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The ISIS Spallation Neutron and Muon Source—The first thirty-three years

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ABSTRACT

Thirty-three years of operational history of the accelerator and target aspects of the ISIS Spallation Neutron and Muon Source are summarised. Data on overall percentages of lost time and distributions of lost time amongst different equipment categories are presented. Areas of difficulty are also described, along with measures taken to overcome the difficulties. Further, on the basis of hard-won experience, recommendations for managing operations are made. Altogether, much valuable operational information spanning several decades is presented, and this should be of interest to designers and operators of large accelerator-based facilities.

1. Brief history

ISIS is the UK's long-lived Spallation Neutron and Muon Source. At 19:16 on Sunday 16 December 1984 ISIS produced its first neutrons. Routine operations began in June 1985, and in October 1985 at its official inauguration the neutron source was named ISIS by the UK's Prime Minister Margaret Thatcher (previously, ISIS had simply been called the 'Spallation Neutron Source' ('SNS')). ISIS was constructed mostly in buildings previously built for and occupied by the 7-GeV proton synchrotron Nimrod [1] which ran between 1964 and 1978 and was probably the last of the large weak-focusing high-energy-physics synchrotrons. Table 1 gives a list of current parameters of ISIS, and Fig. 1 shows a schematic representation of the current configuration.

When it was built, ISIS consisted of an H^- ion source, a 665-kV Cockcroft-Walton DC pre-injector, a 70-MeV 4-tank 202.5-MHz drift-tube linac, an 800-MeV 50-Hz rapidly cycling proton synchrotron, and a target station based on a depleted-uranium primary-neutron-producing multi-plate target, a beryllium reflector, and two water and two cryogenic moderators. Initially the machine ran at only 550 MeV using four synchrotron RF cavities instead of the full complement of six, then ran at 750 MeV on six RF cavities from 1987, and finally ran at 800 MeV from 1990. Inevitably, during the first few years, beam currents could be increased only slowly; Fig. 2 shows the increase in beam current over the first ten years, *i.e.* between 1984 and 1994, as experience was gained and initial difficulties with plant and equipment were overcome.

In order to minimise the cost of building ISIS, some second-hand equipment had been pressed into service — *e.g.* many of the Nimrod beam line magnets, the ~1-MW White-circuit choke from the Daresbury electron synchrotron NINA[2] [2], and the ~1-MW motor-alternator set for the synchrotron lattice magnets from a Swedish tram system and a Sheffield steel works. In addition, the 70-MeV linac, which had been ramped up from its original ~1-pulse-per-second (pps) intended rôle as a replacement injector for Nimrod to its new 50-pps rôle for ISIS, incorporated two tanks from the Proton Linear Accelerator (PLA) [3] which ran between 1959 and 1969.

ISIS was designed in the 1970s and early 1980s [4]. The essence of the design was a 10-superperiod strong-focusing machine with six RF accelerating cavities to provide an average beam current of 200 μA. It had been difficult to find a magnet lattice that fitted into the existing Nimrod buildings, that could use the existing NINA choke for the ISIS dipole AC magnets, that accommodated efficient beam-loss collection, and that satisfied all the requirements for long straights for injection, acceleration and extraction. A reasonably comprehensive account of the as-built ISIS is given in [5], summaries of progress in increasing performance include those in [6], and experience obtained in the design and the first few years of operation is summarised in [7].

Before ~1980, instrumentation used for neutron scattering measurements was fairly simple [8], but the advent of ISIS and other spallation neutron sources spurred the rapid development of neutron instrumentation such as position-sensitive neutron detectors. For example, although work on spin liquids at ISIS initially made use of the HET spectrometer [9], much more detailed information was obtained when the MAPS spectrometer with its large 16-m^2-area detector bank became available [10]. During the 1990s the potential advantages of pulsed spallation sources for facilitating measurements with cold neutrons became evident, and consequently, even though ISIS had by this time become the world's most powerful pulsed neutron source, construction of a second ISIS target station (TS-2) was begun in 2003 aimed principally at promoting progress in the technologically significant areas of soft

