The ISIS target

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1. Introduction

The ISIS Target Station and its Target(s) have been described in many reports, including the Proceedings of the previous nine ICANS Conferences. They are, by now we hope, familiar devices to many of the participants at this Conference. Participants will hear elsewhere in this Conference details of other parts of the Target Station, but this presentation discusses the two target failures that have occurred, gives our understanding of the causes and indicates the steps being taken to alleviate the problems.

At the outset of the design we were aware that the target would have a finite lifetime, due to radiation damage effects, exacerbated by mechanical damage due to thermal cycling and fatigue. Estimates of target lifetime at full intensity are about 2 years for radiation damage swelling and about 10E4 gross thermal excursions. The latter number is the one which gives uncertainty in defining the life of the target, since it is dependent on the reliability of the accelerator and quality of the proton beam.

The commissioning of an accelerator system and bringing it up to high beam intensities have their own special problems. There must be protection of components against uncontrolled beam loss, which produces thermal damage, prompt radiation and induced activity. Fast beam trips for beam loss protection, or equipment failures, result in quenches from high temperature in the target which get bigger with increasing beam intensity. But the target itself is a difficult device to make, taking about 12 months to manufacture. Further, changing one is a complex and time consuming task, not without its hazards. There is thus something of a balancing act to bring the accelerator towards specification before the target fails due to thermal cycling fatigue. In the early days of ISIS beam loss protection was the dominant consideration and the target was regarded somewhat as a sacrificial lamb to the goddess of machine reliability.

During 1987 there were two failures of ISIS targets. The first target had received 92,400 μA-hr of beam, with an unknown number of gross thermal cycles; the second had received 54,000 μA-hr with about 40,000 gross thermal cycles (~ 20,000 beam trips from all causes). Actual lives were 25 months and 3 months respectively.

2. The ISIS Target

A schematic of the ISIS target is shown in Figure 1. The target consists of a 'module' containing 23 disks of depleted uranium of diameter 90 mm and varying thickness (dependent on axial position in the target). The disks are clad in zircaloy-2, 0.25 mm thick, and mounted in square picture frames of stainless steel to form a set of parallel plates separated by cooling channels 1.75 mm wide. The D_2O coolant flows through these channels which are grouped to be fed from 3 main cooling channels via stainless steel manifolds bolted to either side of the module. The module and manifolds are mounted within a stainless steel pressure vessel which has its own independent cooling circuit, the "casing circuit".

The condition of the target is monitored by

a) Thermocouples located at the centres of alternate uranium disks, numbers 1, 3, 5 ... Response time for these thermocouples, including all effects, is about 0.5 sec.

b) Monitoring the water flow and pressures of each cooling channel. The information is collected to define the effective width of the cooling gaps, g, proportional to (flow)/(pressure drop)$^{0.55}$.

c) A Fission Product Monitor which uses a lithium-germanium detector and multichannel analyser to detect and display the gamma spectrum from radionuclides in the D_2O coolant. First indications of spallation and/or fission products can be seen presently in about 30 - 40 minutes after beam turn-off.

