INVESTIGATION INTO THE USE OF DUCTILE CAST IRON AND CAST STEEL FOR TRANSPORT CONTAINERS WITH PLASTIC FLOW SHOCK ABSORBERS

*M J S Smith, I L S Gray & R W T Sievwright **
*J C Miles, B Egid & P Donelan ***
* UK Nirex Ltd, Curie Avenue, Harwell, Didcot, Oxfordshire, United Kingdom
** Ove Arup & Partners, 13 Fitzroy Street, London, United Kingdom

INTRODUCTION

UK Nirex Ltd is responsible for the development of facilities for the disposal of low and intermediate level radioactive waste in the United Kingdom, including the development of the transport facilities for this waste. Intermediate Level Waste (ILW) will be packaged in 500 litre drums or $3m^3$ boxes or drums, and transported to the repository in reusable shielded transport containers (Smith et al. 1989, Sievwright et al. 1991). The transport containers and their contents will form Type B packages and the containers will thus be required to survive impacts up to the equivalent of a 9 metre drop onto an unyielding surface without loss of integrity. The container design concepts rely on absorption of the energy of an accident impact by means of plastic flow of the transport container material, in the form of integral "plastic flow shock absorbers" (Figure 1). Such design features are common practice in the UK nuclear industry, being used for example in transport flasks for irradiated nuclear fuel.

As part of the development programme, Nirex is examining the feasibility of manufacturing these ILW transport containers by means of casting instead of the more usual forging process, as this would bring advantages of lower cost and shorter manufacturing time. Cast materials, however, are perceived to be less tough and less ductile than forged materials. To demonstrate the feasibility of using cast materials for this application it is necessary to show that sufficient fracture toughness can be obtained to preclude low-energy brittle failure modes at low temperatures, and to show that there is sufficient ductility in the plastic flow shock absorbers to absorb the energy of an impact equivalent to a 9 metre drop test.

This paper describes the results of a programme of work carried out by Ove Arup & Partners on behalf of UK Nirex Ltd, in which castings were produced in both Ductile Cast Iron (DCI) and Cast Steel, and subjected to various tests including:

- Non-destructive testing (NDT) to locate and characterise flaws
- Mechanical property tests, including dynamic fracture toughness tests
- Welding and cladding tests
- Drop testing.

The paper concludes with an evaluation of both materials for use as the main material of construction of the Nirex transport containers.

OBJECTIVES

The objectives of the work were:

(a) To generate sufficient data to allow a decision to be taken as to whether cast steel or DCI could be used as the material of construction of Nirex's ILW transport containers

(b) To enable a choice of preferred material to be made for a subsequent programme of full-scale analysis and testing.

MATERIALS EXAMINED

DCI has been in use for many years in spent fuel and radioactive waste containers which have bolt-on shock absorbers and do not have a requirement for plastic flow shock absorbers, and its use is gaining wide acceptance. It was natural therefore to select DCI for evaluation. In addition a cast steel was chosen which, although expected to be more expensive, would also be tougher and more ductile, and therefore might be better suited for plastic flow shock absorbers. The cast steel chosen was a 13% Cr 4% Ni martensitic stainless steel. This steel has excellent low-temperature toughness which can be further enhanced by refinement in an Argon Oxygen Decarbonization (AOD) converter. Its specified properties can be achieved in thick sections, up to 500mm. Its three-stage heat treatment uses air cooling instead of liquid quenching, which results in less cracking and subsequent weld repair.

The materials specifications were:

Ductile Cast Iron:	BS 2789: 1985, Grade 350/22 L40
Cast Steel:	ASTM A352: 1989, Grade CA6NM

CASTINGS PRODUCED

Nirex is intending to produce transport containers in a range of wall thicknesses from 70mm to about 300mm. In this programme, however, only the two extremes of 70mm and 300mm were produced and tested.

For the mechanical and material tests, full-size quarter sections of transport containers were produced in both materials in 70mm and 300mm wall thicknesses (Figure 2). A finite element analysis of the solidification of both quarter sections and the full transport container body was carried out, using OASYS-TOPAZ3D (Shapiro 1985), to verify that solidification conditions, and hence mechanical properties, would be similar in both cases. The results showed that at a distance of approximately two wall thicknesses from the edge of the quarter sections the temperature-time history would be virtually identical to that in the full transport container (Figure 3). Mechanical test samples were not taken from the region within two wall thicknesses from the edge.