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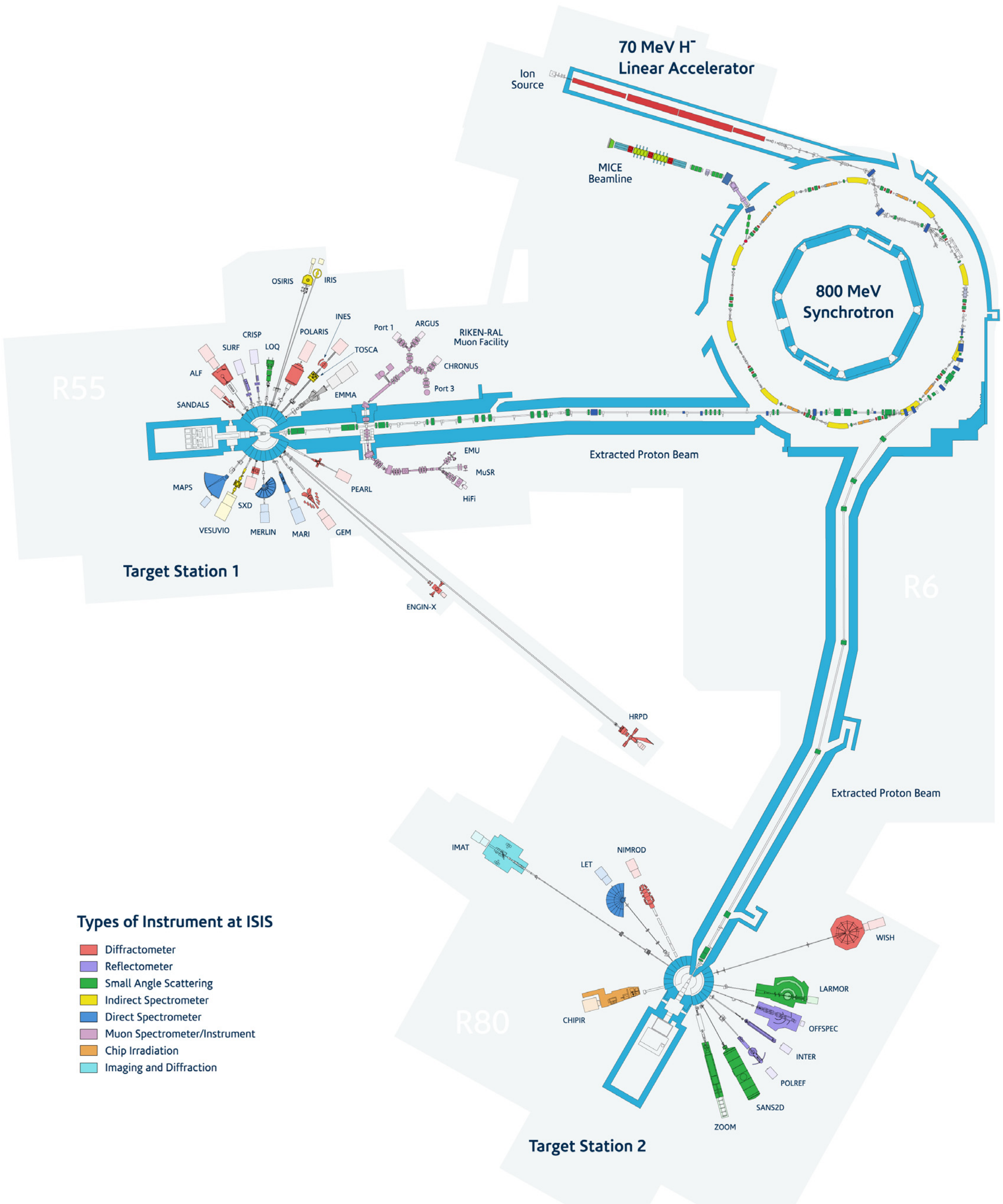

Fig. 1. Schematic representation of the physical layout of ISIS. The light grey areas are the footprints of the buildings.

condensed matter, advanced materials, and bio-molecular science. First neutrons from this target station (see Section 3.1 below) were produced in 2008, and with appropriate sample environments, there has been a step change in the variety of physics, chemistry and biological systems that can be probed by ISIS instrumentation. An example of this is LET, a cold-neutron multi-chopper spectrometer on TS-2 [11] which combines large area detectors, advanced neutron beam transport and state-of-the-art computational tools to maximise the efficiency of delivering neutrons to the sample and to their subsequent detection and analysis. Such instrumentation has the ability to cover a highly diverse range of science from bio-molecular materials through to quantum matter.

Muons provide a unique view of atomic- and molecular-level behaviour in a wide variety of materials, and a muon facility[3] has been in operation on ISIS since 1987 (see Section 3.3 below). Since then, many additions and upgrades have taken place [12], the most recent upgrade being the rebuilding of the primary beamline which has yielded an increase in muon flux of up to a factor of 4 with no change of spot size [13]. And improvements are continuing, such as the development of the SuperMuSR instrument which will represent a step change in data rates and resolution at a pulsed muon source.