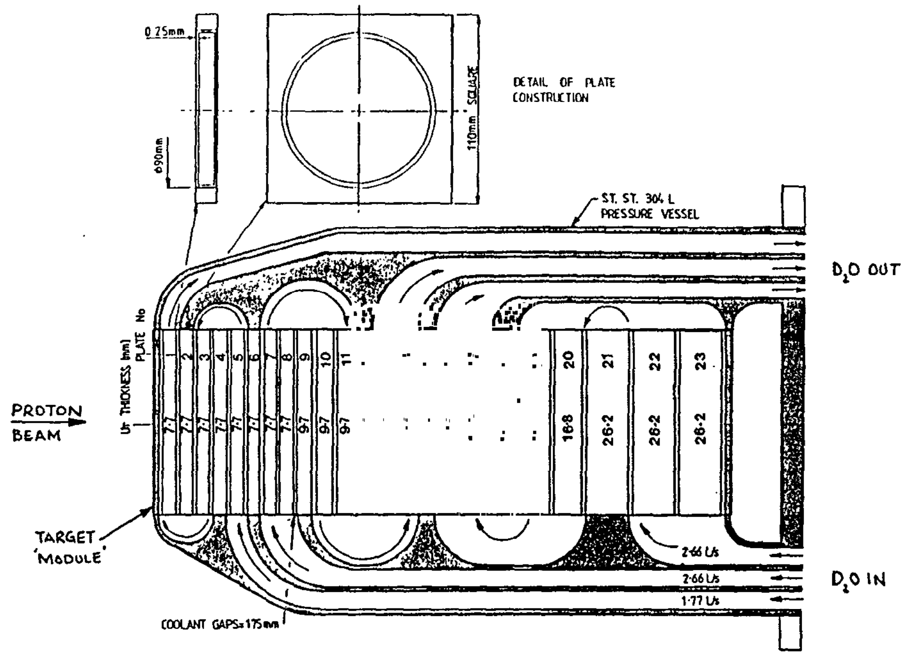

FIG 1. ISIS TARGET SCHEMATIC

The main manifestation of damage to the target, whether due to radiation damage or thermo-mechanical effects, is in swelling of the target uranium. This swelling has the effect of closing the cooling gaps, so reducing the flow and increasing the pressure drop. The reduction of cooling results in increased target plate temperatures. The effects are the first indications of the approaching end of the target life, or a developing serious problem, and in themselves would be sufficient to indicate the need for a target change (regarded as a normal end-of-life target change). This may be confirmed, if after a delay to allow cooldown of general background, fission products are detected in the D_2O coolant.

Both failed targets displayed the above sequence and for both, fission products were seen in the coolant. The onset to failure was quite rapid in both targets (about 16-24 hours), a point that will be discussed later.

3. The Target Failures

a) Target Number 1

Target number 1 had been operating since the start up of ISIS in July 1985. There had been no problems, except for a small internal leak between the plate and casing circuits. The beam intensity had been increased over the operating period so that in August 1987 it was at about 60 μA. There was a suspected blockage in the front cooling channel which was cleared (suspect filter bits) and the target was run normally for a further 2 weeks when the flow fell from its normal 113 $lmin^{-1}$ to 93 $lmin^{-1}$ and the pressure drop increased from 1.85 bar to 2.11 bar (the corresponding gap constant fell from 18.4 to 14.1). These values were outside the limits set for normal operation and the control system reacted, as designed, by warning the operators. The temperatures of plates 1 and 3 rose about 50°C above the operating level of about 250°C causing the beam to be tripped off. The beam was restored at reduced level but the water leak developed to an unacceptable level. The decision was taken to change the target when, in addition to the leakage, the gamma spectrum from the plate circuit D_2O showed fission products, indicating a breach of the cladding. The fission products were individually identified by gamma spectroscopy and the gamma spectrum is shown in figure 2. Fission products gases released to the atmosphere due to this target failure and subsequent operations were less than 10 GBq (i.e. less than 0.05% of a reportable release).