For the drop testing, shock absorber sections were produced whose geometry was similar to that part of a 300mm thick transport container which absorbs the impact in a lid corner drop test (Figure 4). Thermal modulus calculations were carried out to ensure that the shock absorber section would be equivalent to the shock absorber on the full transport container.

Four shock absorber castings were produced in each material; one of each was used for mechanical testing and three of each were used for drop testing.

All castings were produced by Ferry Captain, Joinville, France and were subjected to the NDT verification tests.

NDT VERIFICATION TESTS

Prior to delivery, all castings were examined by the foundry using conventional ultrasonic and magnetic particle inspection techniques. In general very few defects were found.

In order to provide defects for the verification tests, a casting which contained a defect which exceeded the acceptance criterion was accepted without repair.

Lloyds Register were employed to repeat the foundry's NDT, and to carry out additional ultrasonic scans using twin crystal probes and shear wave probes. Selected areas of the quarter section castings were cut to reveal the defects and to compare them with the ultrasonic prediction.

The principal results were:

(a) The ultrasonic techniques were sensitive enough to detect defects smaller than the acceptance criterion (Quality Level 3 to BS 6208) providing the material attenuation met the criteria in BS 6208.

(b) Detecting defects in areas of complicated geometry can be difficult even if the defect is within the detection capability of the equipment. Hence extra care is needed in these areas. Shear wave probes can be very useful in these regions.

(c) Twin crystal probes are useful for detecting defects near to the surface, which would otherwise be missed by a single crystal compression probe (because of its "dead zone").

Figure 5 shows the size of the shrinkage cavity defect in the casting as determined by sectioning, ultrasonics and radiography.

SOLIDIFICATION MODELLING

In order to measure the temperature-time history of the castings during solidification, thermocouples were placed in the moulds of the quarter sections at various locations. The resulting temperature-time data were used to calibrate a computer model of the solidification of the castings. This was a combined thermo-mechanical finite element model using OASYS-TOPAZ3D (Shapiro 1985) and OASYS-DYNA3D (Oasys 1990). Figure 6 shows the computer results for the thin-walled DCI quarter section. The contour shows the progress of the solidification front. The results indicate that a shrinkage cavity will form in the location where in fact one was found (Figure 5).

DROP TESTING

Three shock absorber castings in each material were drop tested at various heights and temperatures as shown in Table 1 below.

Material	Drop Height (m)	Temperature (^0C)	Maximum Deceleration (g)	Knockback (mm)
DCI	9	-40	102	170
DCI	9	-27	100	179
DCI	18	-40	123	275
Cast Steel	9	-40	95	111
Cast Steel	18	-40	130	197
Cast Steel	36	-40	140	162

Table 1: Summary of Drop Test Results

Drop tests were carried out by the Structural Test Centre, Cheddar. Each test consisted of dropping a 65 tonne mass from the specified height onto the casting which was seated on an unyielding target and cooled to the specified test temperature. The 65 tonne mass was fitted with accelerometers to measure its deceleration during the event.

Table 1 summarises the results of the tests, giving maximum deceleration and the "knockback" (the reduction in height of the casting due to the impact). Pieces broke off the castings in all tests. The failure mechanism was ductile in all the cast steel tests. In the DCI tests the failure mechanism was predominantly ductile, but some areas of brittle failure also occurred. Brittle cracks did not propagate outside the immediate impact area, however.

In general, both materials were successful in absorbing the impact energy, the results in Table 1 being similar to those obtained in drop tests on cuboidal spent fuel flasks of similar weight manufactured from forged steel (Barnfield 1985).

Finite element analysis of the impact events was carried out using OASYS-DYNA3D (Oasys Ltd 1990). An elastic strain hardening material model with failure was used to represent both materials. Figure 7 shows the finite element mesh and the calculated and measured acceleration time histories for the 18 metre cast steel drop test.

MATERIAL TESTING

Comprehensive mechanical testing was carried out on all quarter sections, and on one shock absorber of each material. The following testing was carried out:

(a) Tensile, hardness, Charpy, metallurgical, K_{ID}, and J_{1C} tests (by British Steel Technical, Swinden Laboratories).
(b) High strain rate tensile testing at rates up to 3 x 10^3 sec^{-1} (by Oxford University).
(c) J_{1D} testing (by Sandia National Laboratories).