Over the years, most of the increased output of 'science' [14] from ISIS, which now spans a wide range of disciplines, from magnetism to cultural heritage, engineering to food science, and chemistry to environmental science, has resulted from a complete and holistic consideration of the challenges of the scientific theme under investigation. Such an approach requires that all aspects of the facility are considered (source, beam transport, shielding, sample environment, detection, and data analysis). It is this integration that drives the transformative change in research capability for a facility such as ISIS. And the development

[3] The ISIS Muon Facility is unique in Europe, and is one of only four muon facilities world-wide available for condensed matter and molecular studies.

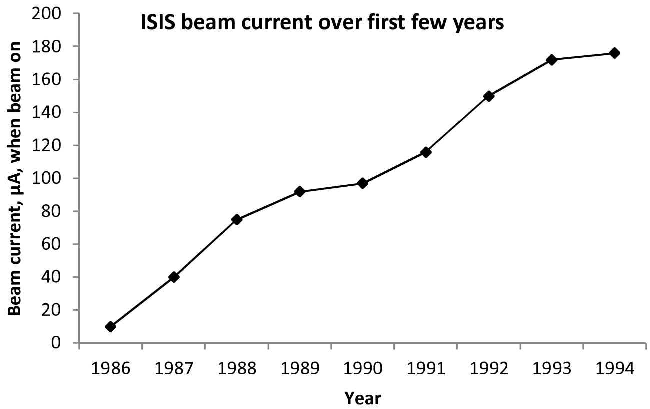

Fig. 2. Proton beam current delivered to target when beam on — gradual increase over ∼10 years from first beam. Since 1994, proton beam currents have remained essentially within the range ∼200 ± 30 μA.

Table 1
Outline list of current ISIS parameters.

		Target Station 1	Target Station 2
Synchrotron injection energy	70 MeV		
Synchrotron extraction energy	800 MeV		
Proton beam current	∼225 μA	∼180 μA	∼45 μA
Beam pulse repetition rate	50 pps	40 pps	10 pps
Proton beam power	∼180 kW		
Operational days per year	∼200		
Tungsten target configuration		Multi-plate	'Solid' cylinder
No. of neutron instruments		17	10
No. of muon instruments		5	
No. of user visits	2278 (in 2017)		
No. of journal publications	486 (in 2017)		

of instrumentation at ISIS continues apace. For example, although in 2003 the engineering materials science instrument ENGIN-X on TS-1 was added to the ISIS instrument suite allowing samples weighing up to one tonne to be accurately positioned to better than 10 μm, in 2018 the IMAT instrument was brought into use on TS-2 enabling materials studies to be carried out more quickly and with much better spatial resolution than on ENGIN-X.

Lists of ISIS instruments and their characteristics are readily available at [15].

2. Operations

ISIS operations are programmed in 'user cycles', periods of ∼30–50 days during which the machine runs 24 hours a day 7 days a week. Machine run-up usually begins ∼10 days before the scheduled start of a cycle, and includes time for accelerator physics; in addition, 2–3 days of accelerator physics are usually programmed immediately after the end of a cycle. Gaps between cycles can range from ∼1–2 weeks to ∼2–3 months. Every four years or so, ∼6–9-month-long shutdowns are scheduled, and major maintenance and upgrade work is concentrated in these long shutdowns. In practice, it is found that constraints of money, available staff effort, preventative and corrective maintenance, and Christmas / New Year and summer holidays favour 4–5 user cycles a year on average.

Day-to-day operations at ISIS are run from the Main Control Room (MCR) by 'the Crew', currently six shift teams of three (Duty Officer, Assistant Duty Officer, and Duty Technician). Although only five shift teams are necessary to provide permanent around-the-clock cover, the sixth team is 'rotated' and can be assigned to work in different areas of ISIS in order to foster experience of evolving technologies and to maintain familiarity with the disposition of the plant and equipment, and the existence of a sixth team also facilitates delivery of Crew training.