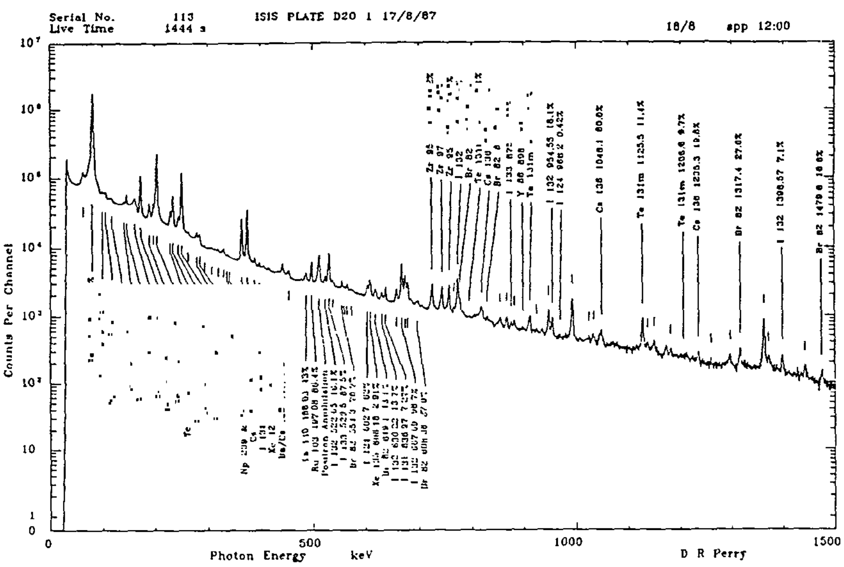

FIG 2. GAMMA SPECTRUM FOR D_2O COOLANT, TARGET NO 1

b) Target Number 2

The experience of target number 2 followed closely that of number 1. There was a small inter-circuit leak which did not however worsen. The target operated from early September to early December 1987 with beam at 70 - 80 μA. Over a period of about 20 hours the gap constant fell from 18.4 to 16.7. Figure 3 shows the gap constants over the last 90 hours of the target's life, the fall-off for channel 1 can be clearly seen. At this stage the beam was turned off and within 3 hours fission products were seen in the coolant D_2O. The target had operated for 3 months at high intensity, up to 85 μA. Early in this period a beam trip counter was installed which registered 19,400 trips. The trips were followed by instantaneous turn-on to full intensity, inducing similar mechanical stress, to give a total for the whole operational period of about 40,000 gross temperature excursions. Gaseous releases from this target, due mainly to water circuit blowdown prior to target removal, were 46 GBq and contained some fission product gases.

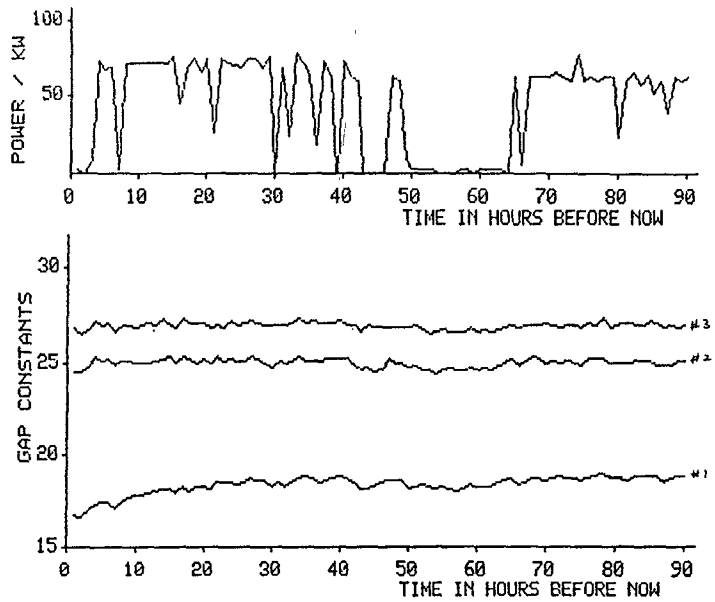

FIG 3. GAP CONSTANTS OVER LAST 90 HOURS OF LIFE OF TARGET NO 2

In both target failures the target control, monitoring and safety systems worked well and gave clear indications of the problems at an early stage. The experiences have led to some refinements in the monitoring systems, both in terms of beam on target and of display of target parameters.

4. The Target Changes

The work to change the targets was done entirely by remote means in the purpose-built Remote Handling Cell (RHC) which is an integral part of the Target Station. Details of the remote handing operations and the lessons learned are reported elsewhere in this Conference (1) and only a few comments will be made here. Though the RHC was substantially complete, much initial preparation was necessary to equip it with TV cameras and tools before work could start. Special tools for use with the manipulators were prepared and, as far as possible equipment and procedures were tested initially in a dummy run. Both changes were very much learning exercises and some modifications and improvements were made between the first and second change. Of the RH problems encountered, only one might have been related to the proton beam, when the pressure vessel of target number 1 was distorted due possibly to beam misalignment which would give non-uniform heating of the stainless steels in the target. Leakage between the plate and casing cooling circuits could also be explained this way.