Table 2 summarises the static tensile, Charpy and K_{ID} test results for each casting, and Figures 8 and 9 show the high strain rate tensile test results for both materials. Figure 10 shows the variation of K_{ID} (obtained from J_{1D}) against dK/dt for both materials from tests at -40^{0}C which were carried out using 25mm thick compact tension specimens. The results indicate that there is little variation of K_{ID} or J_{1D} with loading rate (Salzbrenner).

Casting	Static Tensile Test at Room Temperature				Charpy V Notch at -40^{0}C (J)	K_{ID} at -40^{0}C & at 10^5 to 10^6 MPa$\sqrt{m}$/s (MPa$\sqrt{m}$)
	Yield (MPa)	Ultimate (MPa)	Elongation (%)	Red^n of Area (%)		
DCI Thick Walled Quarter Section	183-262	202-418	12-24	5-31	5-18	51.7, 55.4, 56.3 (Valid Tests)
DCI Thin Walled Quarter Section	236-248	376-396	16-24	15-30	5-8	
DCI Shock Absorber	239-306	382-467	16-30	18-26	5-11	
CA6NM Thick Walled Quarter Section	521-660	756-806	12-24	41-65	73-122	>220.7(K_Q)
CA6NM Thin Walled Quarter Section	552-702	751-830	16-24	53-72	61-132	
CA6NM Shock Absorber	525-529	740-744	20-28	71-75	32-42	

Table 2: Summary of Static Tensile, Charpy and K_{ID}

Notes to Table 2:

(a) The ranges quoted are the maximum and minimum individual values measured in several tests on the specimens taken from the castings (not from test blocks).
(b) K_{1D} was measured on DCI using 137.5mm thick bend specimens and CA6NM using 125mm thick bend specimens. The thickness criterion $B > 2.5(K/\sigma_y)^2$ was not satisfied for the CA6NM specimens. The failure mechanism was cleavage for DCI and ductile for CA6NM.

CONCLUSIONS

The results for DCI are broadly consistent with published data for this material. In the case of the drop tests at both -40⁰C and -27⁰C, the results for DCI show that brittle fracture can occur in the region of the impact, when the material takes the direct impact. Hence it would be necessary with the type of design being considered for ILW transport containers which utilises plastic flow shock absorbers, to base a safety case on the fact that a crack would arrest before it penetrated the containment. Although such crack arrest criteria have been proposed (Weiser et al. 1990) it is a rather complicated approach. This situation does not arise with current DCI Type B(U) containers, eg the CASTOR design, because the DCI does not take the direct impact of the drop test as these containers are fitted with bolt-on shock absorbers.

The cast steel, CA6NM, has greater fracture toughness, and no brittle fractures took place in the drop tests. Hence this material can be readily used without bolt-on shock absorbers, even at -40⁰C.

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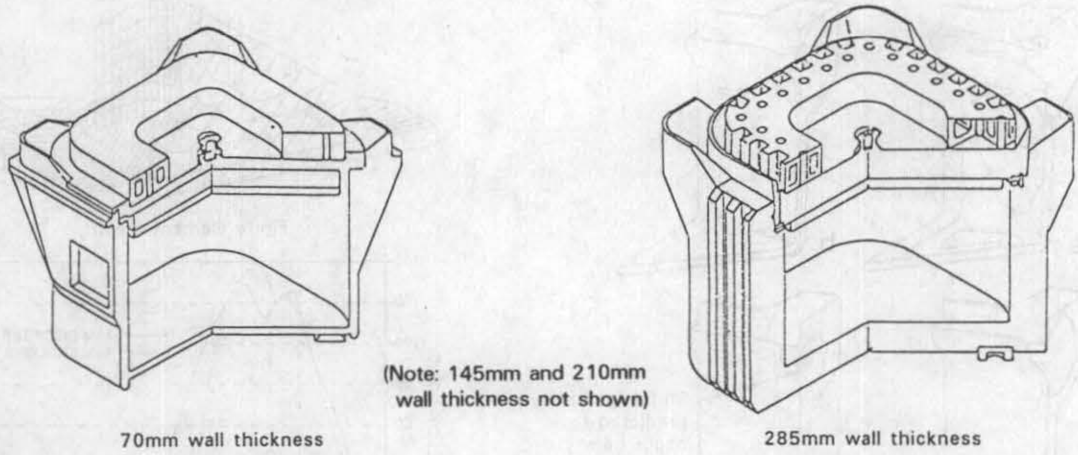