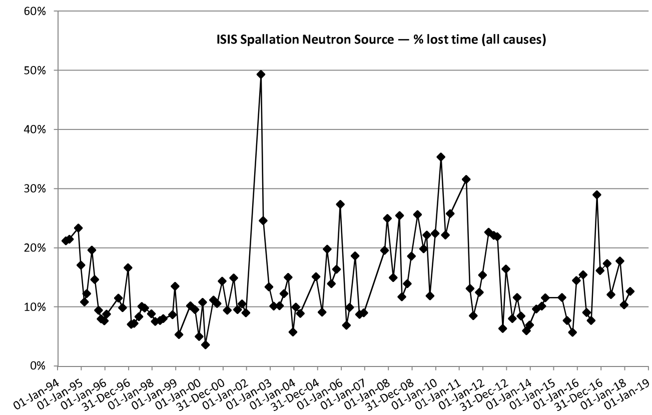

Fig. 3. Percentages of lost time since the year 1994 by user cycle. These percentages are (scheduled time − delivered time) ÷ scheduled time. *All* lost time is included; there is no *de minimis* limit below which lost time 'does not count'. The mean and standard deviation of the distribution of lost time data are 14% and 7% respectively. (The 50% point resulted from an overly optimistic start-up after a long shutdown.) However, in some ways the lost time percentages up to ∼2000 may be slightly optimistic, as during these years there was opportunity to add 'run-on' [16] to cycles with poor availabilities — whereby several 'bad' days could be replaced by additional 'good' days added to the end of the cycle.

An Improvement and Sustainability Programme to replace old plant and equipment and to address issues of optimising lifetimes and reliability was launched around the year 2000. This programme, which started relatively modestly but over the years has on average been running at a level of ∼5%–10% of the total ISIS budget (8%–9% in 2018), has been prioritised so that items of plant and equipment posing the greatest risks to the ISIS running programme are accorded the highest priority.

Fig. 3 shows the percentages of scheduled time lost from 1994 onwards, *i.e.* after the ∼10 years during which the machine had been ramped up to its 'proper' performance. *All* lost time is included; there is no *de minimis* limit below which lost time 'does not count'. The mean and standard deviation of the distribution of the lost time data are 14% and 7% respectively. An alternative representation of the underlying data is shown as a histogram in Fig. 4.

It is tempting to interpret Fig. 3 as follows: a gradual improvement for the first ∼6 years after 1994 as operational skills were consolidated, experience was gained, and all equipment 'settled down'; then a gradual worsening over ∼8 years as equipment became older; then a period of ∼4 years after the ISIS Second Target Station came into use during which the machine was driving two target stations and was consequently under greater strain; then a few years of gradual improvement; and finally (and most recently) a few years of problems from ageing equipment. Whilst such a superficial interpretation may be partly true, there is of course much more to be considered, as described below.

3. Major changes to accelerator- and target-related plant and equipment

3.1. Second Target Station (TS-2)

The addition of the Second Target Station (TS-2) has been the greatest change in ISIS. As already mentioned above, in order to optimise production of high peak fluxes of cold neutrons in a way that was not possible on TS-1, construction of TS-2 began in 2003, and TS-2 was commissioned in 2008. TS-2 runs at 10 pps at ∼40 μA, and uses tungsten targets essentially configured as surface-cooled tantalum-clad solid cylinders of tungsten.

The 143-metre-long proton beam transport line to TS-2 was 'joined on' to the existing 154-metre-long proton beam transport line to TS-1 ∼15 m after extraction from the synchrotron. Two slow kicker magnets were installed to deflect one pulse out of every five into the septum magnet at the beginning of the proton beam transport line to TS-2 [17].

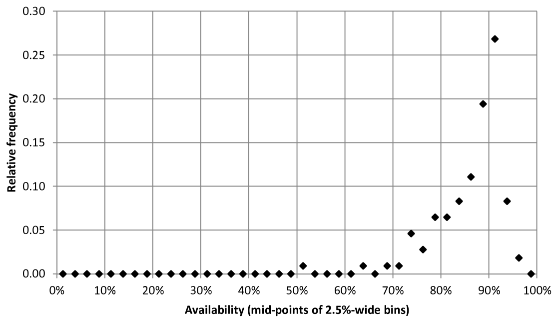

Fig. 4. Histogram of availabilities (100% – percentage lost time) during the 108 user cycles between 1994 and 2017 inclusive. The bins (horizontal axis) have widths of 2.5%, and the relative frequency (vertical axis) is the number of user cycles with availabilities falling within each bin divided by 108.

Unlike TS-1 which has a reflector in the form of close-packed beryllium rods enclosed in stainless-steel vessels and cooled by heavy water, the TS-2 reflector is a tightly-packed composite assembly of blocks of solid beryllium surface-cooled by bolt-on aluminium-alloy pads cooled by light water. TS-2 has two moderators, a solid methane moderator and a liquid hydrogen moderator.

