibrium value.

This will result in lower radiation doses to operating personnel and reduce the level of radiation in any releases of heavy water to the environment.

WHAT IS TRITIUM?

It is heavy heavy hydrogen, i.e. isotope of hydrogen with an atomic weight of 3 compared with the most abundant hydrogen isotope or protium (P) with atomic weight of 1 and Deuterium with an atomic weight of 2. Protium and Deuterium are naturally occurring (albeit in different concentrations), the concentration of deuterium being approximately 150 ppm in normal water. Apart from the atomic weight difference, Tritium differs from Protium and Deuterium in that it is radioactive, emitting weak Beta rays and a sheet of paper would be sufficient as a shield.

O.H. DARLINGTON - TRF

Let me say a few words about the history of the Ontario Hydro Darlington TRF and AECL Chalk River TEP.

Ontario Hydro identified the need for tritium removal and initiated studies approximately ten years ago. At this time the plan was to site the plant at Pickering.

A contract was awarded to Sulzer Canada in 1981 for the process design and equipment package. A decision taken in 1982 to build a duplicate facility at Darlington was rapidly superceded by a rationalization of O.H.'s tritium separation strategy which resulted in the consolidation of the two projects into a single system to be sited at Darlington, Ontario.

Design work on the system was carried out jointly by Sulzer Brothers Limited in Winterthur, Switzerland and Sulzer Canada Inc. in Toronto. The process consists of the following principal parts: feed treatment, vapour phase catalytic exchange, dryer unit, absorber unit, low tritium distillation, high tritium distillation, cryogenic refrigeration system, recombiner system and deuterium make up system. The cold boxes, compressors and recombiner were manufactured in Europe and the balance of the system subcontracted in North America. Construction of the facility is complete and commissioning is now commencing.

AECL CHALK RIVER - TEP

This will be the first industrial scale demonstration of the Liquid Phase Catalytic Exchange (LPCE) process for transfer of tritium from heavy water to deuterium.

In the Chalk River plant the catalyst for isotopic transfer will be the wetproofed catalyst employed in the Liquid Phase Catalytic Exchange (LPCE) process.

The process downstream of the LPCE column is basically similar to DTRF. One significant difference is the use of helium instead of hydrogen as refrigerant. While this is less thermodynamically efficient than hydrogen, practical project specific considerations favoured the use of helium for TEP. The higher specific energy consumption (approximately three times the power consumption of a hydrogen system) would have been a severe penalty for DTRF.

USES OF TRITIUM

The driving force for both the DTRF and TEP projects is removal of tritium from heavy water of reactor moderator and heat transport systems, to reduce operator exposure to radiation and to reduce the level of radioactivity in any heavy water releases to the environment.

However the separated tritium does have a number of commercial applications and is therefore a commodity of significant value (eighteen million dollars per kilogram). For these reasons marketing of Canadian tritium under a stringently controlled regime to avoid any interaction with tritium produced for military purposes is under serious consideration.

Uses include radioactive tracing and self illuminating signs (for remote airfields and emergency exits etc). The application which holds potential for the use of large (i.e. Kilogram) quantities would be the various fusion energy research programs. For the present generation of experiments the "fuel" is an equimolar mixture of deuterium and tritium. With the facility at Darlington, augmented by tritium produced at Chalk River, Canada could supply a substantial proportion of the tritium required for the fusion experiments currently under way.

2. DESCRIPTION OF TRITIUM EXTRACTION PLANT

The plant consists of the following system:

a) feed system with storage facilities and de-gassing unit.

b) catalytic exchange system, where the tritium is transferred from the heavy water into a deuterium gas stream.

c) dryer unit, where the moisture is removed from the deuterium gas.

d) low tritium distillation, where the tritium is concentrated.

e) high tritium distillation, where the tritium is brought to its pure form.

f) tritium transfer and storage system.

g) cryogenic refrigeration system. (show slides where available)

Systems a), b), c) and f) have what we consider "normal" operating and design conditions, i.e. design pressures up to 20 bar with design temperatures up to 250 degrees celsius. However, the systems d) and e) operate at temperatures around 20 Kelvin (minus 253° C) and contain at the same time radioactive substances which are cooled with liquid hydrogen. The size of the equipment covers an extremly wide range from heat exchangers and vessels which weigh only 1 kg to vessels with volumes of 175 m^3 with a weight of more than 50 tons.

3. REQUIREMENTS

In Canada the Nuclear Industry is controlled and governed by the **REGULATORY REQUIREMENTS** of the:

- Federal Government
- Provincial Government

REGULATORY AGENCIES

- FEDERAL - Atomic Energy Control Board (AECB) and AECB Staff
- PROVINCIAL - Ontario Ministry of Corporate and Consumer Relations (MCCR)
  - Quebec and New Brunswick Department of Labour and Manpower (DOL)

AECB FUNCTION

- Assure that Nuclear Facility will be

  - Sited
  - Designed
  - Constructed
  - Commissioned
  - Operated

  In accordance with Established Safety Criteria and Requirements

CODE CLASSIFICATION AND DESIGN REGISTRATION

- Code classificationd approval must first be obtained from AECB.