Figure 1 The NIREX Transport Containers

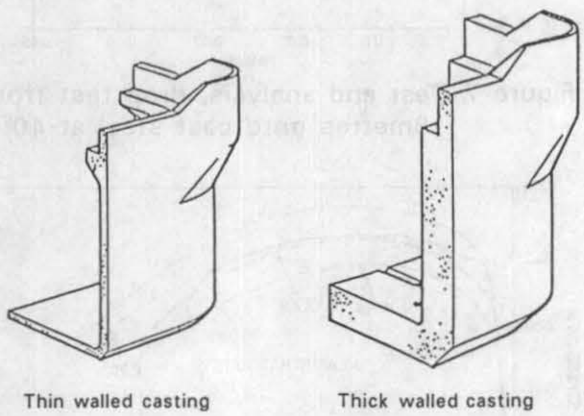

Figure 2 Castings produced -quarter section

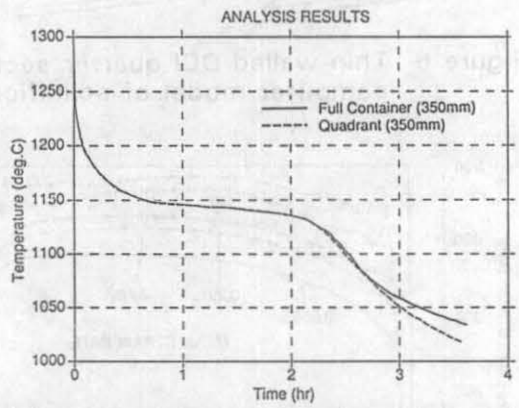

Figure 3 Temperature-time history in full container and quarter section, 350mm from edge

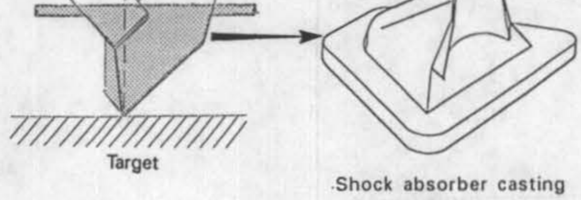

Figure 4 Castings produced -shock absorbers

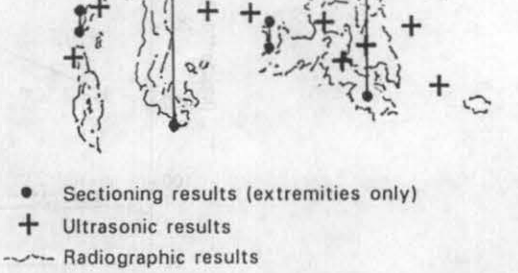

Figure 5 Ultrasonic and radiographic sizing of shrinkage cavity and sectioning results