3.2. Neutron-producing targets

3.2.1. TS-1

Initially, on the original target station (now called TS-1), water-cooled zircaloy-clad depleted-uranium neutron-producing targets were used [18]. A total of nine uranium targets were manufactured, and eight were installed and used, but radiation-induced swelling of the uranium led to reduced widths of the cooling gaps between the target plates and consequently to inadequate cooling, and in addition the uranium targets were expensive both to manufacture and to dispose of. In the early 1990s a change[4] was made to tantalum targets, and of these a total of four were installed and used. Finally, from 2001, in order to increase neutron output slightly, to reduce decay heat significantly, and to take advantage of the much better thermal conductivity of tungsten, tantalum-clad tungsten targets have been used, and at the time of writing of the present paper (2018) TS-1 is running on the fourth of these tantalum-clad tungsten targets. Tantalum-clad tungsten targets have been renewed every ∼4–5 years, but only because of failures of thermocouples reading the plate temperatures; no failures of the targets themselves have occurred.

3.2.2. TS-2

The initial design of target for TS-2 had insufficient provision for cooling on the front face, and consequently the first two targets used in TS-2 failed during the first twenty months of operation. An improved design has been in use since 2011, and no cooling problems have since been encountered. Very small leakages of tungsten into the target water have been seen, however, and minor improvements to the tantalum cladding are still being made.

3.3. Muon production

In 1987 a 1-cm-thick graphite muon-producing (or 'intermediate') target was installed directly in the proton beam in vacuum 20 m upstream of the TS-1 neutron-producing target in order to generate pions that then decay into muons. Muons emitted by pions decaying at rest are selected and transported to several instruments. Muons are sensitive local probes of atomic magnetism, and provide information to complement that obtained from neutron scattering. The passage of the 800-MeV proton beam through 1 cm of graphite produces secondary particle fluxes that induce noticeable radioactivity downstream from the intermediate target.

3.4. Replacement of Cockcroft-Walton by RFQ

The 665-kV Cockcroft-Walton pre-injector [19] served from 1984 to 2004. To overcome problems of breakdown in the voltage-multiplying stack, to reduce radiation from electrons being accelerated backwards along the column, and to improve beam capture by the linac (although a buncher cavity was employed between the Cockcroft-Walton and the input to the linac), a 665-keV 4-rod RFQ [20] was manufactured at the Goethe University of Frankfurt. Extensive commissioning was carried out on a specially constructed test stand [21] before installation on ISIS. After good performance was proven, an identical RFQ was manufactured and is currently held under vacuum as a spare at ISIS.

3.5. Second harmonic RF for synchrotron

In order to reduce beam losses, and also to prepare for higher beam currents, especially when a second target station was added, a second-harmonic component [22] was added to the RF power accelerating the protons in the synchrotron. Four second-harmonic ('2RF') accelerating cavities were added to the synchrotron (in straights 4, 5, 6 and 8) during 2003 and 2004, the 2RF cavities being roughly half the length of the six fundamental ('1RF') accelerating cavities (in straights 2, 3, 4, 7, 8 and 9). Each of the original six 1RF cavities is driven by two high-power tetrodes (Photonis/Burle/RCA 4648), but each of the four additional 2RF cavities is driven by a single 4648 tetrode.[5]

3.6. Summary of major changes

These and other major changes already made to the accelerator and target systems on ISIS are summarised in Table 2. Major changes expected to be made in the future include re-engineering the TS-1 target-reflectors-and-moderators (TRAM) assembly [23], and installing a new Tank 4 (50–70 MeV) for the injector H^- linac [24].

4. Distribution of lost time amongst equipment categories

In Fig. 5 are shown pie-charts giving distributions of lost time[6] amongst equipment categories. A total of twelve categories has been chosen as a compromise between excessively 'noisy' detail and insufficient discrimination.

From the twenty-year pie-chart one deduction could be, probably not surprisingly, that less reliable equipment tends to be associated with greater ratios of peak power to average power (*e.g.* the injection dipole magnets and power supply, the beam-extraction kicker magnet system and the injector high-power RF amplifiers (duty factors ∼2%, ∼0.003% and ∼2% respectively). The five-year pie-charts may suggest evidence of the effect of concentrating on improving certain categories of equipment. For example, in the 1998–2002 pie-chart one of the largest sectors is the 'extraction' sector, but in the early 2000s the synchrotron extraction straight was replaced and significant effort was put into improving the performance of the extraction kicker magnet systems (particularly the pulse-forming networks), and later pie-charts show the extraction sectors to have roughly halved in size. During 2002 and 2003 considerable effort was put into renewing both plant and control-and-monitoring systems for the moderators, and this may have

[4] Also, the move away from uranium targets greatly reduced backgrounds from delayed neutrons — a crucial advantage for flux-limited techniques like inelastic scattering.

[5] A prototype high-power RF driver based on the Thales TH558 tetrode has been developed — an alternative to the use of the 4648 tetrode.