- Code classification according to CSA Standard N285.0.

CLASS 6 SYSTEMS

AECB and Ontario Hydro classified the Tritium Removal Facilities as a Class 6 system, Non-Nuclear and had to meet the following criteria:

(i) Those sections of systems which do not contain radio-active material.

(ii) Those sections of a system containing radioactive material but the failure of which without the containment system, would not result in a hazard to the public exceeding 1% of the AECB dose limits for a serious process failure or to plant personnel which exceeds the AECB annual dose limits for personnel who are NOT atomic radiation workers.

Sections of systems classified as class 6 must meet the requirements of CSA B.51 code for the construction and inspection of boilers and pressure vessels.

It was clear from the very beginning that the ASME-code did not cover these very specific operating and design conditions. A very close cooperation between the system designer Sulzer, the owner and operator Ontario Hydro and the authorities in Ontario, MCCR was the only way to establish the additional requirements for a safe and reliable plant.

Detailed Terms of Reference:

1. To establish the quantities in which elemental tritium and tritium oxide are considered lethal.

2. To assess releases from possible failure modes.

3. To write guidelines on where and why ASME VIII division 1 should be used.

4. To divide the tritium removal system into subsystems for classification.

5. To apply the guidelines to each subsystem.

6. To determine which subsystems require more rigorous design and or fabrication procedures than ASME VIII division 1.

7. To determine which additional procedures would apply to each subsystem.

PROVINCIAL FUNCTION

- ADMINISTER REQUIREMENTS OF PROVINCIAL BOILER AND PRESSURE VESSEL ACT AND ASSOCIATED CSA STANDARDS

PROVINCIAL REQUIREMENTS - DESIGN

- The designer of all pressure retaining equipment must request the department to register the "design" of this equipment.

- The "design" includes:

  - Certified design specification
  - G.A. drawings (component) or flowsheets (system)
  - Adequate detail drawings to completely define the pressure boundary of the equipment
  - Design report (or design calculations, if requested, for non-nuclear and some Class 2 and 3 systems and components.

PROVINCIAL REQUIREMENTS - FABRICATION

The act excercises most of its control over fabrication through the authorized inspector.

- Design must be registered before fabrication.

- Weld procedures must be registered.

- Welders must be tested periodically and certified by the department.

- In Canada the authorized inspector is an employee of the department.

- Manufacturer's Q.A. programs are approved by the department.

DESIGN REQUIREMENTS FOR COMPONENT IN TRF SYSTEMS

After quite a number of discussions and after many disagreements between the involved parties, the TRF system was established as a Class 6 System, and in compliance with the Requirements of CSA Standard B51 code for the construction and Inspection of Boilers and Pressure Vessels and special requirements for Tritium Removal Plants.

This leads to the ASME-Codes

ASME SECTION VIII, DIV. 1,

with the associated sections for:

Material Section II

NDT Section V

Welding Section IX

ANSI B 31.3

with fluid level "M" for lines without secondary containment.

SPECIAL REQUIREMENTS FOR REGISTRATION, DESIGN AND FABRICATION

The registration of equipment is based on the submission of the following additional documents:

- Design description and certified design specifications.
- Analysis of loadings to determine stress levels at all critical points.
- Process diagrams accepted by the Owner and submitted to MCCR.
- Overpressure protection reports.

- Analysis, showing that normal safety precautions against explosions have been considered and are included in the Hydrogen System.
- All material used must be traceable.
- Only seamless piping and fittings shall be used.
- Only full penetration welding joints.
- All nozzles shall be integrally reinforced.
- All welding procedures registered with M.C.C.R.
- Spot radiographic examination and in addition all T-Joints.
- All radiographs shall become part of the history docket.

4. TESTING REQUIREMENTS

A broad range of NDT was applied during the manufacturing process of equipment and components, to assure, that the fabrication meets the design criteria.

- Radiography of welds.
- Ultrasonic test of material.
- Eddy current test of tube material.
- Liquid penetrant, magnetic particle inspection of material and welding.
- Helium leak testing of all equipment and components.
- Impact Test
- Hardness testing.

In addition to the standard tests of tensile and impact tests, the following special tests were carried out:

- Fidelle test to determine the susceptability to hydrogen embrittlement.
- Test to determine the stability of SS 304 L at the temperature of liquid helium.
- Impact testing of small specimen.
- Tensile test at 4K
- Fracture toughness test at 4K.
- Cyclic testing of expansion joint at 4K.
- Cyclic testing of transition joints (connection between ALU and SS), with a combination of mechanical loads and internal pressure.

Today, I would like to address some of the very specific tests carried out on the TRF Project to assure the integrity of the base material and welding of components operating at very low temperatures (4° Kelvin) and for hydrogen service.

HYDROGEN EMBRITTLEMENT TEST OF STAINLESS STEEL 304L & 316L

TEST METHOD

The principal of the test method is described in the article "Disc Rupture Tests" by J.P. Fidelle, ASTM STP 543-74. The method of evaluating the embrittling effect of hydrogen or helium on metals by measuring the pressure required to burst a small metal disc. The metal disc is clamped in a cell and is pressurized from one side until rupture occures.