Generally the work went very much as planned. All work was done with the guidance of a nominated radiation protection supervisor. After removal both targets were placed in the storage well within the RHC, pending further action. Times for doing the work were

Target 1: Remove and store 5 days. Install new, ready for operation 10 days

Target 2: Remove and store 2 days. Install new, ready for operation 12 days

In both cases some preparation time was required. With increasing experience less preparation time would be needed and the overall task might be achieved in 2 weeks.

Dose rate measurements on the targets gave values much as expected from design calculations, i.e. about 80 mGy hr^{-1} at 2 m. The general radiation level in the RHC due to other components was about 200 mGy hr^{-1}, with 800 mGy hr^{-1} on contact with the reflector. The average radiation dose received by the staff on the work was one twelfth of the derived dose based on the ICRP limit for classified workers.

5. Examination of Target 2

Both target failures came sooner than hoped in terms of total current though there was increasing concern at the very large number of beam trips. An examination of a failed target was crucial and Target 2 (which had a better known history) was sent to the Harwell Remote Handling Facility for dismantling and expert examination. Figure 4 shows the inlet side of the target module with the pressure vessel and manifolds removed. The gaps between plates 3, 4 and 5, all part of the first cooling channel, can be seen to be partially blocked. Detailed examination showed that disks 1 through 16 had wrinkling of the zircaloy cladding over a diameter 5 - 7 cm, with the remaining disks appearing undamaged. Wrinkling of the cladding is due to radiation growth of the underlying uranium randomly orientated crystals, and its area reflects the proton beam size (expected to be 7 cm dia at full beam, full emittance). Disks 3, 4 and 5 had localised swelling, with cracks in the cladding. The cracks were both radial and circumferential, and were biaxial due to the underlying localised swelling of the uranium. There were also witness marks due to the ribs, almost all due to pressure from disk number 4. The cracks were black within and outside there were brown rings due to the formation of zirconium hydride due to the loss of cooling with gap closure. By far the most damaged disk was number 4, where figure 5 shows the localised swelling over a diameter of about 3 cm on the front face with several cracks in the cladding. The swelling is clearly offset with respect to the disk centre and was so large as to press into the corresponding faces of plates 3 and 5. The damage was recognised (2) as "entirely commensurate with failure due to thermal cycling growth, probably caused by on/off cycles of the beam, possibly exaggerated by irradiation. There was no evidence of engineering faults in the target".

A zinc sulphide screen was placed in front of disk number 4, to indicate the induced activity in the plate. For comparison purposes, this was repeated with disk number 1, which was relatively undamaged. When the