[6] Data on lost-time hours have been taken from the ISIS Operations Reports, each one of which summarises the performance of the accelerator and target systems during a user cycle.

Table 2
Selection of major changes made to the ISIS accelerator and target systems. Note that when some of the 'new' items were installed they were not immediately pressed into continuous service; for example, for a year or two after the solid-state drivers for the AC for the synchrotron lattice magnets were installed the motor-alternator set was sometimes used while operation of the solid-state drivers was being refined.

Date	Change
1987	Intermediate graphite target for production of muons installed.
2002	Synchrotron extraction straight (including 'bad beam' collectors and extraction septum magnet) replaced. Capacitor bank for 50-Hz resonant LC-circuit for synchrotron lattice magnets replaced. 2RF cavities in straights 5 and 6 installed.
2004	RFQ installed. 2RF cavities in straights 4 and 8 installed. TS-1 reflector replaced (to accommodate possible upgrade to 300 μA proton beam current). New water plant installed. Four ~300-kW solid-state 50-Hz drivers installed to provide 50-Hz AC component of current for synchrotron lattice magnets.
2007	Proton beam line EPB2 to TS-2 joined on to proton beam line EPB1 to TS-1. Entire interlock system replaced. Part of EPB1 refurbished. New beam-extraction kicker PSUs and cables installed. New TS-1 hydrogen moderator system installed. Conversion of single-mode ISIS-wide 50-pps timing bus to three-mode timing bus providing 50 pps, 40 pps and 10 pps.
2010	Window between proton beam line vacuum and TS-1 target replaced.[a] Cabling for synchrotron lattice magnets replaced. Part of EPB1 refurbished. New TS-1 methane moderator installed.
2014	Old Cockcroft-Walton EHT area reconfigured as off-line injector linac test bed. Part of EPB1 refurbished. TS-2 reflector replaced (to accommodate ChipIr[b]). Flammable gas pipework into target services area (TSA1) for TS-1 replaced. Main control room (MCR) refurbished and reconfigured.
2005–2018	Incorporation and accommodation of MICE experiment.[c]
≥2007	Installation of ten new individual chokes for synchrotron main magnet power supply (to reduce dependence on White-circuit ~100-ton 10-section second-hand choke from the 1960s).

[a]Precautionary change; window (~7 Sv/hour when removed) had reached ~10–15 displacements per atom (DPA) according to the BCA/MD model (~30–40 DPA according to the NRT model).
[b]https://www.isis.stfc.ac.uk/Pages/Chipir.aspx.
[c]The MICE experiment is a world-wide collaboration to demonstrate that muons produced by pion decay from a high power proton accelerator can be cooled sufficiently to be subsequently successfully accelerated to GeV energies in a neutrino factory. See M Bogomilov *et al.*, Phys. Rev. Accel. Beams 20, 063501 (2017).

led to the reduction in size of the 'moderators' sector between 1998–2002 and 2003–2007. And the difference in the 'AC magnets' sector between 2008–2012 and 2013–2017 reflects the recent problems with the synchrotron lattice dipoles referred to in Section 6.1 below. But it must be accepted that there are irreducible random components in the year-to-year variations in reliabilities of particular sets of plant and equipment.

4.1. *How can lost time be reduced?*

Since a large assembly of many items of complicated plant and equipment can never be 100% reliable, what figure for availability should be sought for a large accelerator-based user facility? And what resources should be applied to meet that figure? It is easy to say that an availability of 90% or 95% is required, but it is not so easy to achieve such an availability. It is obvious that employment of the best people, use of the best and most robust designs of plant and equipment, and the availability of unlimited quantities of spares offer the best chances of achieving high-availability goals, but in practice funds available for large accelerator-based facilities are always limited, and therefore compromises necessarily have to be made as regards expenditure on people, plant and equipment, and spares holdings.

However, whilst it may not be easy to reduce the probability of failure of a given item of plant or equipment, it may be possible to put in place measures to facilitate its prompt identification and replacement. On ISIS, over the last few years, a 'first-line diagnosis' (FLD) system [25] has been put in place, a fully interactive on-line platform containing a range of operational resources, ranging from fault analysis flowcharts and repair procedures to technical surveys and video tutorials — the information incorporated therein being carefully curated by equipment specialists across the ISIS facility. The FLD system helps to reduce down-time by providing rapid expert guidance on fault diagnosis and resolution.

5. Observations from experience

It may be useful to list the following few observations on the basis of experience gained from ISIS operations over four decades.