TEST SPECIMEN

The test specimen is a 58 mm diameter disc and has a thickness of .75 mm. It must be prepared to a very fine finish of RMS on both sides.

If a welded specimen is prepared for testing, the weld must run dimetrically across the disc.

TESTING

The pressure disc test facility at the Creusot Loire Research Centre, Le Creusot, France, carried out the testing.

The test gases used are helium with a purity of 99.999%, and hydrogen with a purity type U.

The disc holder is evacuated to 10^{-3} TORR and rinsed with test gas several times before applying the test pressure at room temperature, at a rate of 5 bar/min. until bursting of the disc occures.

TEST RESULT

Hydrogen embrittlement is measured by the ratio of the Rupture Pressure of a hydrogen charged disc and the rupture of a helium charged disc of the same material and processing material.

Material determined acceptable and suitable for high pressure hydrogen service must meet the following criteria:

$$P_{HE} : P_{H_2} = < 2.0$$

For high quality material, the test is performed usually three times for each material under each set of conditions to assure good reproducibility.

CONCLUSION

The disc pressure test provided evidence that stainless steel 304L/316L material is suitable for the hydrogen system installed at the tritium removal facility.

FRACTURE TOUGHNESS OF AUSTENITIC STAINLESS STEELS

PURPOSE

To substantiate the theory of "Leak Before Break" for stainless steel 304L & 316L materials as service temperature 24.6K.

BACKGROUND

Austenitic stainless steels are prime-candidate materials for cryogenic or sub-zero temperature applications. It has been reported that even austenitic steel castings have been used in process applications at temperatures as low as the boiling point of helium for a number of years. Service experience has been excellent with no failure due to embrittlement or loss of toughness.

For the TRS process equipment, austenitic stainless steels 316L and 304L are considered for use. Since the TRS vessels are fabricated by arc welding, fracture toughness of the weld will also be considered. The following table shows some reported fracture toughness on 316L austenitic stainless steel and -eldments.

Material	K_{1c}(4K) Ksi in	K_{1c}(4K) MPa $m^{1/2}$	K_{1c}(Weld) / K_{1c}(Base Metal)
Base Metal (316L)	171	188	-
Weld (SMAW)	86	94.6	50 %
	156	171.6	91 %
	181	199.1	106 %
	120	132	70 %
	146	160.6	85.3%
	183	201.3	107 %
	171	188	100 %
	107	118	62.5%

DISCUSSION

The above table demonstrates that the fracture toughness of the austenitic base material remains high even at 4K. Weld metal of 316L varies considerably over a wide range but shows no evidence of brittle behaviour.

Because of the obvious ductility of these materials and the thin wall construction (<1") of the process vessels, it is evident that these vessels would not fail in a brittle manner.

Rupture, if it did occur, would take place in a ductile manner and would not lead to fragmentation of the vessel. Failure mode would be in the "leak before break" category. This can be further illustrated by the following fracture mechanics evaluation.

The K_{1c} of the weld in comparison with that of the base metal as shown in the previous table varies from 50% to 107%. Taking a conservative approach, the K_{1c} of the 316L weld metal can be estimated by using 50% of the base metal fracture toughness.

Since K_{1c} (weld) is less than K_{1c} (base metal), it is more appropriate to evaluate the fracture mechanics of the weld rather than the base metal. Typical fracture mechanics calculation for 316L base metal and weldment are shown in Appendix A and lead to the estimated critical crack size for base metal be 1.92m and 48cm for weld. Of course these are hypothetical crack sizes only. In the real situation, if a small crack does exist in the weld or base metal, it will cause tritium leakage first. Then the sensing devices of the TRS would detect the leakage well before the crack would have the chance to grow to a substantial size.

It has been reported that at 4K the fracture toughness of 304 stainless steel is higher than that of 316. (3) It is reasonable to estimate the toughness of 304L be comparable or better than the 316L at cryogenic conditions. Necause of their excellent ductility properties, both 316L and 304L stainless steels are good materials for the TRS parocess equipment.

CONCLUSION

The fracture toughness of the 316L austenitic stainless steel at cryogenic temperatures is extremely good. Weldments in general appear to be lower than the base metal. However, even at these lower levels, the fracture toughness is still more than adequate for the proposed service conditions.

Should failure occur, it will progress in a ductile manner. The tritium leakage detection system would detect any tritium leakage before a defect or a crack can grow to a size which would cause fracture of the equipment.

REFERENCES

1. ASME Committee Correspondence "Possible Impact Test Requirements for Austenitic Stainless Castings", R. Zawiesucha, ASME Subgroup on Toughness, February 27, 1981.

2. "Materials Studies for Magnetic Fusion Energy Application at Low Temperatures", National Bureau Standard.

3. "A Research Program on the Properties of Structural Materials at 4K", R.P Reed et al, Advances in Cryogenic Engineering Vol. 22, 1975.