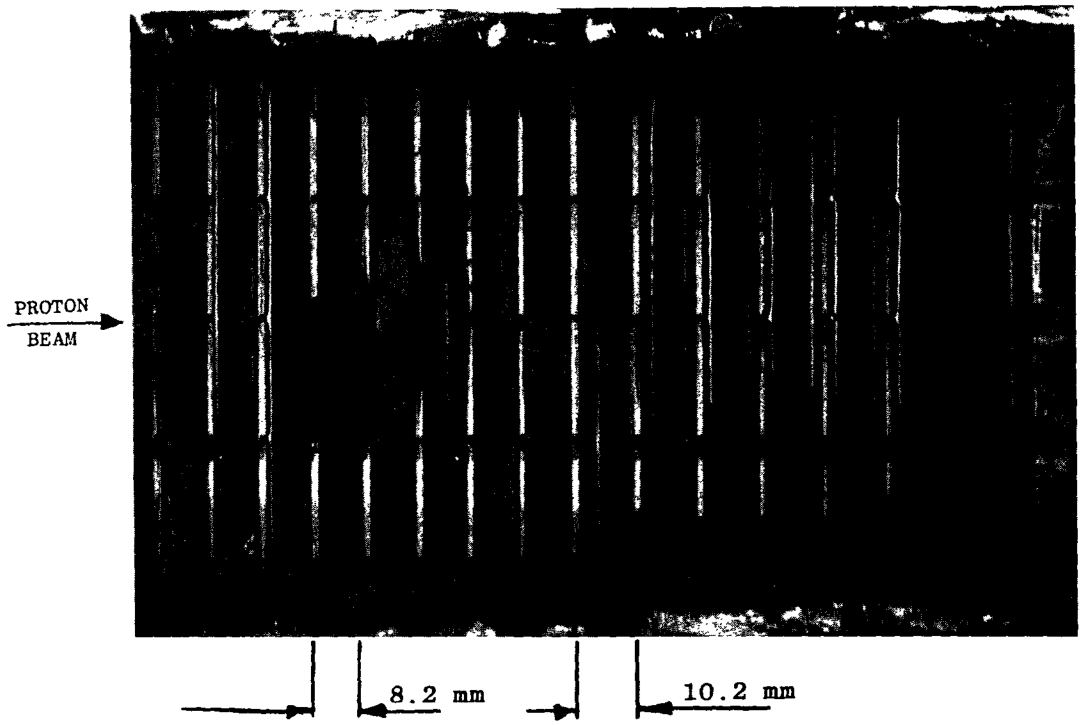

FIG 4. INLET SIDE OF TARGET MODULE, TARGET NO 2

scintillation trace was overlaid on the photograph of disk number 1, it showed a good fit to the wrinkled area of the disk. A contour plot was also made which showed a "humped" elliptic distribution about 7 cm (v) by 5 cm (h) and reasonably well centred on the disk. On disk number 4, however, this scintillation was again a humped elliptic distribution 7 cm(v) by 5 cm (h) but like the wrinkling, offset to the left horizontally by about 1 cm. The region of severe mechanical damage, about 2 cm diameter was offset to the right by about 1 cm and down by 1 cm to the edge of the scintillation with no enhancement of the scintillation, i.e. this damage, and its induced activity occurred in a time short compared with the total irradiation time. Recalling the reduction of gap constant occurred over a period of the last 16 or so hours of the target we conclude this damage occurred in this same period.

How can this effect be so localised and how can it occur so rapidly? Firstly, the beam intensity at this time was 85 μA and the horizontal and vertical emittances were about half the full design value. Due to power supply instabilities in the extracted proton beam line the spot size on

FIG 5. FRONT FACE OF DISK 4 SHOWING LOCALISED SWELLING

target varied both in size and location. Beam transport calculations have shown that such small spot sizes were possible with the result that at these intensities the energy density in the plate could be twice the maximum design value. Secondly, the uranium in the target itself is polycrystalline, of small crystals with random orientation. During a temperature excursion an unrestrained single crystal will not experience mechanical stress. However when the crystals are contiguous some crystals experience compressive, and some tensile, stress during a quench. Plastic elongation is produced in those crystals experiencing tensile stress, which is retained on heating and eventually shared with the other crystals by creep. Successive cycles produce further elongation. The strain of individual crystals increase linearly with the number of cycles but there is no volume change until the voids, defects, etc are filled, when it changes rapidly.

Underlying the above mechanisms, the uranium during operation suffers from irradiation growth. Stress is developed due to the mismatch between the movements of adjacent grains which gives rise to plastic deformation. The internal strain introduced by growth at the boundary between two grains will reach the yield strain in a time t_m dependent on the fissioning rate and, for ISIS at full intensity is about 170 secs. Continuous plastic yielding occurs after this time and the uranium becomes almost devoid of strength at low strain rates. Any external stresses applied in times $\geq$ 170 secs will relax to a low value, but in times $<$ 170 secs will not relax. These times indicate how some of the effects of a quench can be alleviated, by applying external stress at a rate no faster than naturally occurs during burn-up of the uranium.