- It should always be remembered that an accelerator-based user facility is essentially a factory rather than a laboratory for accelerator- and target-related research and development. Conservatism in both design and operation of the accelerator and target systems is important.
- The day-to-day operators at the facility (at ISIS, 'the Crew' (see Section 2 above)) must be knowledgeable, skilled, experienced and dedicated.
- A good system for calling in experienced and skilled staff at any hour of the day or night to resolve problems and/or fix faults is essential (see Section 6 below).
- Maintaining adequate inventories of spares is essential. A liberal number of spares should always be included when items of plant and equipment are being bought, especially as the lengths of time over which manufacturers hold spares for their products and maintain repair capabilities are, on the whole, shorter than they once were.
- New equipment should never be installed without having been suitably tested — and soak-tested if the equipment is critical to the operation of the facility.[7] And, if possible, new and old systems should be run in parallel until there is sufficient confidence in the new system to allow the old system to be permanently decommissioned.
- Lead times for procuring items for a large accelerator-based user facility can be long (sometimes very long), and so a robust strategic approach to procurement is essential.
- Outsourcing too many operations-related technical functions can lead to increased expense and reduced resilience.
- All items of plant and equipment that can reasonably be expected to become radioactive in service should be designed with active handling requirements specifically in mind — *e.g.* by mounting items on rails and pre-aligning them on identical rails in the workshop or laboratory, by incorporating lifting lugs to facilitate rapid craning out, and by using V-band rather than Conflat vacuum seals where possible.
- Ultimately it is radiation doses to people rather than radiation dose rates in the workplace that are important. Dose rates twice as high can usually be tolerated if the job can be done in a quarter of the time.
- If possible, plenty of working space around all items of plant and equipment should be provided, and all parts of the facility should be covered by overhead cranes.
- To minimise problems in the longer term, good control of cooling-water chemistry is important.

[7] Before its installation on ISIS, the RFQ (see Section 3.4) was soak-tested on its own stand-alone test stand for a year or so — very fortunately, as it turned out.

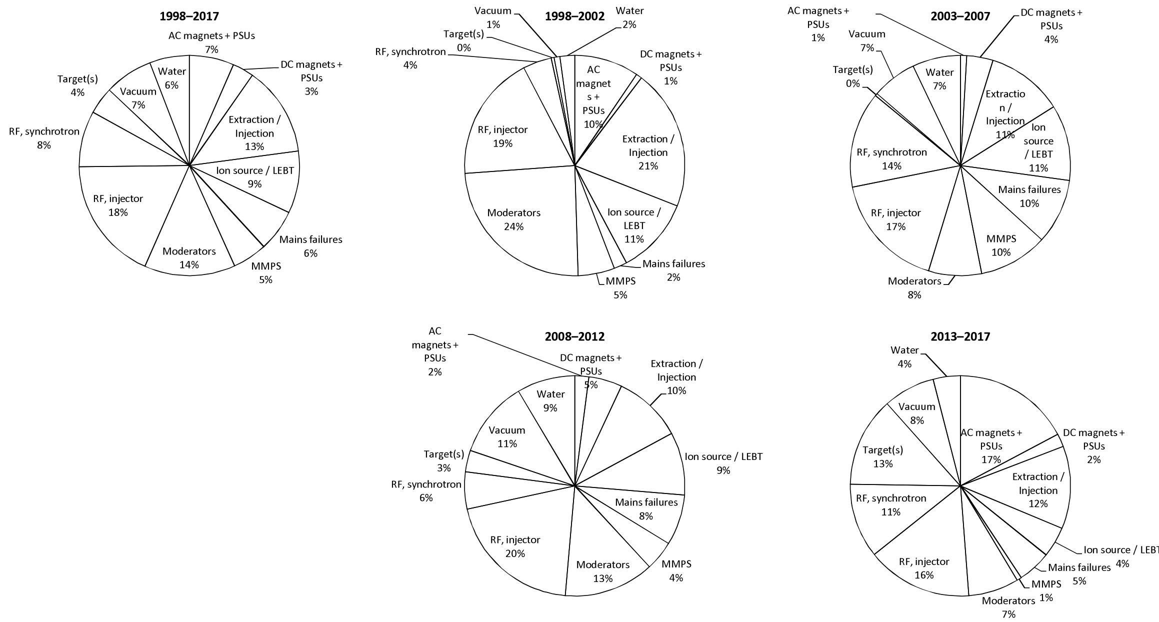

Fig. 5. Distribution of lost-time hours amongst equipment categories covering the twenty years between 1998 and 2017 inclusive, and also in five-year intervals. Of course, assignment of faults to one particular equipment category may involve an element of subjectivity; for example, is an RF vacuum window failure an RF fault or a vacuum fault? The sectors include 'consequential' lost time; for example, electricity supply outages ('mains failures') may last only one or two seconds, but then it usually takes many hours to restore machine operations.