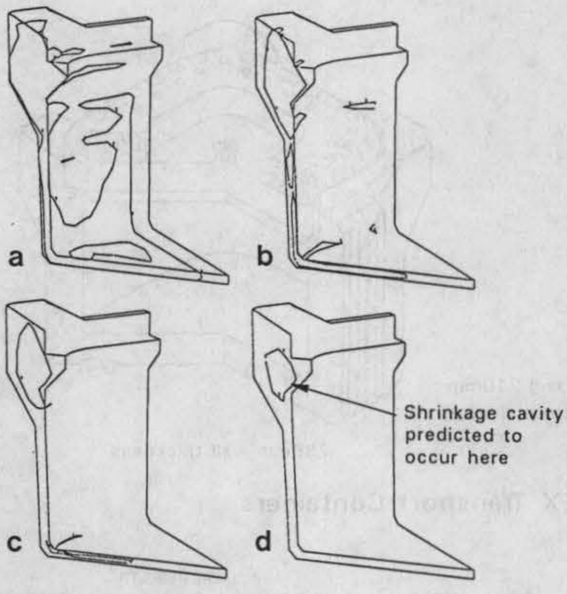

Figure 6 Thin-walled DCI quarter section computer model of solidification

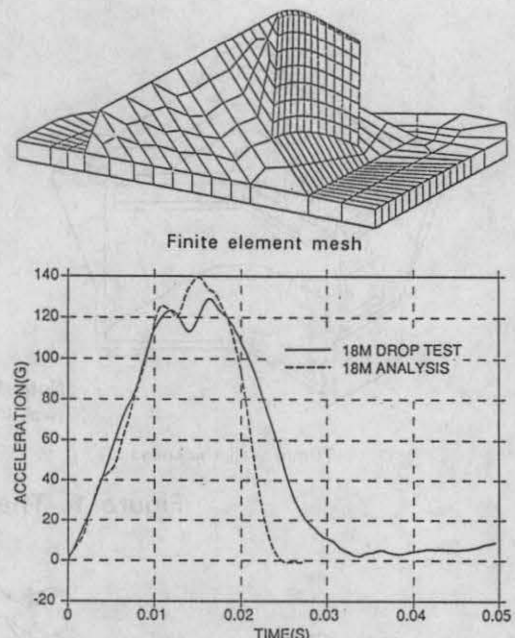

Figure 7 Test and analysis, drop test from 18metres onto cast steel at-40°C

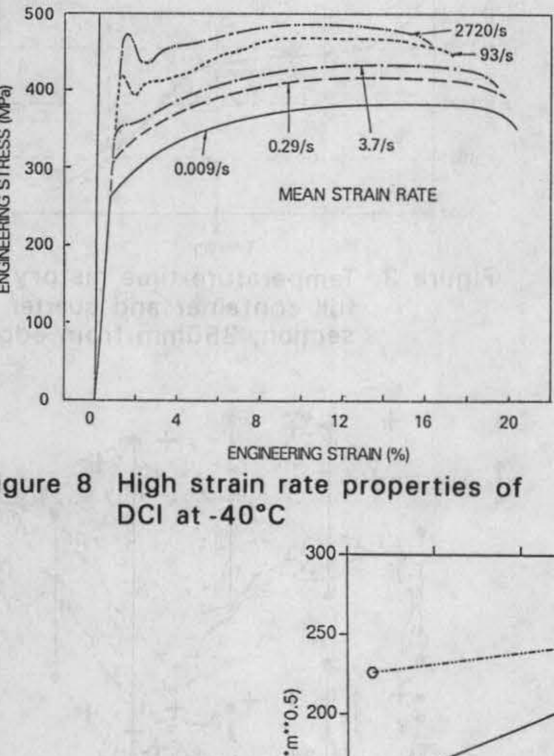

Figure 8 High strain rate properties of DCI at -40°C

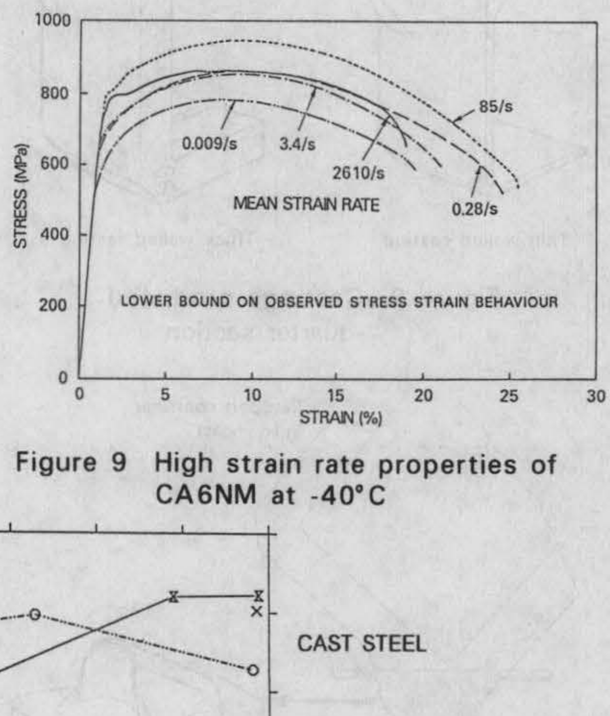

Figure 9 High strain rate properties of CA6NM at -40°C

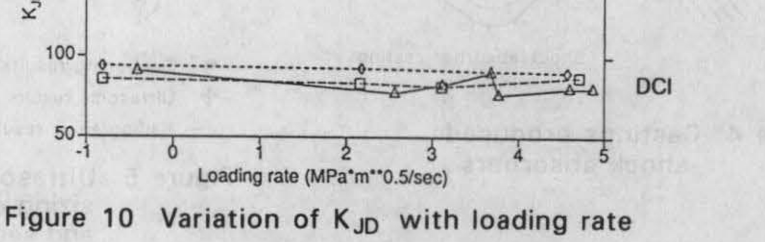

Figure 10 Variation of K_{JD} with loading rate

Session 37:

DROP TESTING-II

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