6. ISIS Operations

As a result of these experiences a number of improvements in the operation of ISIS have been instituted:

i) With the addition of further diagnostics in the EPB together with auto-align programs the proton beam on target has been improved. Further beam line quadrupole programs are coming into use and a long term program to improve power supply stability is underway.

ii) The original halo monitor has been replaced by an 8-sector device, with two sets of 4 thermocouples at 2 different radii. Uniform temperatures are sought and, after warning, the beam is tripped off if the alignment is bad (measured by the difference temperatures of opposite TC's).

iii) The Beam Loss Trip System has been modified so that rather than trip the beam due to one faulty pulse in 50, the trip is initiated by comparing the beam loss at several points in the machine over 3 pulses with a pre-set value, or 4 pulses in the case of the Injector. This has had the effect of reducing the trip rate by a factor 8.

iv) A 'soft start' system is incorporated when, following a beam trip and quench, the beam is brought to operating intensity in 140 - 180 secs. This then avoids the mechanical stress induced by a fast up-cycle by allowing the uranium to plastically yield, so a quench now results in 1 thermal excursion rather than 2. The combination of iii) and iv) gives a factor 16 improvement in trip rate.

v) The gap constant is now determined once per hour and compared with a calculated temperature corrected value (g varies linearly with the bulk D_2O temperature). Warnings are given when the measured value differs by 0.5 (warning) or 1.0 (beam-off), and the problems are investigated. In this way it is hoped to recognise an impending target failure before the cladding is breached. The subsequent target change can then be made without the complication (and possible hazards) of free fission products. This system will be incorporated into auto-control in due course.

vi) As part of the transfer of control of the Target Station from "local" to the main ISIS control room, improved displays are provided, including a colour display of the 7 front plate temperatures, figure 6, also a longitudinal display of plate temperature. These displays have greatly increased the operator awareness of the health of the target.

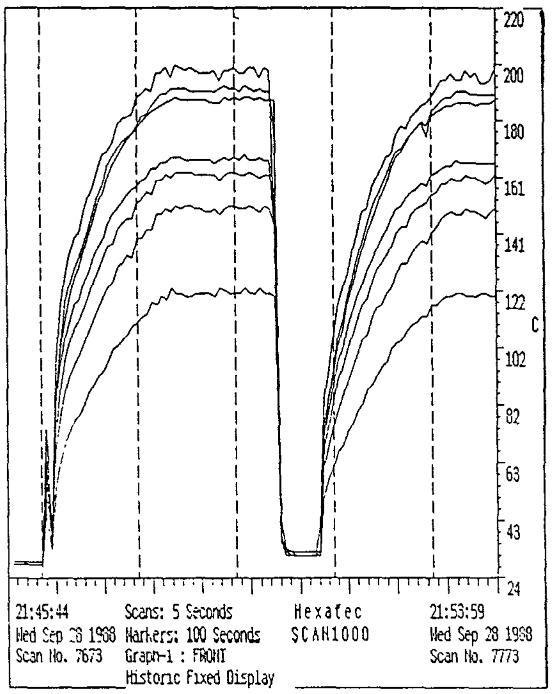

FIG 6. DISPLAY OF FRONT 7 TARGET PLATE TEMPERATURES
(NOTE QUENCH FOLLOWED BY A 'SOFT START')

At 15 September 1988, the beginning of a scheduled short shut-down period for ISIS, ISIS Target number 3 had received 129,300 μA-hr and 8900 soft starts (≈ beam trips). Other parameters appear to be behaving normally. Many isotopes of krypton have been seen in the D_2O coolant but, in the absence of other radionuclides, these are recognised as spallation products of zirconium. Deo Volente ....

7. Acknowledgements

It is a pleasure to record the continued support and efforts of many people on ISIS and the Target Station in particular: David Gray, Brian Boardman, Gordon Grossart, Eddie Fitzharris, Alan Thorne, Ken Roberts, David Perry, Martin Bly, Bob Hall, John Sexton, John Hirst and the late Colin Thomas.

8. References

1) T A Broome and M Holding "Remote Handing for an ISIS Target Change" this Conference.

2) B Hudson. Private communication to A Carne, May 1988