- Eventually, some of the facility will become radioactive waste, and this should be borne in mind during design. However, the primary purpose of a large accelerator-based facility is to perform well, not to minimise waste production.

6. Management issues

Running a large accelerator-based facility is not easy: users expect high availabilities, managers expect costs to be predictable, accelerator engineers tend to want to push limits, and accelerator physicists want publications. Whilst the overall success of a large accelerator-based facility depends on many factors, some technical,[8] some not so technical,[9] ultimately technical success depends on the willingness of high-quality engineers and physicists to maintain high commitment to the facility over many years. Consequently, in the world today, when jobs for life are no longer expected and rates of staff changeover are increasing, it is very important to ensure that engineers have interesting engineering to do and that accelerator physicists have interesting physics to do. Generous provision – in terms of both time and money – must therefore be made for exploratory engineering and for accelerator physics R&D. And since operations staff (at ISIS, 'the Crew') cannot be brought in from outside already *au fait* with all the knowledge, skills and experience necessary to run the facility on a day-to-day basis, on-the-job training within Crew teams is of the highest importance, and effective plans for job progression and succession within teams must be in place.

In addition, adequate provision must be made for accommodating regulatory overheads, especially as nowadays they are becoming more onerous. Whilst some of the work of regulatory compliance can be outsourced, it is essential that sufficient high-quality expertise is retained in house to challenge the imposition of overly restrictive 'precautionary' régimes.

As mentioned in Section 2 above, long shutdowns at ISIS are scheduled roughly every four years so that major maintenance tasks and replacement/upgrade programmes may be carried out. The long shutdowns are managed as formal projects, and planning begins ~2–3 years in advance, with two sets of regular meetings being held, one set design-oriented, the other set installation-oriented. Since significant radiation dose rates may be present in working areas (up to several mSv/hour), the work programme is systematically broken down into a series of many relatively small tasks, each task is assigned its own radiation dose, the radiation doses are summed, and the tasks are revised and/or re-planned if necessary. Sometimes, inevitably, trade-offs have to be made between minimising radioactive waste arisings by re-using components and minimising radiation doses to workers.

6.1. Responses to acute problems

Inevitably, unexpected severe problems arise from time to time. Therefore it is essential that a sufficient number of sufficiently knowledgeable, skilled and experienced people can be called in at any hour of the day or night to deal rapidly and effectively with the problem. As an example, over the past year or two several of the ISIS synchrotron lattice dipoles have failed, but every time such a failure occurred teams of physicists, engineers and technicians were immediately called in to diagnose the problem and then to replace the failed dipole. Of course, in parallel, concerted efforts were made to identify the root cause of the problem and to develop a long-term strategy to cure the problem.

Some of senior managers' most important responsibilities are to develop and maintain environments and cultures in which physicists, engineers, and technicians are all happy to respond willingly, rapidly and generously.

7. Plans for the future

A recent STFC report [26] has established that central to all the options for future neutron provision in the UK is the need to maintain the ISIS facility. This will involve sustainable support for the accelerators and targets (two major future changes to ISIS have already been mentioned in Section 3.6) and development of new state-of-the-art instruments. Furthermore, a report from ESFRI [27] recommends that for Europe to match the American and Japanese short-pulse neutron sources (SNS [28] and J-PARC [29]) by far the most cost-effective solution would be to build a MW-class short-pulse facility at ISIS (which would be complementary to ESS [30] and provide enhanced neutron

[8] For example, source strength, reliability and range of R&D facilities offered to researchers.

[9] For example, embrace of innovation, provision of support services, and even the quality of the food in the restaurant.

capability in Europe beyond 2030). ISIS has produced a comprehensive roadmap [31] for the feasibility and design studies and associated R&D required to enable a fully informed decision (by ∼2027) on the optimal proton driver and target system architecture to build 'ISIS-II' — a MW-class short-pulse neutron and muon facility at ISIS with the best balance of technical capability and lifetime cost. This could be either a stand-alone facility, or make use of existing ISIS infrastructure.

8. Summary and conclusions

A summary of the operational history of the accelerator- and target-related aspects of the ISIS Spallation Neutron and Muon Source has been presented. Detailed information on overall availabilities spanning three decades has also been given, along with distributions of lost time amongst equipment categories and suggestions for management of operations. Finally, it has been pointed out that one of the keys to success is good management *in all its senses*, and that ISIS or its successor will, for the foreseeable future, be expected to remain central to the provision of neutrons in the UK and Europe.

Acknowledgements

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